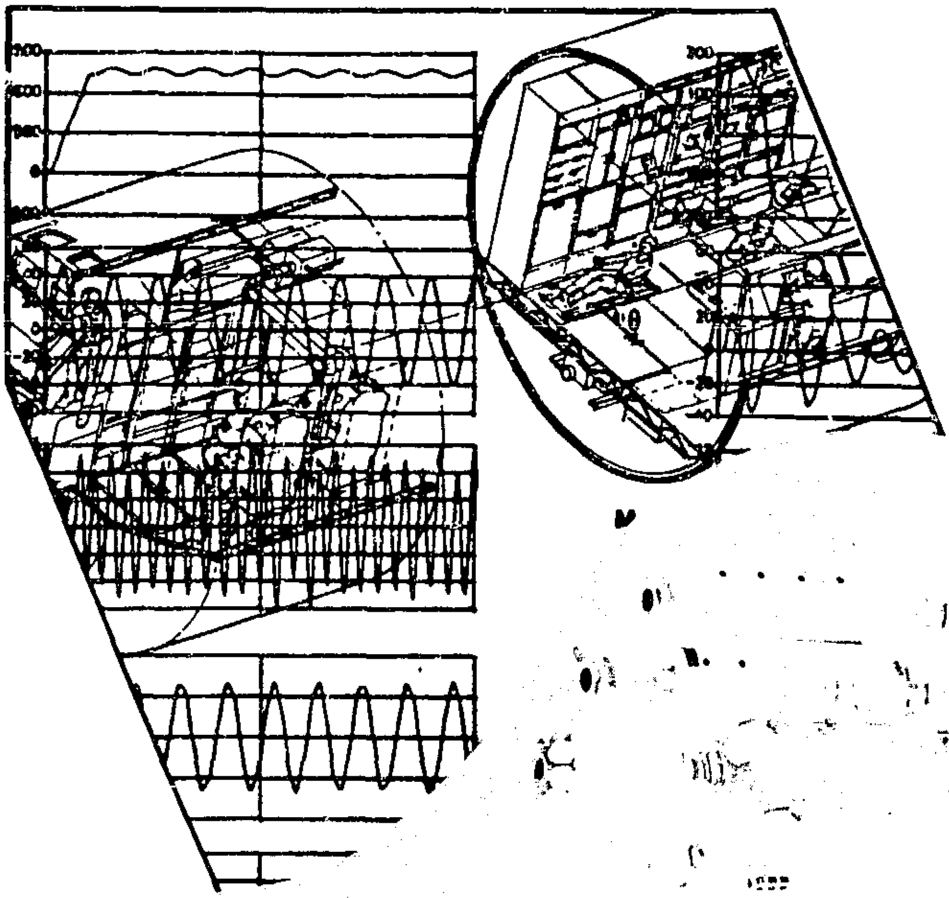
Final Report Volume II
Trade Study and Technology
Selection Technical Report
D483-10012-2

Space Station Systems Technology Study

(Add-on Task)



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SPECTRA RESEARCH SYSTEMS (SRS)

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SPACE STATION SYSTEMS TECHNOLOGY STUDY
(Add-on Task)

Final Report

VOLUME II

TRADE STUDY AND TECHNOLOGY SELECTION, TECHNICAL REPORT

D483-10012-2

Conducted for NASA Marshall Space Flight Center

Under Contract Number NAS8-34893

February 1985

Boeing Aerospace Company

Spectra Research Systems

FOREWORD

This Space Station Systems Technology Study add on task (Contract NAS8-34893 S/A 6) was initiated in June 1984 and to be completed in February 1985. The study was conducted for the National Aeronautics and Space Administration, Marshall Space Flight Center, by the Boeing Aerospace Company with Spectra Research Systems as a subcontractor. The study final report is documented in three volumes.

D483-10012-1	Vol. I	Executive Summary
D483-10012-2	Vol. II	Trade Study and Technology Selection Technical Report
D483-10012-3	Vol. III	Technology Advancement Program Plan

Mr. Robert F. Nixon was the Contracting Officer's Representative and Study Technical Manager for the Marshall Space Flight Center. Dr. Richard L. Olson was the Boeing study manager with Mr. Paul Meyer as the technical leader, and Mr. Rodney Bradford managed the Spectra Research Systems effort. A listing of the key study team members follows.

KEY TEAM MEMBERS

Subject	MSFC-Management Team	Contractor Team
Study Manager	R. F. Nixon	R. L. Olson
Technology Category		
Autonomous Functional Control	H. E. Brown	D. P Meyer O. Bakken
Attitude Control	P. D. Nacaise	M. H. Bantell
Free Flier Controls and Displays	F. Roe	J. Qualy-White
Test Planning (SRS)		R. Bradford, Management J. Cody S. Montgomery

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LIST OF ACRONYMS AND ABBREVIATIONS

ACCEL	remote body station 1501
ACOR	body station 100
ACS	attitude control subsystem
AFB	Air Force Base
AI	artificial intelligence
APSTS	Advanced Platform System Technology Study
BAC	Boeing Aerospace Company
BIT	built in test
BITE	built in test equipment
C&D	controls and displays
CAE	computer aided engineering
CDG	Concept Development Group
Cg	center of gravity
CG and IM	center of gravity and inertial momentum
CGI	computer generated imagery
CMG	control moment gyro
GN_2	nitrogren gas
CO_2	carbon dioxide
CP	co-pilot
CPU	central processor unit
CRT	cathode ray tube
DARPA	Defense Advanced Research Projects Administration
dc/ac	direct current/alternating current
DEC	Digital Equipment Company
deg/sec	degrees per second
DMS	data management subsystem
DoD	Department of Defense
EASY	Engineering Analysis System
EC/LSS	Environmental Control/Life Support Subsystem
EL	Electroluminescent

EPS	Electrical Power Subsystem
EVA	extra vehicular activity
FO	fiber optics
FF	Free Flyer
ft	feet
GL/EP	glass/epoxy
GN&C	guidance, navigation and control
GR/EP	graphite/expoxy
GPS	global positioning system
GSTDN	Ground Station Tracking Data Network
HR	hour
H_2O	water
HUD	head up display
Hz	Hertz (a measure of frequency)
IAC	integrated analysis capability
IC	integrating controller
I.D.	inside diameter
IEEE	Institute of Electrical and Electronic Engineers
INDA	interface from NASTRAN dynamics analyzer
INTF	interface
I/O	input/output
IOC	initial operational capability
JSC	Johnson Space Center
KG	kilograms
KW	kilowatts
lb	pounds
lbm	pounds-mass
LCD	liquid crystal display
LED	light emitting diode

LIOH	lithium hydroxide
LISP	list processor
LR	line replaceable
MACLISP	Macro Lisp
MBPS	million bits per second
MCR	Martin Company Report
MHz	megahertz
MIL-STD	military standard
MIPS	million iterations per second
MMH	Monomethyl Hydrazine
MPA	multi-beam phased array
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NASTRAN	NASA Structure Analyzer
NIU	network interface unit
n-m-sec	Newton-meter-seconds
ns	nanoseconds (10-9 seconds)
O.D.	outside diameter
OMV	orbital maneuvering vehicle
OPS4	an expert system development tool
ORACLS	optimum regulator and control of linear systems
ORU	orbital replaceable unit
C/O	check out
OSI	operator system interface
OTV	orbital transfer vehicle
P	pilot
PDP	model designator for line of DEC computers
P/L	pay load
PRLCH	pre launch
PSI	pounds per square inch
Psia	pounds per square inch absolute

Psid	pounds per square inch differential
Pwr	power
QWERTY	Top left hand row of keys on a typewriter
R&D	research and development
RCA-PRICE	Radio Corporation of America Price Modeling Program
RCS	reaction control system
RF	radiofrequency
RI	name of expert system to configure VAX installations
RMS	remote manipulator system
R/T	receiver-transmitter
SAR	synthetic aperture radar
Sec	second
SEPS	solar electric propulsion spacecraft
SOA	state of art
S/C	spacecraft
SRI	Stanford Research Institute
SRS	Spectra Research Systems
TBD	to be determined
TDMA	time division multiple access
TDRSS	tracking and data relay satellite system
TFEL	thin-film electro luminescent
TI	Texas Instruments
TVC	thrust vector control
VAX	virtual address extension
VHSIC	very high speed integrated circuit
VLSI	very large scale integration
VM	ventilator manager
XCVR	transceiver

1.0 INTRODUCTION

This is volume II of the final report on the Space Station Systems Technology Study add on task conducted for the Marshall Space Flight Center (MSFC) by the Boeing Aerospace Company (BAC) and Spectra Research Systems (SRS). The overall study objective continues to be to identify, quantify, and justify the advancement of high-leverage technologies for application primarily to the early space station. The objective has been addressed through a systematic approach tailored to each of the technology areas studied. This volume presents the results of the technical effort. Volume III discusses the research plans developed for each of the selected high-leverage technologies.

The current Space Station Systems Technology Study add-on task was an outgrowth of the Advanced Platform Systems Technology Study (APSTS) that was completed in April 1983 and the subsequent Space Station System Technology Study completed in April 1984 for MSFC by the Boeing/SRS team. The first APSTS proceeded from the identification of 106 technology topics to the selection of five for detailed trade studies. During the advanced platform study, the technical issues and options were evaluated through detailed trade processes. Individual consideration was given to costs and benefits for the technologies identified for advancement, and advancement plans were developed. An approach similar to that was used in the subsequent study, with emphasis on system definition in four specific technology areas to facilitate a more in-depth analysis of technology issues. The results of the initial study are reported in Boeing document D180-27487 and the subsequent study was reported in D180-27935.

The current add-on task continued investigation of two of the areas considered in the previous studies and added a new area for free flier controls and displays. The two areas that were continued were autonomous functional control which was an outgrowth of the integration of automated housekeeping considered previously and Space Station attitude control. The principal extension in the autonomous functional control area was to consider integration of three new subsystems (attitude control, communications, and data management) and to drive toward a more specific definition of requirements on the integrating controller. The attitude control area was extended to use the simulation tools developed in the previous studies to take a look at combined disturbances and to investigate passive damping techniques. The topics of discussion in this report volume include the planned approach, technical discussion, summary of results, conclusions, and recommendations for each of the three study areas.

The overall study was divided into three tasks. During task 1 the design concepts required in each of the three study areas were refined. The concepts were used to describe specific technology options upon which comparative studies were conducted. Candidate high-leverage advancement technologies were then selected from the options. The cost, benefits, schedules, and life cycle costs for each of the options were evaluated in task 2. Selection of the technology advancement items was made during this latter task. Technology advancement plans were prepared for each of the selected items in task 3. The overall study schedule is shown in figure 1.0-1.

Twelve potential technology advancement items were identified during this study. These items were analyzed and evaluated in task 2, considering technical as well as cost benefits and schedule criteria. Figure 1.0-2 gives a prioritized listing of the twelve candidates identified. The attitude control analysis did not produce candidates for technology advancement because the simulation results indicated that available control techniques were adequate.

This volume presents the technical work performed to select these high-leverage items. The total final report is made up of this volume, Volume I: Executive Summary, and Volume III: Technology Advancement Program Plan.

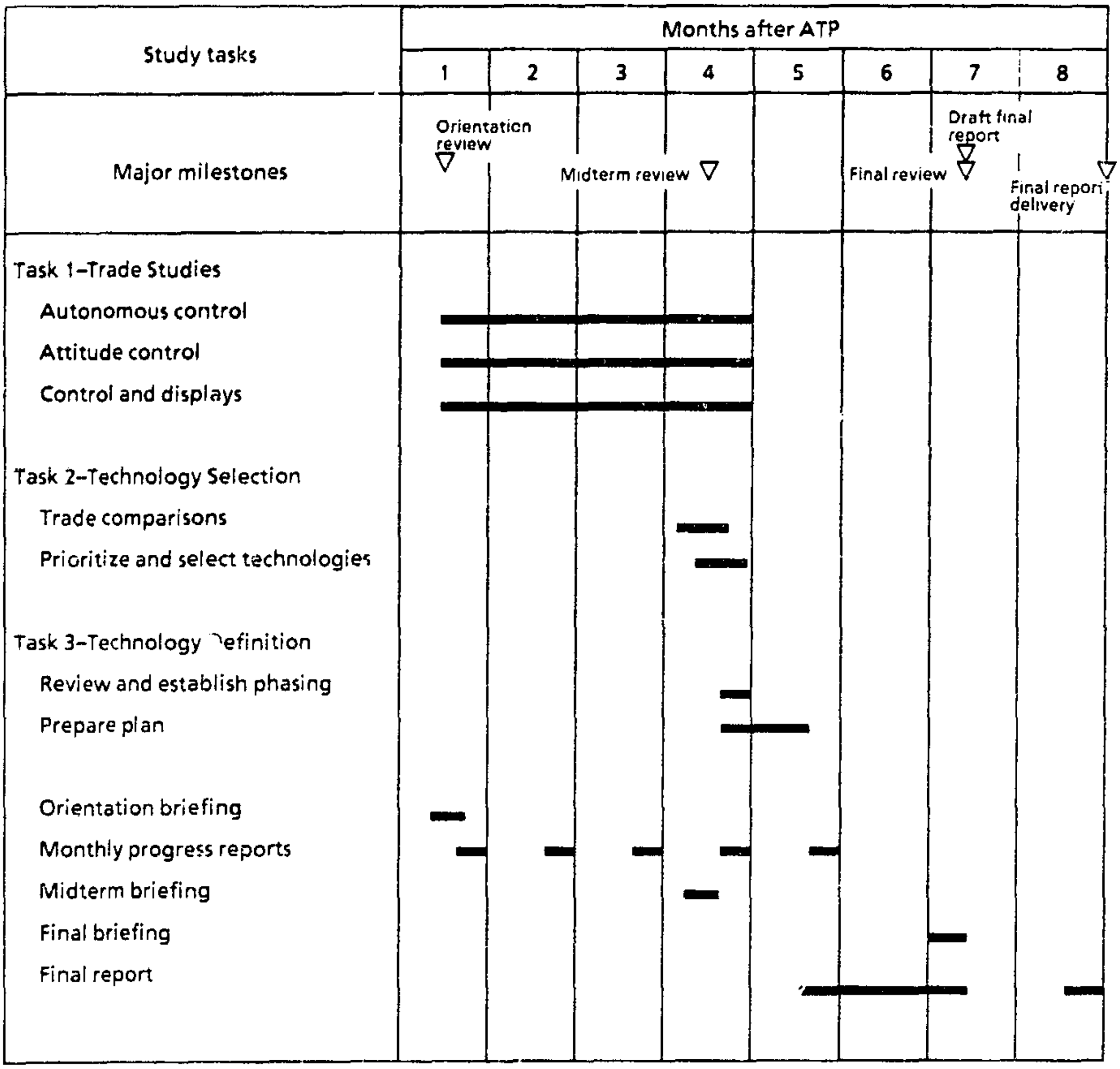

Figure 1.0-1. Program Schedule

Candidates	Schedule pressure	General usefulness	Benefits/cost
Expert systems to conventional S/W	1	2	3
Real time expert systems	4	1	2
Developing effective models	2	5	4
Voice recognition and synthesis	9	3	1
Graphics generator	7	4	6
Flat panel	3	7	10
Advanced knowledge engineering	8	8	7
Programmable switch	10	9	5
Input devices	11	6	8
Head up displays	5	11	11
Space qualified LISP machine	6	12	12
Hand controller	12	10	9

Figure 1.0-2. Prioritized Technology Advancement Candidates

2.0 AUTONOMOUS FUNCTIONAL CONTROL

This section presents the results of an add-on study conducted to further characterize a system for integrating the automation of the subsystems on an inhabited space station. It goes beyond the previous Space Station System Technology Study in order to further identify high leverage technologies.

2.1 INTRODUCTION

In the previous technology studies, an integrating controller for automated housekeeping subsystems was identified and characterized as a prime area for technology advancement to support the Space Station. This study extends the systems analyses to characterize the functions of an integrating controller at a level of detail which will allow initial functional requirements to be defined. In addition to extending the systems analysis to greater detail, the study has been expanded to cover more of the subsystems which will be automated on the Space Station. In particular, the guidance, navigation and control, communications, and data management subsystems will be added to the electrical power and thermal control subsystems considered in the previous study phases. The life support subsystem automation has been considered significantly in the previous studies and will not be analyzed further in this add-on study.

The following paragraphs report on the approach, results, conclusions, and recommendations resulting from this characterization study and also provide a technical discussion of the study elements.

2.2 APPROACH

2.1.1 Task 1 - Trade Study Approach

The following paragraphs describe the nine sub-tasks which make up the trade study task of this add-on study of autonomous functional control for the Space Station.

2.2.1.1 Describe the Subsystems to be Integrated

Three housekeeping subsystems of the Space Station were considered in the previous phase of the study and that consideration was based primarily on generic subsystem descriptions. In the time since the start of that previous study phase, the Space Station Concept Development Group (CDG) has defined alternate space station configurations as well as an additional understanding of space station subsystem functions. The integrating controller functional definitions which were a result of the previous study phase indicated that the process should appropriately cover subsystems other than the three which had been considered. For these reasons, a review of subsystem descriptions for the Space Station was conducted as a first step in this expanded study. In performing this first step, each of the five subsystems is considered: guidance and control, electrical power, communications, thermal control and data management, were described. The descriptions were based on Space Station subsystem information available, from results of previously completed Space Station configuration studies, and from experience held by subsystem engineers who were interviewed.

2.2.1.2 Define Subsystem Functions

A listing of subsystem functions to be automated was developed to a level of detail where the control parameters are sensed. These functions were based on the descriptions developed in the previous sub-task and on updates of the lists developed in the previous study phase for electrical power and thermal control. The listing also included new functions and sensed quantities for elements to be automated in the guidance and control, communications and data management subsystems. Emphasis was placed on identifying subsystem state controlling functions rather than the individual closed loop functions such as those for feedback attitude control. An example of such state controlling functions is the state of control moment gyro wheel inertia loading for attitude control. Control of such functions requires integration with respect to other entities on the Space Station. Controller development is concerned with integration of these entities.

2.2.1.3 Identify Where Integrating Control of Subsystem Functions is Appropriate

Once the subsystem function and sensed quantity lists had been developed, a systems analysis review was conducted. This review identified where interac ıs between subsystems could occur, where common outside factors could influence subsystem states, or where common and recurring events could occur in more than one subsystem. These factors pointed to functions which the integrating controller would need to perform if Space Station autonomy is to be implemented.

2.2.1.4 Define Integrating Controller Functions

The factors identified in the previous sub-task were reviewed to characterize functions to be performed by an integrating controller. The result of the review was a description of the functions needed to integrate each of the subsystems with the rest of the Space Station, and a description of those functions which are common to more than one subsystem and therefore are candidates for implementation through common processing by an integrating controller. The Space Station system requirements for autonomy and for automation served as a guide for defining these functions. Figure 2.2-1 lists those requirements.

2.2.1.5 Compare Integrating Controller Functional Definitions with those from the Previous Study Phase

Six functions were identified for an integrating controller in the previously conducted study phase (see table 2.2-1 for list). It was desirable to build on those definitions as much as possible in this add-on study. For that reason, a comparison at some detail was made between the functions defined in this study and the descriptions developed and reported for the last study phase.

2.2.1.6 Diagram New or Changed Integrating Controller Functions

For those integrating controller functions which are new or changed from those described in the previous study phase, logic/functional diagrams were prepared to describe the functions.

- Crew productivity
  - Maximize by extensive use of automated systems
- Degree of automation
  - Increase with growth and technology–evolutionary
- Ground crew support
  - Minimum support after initial startup

<u>Crew/machine interface</u>

- Checking
- Reconfiguration
- Implementing
  - Plans
  - Schedules
  - Inventory
- Controlling
  - Space Station
  - Spacecraft
- Maintaining
- Communicating
  - Internal
  - External

<u>Ground/Space Station interface</u>

- Space Station health and performance
  - All subsystems
  - Structure
  - Crew
- Housekeeping
- Science data
- Trend data
- Instructions
- Entertainment
- Etc.

Automate

Figure 2.2-1. Basic NASA Space Station Requirements

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Table 2.2-1. List of Integrating Controller Functions

- Startup integration
- Electrical power load management
- Inter-subsystem redundant path selection
- Maintenance schedule management
- Materials transfer management
- Inter-subsystem failure isolation

All of the sub-tasks described to this point have been performed to characterize the integrating controller system. The processes are similar to those used in the previous study but the subject subsystems are different. These sub-tasks constitute, at most, 1/3 of the total trade study effort for autonomous functional control.

2.2.1.7 Determine Implementation of Diagrammed Steps for the Integrating Controller

A step-by-step analysis has been conducted to describe the processes needed to implement each controller element. The implementation description covers software as well as hardware for controller processing. The emphasis in this sub-task was on implementations for use on an early Space Station with some recognition of the need for evolutionary growth planning.

These implementation descriptions were supported by diagrams where appropriate. As the implementations were described, they were also categorized so that types of software and devices were identified and isolated for needed technology advancements. This sub-task constituted about 1/3 of the trade study effort for autonomous functional control study. In conducting this sub-task, support from data processing and software technology personnel was utilized.

2.2.1.8 Prepare Preliminary Functional Requirements for an Integrating Controller for Automated Subsystems of the Space Station

A functional specifications listing was prepared to define preliminary requirements, based on the logic and functional diagrams and the implementation descriptions developed in the previous sub-tasks. These requirements covered functions, inputs, outputs, software features, and hardware characteristics of an overall controller for an early Space Station system.

2.2.1.9 Identification of Technology Needs/Benefits

An assessment was made of specific needs for technology based on all of the descriptive information provided by the functional diagrams, implementation definitions and the functional requirements. Once these technology needs had been identified, trades were conducted to compare benefits in system performance and life cycle cost savings with developmental cost expenditures.

2.2.2 Task 2—Trade Study Comparison/Technology Selection Approach

The technology candidates identified by the trades for autonomous functional control were compared and evaluated on the basis of performance, mass, technology advancement, cost, risk, schedule, operations simplification, safety improvements, increased lifetime, and other appropriate criteria in order to select and rank the technology candidates against those from the other study areas. This comparison produced a cross-technical area evaluation of the selected technologies.

The following paragraphs describe the sub-tasks of the comparison/technology selection tasks for this add-on study.

2.2.2.1 Compare Trade Study Results

The technology candidate selections resulting from the task 1 trade studies were compared and evaluated on the basis of appropriate criteria in task 2. Table 2.2-2 gives a listing of criteria which have been developed in the previous phases of the Advanced Platform Systems Technology Study and which served as a guide for comparison criteria for this add-on study phase.

2.2.2.2 Prioritize Technology Advancement Candidates

Using the results of the comparisons, the candidates were ranked according to each of the following categories: (1) schedule pressure, (2) general usefulness of the technology and (3) benefits/cost ratio. These rankings were combined to give an overall prioritization of the candidates which provided a focusing in order to clarify the technology advancement needs, but was not intended to eliminate any candidate which had been identified by the task 1 trades.

Table 2.2-2. Technology Trade Study Comparison Criteria

The following listing of criteria will be used to evaluate the technology advancement topics identified in each technology area:

1. Does the identified technology topic require development?

   a. What is current level of development?
   b. Is technology area already being developed?
   c. Has the technology been developed to a point where it is operationally usable on space stations?

2. Is the identified technology required to support development of current space station concepts or evolutions from those concepts or is it only enhancing technology?

3. Does the envisioned advancement of technology produce a benefit to the space station concept in any of the following areas:

   a. Does the technology advancement facilitate a reduction in the cost of producing, launching, or operating the space station?
   b. Does the technology advancement extend the operational lifetime of the space station?
   c. Does the technology advancement facilitate a necessary operational aspect of the space station or does it simplify operation?
   d. Does the technology advancement reduce the mass of the space station or of the ASE required to deliver the space station components to orbit?
   e. Does the technology advancement reduce the volume of the space station components for transport to orbit, i.e., does it allow for more efficient packing of the space station components in the shuttle bay?
   f. Does the technology advancement facilitate repair and/or maintenance of space station elements on orbit?
   g. Does the technology advancement facilitate a necessary performance aspect of the space station such as pointing accuracy for science appendages or antennas; orbit adjust capability, communications or tracking capability, power generation, or thermal control ?
   h. Does the technology advancement improve the safety or comfort of human habitation of a manned space station?
   i. Does the technology advancement facilitate evolutionary expansion of the space station on orbit?
   j. Does the technology advancement facilitate development of future space station use concepts and configurations?

4. Is the technology advancement possible in the time frame of the envisioned large space station usage (between now and the mid-1990's)?

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2.3 TECHNICAL DISCUSSION

This section presents in a detailed discussion of the study outputs along with the associated data and conceptual illustrations. The output discussion given by the following paragraphs is structured according to the sequence of the approach subtasks.

2.3.1 Subsystem Descriptions

The subsystem descriptions for the five subsystems considered for autonomous functional control were obtained by interviewing the appropriate Space Station and engineering technology subsystem engineers to obtain diagrams and definitions for each of the subsystems. The descriptions needed to support an analysis of autonomous functional control were not for the internal operations of the subsystem but rather were for the states that the subsystem would assume as they performed their functions.

Figure 2.3-1 shows a typical Space Station guidance, navigation and control subsystem: primary functions are shown on the left, simple flow diagrams are shown in the middle, and typical displays to the crew and controls interactions are shown on the right. This figure shows that there are many modes of guidance and control operation and that significant state control is needed.

The electrical power subsystem consists of elements for power generation, power transmission, energy storage, power distribution, and power conditioning. Figure 2.3-2 shows a typical electrical power subsystem (EPS) configuration for the Space Station. On the left the figure shows an overall Space Station distribution of EPS elements and on the right EPS elements within a single module of the Space Station are shown. Figure 2.3-3 shows a flow diagram and a listing of display and controls factors for the power generation function of the EPS. Table 2.3-1 lists factors which require integrating control in order to provide autonomous operation of the power generation elements. Figure 2.3-4 gives a flow diagram and a display and control factor listing for EPS energy storage and Table 2.3-2 lists the associated factors for autonomous control. Figure 2.3-5 shows a flow diagram for a power distribution system for Space Station and Table 2.3-3 lists the display and control elements. Table 2.3-4 lists factors needing integration control to

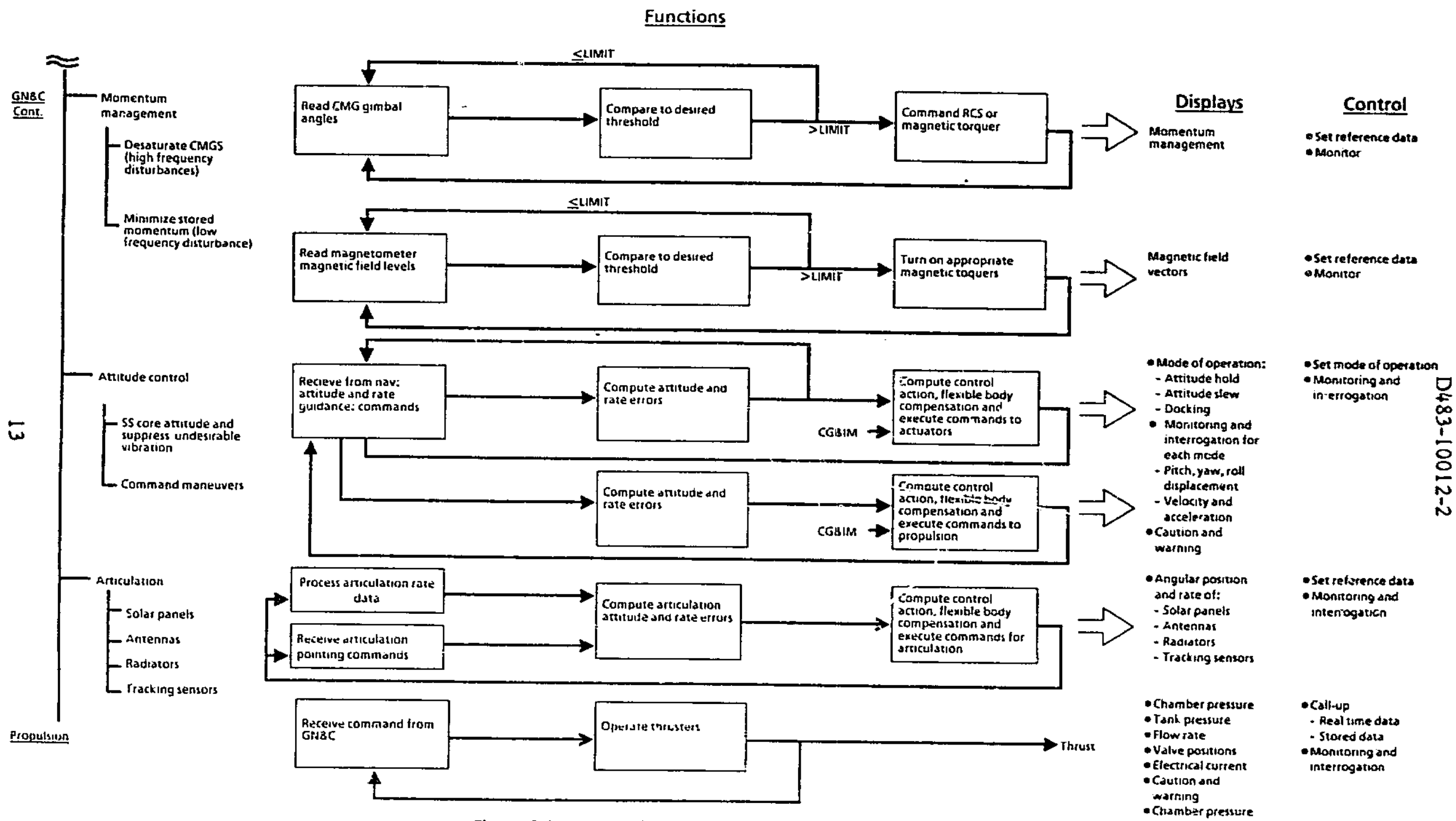

Figure 2.3-1. Typical Guidance, Navigation and Control

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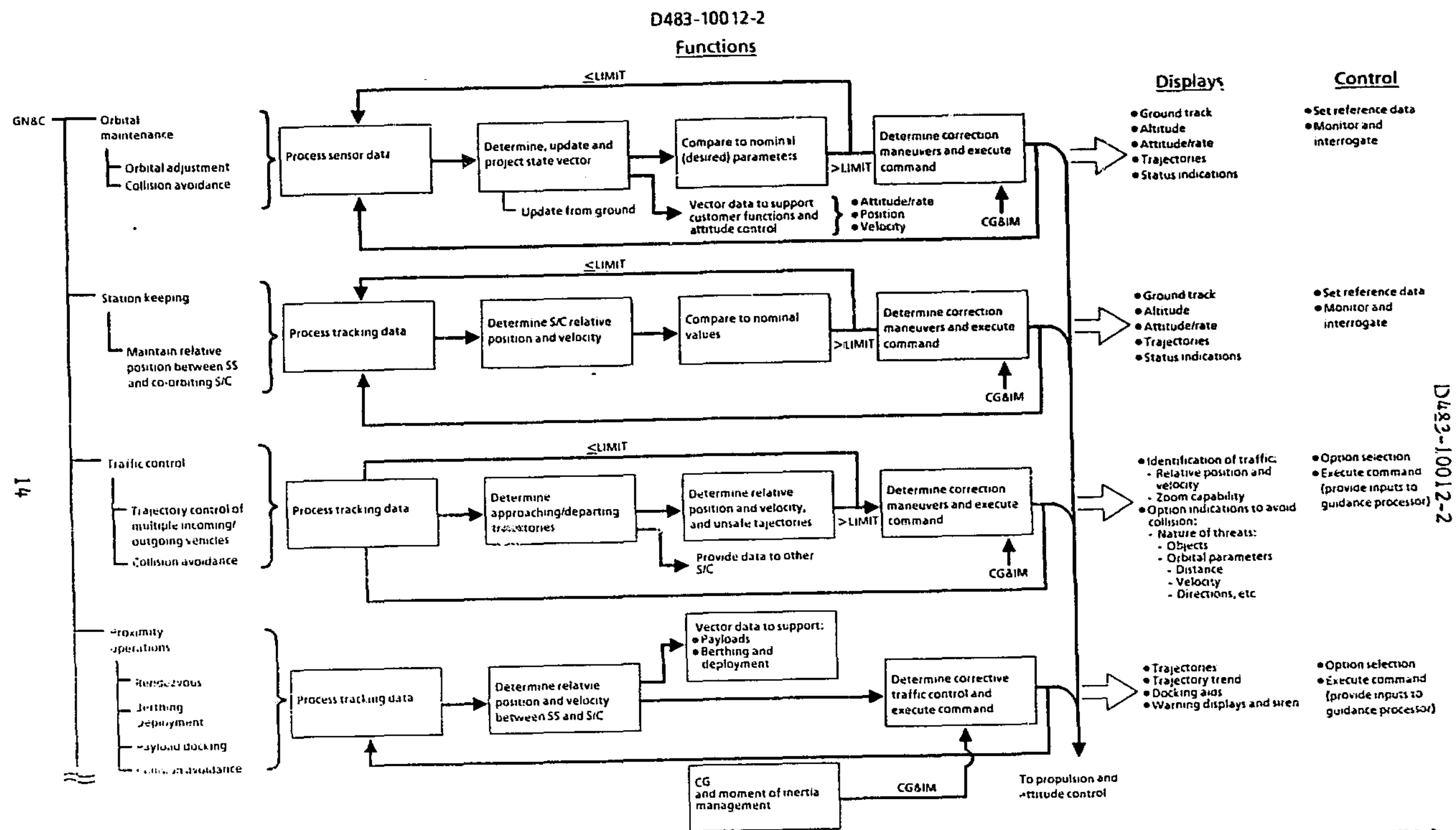

Figure 2.3-1. Typical Guidance, Navigation and Control (Continued)

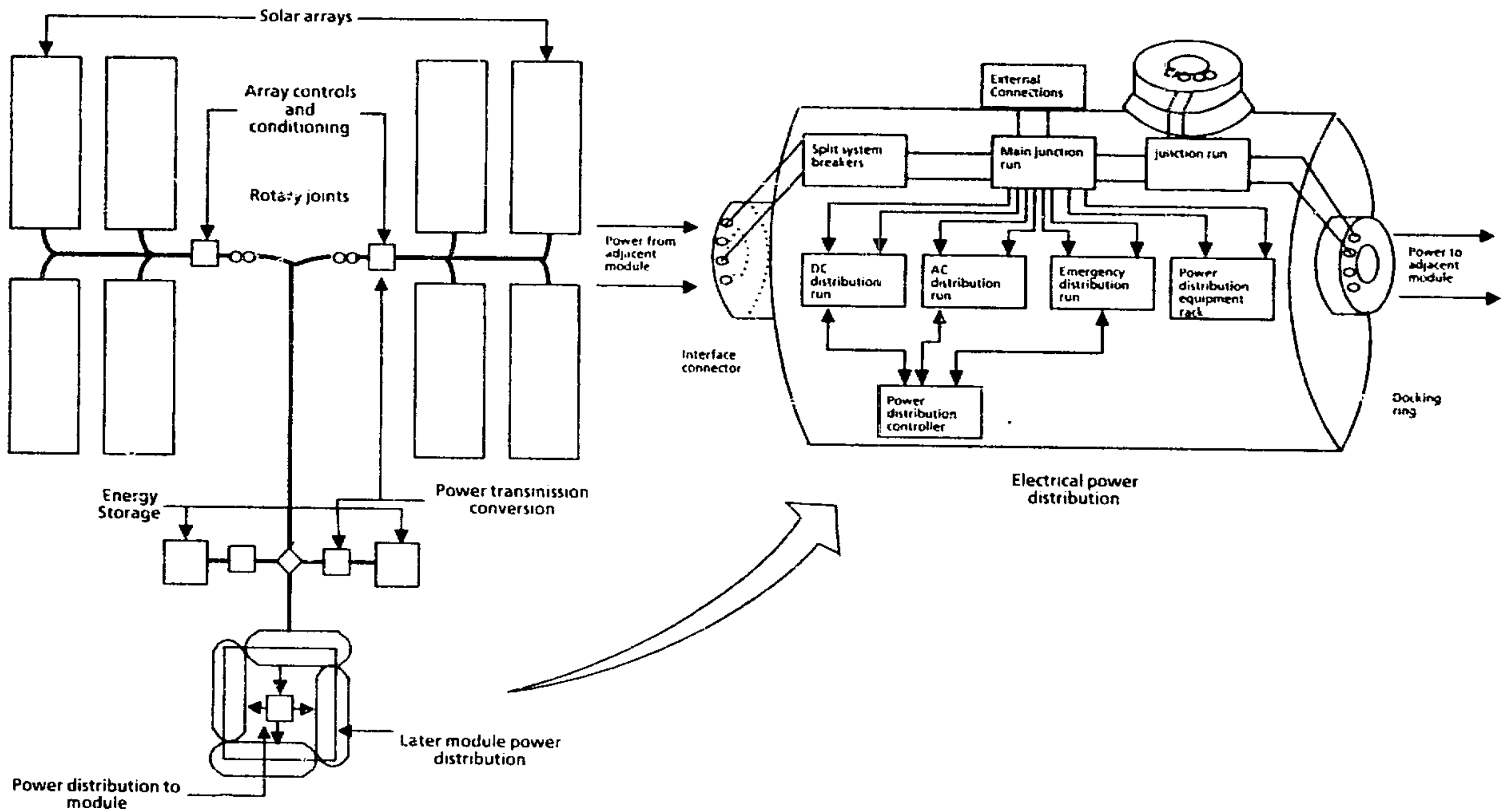

Figure 2.3-2. Typical Space Station EPS Configuration

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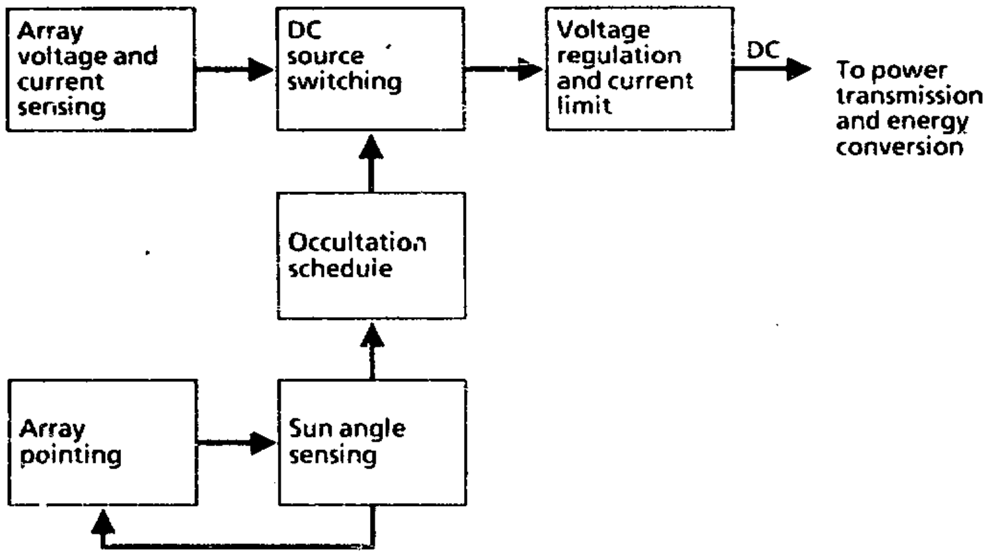

Displays	Controls
• For each array section: – Voltage – Current – Temperature – Power % • Solar sun angle • Diurnal clock • Configuration • Fault identification	• Call-up, monitoring and interrogation – Array • Drive • Section switching • Transmission disconnect • Fault management

Figure 2.3-3. Power Generation

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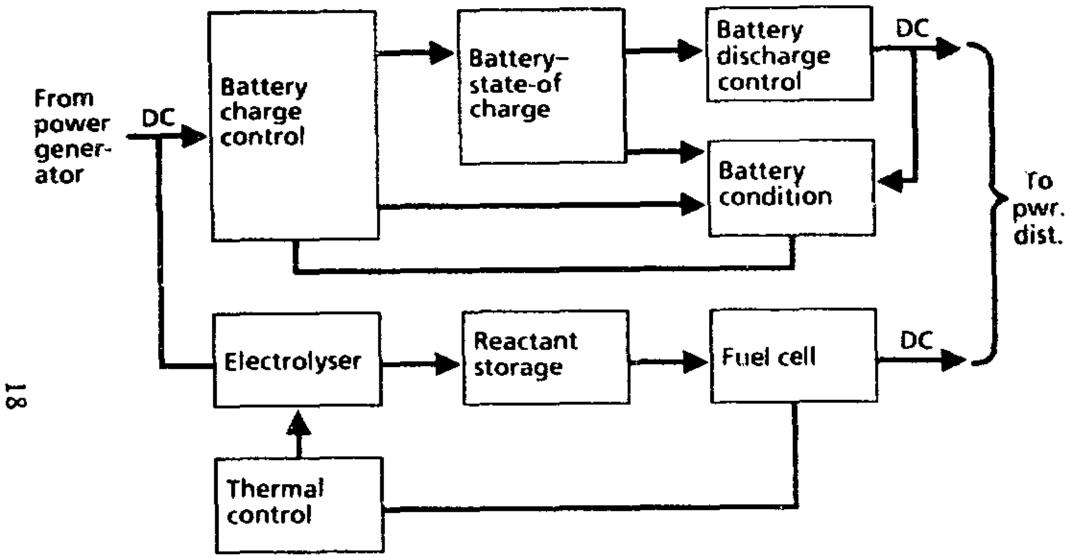
Table 2.3-1. Power Generation Autonomy Factors

• Diurnal occultation entry and emergence • Fault detection, isolation, reconfiguration • Energy balance management as a function of degradation	• Trend analysis of cyclic output versus load scheduling • Projection of array performance for maintenance scheduling • Optimize power generation based upon trend data



Displays

- For each battery
  - Cell voltage and current
  - Temperature
  - Discharge cycles
- Reconditioning schedule
- Diurnal clock
- Configuration
- Fault identification

Controls

- Call-up, monitoring and interrogation
  - Charge/discharge
    - Switching
    - Rate limit
  - Reconditioning
  - Fault management

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Figure 2.3-4. Energy Storage

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Table 2.3-2. Energy Storage Autonomy Factors

• Schedule and perform battery reconditioning • Reconfigure cell interconnection to maintain energy balance (voltage/current) • Fault detection, isolation, reconfiguration	• Trend analysis of cell cycling and performance for reconditioning scheduling • Projection of cell performance and reconfiguration and replacement scheduling • Optimize energy storage capacity based upon trend data

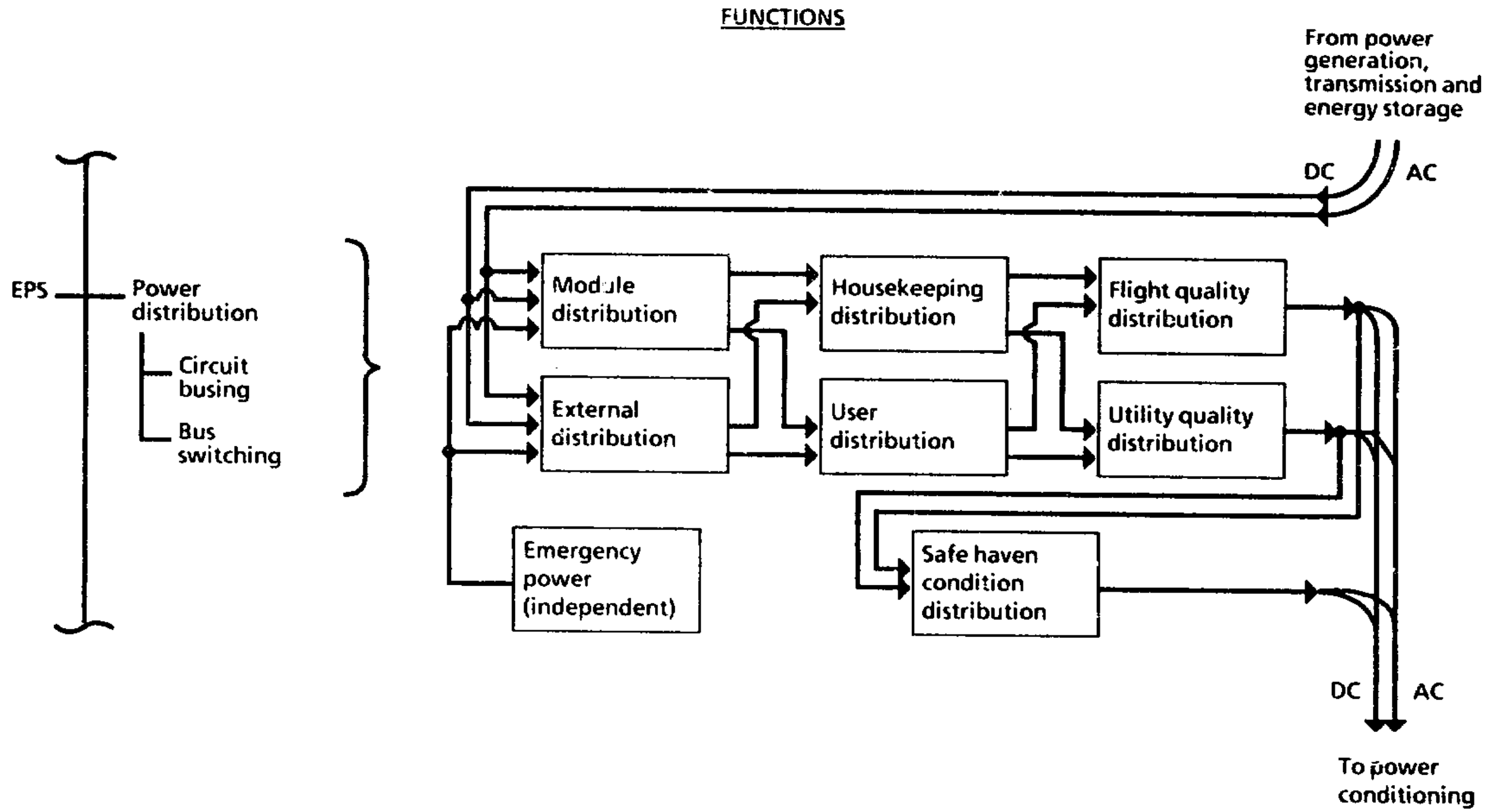

Figure 2.3-5. Space Station Electrical Power Distribution

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Table 2.3-3. Display and Control Factors for EPS Distribution

Displays	Controls
• Bus configuration (if variable)	• Bus reconfiguration
• Bus	• Circuit breaker reset
–Voltage	• Voltage regulation
–Current	• Current limit
–Temperature	• Frequency compensation
• Line contactor and circuit breaker states (open-closed)	• Amplitude compensation
• Bus frequency	• Power factor compensation
• Phase angle	• Phase balancing
• Power factor	• Fault isolation
• Power factor compensation loads	• Data interrogation
• Power distribution (network loading)	• Self test ("BITE")
• Power available by location (i.e., power available for use in life science module)	
• BITE status	
• Fault identification	
• Maintenance status (out-of-tolerance or failed equipment)	

Table 2.3-4. Power Distribution Autonomy Factors

- Load switching (scheduled loads management)
- Reconfigure network to match load demand (energy balance)
- Perform periodic system test (BITE) to measure performance
- Redundancy management to detect and isolate faults or failed equipment and reconfigure alternate interconnection
- Trend analysis of power distribution for load scheduling
- Projection of load trends for power management and growth planning
- Update power availability based upon power distribution planning and circuit availability

support automation of the EPS power distribution function. Figure 2.3-6 shows a power conditioning system flow diagram and Tables 2.3-5 and 2.3-6 give control and display factor and autonomy factor listings for the power conditioning element of the EPS.

The communication subsystem for the Space Station will function through many different links. Figure 2.3-7 shows a typical link diagram for Space Station communications. Automation of the controller for the communications subsystem will need to consider elements of network control, subsystem element reconfiguration and mode control and command processing control. Figure 2.3-8 shows elements of a typical communications subsystem controller.

The control of a typical local area network data management subsystem (DMS) is accomplished by control software called the network operating system which is resident in the DMS processors. Figure 2.3-9 shows interfaces considered by a network operating system. The distributed controllers for the DMS are described by the network interface units. Figure 2.3-10 shows functional partitioning for a typical network interface unit. Because the integrating controllers at the module and Space Station level as well as the subsystem controllers are likely to be embedded in the DMS processors, it is easy to overlook the need for DMS control to be considered as a subsystem management function. The modes, reconfiguration, and scheduling for the DMS will need to be integrated just as they are for other subsystems.

The last subsystem considered in this study is the thermal control subsystem. Figure 2.3-11 shows a flow diagram for a typical thermal control subsystem element the space station. The management of the configuration of the elements of a thermal control subsystem distributed on the Space Station would be part of the function of any integrating controller.

2.3.2 Subsystem Functions to be Automated

Before an analysis of subsystem functions for automation can be conducted, it is necessary to describe the candidate architecture for integrating control. Figure 2.3-12 shows a typical controller architecture for the Space Station indicating subsystem

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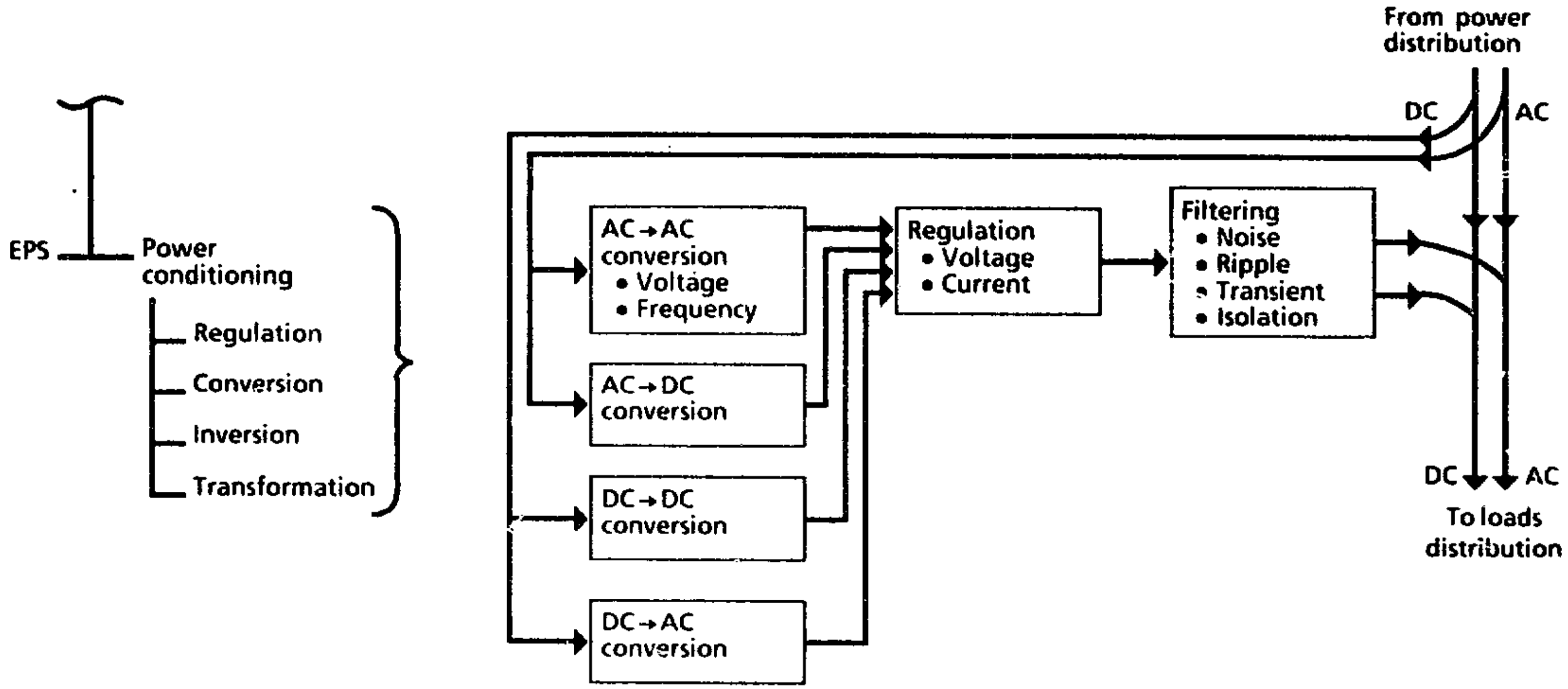

Figure 2.3-6. Space Station Electrical Power Conditioning

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Table 2.3-5. Displays and Control Factors for EPS Conditioning

Displays	Controls
• Load	• Conditioned bus reconfiguration
–Voltage	• Power conversion
–Current	–AC to AC
–Temperature	–AC to DC
• Frequency	–DC to AC
• Noise and ripple	–DC to DC
• Line isolation	• Regulation
• Phase angle	–Voltage
• Power factor	–Current
• Duty cycle	–Frequency
• Power quality data	–Phase
–Noise	–Power factor
–Ripple	• Conditioning
–Transient activity	–Switching for timing circuits and pulse width control
• Power availability in each conditioned bus (in watts)	• Self test ("BITE")
• "BITE" results	• Fault isolation
• Fault identification	• Data interrogation
• Maintenance status (failed equipment)	

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Table 2.3-6. Power Conditioning Autonomy Factors

- Circuit adjustment to change bias, correct out-of-tolerance or reprogram power conditioning
- Perform periodic system test (BITE) to measure performance
- Redundancy management to detect and isolate faults or failed equipment and reconfigure to alternate conditioning units
- Trend analysis of conditioned power quality for maintenance scheduling
- Projection of conditioned power quality with time or predictable events
- Update conditioned power availability based upon performance and maintenance schedule

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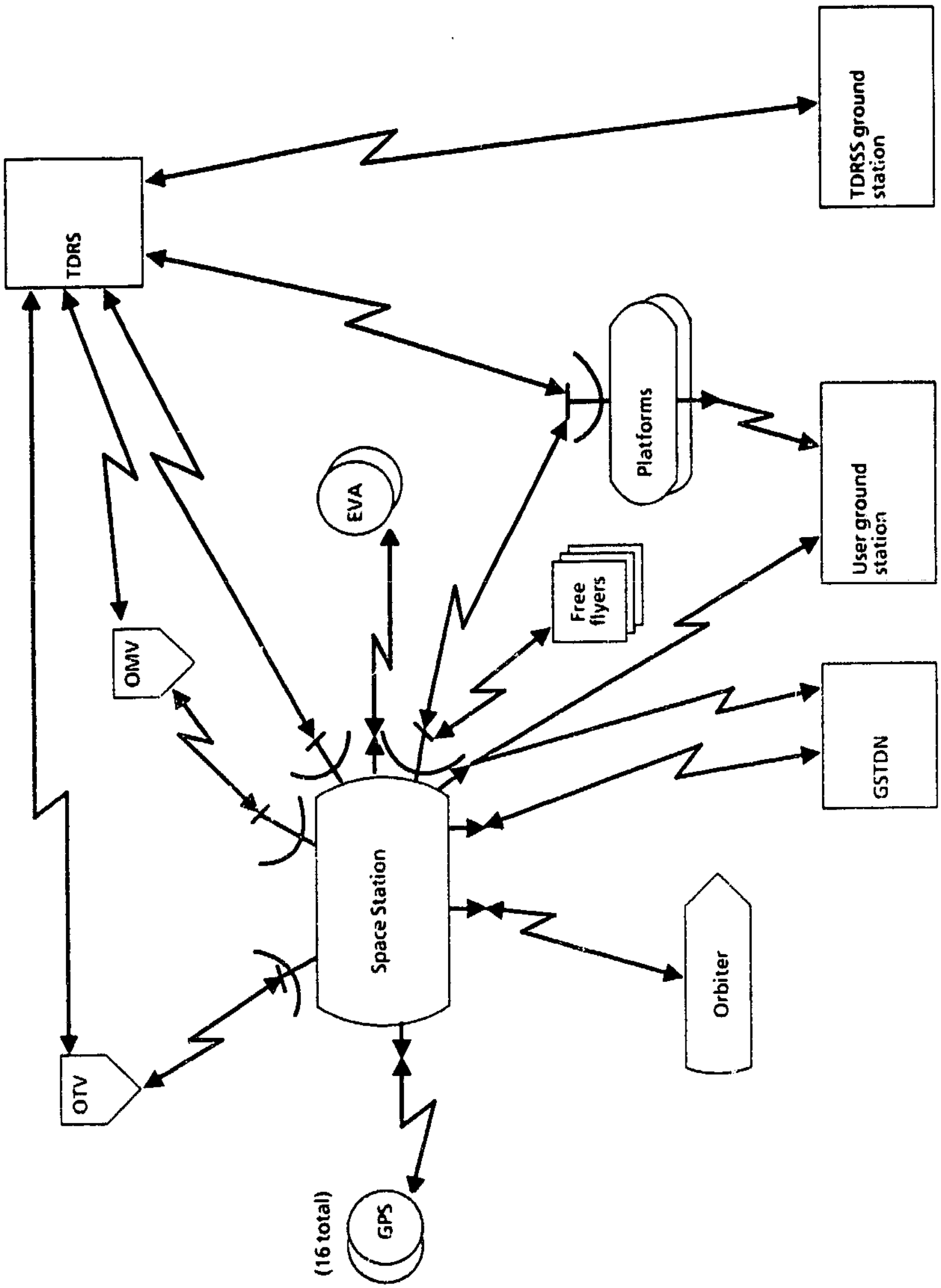
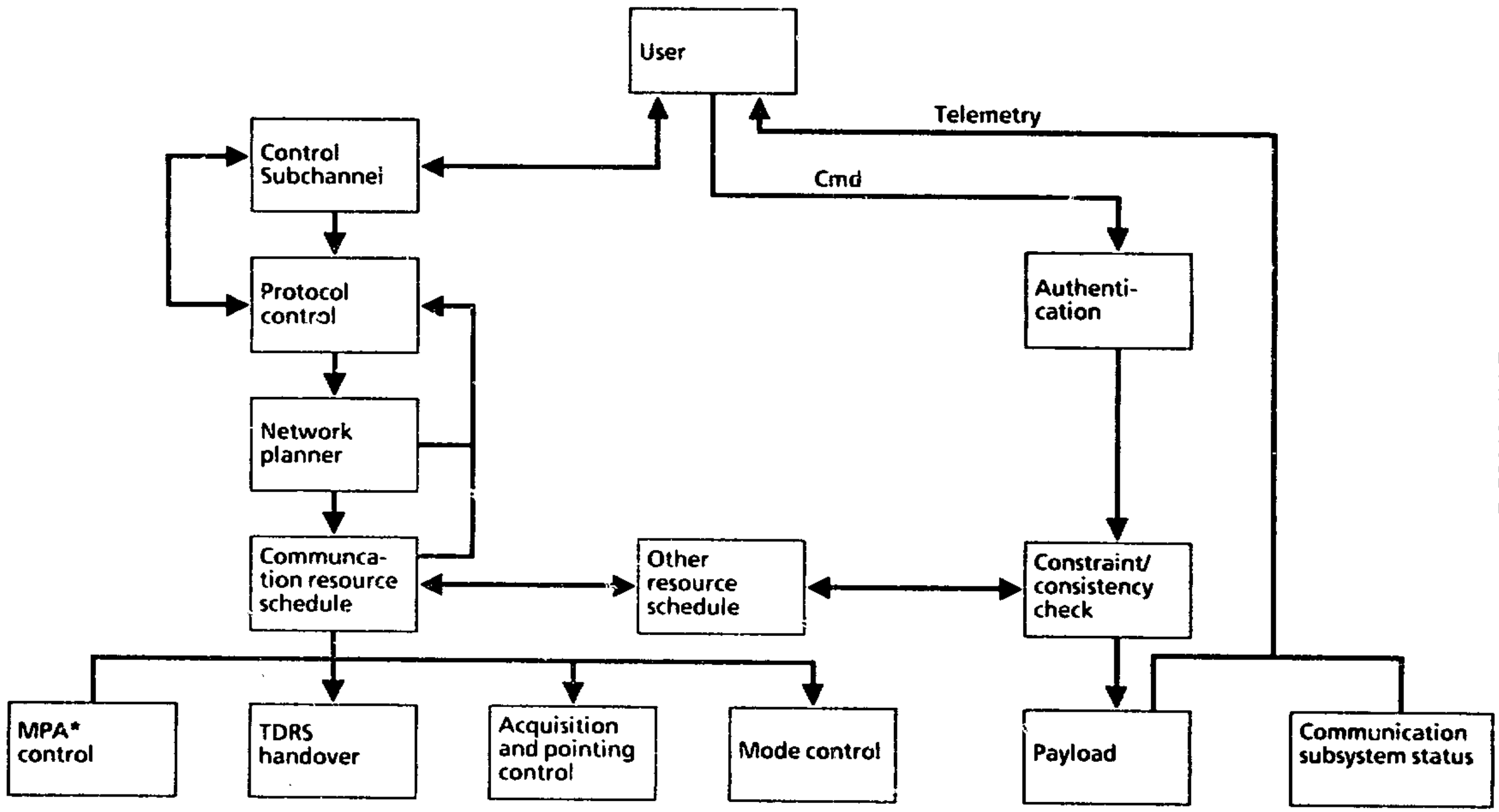


Figure 2.3-7. Typical Communication Subsystem Links



* Multi-beam phased array

Figure 2.3-8. Typical Communications Subsystem Controller

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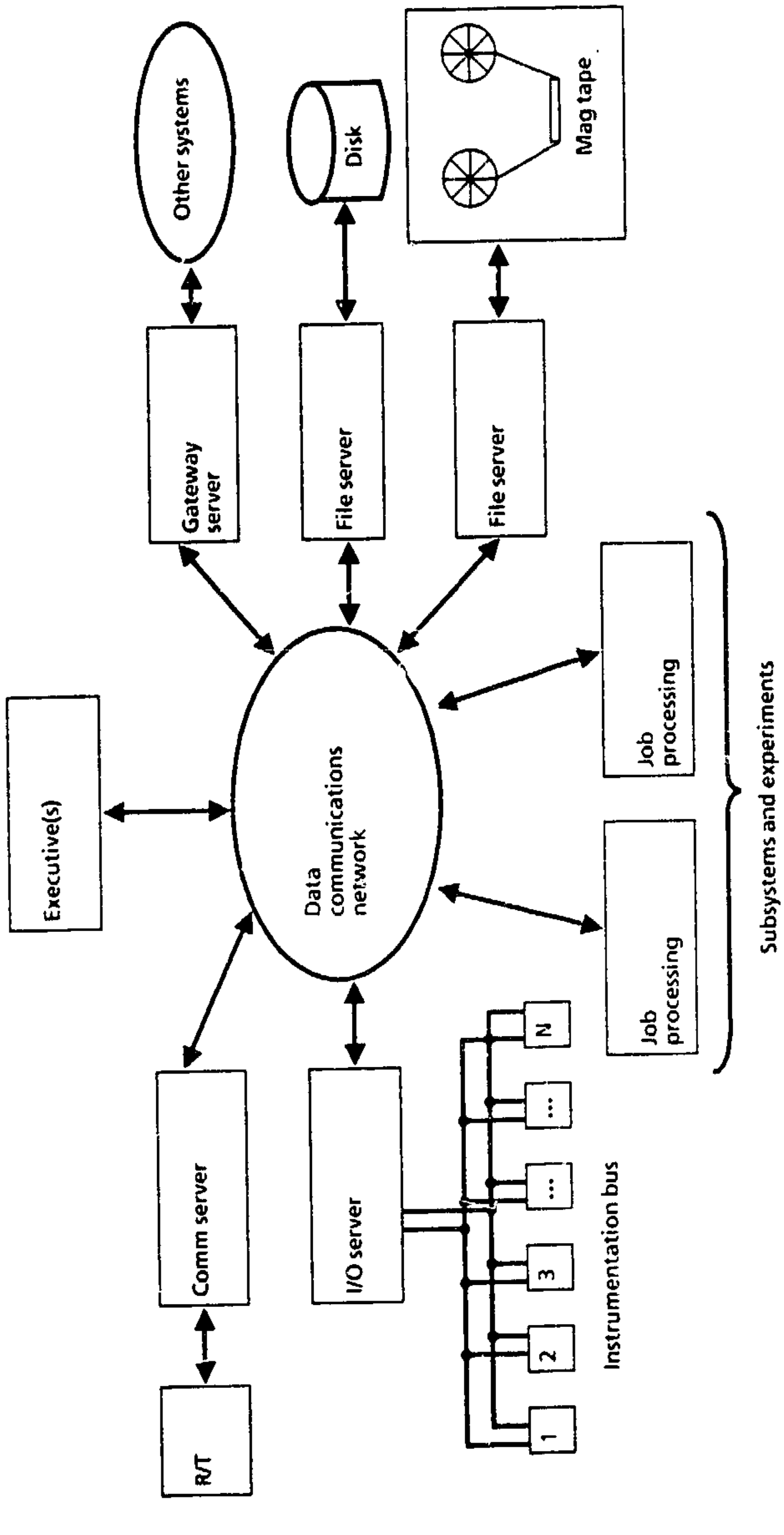

Figure 2.3-9. Typical Data Management Subsystem Network Operating System

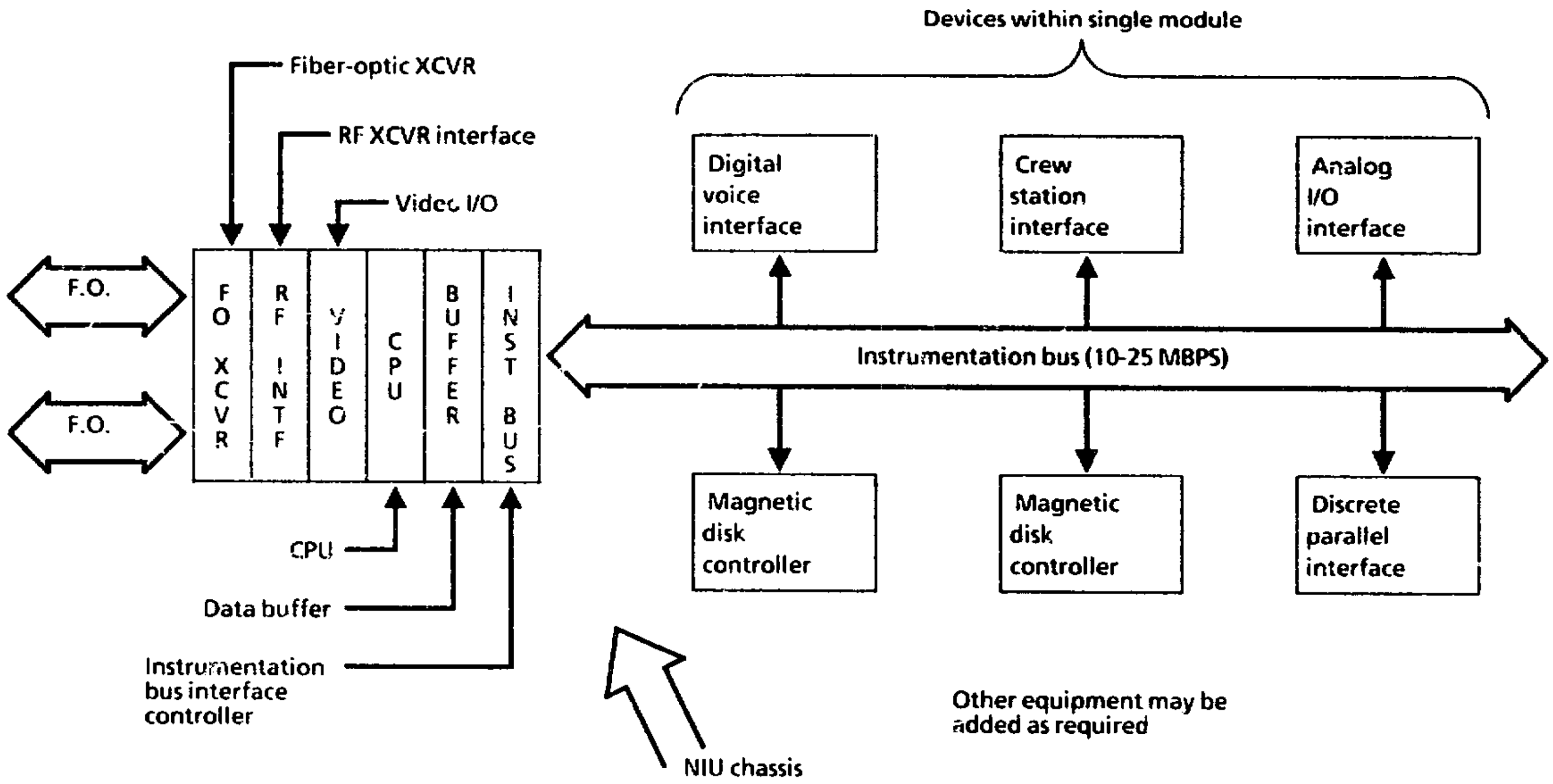

Figure 2.3-10. Typical Network Interface Unit

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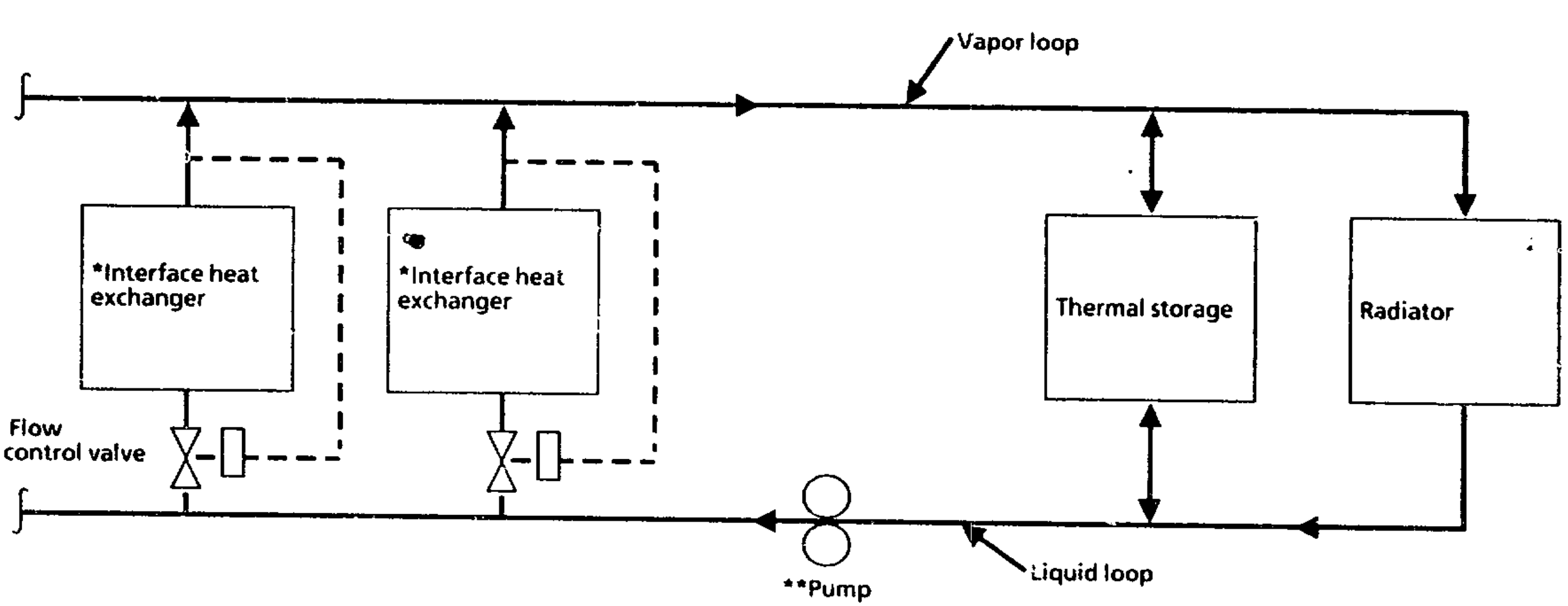

* Docked modules, cold plates, etc.

** Baseline uses mechanical pump in liquid loop
Alternatives include

Pump in vapor loop
Osmotic pump system
Ion drag pump system

Figure 2.3-11. Typical Pumped Two Phase Heat Transport System

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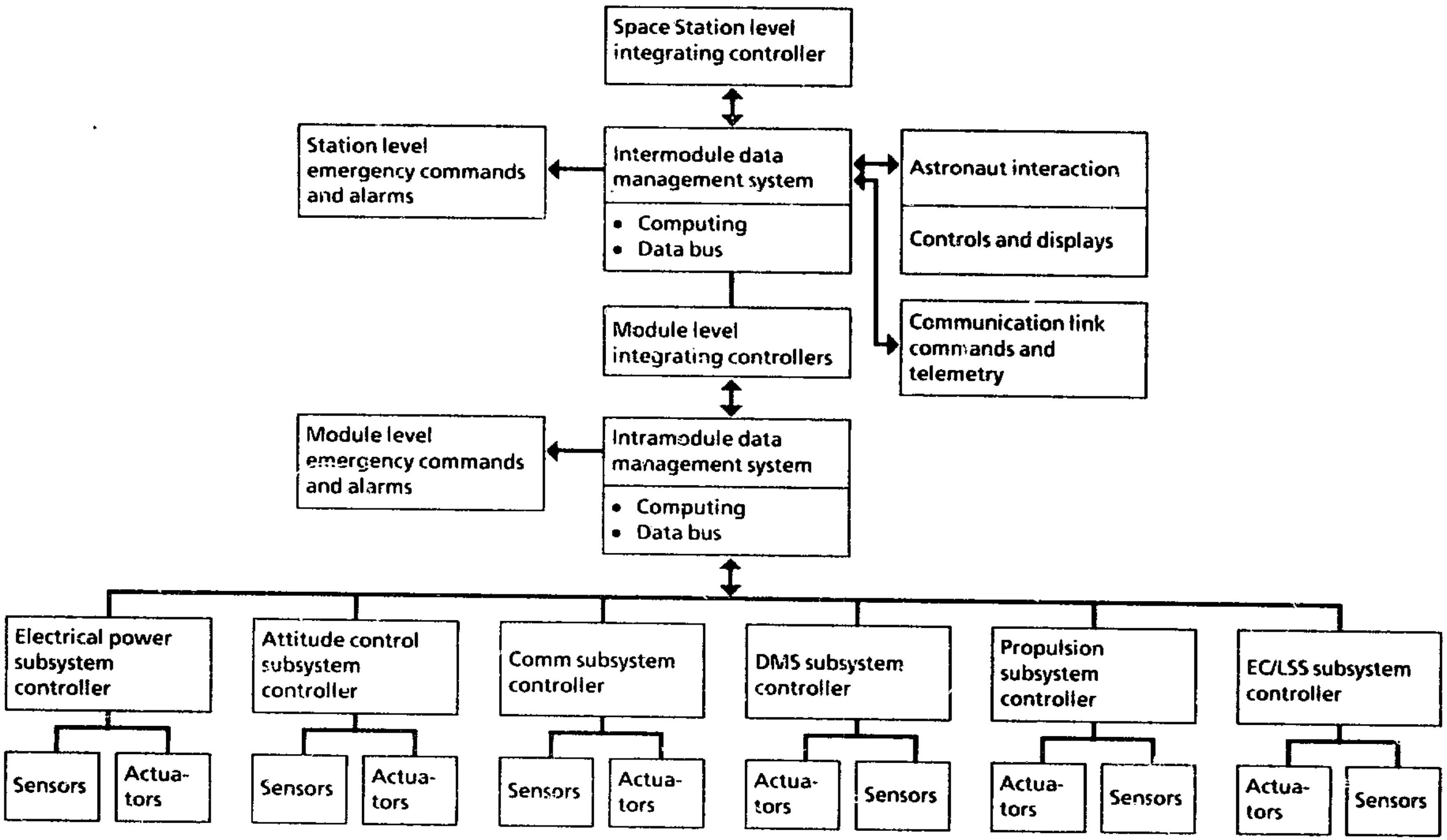

Figure 2.3-12. Architecture for Subsystem Management

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controllers, module integrating controllers and Space Station level integrating control. It is desirable for reasons of reliability, commonality, system evolution and conservation of data flow to adopt a distributed architecture philosophy for Space Station data management. The use of integrating controllers at the module and Space Station level indicate that functionally at least there will be some centralization of control functions within data management. It is, of course, possible to distribute those controller functions physically over different processors or with redundant processors while a centralized functional aspect is retained. The hierarchal character of integrating control for subsystem management led to a focusing on commonality within subsystem operational functions. This came about because the principle function of the integrating controller would be to handle the common aspects of overall Space Station mode and operations control at the interfaces between subsystems. Tables 2.3-7, 2.3-8 and 2.3-9 list typical subsystem modes, subsystem reconfigurations, and subsystem state change factors respectively for the five subsystems considered. To integrate the operation of these subsystems with the overall operations and missions of the Space Station, the integrating controller will need to orchestrate these modes, reconfigurations and subsystem states.

2.3.3 Identification of Needs for an Integrating Control

Because the Space Station will operate with limited resources over a long period of time and serve a wide and changing variety of missions, predetermined operations of the subsystems are not possible. If the on-board crew were tasked to manage all of the modes, reconfigurations and state changes for the subsystems, it is unlikely that they would have time to support Space Station operations or missions. It is therefore necessary that a high level of machine autonomy for subsystem management be included in the Space Station System requirements.

In addition to providing automated subsystem management functions, the integrating controller will be needed to provide the automated decision makers and trend analyzers necessary to support automation and robotics for other applications on the Space Station such as space manufacturing, space construction, satellite servicing, and external space station maintenance.

TABLE 2.3-7 SUBSYSTEM MODES

GUIDANCE, NAVIGATION AND CONTROL

- o Attitude hold
- o Attitude slew
- o Attitude control with orbiter docked
- o GMG wheel desaturation
- o TVC for orbit trim thrusting
- o Acquisition and start up
- o Off
- o Reconfiguration

ELECTRICAL POWER

- o Sunlight normal
- o Darkside normal
- o Battery reconditioning
- o Solar array degradation
- o Reconfiguration
- o Off

COMMUNICATIONS

- o Direct with other spacecraft
- o With other spacecraft via TDRSS
- o Tracking
- o Downlink via TDRSS
- o Downlink via GSTDN
- o Downlink to user ground station
- o Unencrypted (not IOC)
- o Reconfiguration
- o Off

DATA MANAGEMENT

- o Normal (full service)
- o Reduced service
- o Data dumping to archival memory
- o Reconfiguration
- o Off

THERMAL MANAGEMENT

- o Normal
- o Reduced
- o Reconfiguration
- o Off

TABLE 2.3-8 SUBSYSTEM RECONFIGURATIONS

GUIDANCE, NAVIGATION AND CONTROL

- Thrusters in use
- Allocation of control signal to controllers
- Redundant paths
- Alternate paths
- Sensors in use

ELECTRICAL POWER

- Batteries in use
- Solar array sections in use
- Redundant paths
- Alternate paths
- Power busses in use

COMMUNICATIONS

- Antennas in use
- Redundant paths
- Alternate paths

DATA MANAGEMENT

- Gateway devices engaged
- Redundant paths
- Alternate paths

THERMAL MANAGEMENT

- Radiators in use
- Thermal busses in use
- Pumps in use
- Heat exchanger in use
- Redundant paths
- Alternate paths

TABLE 2.3-9 SUBSYSTEM STATE CHANGE FACTORS

GUIDANCE, NAVIGATION AND CONTROL

- Slew rate
- Dead band size
- Identification of principle axes
- System gains
- Wheel desaturations interval
- Wheel desaturation rate
- Wheel desaturation controller gains
- Storage of RCS propellant
- Maintenance schedule
- Failure modes/anomalies

ELECTRICAL POWER

- Load management
- Power source management
- Energy balance
- Management of excessive power
- Light/darkside passage
- Maintenance schedule
- Failure mode anomalies

COMMUNICATIONS

- Frequencies (S-band or Ku-band)
- Data rates
- TDRS in use when more than one available
- Maintenance schedule
- Failure modes/anomalies

DATA MANAGEMENT

- Data rates
- Computer operation rates
- Data stored
- Maintenance schedule
- Failure modes/anomalies

THERMAL MANAGEMENT

- Temperatures
- ΔT's
- Light/darkside passage
- Maintenance schedule
- Failure mode/anomalies

2.3.4 Definition of Integrating Controller Functions

Because there is a large volume of data associated with the subsystem management, automation and robotics support functions of an integrating controller, the overall system must be designed to minimize the flow of information between the elements. For that reason the concept discussed here operates on a philosophy of management by exception. This means that each subsystem controller will manage its own affairs so long as everything is normal and going according to plan. When a subsystem controller detects a change such as a failure condition, the integrating controller will be advised, and the overall situation is then examined by the integrating controller so that directions are given back to the subsystems. Figure 2.3-13 illustrates an example of the automated decision making process using attitude control as an example subsystem. The subsystem controller in this example checks its status every few milliseconds. As long as the status is okay no integrating controller action is requested. When the status is not okay, the subsystem controller performs its internal diagnostics and informs the integrating controller. In this example the attitude control subsystem controller detects a failure in LR-22 and assesses the consequences of a switch to the redundant element as a transient in pitch, yaw and roll attitude. The integrating controller checks the status of Space Station subsystems and mission operations and determines that experiment #16 cannot tolerate the predicted attitude transient. The integrating controller therefore directs the attitude control subsystem controller not to switch to the redundant element.

This example indicates one type of decision making to be performed by an integrating controller. Another type is scheduling an operation on the Space Station which changes for some unforeseen reason. Again, the integrating controller will be informed and that function causes directions to be issued to subsystem controllers. The outputs that an integrating controller would provide to subsystem controllers would be directions to change control elements within the subsystem controllers. The following is a list of typical status elements that the integrating controller will direct a subsystem controller to change.

- Prioritization lists
- Scheduling

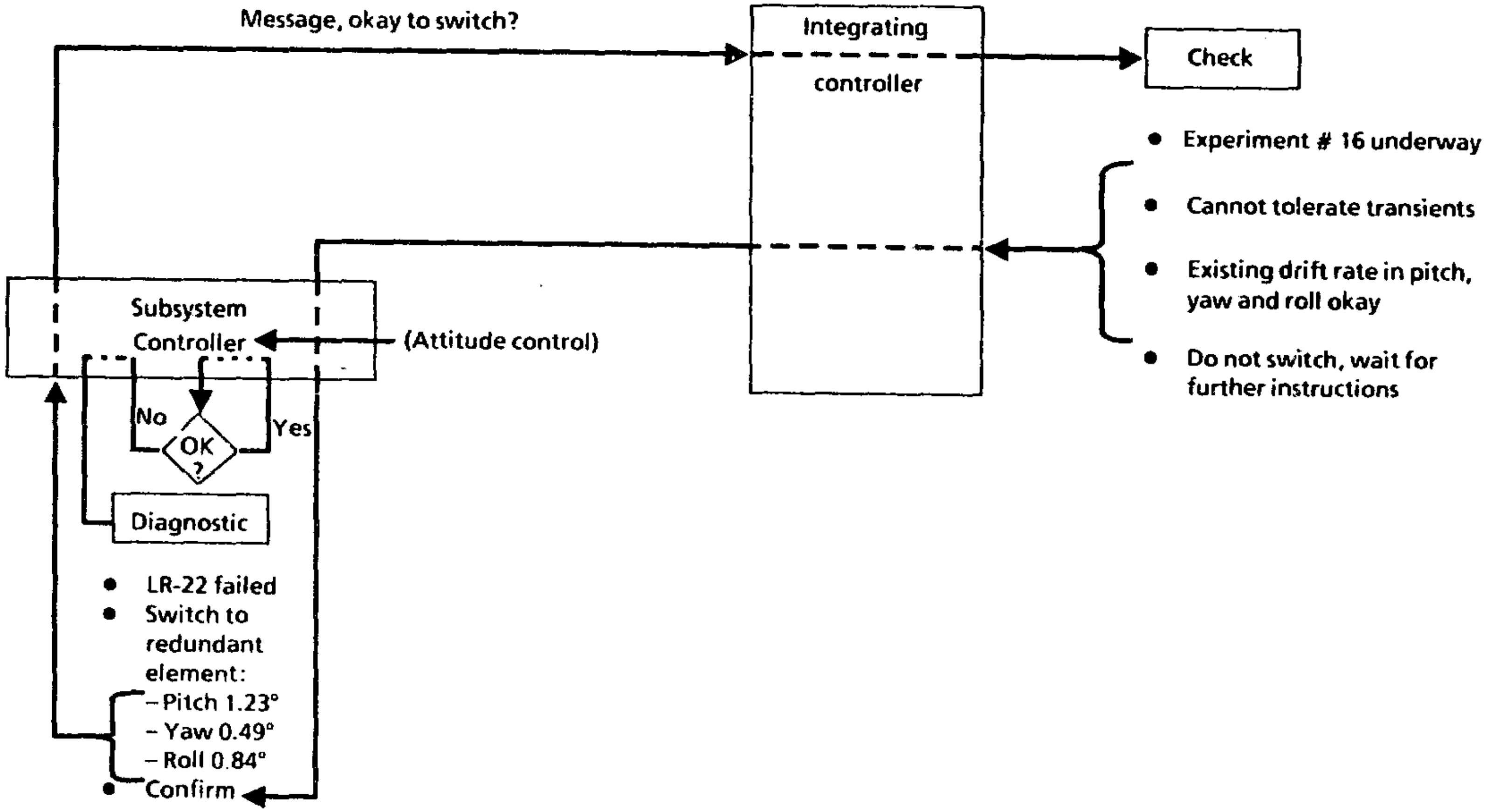

Figure 2.3-13. The Automated Decision Makers

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- o Operating constraints
- o Override commands for emergency conditions.

These directions for change would affect mode and state control of the individual subsystems in response to anomalies or unscheduled events.

2.3.4.1 Prioritization Lists

These are ordered lists of characteristics which will identify which reconfiguration, out of several possible, the subsystem will execute if a particular anomalous or a deficient condition is sensed by the subsystem controller.

2.3.4.1.1 Example of Priorities in Use

The EPS subsystem controller senses a rapid decrease in battery charge state. It needs to reduce load on the system so it opens the switch to the lowest priority load. If the problem still exists the EPS controller opens switch to next highest priority load, etc., until the problem is resolved. In addition to opening load switches to low priority loads the EPS controller conducts internal fault analysis on the battery and finds that the battery is shorted intermittently. The Controller removes the battery from services and notifies the IC of the degraded condition.

The IC adjusts the EPS controllers priorities list to indicate that the second priority load which had been switched off is moved to fifth from bottom in priority. The EPS controller responds by shutting down the former third in priority load and reinstates the former second which is now the fifth. If excessive power drains still exist the EPS controller shuts down the next higher priority load to solve the problem.

The IC alerts astronauts that battery maintenance is required and adjusts the mission and operations schedules to delay high power use events until after the maintenance. The IC gives advisories to astronauts on lower power use mode which is then in effect.

2.3.4.1.2 Typical Space Station Items to be Prioritized

The following is a list of typical items to be prioritized within Space Station subsystem controllers.

- Users of power
- Locations of cold plates
- Locations of cabin air heaters
- Locations of cabin air supply points
- Locations of cabin potable water supply points
- Venting locations around Space Station
- Locations of data storage devices
- Storage locations for various substances

2.3.4.2 Schedules

These are schedules of specific reference point settings, mode shifts, or reconfigurations anticipated for the subsystems over a particular period of time. The operation of the various subsystems shall be in accordance with schedules applying to each of them which is in concert with the overall master schedule of the Space Station. The IC will adjust schedules in response to anomalies on the Space Station or in response to new schedules for outside events which may be input by the astronauts.

2.3.4.2.1 Example of Schedules in Use

Attitude Control (ACS) receives a change in the pointing schedule from the IC to support needs of earth viewing experiments. ACS controller adjusts the dead band size references in accordance with the new schedule, computes a change in the CMG saturation rate and schedules a new time for wheel desaturation activities. The ACS controller then relays this changed schedule to IC which determines that the new schedule for desaturation is incompatible with the available power since it would be during a darkside passage. The IC sends an adjustment in wheel desaturation schedule to the ACS controller which is the best fit between EPS power availability and ACS needs. The ACS controller then adjusts the desaturation schedule accordingly.

2.3.4.2.2 Typical Items to be Scheduled

The following is a list of typical items to be scheduled within Space Station subsystem controllers.

- o Attitude pointing requirements versus time
- o ACS wheel desaturation
- o Orbit trim times
- o TDRSS viewing times
- o High/low data rates versus time
- o ACS maintenance schedule
- o Communication maintenance schedule
- o Data storage versus transmission schedule
- o DMS maintenance schedule
- o Battery reconditioning schedule
- o Solar array maintenance schedule
- o EPS maintenance schedule
- o Power user scheduling
- o Thermal control user scheduling
- o Thermal control maintenance scheduling

2.3.4.3 Constraints

These are standing orders which restrict or structure the operation of subsystems in some manner while the constraints are in effect. The operational constraints include particular ranges of reference points, holds on mode shifts, schedule constraints, or reconfiguration restrictions.

2.3.4.3.1 Example of Constraints in Use

Life sciences experiments require that the temperature of the air in the life sciences module be elevated by 15°F for the next 6 hours (incubation period for a large number of plants being tested). This puts a constraint on the configuration of thermal control system air heaters and on priorities for power use as well as the set point for air temperature in the life sciences module.

Because of the extended period which goes through light and shadow, the constraint will migrate to affect the power available to other systems and may require shut down of certain functions. Constraints may also be applied to maintenance operations for other subsystems. An example would be, advancing maintenance which is connected with reduced power usage while delaying maintenance which demands greater power usage.

2.3.4.3.2 Typical Items of Constraint

The following is a list of typical items of constraint through Space Station subsystem controllers.

- ACS pointing accuracy limitations
- ACS slew rate limitations
- ACS wheel saturation limitations
- Communication data rate limitations
- Data storage limitations
- Power availability limitations
- Voltage limitations
- Temperature limitations
- Heat removal limitations
- Mode limitations for any subsystem
- Configuration limitations for any subsystem
- Scheduling limitations for any subsystem

2.3.4.4 Emergency Commands by the Integrating Controller

Emergency commands would override all subsystems controllers in the event of predetermined life or mission threatening emergencies. The astronaut interaction would be facilitated both as inputs and outputs. The inputs would include a complete manual override of real time functions when selected by the astronauts. The ground mission control interface would also include inputs and outputs to the integrating controller but evolution of Space Station autonomy would have a goal of minimizing this.

2.3.5 Comparison of Integrating Controller Functional Definitions With Those From Previous Study Phase

The functions defined for the integrating controller as a result of this study are different from those of the last study in several respects. First, the expanded list of subsystems motivated a more generic look at the functions performed. This resulted in the generalized priority, constraints and schedule functions. Secondly, the desire to consider a more distributed overall function lead to the concept of embedding the controls for each subsystem in that particular subsystem's controller and having the changes in state control parameters generated by the integrating controller. This would give the integrating controller the management by exception role that was mentioned earlier. That role is intended to keep the data transfer rates between controllers at a minimum. The third variation is that the need to move toward requirements motivated a step-by-step look at how an integrating controller might perform its generic functions. This has produced the flow diagram described in the next paragraph.

2.3.6 Diagram New or Changed Integrating Controller Functions

Figure 2.3-14 gives a flow diagram to describe at a top level those steps to perform integrating controller functions.

1. Information is collected by the integrating controller from the astronauts via control and display units, from the subsystem controllers via the data management system, and from the ground via the telecommunications system (IOC especially but less of this as Space Station autonomy is developed). This information will indicate state changes, reconfigurations, schedule changes, environment changes, and anomolies which effect the operation of the Space Station.

2. A state and mode simulation will be run for all Space Station subsystems. This will produce a description of the mode, configuration and output performance parameters of all of the subsystems resulting from the passage of time as the simulation is periodically updated based on the collected information.

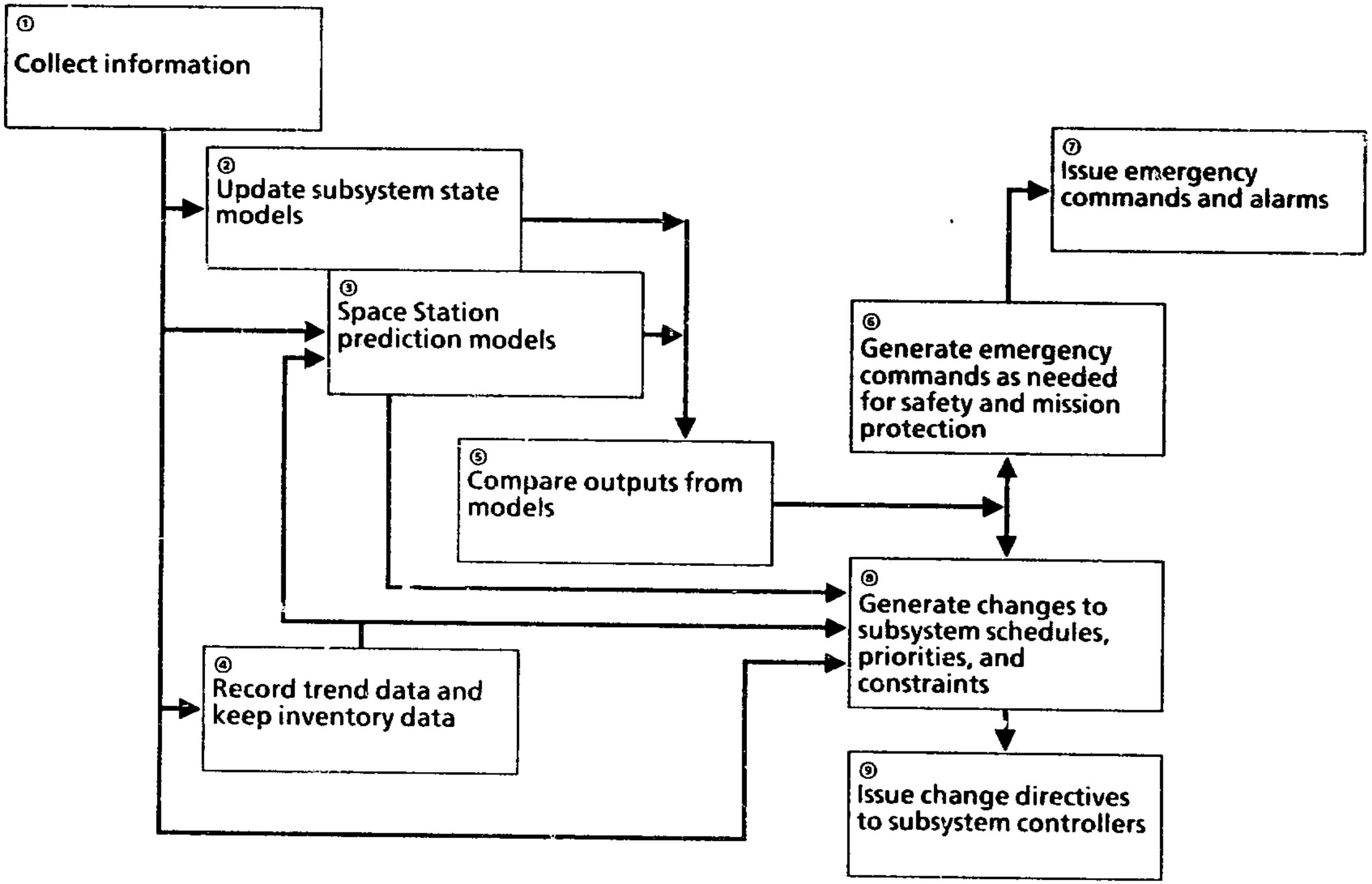

Figure 2.3-14. Flow Chart for Integrating Controller Functions

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3. Separate state simulations will be run faster than real time to predict the consequences of letting the current situation continue or to predict the results of hypothetical inputs to subsystem controllers in response to anomalous conditions.

4. Trend data and other historical data are updated to reflect the latest collected information.

5. An assessment is made for each subsystem interface based on current state outputs from the mode simulation and the predicted consequences of letting the current situation continue. Unsatisfactory situations are identified by the integrating controller and assessed (probably an E.S. application) to be either life or mission threatening indicating an emergency condition or non-threatening indicating an anomalous condition.

6. When an emergency condition exists, the integrating controller will generate emergency commands to be issued to the subsystem controllers. These commands will be designed to place the station in a condition which will support the life of the crew and sustain the mission in accordance with predetermined priorities. Another part of the emergency command process will be the activation of alarms and emergency (explain type) information displays to the crew and transmissions of data to earth.

7. The integrating controller will issue the emergency commands to the appropriate subsystems, and alarms and will determine the schedule and sequence for removing those commands either with a continuation of the emergency state or after collected information shows a return to normal.

8. For those conditions which are judged to be anomalous, but not life or mission threatening, subsystem change directives are needed. For these, the integrating controller will determine (again E.S. technology may be needed) a workable compromise using the various predictions from the hypothetical simulations as well as trend data and direct input data. Once a workable compromise has been

selected, the integrating controller will generate change directives to be issued to subsystem controllers.

9. This is similar to step 7 in that appropriate subsystems will be directed and the schedule for retaining those directives will be determined.

2.3.7 Implementation of Integrating Controller Functions

Based on the flow diagram in Figure 2.3-14, the integrating controller can be partitioned into seven primary software components. These are:

I/O Handler - This module collects and distributes all of the data required by the integrating controller. This includes subsystem data for the subsystem state models, the Space Station prediction model and to the recording and trending function. In addition, external changes from the ground controllers and the astronaut are provided to the Space Station need model and the recording and trending function. It also distributes change information to the subsystems and reports status to the ground controllers and astronauts as appropriate.

Subsystem Models - These modules, one for each subsystem, are independent, discrete time, discrete state models. However, the attitude control, electrical power and thermal management subsystems may incorporate some continuous state simulation elements as part of the models. These modules operate on each update of subsystem data to construct a complete description of the current subsystem states.

Space Station Prediction Model - These are also discrete time, discrete state simulation modules. They operate faster than real time on subsystem data plus data from ground controllers and astronauts, and also use trend analysis results from the recording and trending functions. The results of these modules are projections of subsystem and overall Space Station states resulting from hypothetical changes to subsystem priorities and schedules or constraints and also predictions of future states when no changes are made. Expert system implementation would be used to select the hypothetical changes for the predictors to model.

Change Monitor - This module examines the results of the modeling to determine when an undesirable situation exists or when an undesirable situation is predicted. The purpose of this examination is to determine when changes in subsystem operation are required. It also identifies life threatening or mission threatening situations which need to be handled as emergencies. It's expected that portions of this module would be implemented as an expert system.

Emergency Handler - This module generates all commands to the subsystems and necessary communications to the ground controllers and astronauts to respond to emergency situations.

Change Handler - This module generates the necessary changes to subsystem schedules, priorities and constraints in response to anomalies reported by the subsystems or detected by the change monitor. It also processes changes generated externally or as a result of the trend analysis. To optimize Space Station operation, and select results of the hypothetical predictions, an expert system may be used.

Recording and Trending - This module records system and subsystem data to maintain a historical record of operation and to perform trend analyses on data for which changes may not be detected by the change monitor. These are important in subsystems which are susceptible to longer term degradation. An expert system may be used to assure efficient storage and retrieval of appropriate data.

The key components of the integrating controller are the simulation modules and the expert systems. Most of the feasibility assessment depends on the feasibility of developing and implementing these items. Some of the factors to be considered are -

Can the modules be developed?
Validity and verification of the models

Speed of the models
Cost to develop the models

The state change rate is expected to be low relative to the processing speed so several software modules can be executed in series in a single processor, but more than one processor will probably be needed for all of them. The same is also true of the expert systems. They may require separate processors, but may also be executed on the same processor if the time is available.

The impact of the integrating controller on the data management subsystem depends on the program size and processing throughput required for the various program modules. Quantitative estimates cannot be made without further specification of the data management subsystem computers and additional characterization of the integrating controller functions. Some qualitative estimates however can be made and are summarized in Table 2.3-10. Size refers to the amount of memory required for the program modules and their data. Those indicated as large are the simulations models and the expert systems. These are expected to require on the order of half of the memory of a DMS processor. The subsystem models may require much more since they are multiple models. The timing column indicates demand for processor throughput (operation per second). This is given in two parts, frequency and loading. The frequency indicates how often the module needs to be executed. As shown, all are required continually except the Emergency Handler and Change Handler which are required in response to changes in conditions. The loading refers to how much of the processor's throughput is required.

Another important factor in implementing the integrating controller on the data management subsystem is the data flow required. Table 2.3-11 indicates, for the major sources of data flow, the frequency and amount of data flow from the subsystems, from external sources and to the subsystems. The only data item likely to place demands on the data management subsystem data buses is operational data. Care must be taken in the development of the integrating controller in selection of the operational data items needed for integrating controller operation.

Table 2.3-10. Integrating Controller Software Sizing and Timing

Module	Size	Timing (Frequency/Loading)
I/O handler	Small	Continuous/Moderate
Subsystems models	Large	Continuous/High
Space Station prediction models	Large	Continuous/High
Change monitor	Large	Continuous/Moderate
Emergency handler	Small	Infrequent/Low
Change handler	Large	Occasional/Moderate
Recording and trending	Large	Continuous/Moderate

TABLE 2.3-11 INTEGRATING CONTROLLER DATA FLOW

From/to	Type of Data	Freq.	Amount
From Subsystems	Operational Data	High	Large
	State Changes	Moderate	Small
	Mode Changes	Low	Small
	Anomalies/Failure Data	Low	Small
	Reconfigurations	Low	Small
	Environmental Changes	Low	Small
From Ground and	Schedule Changes	Low	Small
Astronauts	Prioritization Changes	Low	Small
To Subsystems	Schedule Changes	Low	Small
	Prioritization Changes	Low	Small
	Changes to Constraints	Low	Small
	Override Commands	Low	Small

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2.3.7.10 Feasibility Assessment for Expert Systems

This section will consider the feasibility of applying expert system technology to the integrating controller concept described by Figure 2.3-14. This will be done by presenting two separate high level designs for an expert integrating controller.

2.3.7.10.1 Ventilator Manager - Based Design

This section describes an expert integrating controller based on the design of Ventilator Manager (VM), an existing expert system described in Reference 1. As described in the literature, VM helps clinicians at the Pacific Medical Center in San Francisco manage a mechanical ventilator. The latter device provides total or partial breathing assistance to patients who have undergone cardiac surgery.

2.3.7.10.1.1 Rationale for VM - Based Design

VM was chosen as the basis for an Integrating Controller (IC) design for several reasons. First, both VM and an IC involve interpretation of data over time. This contrasts with most expert systems which are intended to handle static rather than dynamic problems. Static systems base their conclusions or actions on data available at one particular time.

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Second, both involve the use of models to assist in the decision making progress. VM incorporates a state transition model of the therapies provided by a mechanical ventilator. The IC concept, as shown in Figure 2.3-14 involves models that permit determination of the current as well as required states. In addition, both systems use the models to generate expectations of future states. These expectations are compared with the system state at subsequent times to determine if the system is behaving as desired.

Third, both systems involve physical configurations that are similar in their broad outlines. This point is covered in greater detail in Paragraph 2.3.7.10.1.2.

Fourth, both systems involve similar functions. This point is covered in greater detail in Paragraph 2.3.7.10.1.3.

Despite the similarities, there are several apparent differences between VM and an IC. For example, VM does not perform an integration task. However, because the functions of VM and an IC are similar, it is not clear that this is a crucial difference. In addition, VM does not actually control the mechanical ventilator but makes suggestions to a clinician. This does not appear to be due to technical limitations but because clinicians are unwilling to surrender control of the mechanical ventilator to VM.

2.3.7.10.1.2 System Configuration

Figure 2.3-15 shows the VM system configuration. This suggests the plausible IC system configuration shown in Figure 2.3-16. Table 2.3-12 shows the correspondence between the elements of the two configurations.

Table 2.3-12 Comparison of VM and IC Configurations

VM Element	IC Element
Clinician	Crew
Patient	Space Station
Life Support	Sub Systems
Monitoring	Information Collection
VM	IC

With the exception of data flows, the two configurations are quite similar. The data flows are different because of the different requirements of the two systems. In the case of VM, it is necessary that the clinician maintain total control of the system; hence, VM acts as an assistant who makes suggestions. In the case of an IC, it is desired to relieve the crew of the need to actively control the on-board subsystem; hence, an IC acts as an assistant who is expected to perform subsystem control under the direction of the crew.

The configuration proposed for an IC by Figure 2.3-16 contains one feature not explicitly present in the IC concept of Figure 2.3-14. In particular, the crew is permitted to state

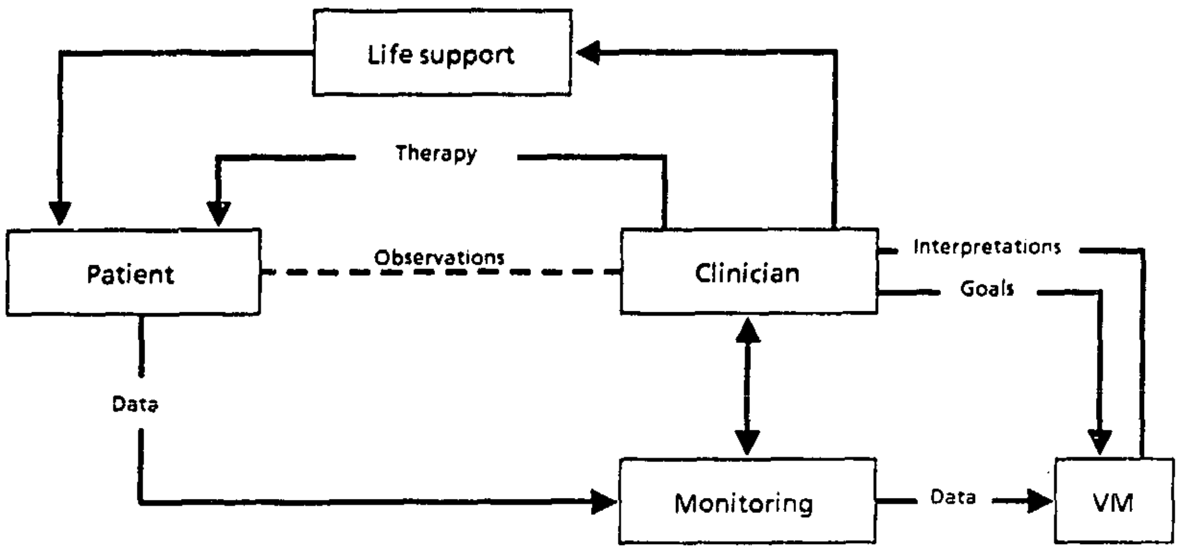

Figure 2.3-15. VM System Configuration (from Reference 1)

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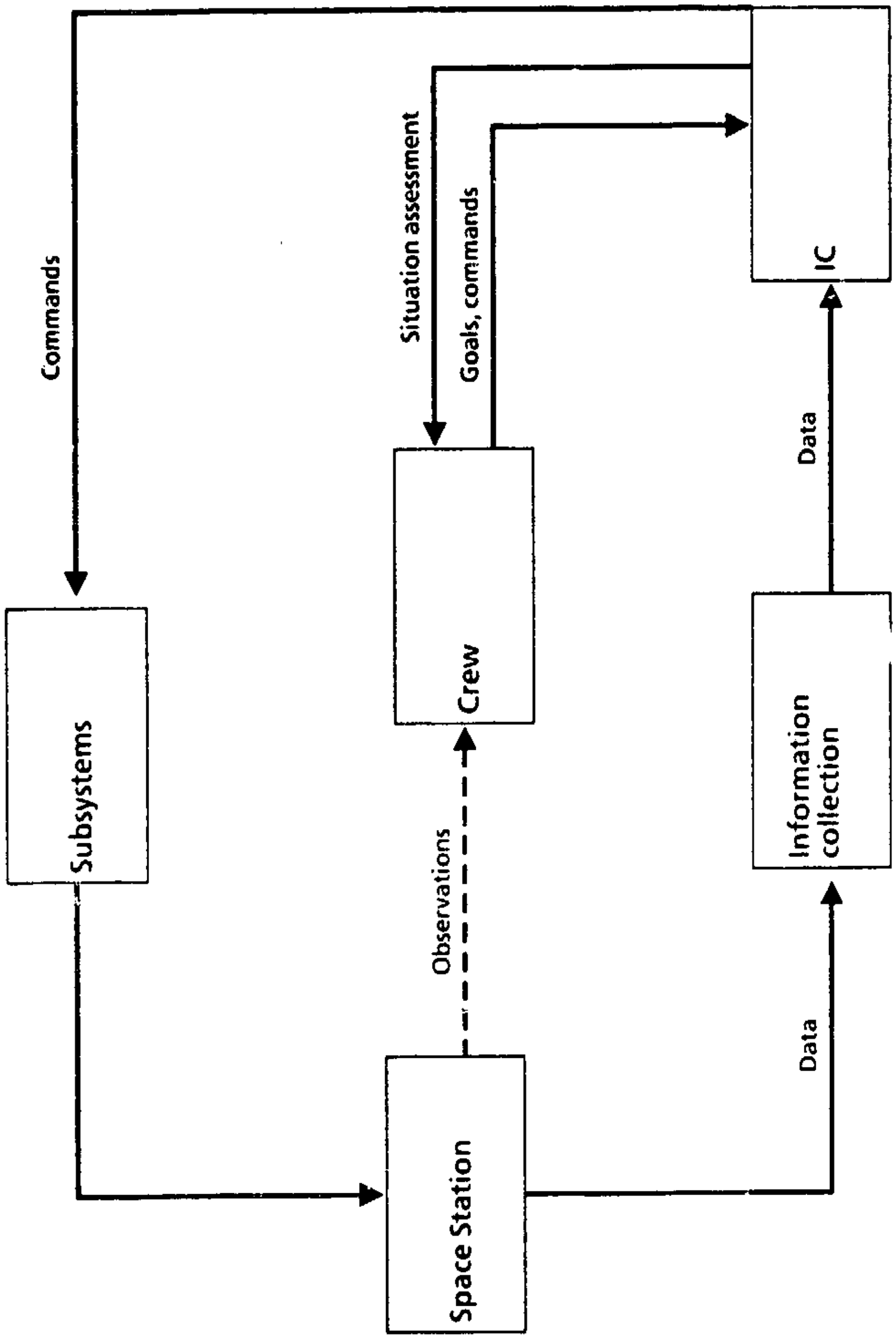

Figure 2.3-16. Potential IC System Configuration

goals rather than issue commands if they so desire. For example, the crew could state that the goal of the day is to prepare for a shuttle rendezvous. The IC would then translate this goal into specific priorities, schedules, and so forth. The crew would be given the option of reviewing the latter. By permitting the crew to state what is to be done (i.e., a goal) rather than how to do it, more time will be available for mission-related activities. Because AI researchers have extensively studied the design of goal-oriented systems, the use of AI techniques is particularly appropriate for the implementation of such systems.

2.3.7.10.1.3 System Functions

VM and an IC have similar functions. Table 2.3-13 lists the VM functions given on Figure 2.3-15. In addition, this table lists the analogous functions for an IC. Table 2.3-14 shows how the analogous IC functions correspond to the IC functions shown in Figure 2.3-14. The correspondence shown in Table 2.3-14 is not claimed to be precise, but rather points out similarities between VM and IC functions. For example, VM function e is clearly quite similar in intent to IC function 4.

Besides pointing out the similarities between VM and IC functions, Table 2.3-14 suggests another organization for the IC function flow diagram. Figure 2.3-17 shows this organization. The following paragraphs describe each function on the new flow diagram in greater detail.

1. This function corresponds to function 1 shown in Figure 2.3-14. In addition, mission goals will be collected from the crew.

2. The information collected by the previous function will be validated. For example, if a data item represents a sensor reading, it will be determined if the reading is consistent with one likely to be given by a properly functioning sensor.

3. An overall system state estimate will be performed (situation assessment). Because some of the input data may be invalid, this function must be capable of coping with erroneous, incomplete, or missing data.

Table 2.3-13. Analogies Between VM and IC Functions

VM Functions	Analogous IC Functions
a. Detect possible errors in measurement	a. Detect possible data errors
b. Recognize untoward events in the patient/machine system and suggest corrective actions	b. Detect subsystem anomalies and initiate corrective actions
c. Summarize the patient's physiologic status	c. Summarize subsystem status
d. Suggest adjustments to therapy based on patient's status over time and long-term therapeutic goals	d. Initiate adjustments to priorities, schedules, constraints, and so forth based on subsystem status over time and overall mission goals
e. Maintain a set of case-specific expectations and goals for future evaluation by the VM	e. Maintain a set of subsystem expectations and mission goals for future evaluation by the IC

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Table 2.3-14. Correspondence Between VM and IC Functions

Original IC Functions

Analogous IC Functions	1	2	3	4	5	6	7	8	9
a	X								
b					X	X	X		
c				X					
d					X			X	X
e				X					

Note: – Original IC functions are defined in Figure 2.3-14
– Analogous IC functions are defined in Table 2.3-13

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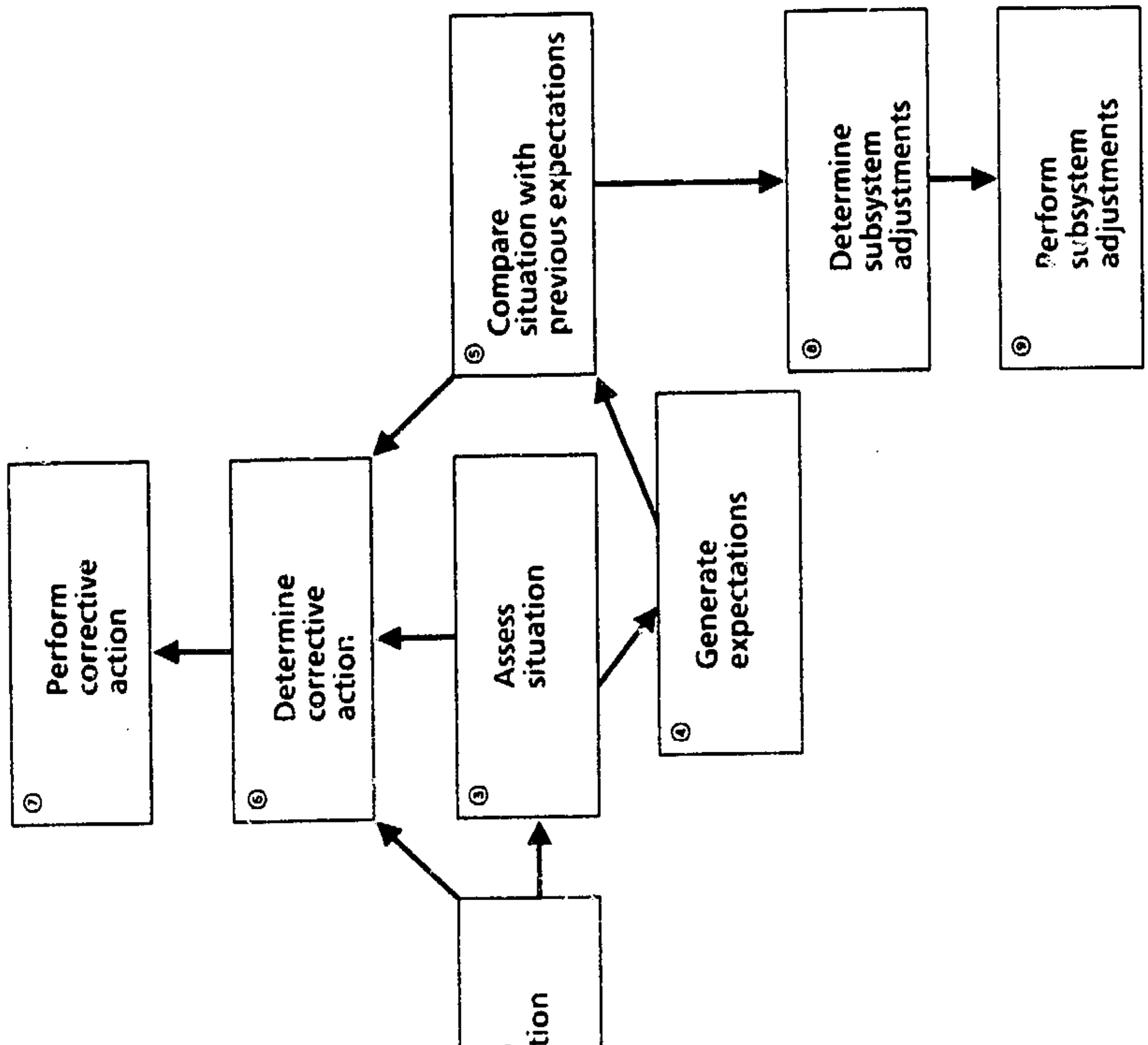

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Figure 2.3-17. Reorganized IC Functional Flow

4. Based on the current system situation as well as trends and mission goals, an estimate will be made of the future state of the system.

5. The current state of the system will be compared with previous estimates of what the current state should be. This will permit detection of system anomalies as well as routine adjustments required by subsystems.

6. Corrective actions will be determined for anomalies detected by functions 2, 3, and 5 above.

7. The actions selected by function 6 are performed.

8. Actions will be determined for normally occurring events such as scheduled reprioritization.

9. The actions selected by function 8 are performed.

2.3.7.10.1.4 Summary of VM—Based Design

The preceding paragraphs have shown how the design of VM might be adapted to the design of an IC. Since VM is an existing expert system, this provides strong evidence of the feasibility of applying expert system technology to the IC concept.

2.3.7.10.2 Planning-Based Design

This section describes an expert IC based on AI work done in the area of planning. There are several reasons for describing another design besides the VM-based design. First, another but dissimilar design shows that it is feasible to apply expert system technology to the IC concept. Second, the two designs have complimentary strengths and weaknesses. For example, VM is very good at responding quickly to unexpected changes in the system state whereas a planning-based approach is not. On the other hand, a planning based approach is good at scheduling tasks, an issue VM largely ignores. Thus, an actual IC design would probably combine aspects of both VM and planning. Finally, a planning-based approach is more directly applicable to the IC concept give by Figure 2.3-14.

2.3.7.10.2.1 Rationale for Planning-Based Design

In AI, "planning" is defined as finding a sequence of actions that achieves some goal. Much of the early AI work in planning involved control of mobile robots. For example, SRI developed a robot call Shakey which had a vision system. It could move about a room and interact to a limited extent with objects in the room. Shakey could be given a goal such as "go to location (X,Y)". Using a planning process, Shakey would determine a sequence of moves that would get it from its current location to the new location while avoiding obstacles in the room.

The IC concept strongly suggests the applicability of planning. In particular, function 8 can be viewed as a planning process that determines how to get from the current state as determined by function 2 to the goal state as projected by function 3.

2.3.7.10.2.2 Planning Issues

In this report, we will not go into as much design detail as we did in the case of the VM-based design. This is because there are a wide variety of approaches to planning and there is not sufficient time to do a trade study of the various approaches. A survey of AI approaches to planning appears in Reference 2. We will, however, describe one of the more salient issues in planning.

A planning-based system generally involves three components: a planner, a plan executor, and a plan monitor. The purposes of the planner and the plan executor should be self-evident. However, when planning is applied to a physical system such as a space station, there is a distinct possibility that the results of executing the plan deviate from the results expected by the planner. This may happen for a variety of reasons. For example, a physical system might be slightly out of calibration. In addition, an unexpected event may occur that invalidates the plan. The important point is that a plan monitor is necessary to detect deviations from the plan and initiate corrective action.

The IC concept does not explicitly incorporate a plan monitoring function. It is probably desirable to do so.

2.3.7.10.2.3 Summary

Planning provides an alternate approach to designing an IC. It provides additional evidence that it is feasible to apply AI to the IC concept. In addition, an actual IC design would probably synthesize the VM-and planning-based approaches.

2.3.8 Requirements for an Integrating Controller on the Space Station

This section provides a preliminary listing of function requirements for an integrating controller for the Space Station.

The integrating controller shall provide data outputs to subsystem controllers to update priorities, constraints, and schedules based on integrating controller assessments of the overall Space Station condition with respect to:

- o Safety of the crew
- o Survival of station subsystems
- o Survival of mission
- o Crew comfort
- o Efficient operation of station
- o Consistency of operations with schedules

The controller shall determine the updates to be supplied to subsystem controllers using state change and performance change data from subsystem controllers as well as from the operator system interface (OSI) and developed trend data. The determinations shall be made and updates provided once every TBD seconds and shall be addressed to the appropriate subsystem controllers by the integrating controller.

The priorities updates shall include changes to the rank order of resource users which may be considered for shut down in the event of supply shortages. These priorities shall be organized to be consistent with Space Station resource supply categories.

Constraints which are updated shall include items which are not allowed during the period of the constraint or, which are allowed only in a fashion which is limited to normal operations. Updates shall include definition of the constraint and the duration of the constraint. Mode shifts or reconfigurations, as well as subsystem performance and schedules, are examples of items which may be constrained.

Schedules which are updated shall include maintenance and mode shift schedules for the subsystems. The integrating controller shall update those schedules based on the integrated needs of the Space Station, its crew, its missions, and any anomalies which exist. Updates shall include the definition of the schedule change the duration of the change.

In the event that no update of priority, constraint or schedule is generated for a given iteration of the integrating controller, an output shall be issued to indicate no change to the appropriate subsystem controllers.

The integrating controller shall assess the overall state of the Space Station for each iteration and shall issue the above identified change commands to subsystem controllers on the completion of each iteration.

The integrating controller shall determine if an emergency state exists on the Space Station and shall issue commands to the subsystem controllers and to an on-board alarm system.

To determine if an emergency state exists on the Space Station, the integrating controller shall use subsystem state inputs, astronaut inputs, direct sensor input data, and trend data as well as outputs from state and predictor simulations.

If an emergency condition is detected, the integrating controller shall issue commands to the subsystem controllers to configure the Space Station as appropriate for survival of the crew, and to the extent possible for survival of the missions. The integrating controller shall alert and direct the crew through the on-board alarm system and shall issue appropriate data to the ground automatically.

The integrating controller shall provide diagnostic information and advisory data to the crew on request. The controller shall provide explanation of all change commands on request, and the controller shall automatically provide emergency information to the crew at safe haven displays.

The integrating controller shall utilize computing and mass memory equipment which is part of the Space Station data management subsystem. The equipment used by the integrating controller shall be capable of performing the integrating controller functions after any single fault within that equipment.

2.3.9 Technology Needs/Benefits

The objective of this section is to identify the appropriate technologies for implementing the integrating controlled concepts. In addition, a discussion will be included concerning quantifiable attributes of these technologies.

2.3.9.1 Simulation Models

The keys to developing the integrating controller are: the ability to develop effective models of the subsystems and the Space Station, and the ability to develop effective decision making expert systems. For the models, this involves selection of an adequate model development language, determining how to assess the accuracy of the models, and how to translate the models into softwares suitable for real-time control. Without building any models this is a 3 to 6 man-month effort. To develop an experimental model of a Space Station subsystem and convert for real time use is a 1 to 2 man-year effort. The number of subsystems multiplied by 2 man-years each gives an indication of the scope of effort to develop subsystem models. The prediction modeling effort would be at least as much as the subsystem modeling but would also involve the use of expert system technology.

2.3.9.2 Background on Expert System Technology

A software system, including expert systems, can be viewed as comprising the following conceptual hierarchy:

1. Software system
2. System development tools
3. Language
4. Operating system
5. Hardware

The expert system R1, which configures VAX computers, illustrates this hierarchy. R1 itself corresponds to level 1. According to Reference 3, the original version of R1 was implemented using the expert system development tool OPS4, which corresponds to level 2. OPS4 is written in MACLISP, which corresponds to level 3. Reference 3 does not identify the operating system used. The hardware used (level 5) is a PDP-10.

Part of the process of designing an expert system is making the appropriate choice at each level of the hierarchy that is not otherwise constrained by system requirements. Software technology experts believe that the choice of development tools at level 2 is particularly critical. In the case of expert systems, the metrics of most interest are generally the following:

- number of rules
- memory used
- computer (which implies MIPS)

2.3.9.3 Discussion of Expert System Metrics

Based on experience, the following metrics for an IC are "guestimated." Approximately 1000 to 5000 rules will be required. The computer used should run at about 2 MIPS and have from 1 to 4 megabytes of memory.

Reference 4 provides some data on the level of effort required to develop R1. Essentially, R1 was developed over a four year period at a rate of about 850 rules per year. There was an expenditure of about 4 man-years of effort per year. Based on these figures and the estimates of the preceding paragraph, an IC will require from 1.25 to 6.25 years to develop and from 5 to 25 manyears of efforts.

2.3.9.4 Expert Systems Technology Gaps

The objective of this paragraph is to identify the technology gaps that must be closed before expert system technology can be applied to the problem of IC's for manned space stations. The following paragraphs describe specific technology gaps.

2.3.9.4.1 Development Tools

The use of expert system development tools is essential if an acceptable level of productivity is to be achieved during the development process. Unfortunately, most existing tools are not suitable for developing an expert system. They suffer from three general types of deficiencies.

First, existing tools are designed to handle static rather than dynamic situations. An IC, of course, requires the ability to monitor and respond to situations that develop over time.

Second, most tools interface very poorly with existing software or software based on conventional rather than AI principles. A successful IC will require a blend of conventional and AI techniques.

Third, and related to the second deficiency, most existing tools are designed to interface with a human user rather than other systems. Clearly, the latter capability will be required in an IC.

2.3.9.4.2 Hardware

Currently, no AI hardware is available that is suitable for "field" use such as on a space station. This problem may correct itself in the future since TI has announced the development of a compact Lisp machine for the Navy.

2.3.9.4.3 Methodology

Existing expert system technology has been generally applied to fairly stable, comparatively well understood technology. If the Space Station involves significant amounts of novel technology, it will be very difficult to apply existing knowledge engineering techniques.

2.3.9.4.4 Personnel

Industry's intense recent interest in expert systems has created a shortage of experienced knowledge engineers. This lack of personnel will probably hinder the application of expert system techniques more than the more technology-oriented gaps discussed in the preceding paragraphs.

2.4 Summary of Trade Study Comparisons and Technology Selection

The purpose of this section is to discuss the comparisons that have been made of the technologies suggested to support implementation of an integrating controller concept. The purpose of the comparisons is to provide the basis for prioritization and selection of technologies that are recommended for advancement.

Section 2.3.9 suggests several technology areas needed for implementation of the integrating controller concept. The following is an unranked listing of those suggested technologies.

- o Developing effective simulation models
- o Adapting expert systems to real time operations
- o Developing expert systems that interface well with conventional software

- o Developing knowledge engineering techniques to cope with emerging technologies
- o Space-qualified compact LISP computer

2.4.1 Comparison of Technology Candidates

The technology candidates suggested above were compared on the basis of three general criteria topics. These three topics are: (1) Schedule pressure or the urgency of initiating the advancement of the candidate in order to support a mid-1990's Space Station system; (2) General usefulness of the technology including usefulness on the Space Station as well as usefulness to other applications; and (3) The benefits to advancement cost ratio for the candidates.

2.4.1.1 Schedule Pressure

The comparisons of schedule pressure have considered the following: (1) The anticipated duration of the advancement program, (2) contributions from other advancement activities such as the DARPA strategic computing initiative program, and (3) the anticipated need date of the technology.

For the simulation model advancement, we assume eight subsystems (the five considered in this study plus controllers for EC/LSS, mission functions and operations functions of the Space Station). This subsystem modeling could not reasonably advance until some definition of the Space Station has been established. This means that modeling of subsystems would probably start after the phase B effort is complete. From that point, a two year simulation effort seems reasonable for the subsystem models. Once the models have been completed they need to be integrated. After integration the predictor modeling can be established. The effort following the completion of subsystem modeling could easily run another two to three years. Validation and verification effort would be an additional two years. The total duration of the simulation modeling effort for the integrating controller would easily stretch from the present to 1994. This indicates a tight schedule for this advancement since the need date has been indicated as the mid-1990's. Because Space Station modeling is unique, efforts by other advancement agencies such as DARPA are not applicable. The schedule pressure is therefore high for this technology.

For the technologies associated with adapting expert systems to real time operations the advancement seems to be independent of Space Station unique functions so the 6.25 years identified in paragraph 2.3.9.3 seems appropriate. This indicates a technology availability by 1992 if the advancement starts in 1985. Because the DARPA strategic computing initiative is intended to address this technology, it is likely that advancement effort will be started in the near future. For these reasons the schedule pressure for this advancement candidate is relatively low.

There is a unique aspect to developing expert systems that interface well with conventional software; the conventional software needs to be defined first. This means that Space Station technology cannot advance until the simulation software is well along. We have concluded that it will be about five years after phase B is complete before the simulation models are likely to be ready for validation testing. The start point for integration with expert systems could only be a few years prior to that. If we add the 6.25 years of paragraph 2.3.9.3 to that we have 1995 or 1996 for availability of the technology. It is true that some of the generic background for this technology could come out of the DARPA study so perhaps the 6.25 years is pessimistic. Let us say 4 years so we may be looking at 1994 for this technology which also puts it in the high schedule pressure category.

The technology of developing advanced knowledge engineering procedures can be pushed independent from the Space Station design. It is also true that the DARPA study intends to consider this area so Space Station may benefit. It appears that the schedule pressure is lower than any of the other candidates.

Developing a space qualified compact LISP computer is a candidate which has a fairly long expected duration for advancement. It is reasonable to expect a full 5 to 6 years for such a program. It could however be started early and might benefit from the computer development part of the DARPA study. It appears that a 1990 or 1991 availability is likely if the program were started in 1985 so the schedule pressure is moderate.

Based on schedule pressure, the candidates rank from highest pressure at the top toward lowest pressure at the bottom as follows:

1. Expert systems interface with conventional software.
2. Simulation modeling.
3. Space qualified LISP computer.
4. Real time expert systems.
5. Knowledge engineering advancement.

2.4.1.2 General Usefulness

General usefulness consists of two parts: (1) usefulness of the technology to the integrating controller and (2) usefulness of the technology to other parts of the space station and other parts of the technical community.

For the simulation model advancement the usefulness to an automated integrating controller is unquestionable. It is, however, possible for an interim version of the integrating controller to be deployed which essentially makes decisions based on data inputs, trends and astronaut inputs. The mid 1990's integrating controller is likely to be the interim version so the usefulness of the simulation models is somewhat deferred. The general usefulness of real time and faster than real time modeling for the general advancement of automation and robotics has been recognized by investigators such as NASA's Advance Technology Advisory Committee. The general usefulness of this technology candidate is therefore on the high side of moderate.

Real time expert systems are essential even to the interim integrating controller mentioned in the previous paragraph. The general usefulness of the technology is indicated by DARPA's attention to it in their strategic computing study. This candidate places higher than the simulation modeling on the general usefulness list.

The technology of interfacing expert systems with conventional software has benefits for other users as well as application to initial versions of the integrating controller. The application to interfaces with simulation software, however, would not be essential for the interim integrating controller as was discussed above. This candidate is probably as high on the list resulting from general usefulness comparisons as the real time expert system software.

The effective knowledge engineering advancement has obvious general utility; it is included in the DARPA strategic computing initiative. The usefulness to the integrating controller for the Space Station is not unique and may not be significant until several years after IOC when rapid Space Station changes emerge. This candidate is considered to be moderate on the general usefulness list.

The space qualified compact LISP computer has little use to the general user community. The integrating controller could conceivably be implemented using a conventional computer by converting expert system code to conventional code. Such a practice would add time to the implementation of an integrating controller and would therefore not be desirable. However, it would be possible to deploy an interim integrating controller without an on-board LISP machine. This candidate is at the bottom of the general usefulness comparison list.

Based on the general usefulness comparison then the candidates rank as follows:

1. Real time expert systems
2. Expert systems that interface with conventional software
3. Simulation modeling
4. Knowledge engineering advancement
5. Space Qualified LISP Computer

2.4.1.3 Benefits to Advancement Cost Ratios

The benefits resulting from an on-board integrating controller over the first ten years of Space Station operation were estimated in the previous study phase and no new information has been developed in this phase. The estimate is described in some detail by paragraph 5.3.8 of Boeing document D180-279354-2 but Table 2.4-1 is included here to summarize the benefits estimate metrics.

Table 2.4-1. Integrating Controller Benefits Estimate

- Monitoring effort phased out over five years
  - First year full mission control center coverage
  - Second through fifth years—mission controllers reduced by 5
  - After fifth year—mission controller and onboard monitoring reduced to 1/10 time for each
- Labor rate for mission controllers is $1500 per day and astronaut is $77,000 per day
- Efficiency and maintenance cost savings is $2.5M per year
- The integrating controller provides half of total benefits = $54M for ten years.

Table 2.4-2. Technology Advancement Cost Estimates

- o Developing effective simulation models
  - o 2 man-year effort per model X 8 models = 16 man-years plus real time simulation development costs = $2.0M
- o Adapting expert systems to real time operations
  - o Estimate 4 man-years to adapt DARPA results to I.C. usage = $480K
- o Developing expert systems that interface well with conventional software
  - o Estmate DARPA results require a ten man-year effort to adapt software concepts to I.C. use = $1.2M (note: $2.04M effort under technology definition includes effort to integrate software with Space Station processors)
- o Developing knowledge engineering techniques to cope with emerging technologies
  - o Estimate DARPA results plus 2 man-year effort to adapt to Space Station usage = $240K
- o Space qualified compact LISP computer
  - o Estimate $4M development and testing effort in addition to DARPA work

The advancement costs have been estimated and are reported in some detail in volume III of this report. Table 2.4-2 summarizes the estimates.

The estimates of Table 2.4-1 need to be partitioned according to the contribution of the technology candidates to the integrating controller. Using the general usefulness considerations for the integrating controller as a guide we can conclude that simulation modeling would receive slightly more than one fifth of the $54M, because it is somewhat higher than moderate ($12M).

Real time expert systems is considered essential for the integrating controller so its share should be significantly greater than one fifth ($18M). The technology for interfacing is nearly as significant as the real time expert systems ($15M). This leaves $9M for the remaining two technologies. The LISP computer seems more crucial to effective implementation of an integrating controller than does the knowledge engineering ($8M) and the remaining ($1M) for knowledge engineering.

Taking the advancement cost figures from T[illegible] 2.4-2 gives ratios shown by Table 2.4-3 in rank order from highest to lowest.

Table 2.4-3 Benefits/Cost Ratios

	Candidates	Benefits /Cost
1.	Adapting expert systems to real time operations	37.5
2.	Developing expert systems that interface well with conventional software	12.5
3.	Developing effective simulation models	6.0
4.	Developing knowledge engineering techniques	4.17
5.	Space Qualified Compact LISP Computer	2.0

2.4.2 Prioritization of Technology Candidates

Based on the comparisons discussed in the previous section the five technology candidates for autonomous functional control can be prioritized as indicated by Table 2.4-4.

It should be recognized, however, that the efforts planned in volume III of this report are essential if an integrating controller is to be available for a mid 1990's Space Station. If the DARPA strategic computing initiative is not started or is delayed by a year or more all five of the technol candidates should be pursued.

Table 2.4-4 Prioritized Technology Candidates

Candidate	Sched	Use	Benefit/Cost	Combined
Expert systems that interface well with conventional S/W	1	2	2	5
Adapting Expert Systems to Real Time Operations	4	1	2	6
Simulation Modeling	2	3	3	8
Knowledge Engineering Tech.	5	4	4	13
Space Qualified LISP Computer	3	5	5	13

2.5 CONCLUSIONS

The conclusions that can be drawn from the study reported here are that several technology advancements are necessary if an automated integrating controller is to be part of the Space Station system. The urgency of NASA initiatives in each of these areas is tempered somewhat by the DARPA plans described below

The Defense Advanced Research Projects Agency (DARPA) has plans to establish a Strategic Computing study (reference Strategic Computing, New Generation Technology: A Strategic Plan for Its Development and Application to Critical Problems in Defense, AD-A141982.). In this study the development of basic artifical intelligence technology is planned, including real time expert systems. This will be a large program in which 6 to 10 research centers across the country will be established with a staffing of approximately 100 professionals each. Funding was planned to be $50M for FY84, $95M for FY85, $150M for FY86, and unspecified amounts for the out years. The total amount for the first three years was planned to be nearly $300M. Schedules show the development of a real time capability by 3rd quarter FY90. An initial one third to one half real tim~ capability was shceduled for completion in 4th quarter FY86.

Because the technologies associated with adapting expert systems to real time operations and the advancement of techniques for knowledge engineering are significant parts of the DARPA study, and because those two candidates have limited connection with the unique characteristics of the Space Station, this add-on study has not developed advancement plans for them.
The three advancement candidates that are being considered in the advancement planning for this add-on task will also benefit from the DARPA study. The effect of that benefit will be an improvement in the benefits to cost ratios for the candidates as was dicussed in paragraph 2.4.1.3 above. If the DARPA study proceeds immediately there may also be a schedule benefit for the candidates identified here. It will be necessary for NASA to be in close contact with the DARPA study to insure that the advancements produced are applied to the Space Station in a timely manner. It will also be necessary to adapt the DARPA results for Space Station use and that will be facilitated by close contact with the development of those results.

The general conclusions listed in paragraph 5.5 of the final report from the previous study phase are still valid and are repeated here for completeness.

1. The integrating controller has real and useful functions on a Space Station.

2. The implementation of the controller would profit from expert systems programming.

3. The implementation will be phased and updated during the early years of the Space Station operations.

4. The costs are high but so are the benefits.

5. This technology advancement is essential if the Space Station autonomy/automation philosophy is to be implemented.

2.6 RECOMMENDATIONS

The recommendations of this add-on study are: proceed with the technology development for the subsystem simulations, proceed with the predictor simulations for the integrating controller, adapt the results of the DARPA study to the other four technology candidates, have a significant parallel effort to interface expert systems with conventional software for the integrating the controller, and have a significant parallel effort in space qualification of a compact LISP type computer.

Volume III of this report includes a section that defines a plan for development of three technology candidates for implementation on a Space Station during the mid 1990's which do not appear to be adequately covered by the DARPA study.

2.7 REFERENCES

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3.0 ATTITUDE CONTROL IMPACT FROM STRUCTURAL DYNAMIC MOTIONS

3.1 INTRODUCTION

3.1.1 Summary of Previous Study Results

The objective of the previous study phase was to initiate the identification of technologies required for the solution of the control-structure interaction problem in Space Station design. The approach was to determine, through analysis and simulation, the degree to which conventional controller technology is applicable to attitude regulation of a space station with large flexible solar arrays.

At the outset of the study, it was surmised that attitude stability might be jeopardized when the control band interacted with the flex modes. However, analysis has shown that when the modular station core station can be assumed rigid with respect to the required control bandpass, then the controlled response is asymptotically stable when the sensors and actuators are collocated anywhere on the core. A simulation of the flexible station and a control system consisting of band limited multiple two axis double gimballed CMGs and attitude position and rate sensors was implemented. The attitude response of the system to impulsive disturbance verified overall stability and showed substantial improvement in the damping of structural vibration in most cases. A modal survey analysis (reference 1) indicated that controllable normal modes contain motions of all structure elements with the exception of twist of the solar panels. The time responses support this claim and would indicate that torsional vibrations of the solar panels are not controllable with torquers and angular motion sensors mounted on the rigid core as expected.

The previous phase of the study considered only the anti-symmetric modes of vibration. This was justified under the assumption that the disturbances were manifest as pure couples. This assumption is not valid since the most frequent source of disturbance is derived from crew activity which imparts both force and torque to the vehicle. Figure 3.1-1 defines symmetric and antisymmetric bending modes. The sketch depicts typical normal mode shapes for a simple structure where the mass of the solar arrays are concentrated at the tip of the boom. Symmetric and antisymmetric bending is excited by forces and torques respectively as shown. The actual motion of a multiply connected set of flexible appendages is of both types of bending.

3.1.2 Current Study Objectives

The objective of the current phase of the study will be to extend the efforts of the previous study to include symmetric mode analysis, elemental structure damping, active controller evaluation and incorporation of stiffer structure in the solar array design. Accordingly, a detailed evaluation of Space Station control and dynamic performance in the presence of structural interaction excited by orbiter berthing operations and crew activity was performed. Control requirements for the symmetric modes were derived and motion of the flexible appendages was studied in detail. The uncontrollable modes identified in the previous study phase were controlled by selected techniques including passive and active stabilization. Passive stabilization of solar array torsional vibration focused on the design of discrete viscous damping mechanisms in the astromast structure. Active torsional vibration suppression considered the use of the beta tilt and sun tracking actuators. Variations to the existing structural configuration considered alternate solar array deployment schemes which offer substantially stiffer structures in torsion.

3.1.3 Overview

In the following sections the results of the analysis and simulation tasks are discussed. Section 3.2 presents the details of the technical approach. The subtasks are introduced and the technical objectives are stated. The analysis and simulation results are discussed in Section 3.3. Section 3.4 summarizes the significant results. Conclusions and recommendations are presented in sections 3.5 and 3.6. References are given in section 3.7.

3.2 APPROACH

3.2.1 Summary of Current Structural Configuration

The structural model developed in the previous phase of study will be reviewed here. This brief discussion will help to establish a reference for subsequent discussions.

A pictorial view of the study configuration is shown in Figure 3.2-1. This configuration represents the all-up fully evolved configuration with SEPS type solar panels partially deployed. Each boom center pivots two panel sections, each section containing four

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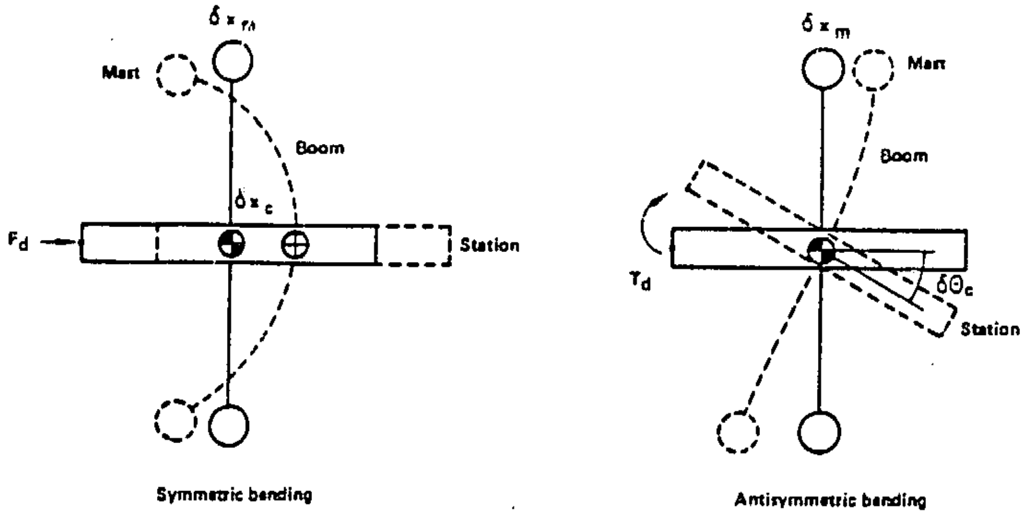

Figure 3.1–1. Definition of Symmetric/Anti-symmetric Bending

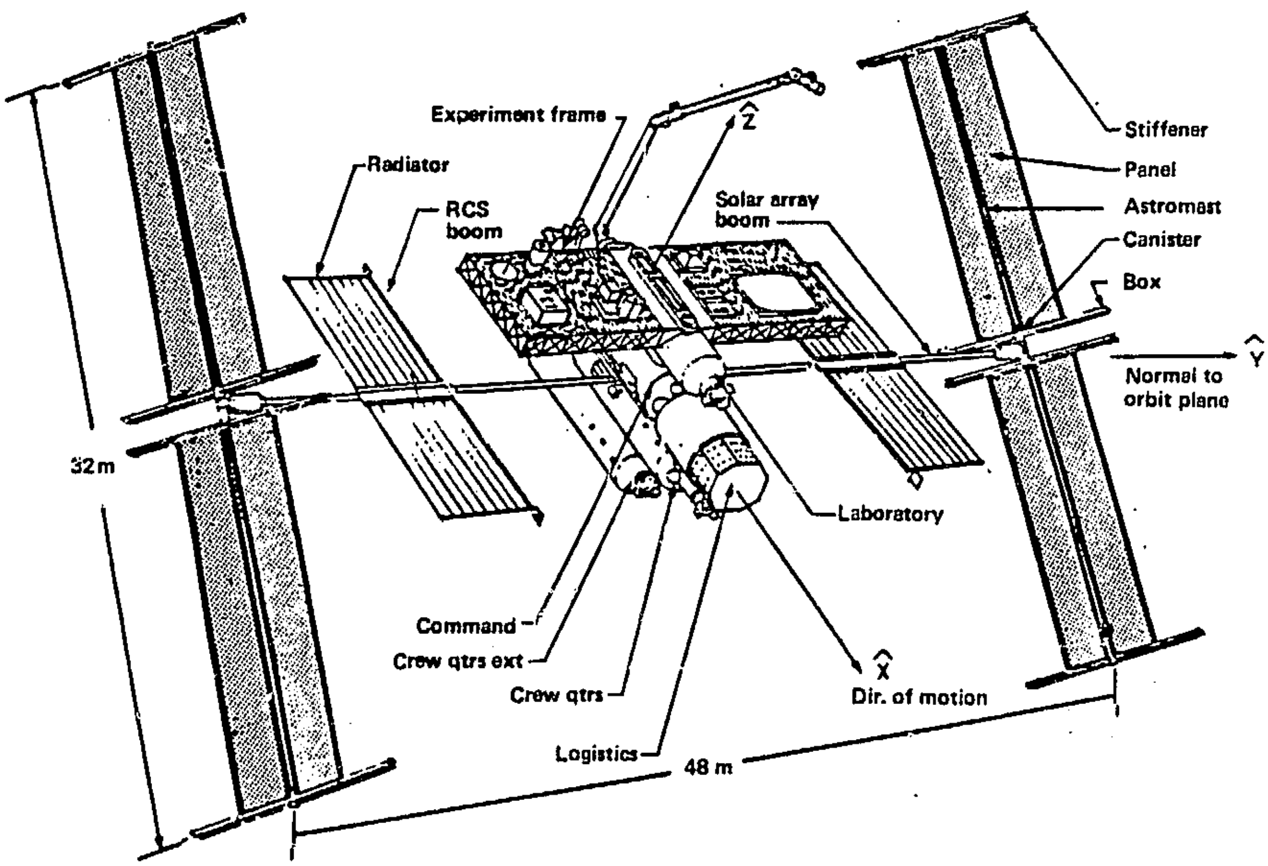

Figure 3.2–1. Balanced Array Concept Astromast Deployment for NASTRAN Analysis

separate blankets. The blankets are deployed along cables attached to the stiffer end plate. Section properties and dimensions for all structural elements are given in Table 3.2-1.

The solar array booms were modeled as graphite/epoxy tubes, 24 meters long. The solar array astromasts were modeled as triangular trusses with a design by AEC-ABLE called Continuous-Longeron Able Boom. Sizing of the boom and astromast was done assuming a maximum static load of 0.1g.

The five modules were assumed to be rigid bodies with flexibility at their connection points with each other and with the orbiter. The stiffness at the ends of the modules was computed separately for the module and for the docking tunnel, then springs in series were assumed and the stiffness for the module including the docking tunnel was computed.

The masses of all the structural members are uniformly distributed along their lengths. The masses of the solar panels are lumped half at either end of the astromasts and mass moments of inertia are added to reflect the actual mass distribution. The module masses are lumped at their c.g.'s with moments of inertia to reflect the actual mass distribution.

The Space Station mass properties for the test configuration is given in Table 3.2-2. The principal axis basis vectors are the columns of matrix M.

3.2.2 Statement of Tasks

The following four tasks were performed with the structural configuration using SEPS type solar arrays as described above. The fifth task requires modification of the current configuration to include arrays with improved structural properties to be described in discussions to follow.

3.2.2.1 Loads and Motions Analysis

The current formulation of the model for the crew activity forcing function assumes a pure torque couple about the center of mass with no resultant translational forces through the center of mass. This task incorporates the capability to apply both forces and torques at any desired point of application on the structure and to monitor the

Table 3.2-1. Flexible Element Section and Material Properties for Space Station

MEMBER	NASTRAN ELEMENT	DESCRIPTION	MATERIAL	A(m^2)	I(m^4)	J(m^4)
Array Boom	Bar	Tube d = .381m t = .0025m	GR/EP	2.99E-3	5.43E-5	1.09E-4
Astromast	Bar	triangular truss d = 9.E-3m h = .3m	6-GL/EP	1.91E-4	3.82E-6	3.82E-6
RCS Boom	Bar	Tube d = .254m t = .0005m	GR/EP	3.99E-4	3.22E-6	6.44E-5
Cannister	Bar	Tube d = .302m t = 7E-4m	GR/EP	7.08E-4	7.57E-6	1.51E-5
Box	Bar	Tube d = .13m t = 5E-4m	GR/EP	2.03E-4	4.22E-7	8.44E-7
Stiffener	Bar	Tube d = .1m t = 5E-4m	GR/EP	1.56E-4	2.1E-7	4.2E-7
Cables	Red	Cable d = .001m	CELION	7.85E-7	NA	1.E-11

Material Properties

Celion Fiber Cables	E = 172E9 N/m^2	
S Glass/Epoxy	E = 52E9 N/m^2,	G = 6E9 N/m^2
Graphite/Epoxy	E = 108E9 N/m^2,	G = 15E9 N/m^2

Table 3.2-2. Mass Properties of Space Station

Quantity	All-Up Configuration	Units
I_x	2.85	
I_y	3.32	$Kg\text{-}m^2$ x 10^6
I_z	3.00	
I_{xy}	0	
I_{xz}	.36	$Kg\text{-}m^2$ x 10^6
I_{yz}	0	
$m^{(2)}$	94011	Kg
$x^{(1)}_{cg}$	1.38, 0, .628	meters
I_p	3.30, 3.32, 2.55	$Kg\text{-}m^2$ x 10^6
	.632 0 .774	non M 01 0dim -.7740.632

NOTES

(1) cg location with respect to node d, the attach point of the solar panels, cf fig. 3.3-1.

(2) The total mass of the solar panels is 1652 Kg. The total area of the solar panels is 1111 m^2.

resultant state vector (rotational plus translational states) and accelerations at any selected point of interest. Simulated acceleration data at selected body stations are derived. These data are used to establish control requirements as a function of acceptable levels of acceleration.

The crew activity profile is formulated to accentuate the uncontrollable modes to the extent that sustained or increasing levels of vibration in various structural elements especially the solar arrays, is evident.

3.2.2.2 Passive Vibration Suppression

The uncontrolled vibration in the solar array structure is damped by introducing discrete passive torsional control elements at either end of the mast. Design concepts for both tip and root mounted dampers are presented and feasibility for space application is discussed. It is noted that mechanical vibration dampers act on relative acceleration, velocity and position in terms of mass, damping factor and spring rate and therefore qualify as collocated sensor-actuator pairs. In this regard there is no apparent distinction between passive and active control when the active control is a collocated electromechanical measurement-actuator pair. Active control is usually defined in terms of electromechanical sensing and actuation, the extension being the capability to spatially separate the two functions.

3.2.2.3 Active Vibration Suppression

Active stability augmentation when applied to a large structure like Space Station should incorporate both aspects of performance and vibration suppression. The issue of performance deals with the pointing of multiply connected flexible bodies where the terminal bodies have different pointing requirements. The terminal bodies in this case are the core station and the solar arrays, the core station being rigid at control frequencies of interest and the solar panels extremely flexible. The control objective for performance would be to shape the closed loop response such that motions of core and solar arrays are decoupled. This would imply for example, that disturbances due to crew activity would impart motion to the core but would tend to keep the solar panels fixed with respect to the sun. The approach used here will be to apply the technique of eigenstructure assignment (reference 3.7-2) where both poles (stability augmentation) and zeros, or more appropriately the eigenvectors, (performance augmentation) are specified in a limited sense and closed loop gains computed accordingly. The actuator package includes a three axis linear core mounted torquer, solar array sun tracking and beta tilt actuators. The sensors include a core mounted rotational sensor package, and rotational motion measurements at critical locations on the flexible elements. The preliminary design of an active vibration suppression is presented where collocation of sensors and actuators is not a constraint. Sensor and actuator functional requirements will be highlighted and computational requirements are discussed.

3.2.2.4 Vibration Suppression of Symmetric Modes

The current Space Station is configured such that attitude control with torque actuators alone cannot control the symmetric modes of vibration. Symmetric bending of the flexible appendages, after referred to as the "butterfly mode", is manifest as motion where the core translates in a direction opposite the solar panels. A symmetric mode vibration suppression system was designed using a low thrust reaction jet control system. The control objective was to null translational rates of the boom and mast relative to the core using resisto jet controllers mounted on the solar panel booms as shown in Figure 3.2-1. The working fluid is specified to be carbon dioxide which is assumed plentiful in a fully operational space station. The control requirements are derived and the feasibility for application to space station is discussed. The use of reaction jets for flex body control is documented in the literature. However the application to active vibration suppression of large space structures is believed to be new. This mode of control is investigated as an alternative to redesign of the boom and mast servoactuator system. It is noted that translational control can be realized with torques if the solar panels can be independently torqued about all three vehicle axes.

3.2.2.5 Modeling of Stiffer Solar Array Structures

Stiffer solar array structures are incorporated into the existing elastic model. The basic core structure remains unchanged from the reference configuration shown in Figure 3.2-1. The solar array configuration is typical of the design concepts of current interest at Boeing. The control and dynamic performance of the structure is evaluated assuming core mounted linear torquing actuators and rotational motion sensors. The objective is to attempt a reduction in the amplitude of the uncontrolled solar panel modes without introducing other serious side effects. Such an effect would be increased level of acceleration at the modular core due to a significant solar panel mass increase. The implications of stiffer solar array structure are examined and application of the given design to Space Station is discussed.

3.3 TECHNICAL DISCUSSION

3.3.1 Station and Solar Array Regulation Strategies

A principal purpose of the vibration suppression study is to examine the amount of damping induced in the flexible elements as a matter of course in the positioning of the station and solar panels. The basic concept then, is to treat the problem as the design of five independent rigid body controllers with collocated and coordinated sensors and actuators at the hinge points. A variation to this strategy would require decoordination of sensors and actuators in an attempt to decouple the dynamics of station core and solar panels.

3.3.1.1 Relative Positioning

A relative positioning strategy implies that the panels track the sun in elevation and azimuth by commanding a position profile perhaps through a rate command with periodic position updates to account for rate sensor errors. This strategy would use shaft tachometer and position measurements collocated with the actuators as state variables to be regulated. Since the tilt angle for sun elevation has yearly variation, the tilt actuator could be locked and activated only at discrete intervals. If the tilt actuator is locked, some passive augmentation of the panel torsional modes is required. Locking the roll actuator then serves to justify the investigation of passive means to control the uncontrollable panel torsional modes. The relative positioning strategy is reasonable if panel and station pointing requirements are compatible.

3.3.1.2 Absolute Positioning

An absolute position strategy implies that the panels track the sun in elevation and azimuth by regulating panel attitude through the use of sun sensors. The rate loop could be implemented either by direct rate measurement or a derivation resulting from base (core) rate and shaft tachometer signals. The latter measurement set represents a controller decoordination and system stability must be considered. Further refinements to attempt base motion decoupling results in a decoordinated controller and here again

C - 2

system stability is a consideration. The absolute positioning strategy is reasonable if allowable base motion is far in excess of solar array pointing requirements.

3.3.2 Measurement and Controller Definition

A description of the static (panels fixed) configuration indicating the location of all input disturbances is provided to facilitate the following discussions. In addition, the control system composition for all passive and active controllers is given here for future reference. Accordingly, the location of the control system elements is shown in Figure 3.3-1. Test forces for crew activity were applied at body stations A, B and C. Docking tunnels exist at the end of the crew and crew extension modules via body stations A and C. The c.g. of the structure is approximately one meter from the boom centerline, body station D being the point of attachment of the boom to the raft.

The active controllers are the CMG cluster, sun track and tilt panel drive actuator. Measurements ϕ, θ, ψ indicate absolute (inertial) roll, pitch and yaw angular position and rate about body axes X, Y, Z. The sensors are collocated with the actuators. Measurements $\Delta\phi_b, \Delta\dot{\phi}_b, \Delta\theta_b, \Delta\dot{\theta}_b$ represent local (relative) angular position and rate as sensed by shaft position and tachometer sensors also collocated with the actuators. Points E, b and F indicate probable locations for sun sensors. Passive controllers were modeled as linear spring and dashpot elements and are located either at the root position (r) or the tip position (t). The root damper isolates the mast from the solar panel storage box, dissipating the energy of point (r) relative to point (b). The tip damper is tuned to the torsional frequency of the mast and dissipates the energy of point (t) relative to point (c).

The controllers evaluated for this study are given in Table 3.3-1. Controllers I - V are comprised of linear continuous elements, operating principally on the antisymmetric normal modes. The reaction jet control system operates exclusively on the symmetric normal modes. Controllers I - IV constrain all sensors and actuators to be pair wise collocated and measurements are derived from differenced absolute quantities. Control gains are computed to connect pairwise (local) sensor outputs to actuator inputs. Controller V requires that sensors and actuators be pairwise collocated. However, the measurements are all absolute quantities and crossfeed gains between spatially separated sensors and actuators are computed to provide augmentation for pointing performance and response of the rigid modes. It is noted that absolute positioning of the panels in roll

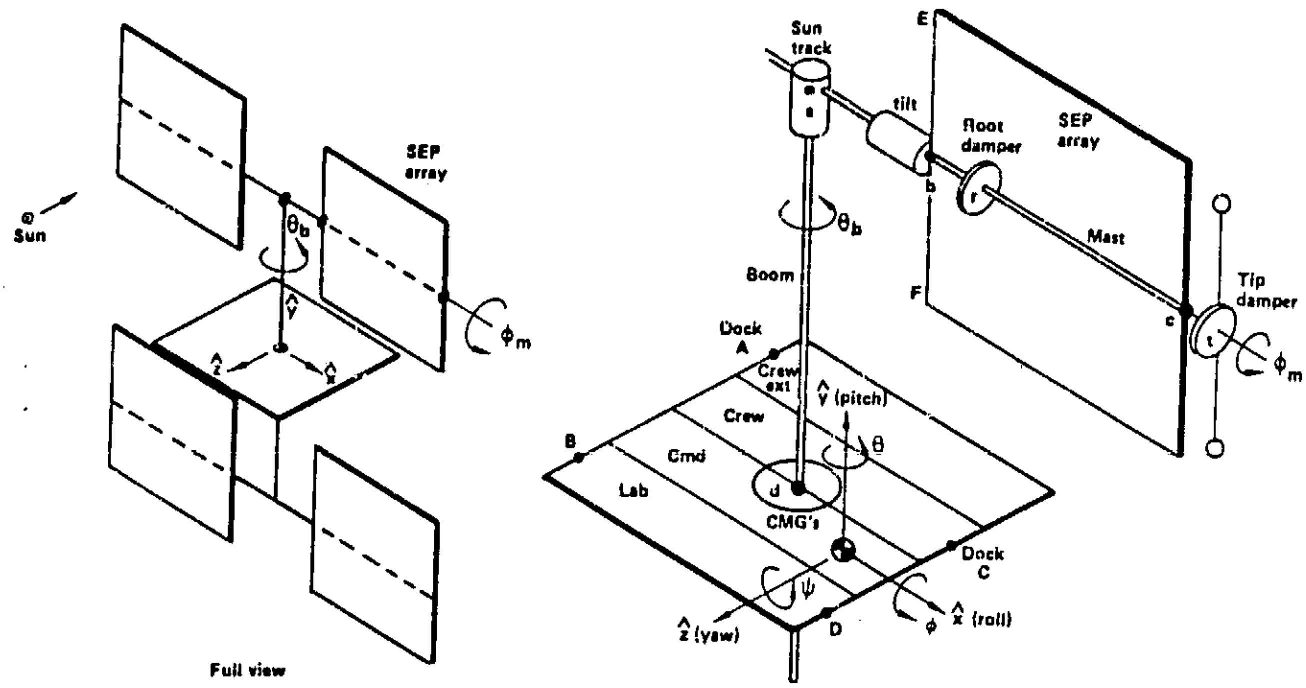

Figure 3.3–1. Loads and Motions With Colocated Linear Controllers

Table 3.3-1 Linear Controller Identification with Sensor and Actuator Specification/Location

Control Element	I	II	III	IV	V
<u>Actuators</u>					
CMG cluster	d	d	d	d	d
Suntrack actuator		a			a
Tilt actuator		b			b
Root damper			r		
Tip damper				t	
<u>Sensors</u>					
Rate gyros	d	d	d	d	a,b,d
Abs. angular position	d	d	d	d	a,b,d
Tachometer		a,b			
Rel. angular position		a,b			

Table 3.3-2 Indealized Impulse Imparted from Orbiter Berthing

Orbiter Approach Conditions	Body Station	Disturbance (Impulse) (N-m-sec)
Linear velocity = .030 m/sec	A	4000
Angular Velocity = .35 deg/sec	D	5000

would most likely receive position updates from sun sensor measurements at inboard tips at points E, F. The structure of the controllers and accompanying selection rationale will be discussed in the appropriate sections to follow.

3.3.3 Loads and Motions Analysis

The loads and motions study was formulated to investigate the uncontrolled motions of the flexible appendages when the station is attitude stabilized by core mounted linear torquers. The implication here is that dedicated vibration suppression systems are absent. A secondary objective was to compute the stress levels at the root stations of critical flex members during forced motion due to crew activity and orbiter berthing. The orbiter berthing operation was modeled as a simple impact shock and impulsive inputs were computed accordingly.

3.3.3.1 Disturbance Models and Profiles

Crew Activity Model

The disturbance profile for modeling crew activity is shown in Figure 3.3-2. The model represents an astronaut in a soaring maneuver within the Space Station. The motion is envisioned as being a pushoff from one wall and a deceleration on the far wall. The parameters of the motion are presented for a large astronaut in the flight within a module of about 12 feet in diameter. The resulting impulse disturbance is 40 n-sec for each element of the doublet. In order to establish a highest upper bound from all internal sources a value of F_0 = 100 N-sec was used for simulation and analysis.

Crew Motion Profile

The crew motion force and resulting torque profile is shown in Figure 3.3-3. Crew motions are assumed to originate at body stations A, B and D as indicated. Only forces along Z and Y are introduced since forces along X would imply crew mobility along the axial dimension of the module. Partitioning of the module prevents knowledge of the free flight time along with the realization that forces along Z will induce almost identical motions in pitch. However, the structural motions in the XY, and YZ planes do differ markedly although the panels are very stiff in the XY plane. The intent of the profile was to produce a set of crew motions that forced the structure at frequencies

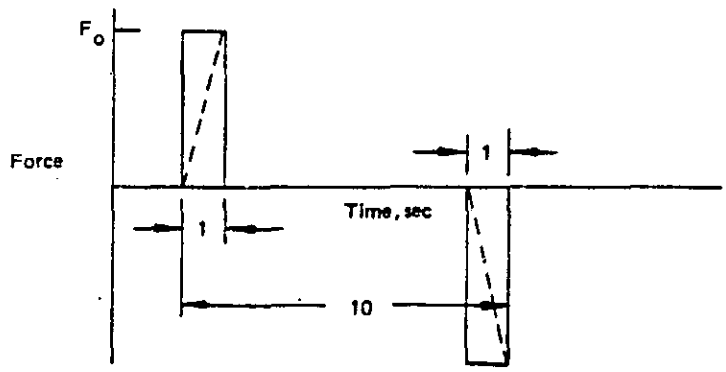

Figure 3.3—2. Disturbance Model for Crew Activity

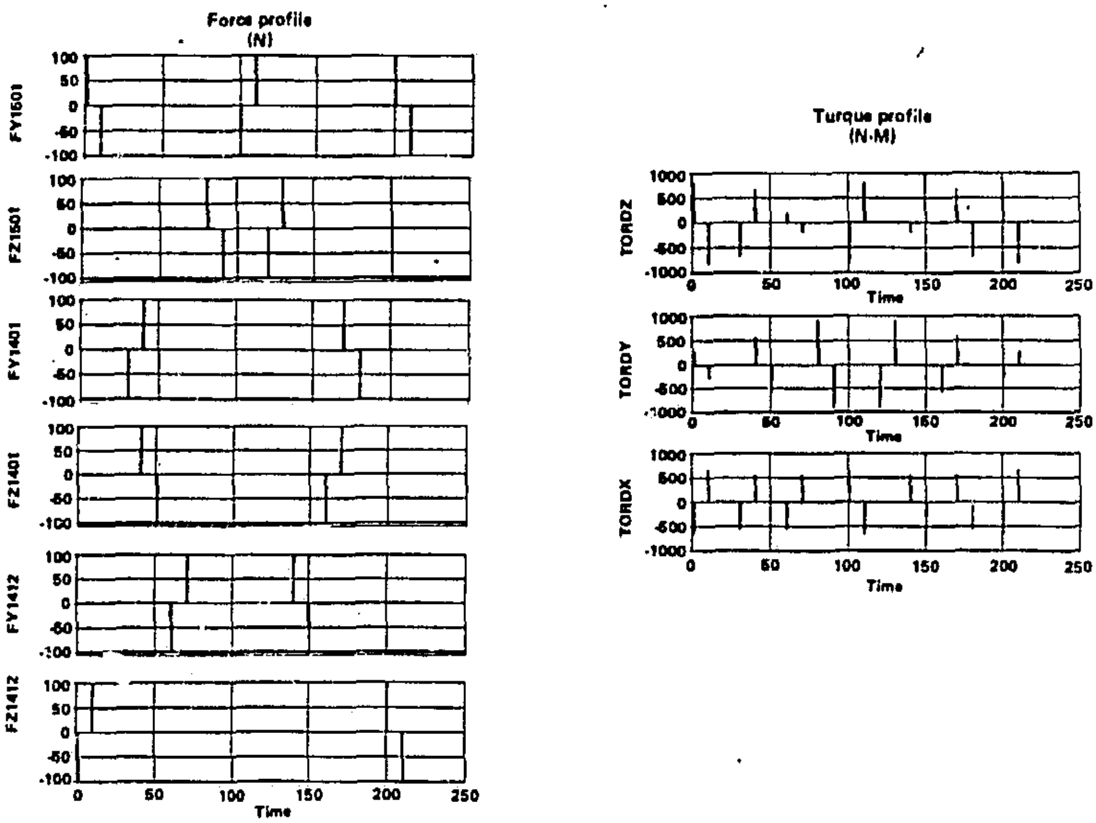

Figure 3.3—3. Crew Motion Force and Torque Profile

which corresponded with the normal modes, especially those modes which were the natural frequency of the solar arrays in torsion. It is also noticed that the resulting torque profile for each axis exhibits a somewhat random pattern in torque magnitude.

Docking Geometry

A schematic drawing of the Space Station with orbiter docked is shown in Figure 3.3-4. The longitudinal axis of the orbiter is assumed colinear with the yaw axis of the space station. The impulsive docking loads were estimated based on the approach conditions of the orbiter shown in Table 3.3-2.

3.3.3.2 Motions Analysis for Controller I

Response to Crew Motion

The acceleration response at remote body station A to the crew motion profile are shown in Figure 3.3-5. Open loop data represents the free response of the structure. Closed loop data represents the response with CMG controllers only. It is seen that without the controllers, the accelerations grow with time markedly, when the "energetic" crew profile is introduced. The closed loop results also indicate that accelerations along X and Z are growing at a very slow rate although it is not known whether or not the effect would be dissipated if the profile were truly random. Steady state accelerations are the largest along Y at A due to rotational effects induced by antisymmetric boom bending. The tendency for accelerations to grow in X and Z is due to uncontrolled symmetric boom bending induced by forces along Z and pitch coupling into X.

The appendage response to the crew motion profile is shown in Figure 3.3-6. The subletter designation indicates the rotation of the first letter with respect to the second letter, the letters representing points on the structure. Designations $\Delta\theta$,$\Delta\theta$,$\Delta\psi$ indicate local rotations about X, Y, Z at body stations. For example $\Delta\theta_{ad}$ represents the rotation of point a (boom tip) relative to d (boom root) about the vehicle X axis. The situation on the other side of the structure is similar although the signature will depend on the symmetry or antisymmetry of the motion. Open loop data shows that appendage motions grow without bound. Closed loop results would seem to indicate that bending and twist of the boom are boundable. However the twisting motion of the mast $\Delta\phi_{cb}$ is clearly growing with time. Residual bending motions of the boom and mast are again due to

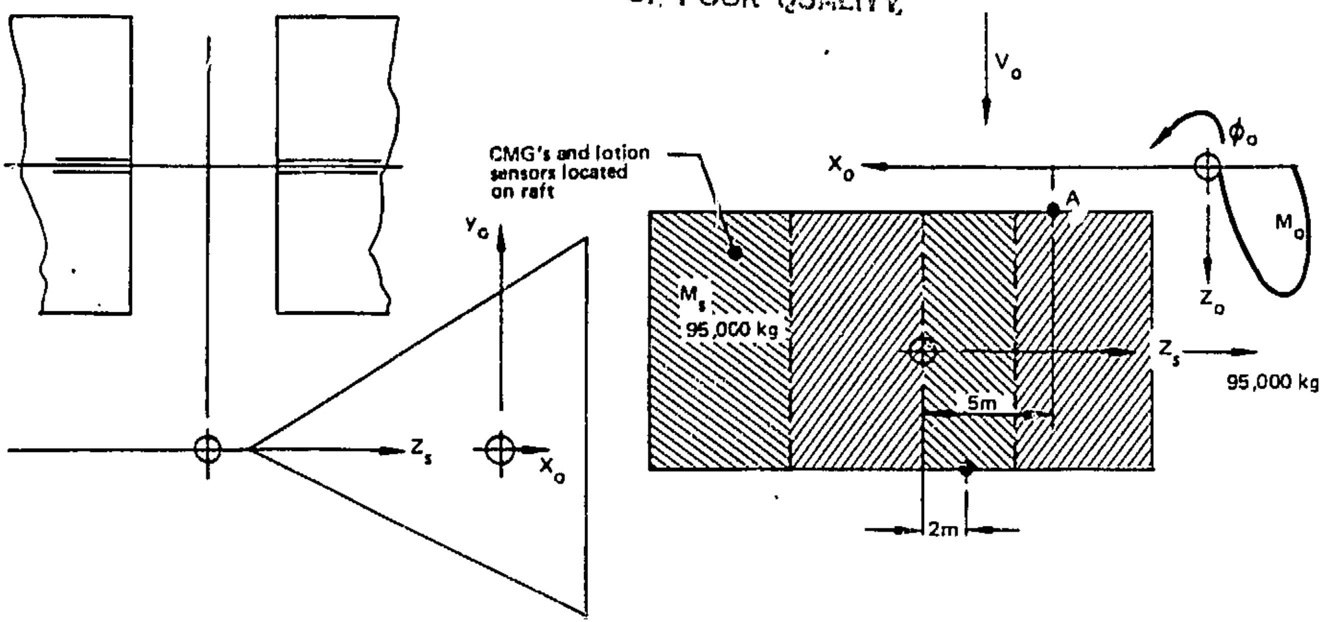

Figure 3.3–4. Berthing Configuration for Orbiter and Disturbance Impulse

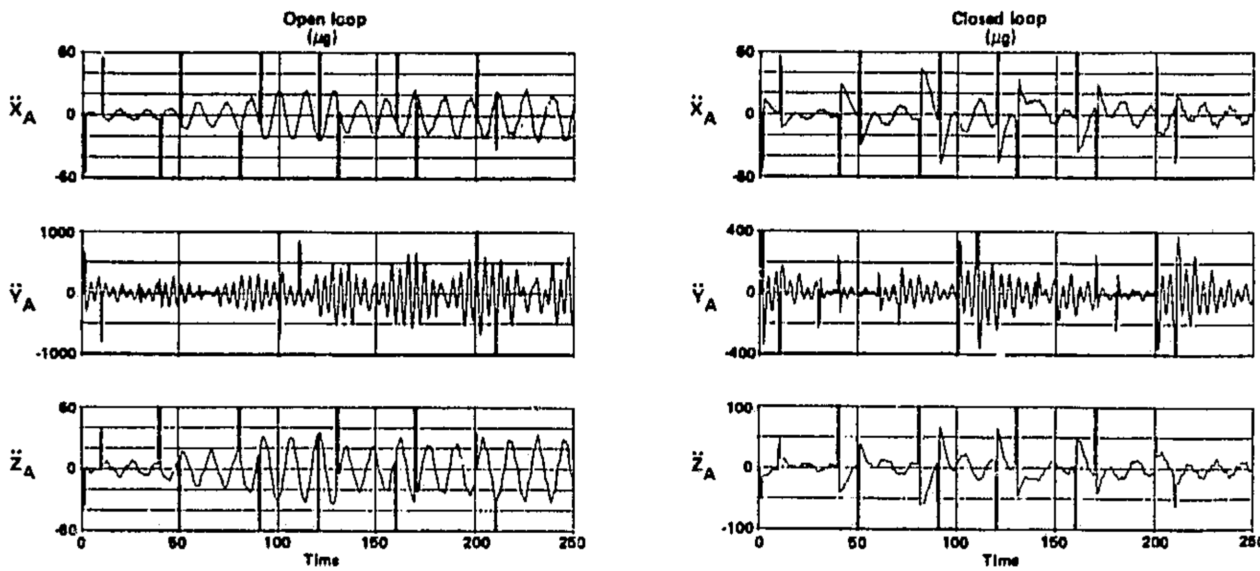

Figure 3.3–5. Station Acceleration Response with CMG Controller Crew Motion Profile Input, Servos Locked

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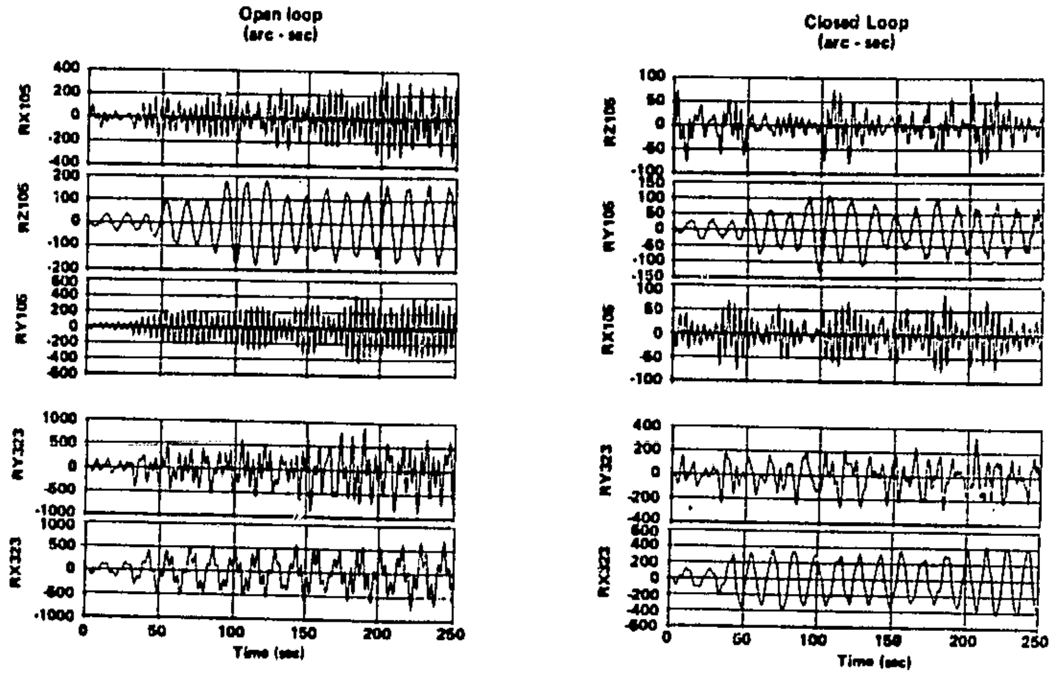


Figure 3.3–6. Appendage Response with CMG Controller Crew Motion Profile Input

uncontrolled symmetric mode motion due to force inputs. Note that the twisting motion of the boom is poorly damped and the twisting motion of the mast is virtually undamped.

Response to Orbiter Berthing

The response of the structure without control to a berthing impact at body station A is shown on Figure 3.3-7. The maximum transient acceleration is 10000 μg (.01 g) in X. The stress units are given in millions of N/m^2. Note that the stresses at the root of the boom and mast are well within the yield limits of the materials. The appendage motions are relatively large. However even the largest defection of 3000 arc-sec ($\Delta\theta_{tb}$), which represents the slope of the elastic curve at the tip of the mast given as a rotation about Y is roughly 1 degree. Again, note that even the most severe loads induce only small motions of the structure. The loads are small and the motions do not appear to be detrimental in any perceived sense.

The response of the core attitude in pitch to a berthing impact at body station C is shown on Figure 3.3-8. The response of pitch attitude without any controller constraints shows that the peak torque required to null out the transient is about 4500 N-m. In contrast, the response of the CMG cluster shows that a set of three skylab class CMG's in a parallel mounted configuration with magnitude and rate limits as indicated is unstable in pitch. The control authority of the cluster is easily exceeded as evidenced by the saturation behavior of the three inner gimbals. If the structure is subjected to loads of the size indicated here, some form of auxiliary control will be required.

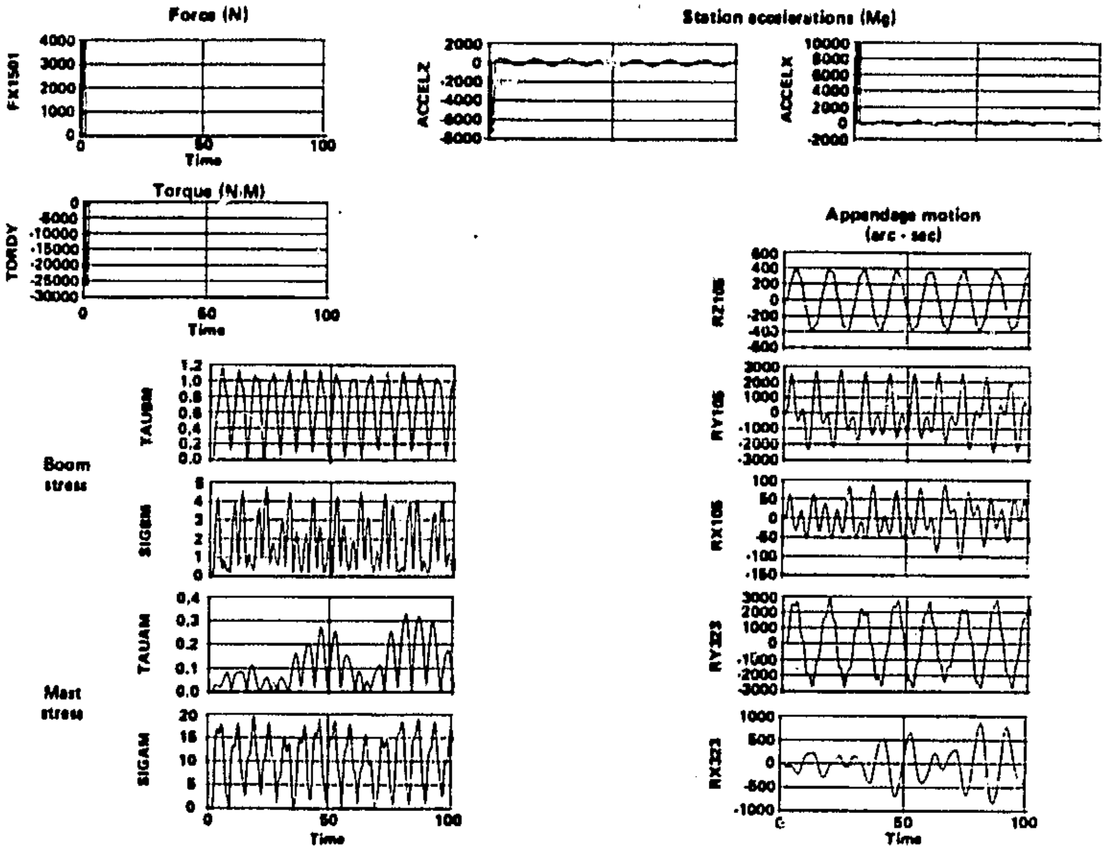


Figure 3.3–7. Orbiter Docking Impact at Body Station A No Attitude Control

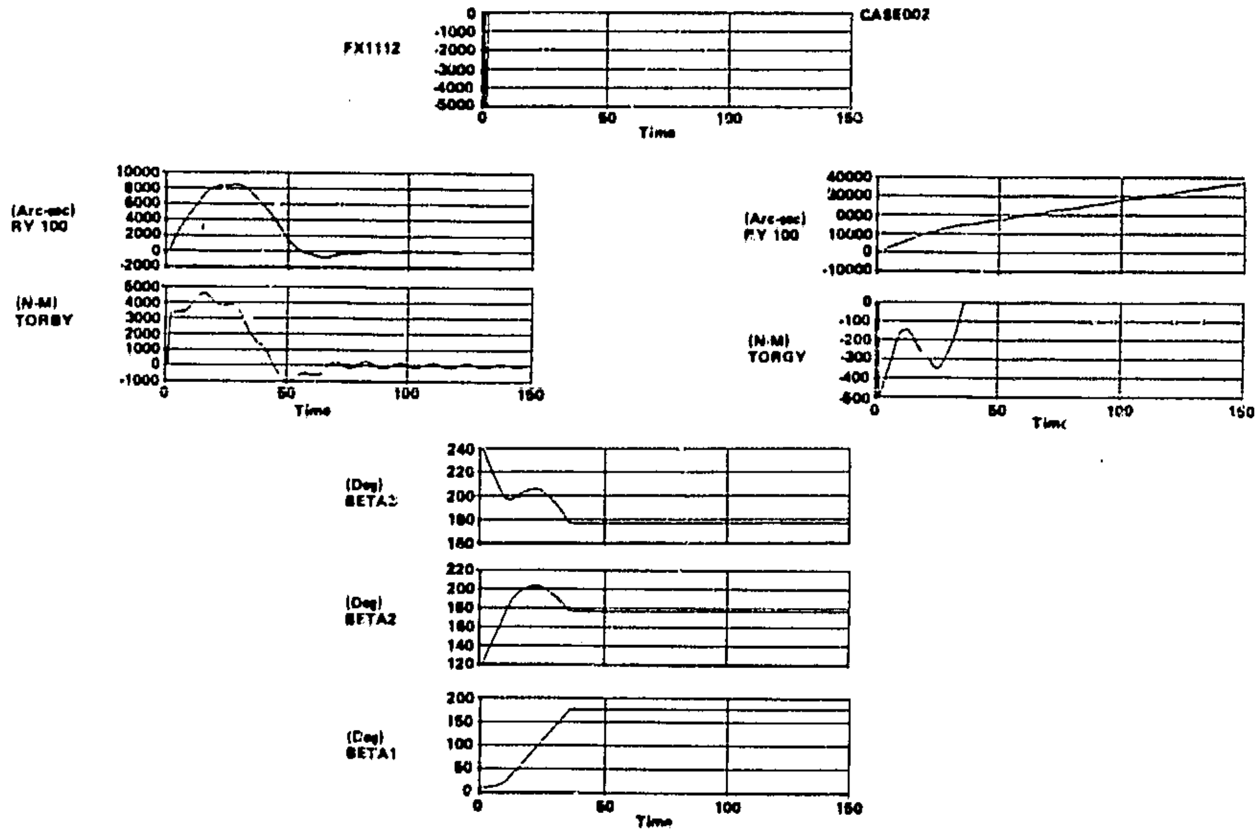


Figure 3.3–8. Orbiter Docking Impact at Body Station CMG Control with/ Without 6 deg/sec Gimbal Rate Limit

3.3.4 Passive Vibration Suppression

Passive suppression of solar panel torsional vibrations is incorporated in controllers II and III (c.f. Table 3.3-1). The mast torsional response performance of these controllers in terms of an impulse response analysis is summarized in Figure 3.3-9. The following discussions summarize the findings of the preliminary design for the solar panel root and tip mounted damper mechanisms.

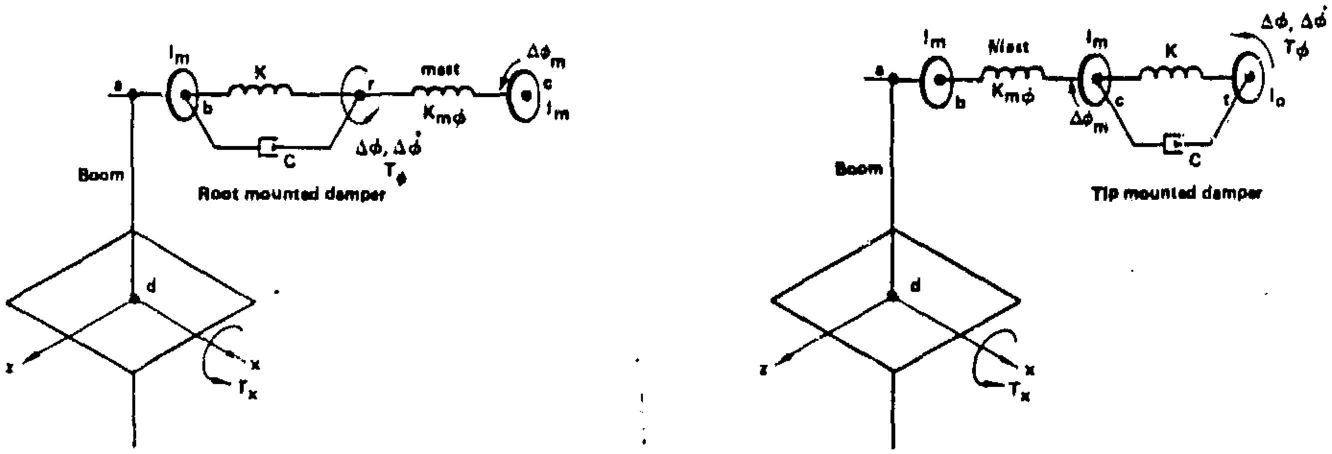
3.3.4.1 Motions Analysis for Controller II (Root Mounted Damper)

The root mounted damper was designed to isolate the deployment mast from the base where the solar blanket is attached. The spring constant was selected to be a factor of 100 less than the torsional spring rate of the mast. Also note that the torsional stiffness of the mast is about a factor of 100 less than the bending stiffness. The results show that the isolation system has essentially allowed the panel to remain stationary with respect to an inertial coordinate reference. The low value of the peak displacement and rate indicate that the damping constant should be realized either by direct interference friction from some sort of counter rotating coil spring arrangement or from an eddy current device. Also note that 20% damping was selected arbitrarily and no attempt was made to optimize the damper design.

The time histories for the appendage and damper impulse response of the root mounted damper in controller II are shown in Figure 3.3-10.

3.3.4.2 Motions Analysis for Controller III (Tip Mounted Damper)

The tip mounted damper was designed to provide damping to the panel torsional mode for a reasonable penalty in mass. For a given damper to panel inertia ratio, the spring and damping constants were tuned to the natural frequency of the mast. For an inertia ratio of .10, the mass required to implement the rotational inertia of the damper is about 36 kg, assuming a uniform rod. Note that the optimal damping achieved (15%) is sensitive to the panel parameters, especially the torsional stiffness. However, for worse case parameter ignorance, the degradation in damping is not severe. The peak displacement and rate is small and the comments made above for the root mounted device relative to mechanical realization apply here. The time histories for the



Damp loc	Constants		I_o Kg-m^2	Peak variables for T_x = 1000 n-m at d			Mast twist	Damping %
	K n-m/r	C n-m-sec		T_ϕ n-m	$\Delta\phi$ deg	$\Delta\dot{\phi}$ deg/sec	$\Delta\phi_m$ deg	
Tip	1490	169	768	.10	.082	.027	.05	15
Root	14.90	500	—	.30	.044	.036	.0004	20

Figure 3.3—9. Torsional Vibration Suppression Performance with CMG and Root or Tip Mounted Dampers

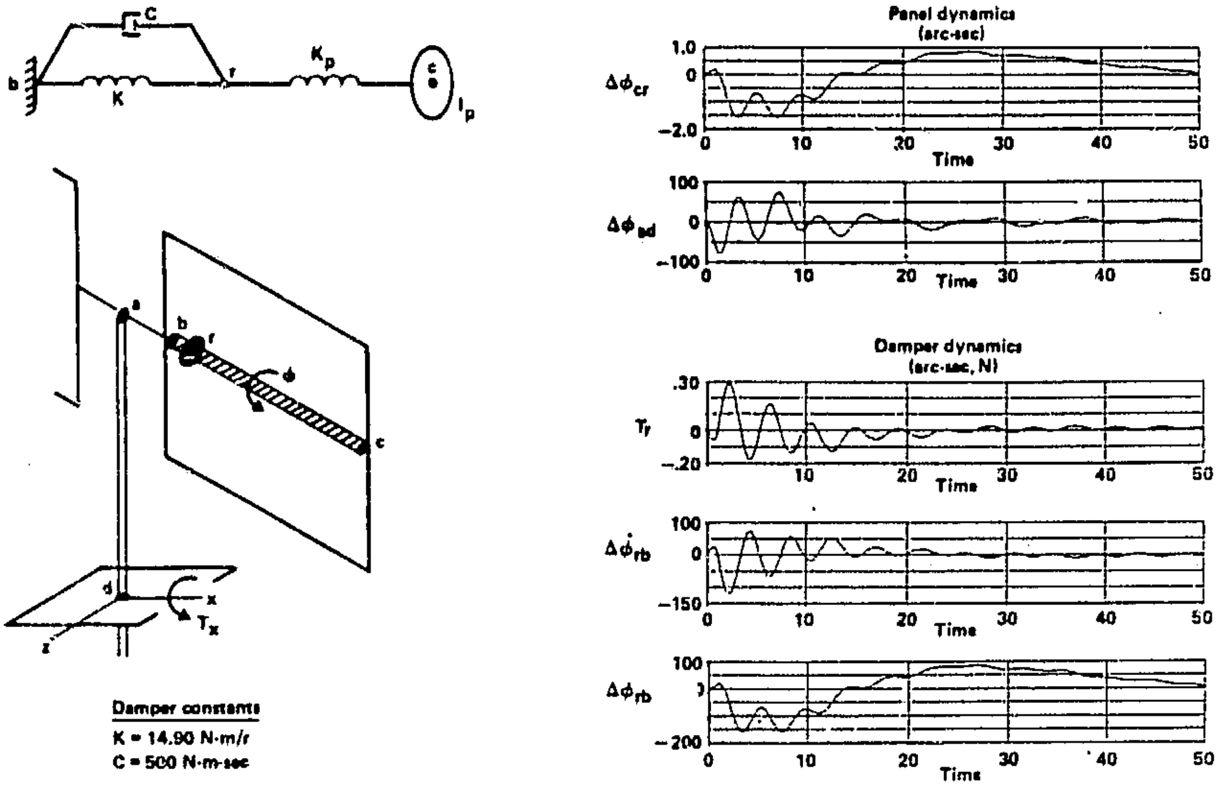


Figure 3.3—10. Simulated Response of Root Mounted Torsional Damper for 20% Damping Tilt Actuator Locked, T_x = 1000 N-m

appendage and damper impulse response of the tip mounted damper in controller III are shown in Figure 3.3-11. The damper design curves are shown in Figure 3.3-12.

3.3.5 Active Vibration Suppression

Active vibration suppression of both boom and mast torsional modes is incorporated in controllers IV and V. Controller IV utilizes coordinated feedback of relative angular motion variables to the pairwise collocated set of sensors and panel drive actuators. Controller V utilizes crossfeeds of absolute angular motion variables to the panel drive actuators in order to decouple base motions from solar panel motions as previously discussed.

3.3.5.1 Motions Analysis for Controller IV

Boom and mast torsional response performance of controller IV is summarized in Figure 3.3-13. The following discussions summarize the findings of parametric analysis for position and rate gains required to achieve the given level of performance.

Panel Roll (Tilt) Axis

The tilt actuator was used to drive the base of the panel in response to perturbations in panel roll attitude and rate relative to station fixed coordinators measured at the actuator. Design parameters and peak control response to a test torque impulse of 1000 N-m-sec in roll are shown on Figure 3.3-13. The gains K_P and K_V were tuned to give maximum damping of the panel fundamental torsional mode. The solution is sensitive to knowledge of the panel parameters. However, a sensitivity analysis indicated that the degradation in damping due to reasonable ignorance of the panel torsional properties was not severe. Control variations achieved reasonable limits. Physical realization of this controller seems feasible.

Panel Pitch (Pivot) Axis

The suntrack actuator was used to drive the pivot point of the panel set in response to perturbations in panel pitch attitude and rate relative to station fixed coordinates measured at the actuator. The table on Figure 3.3-13 shows design parameters and peak control response to a test torque impulse of 1000 N-m-sec in pitch. The controller

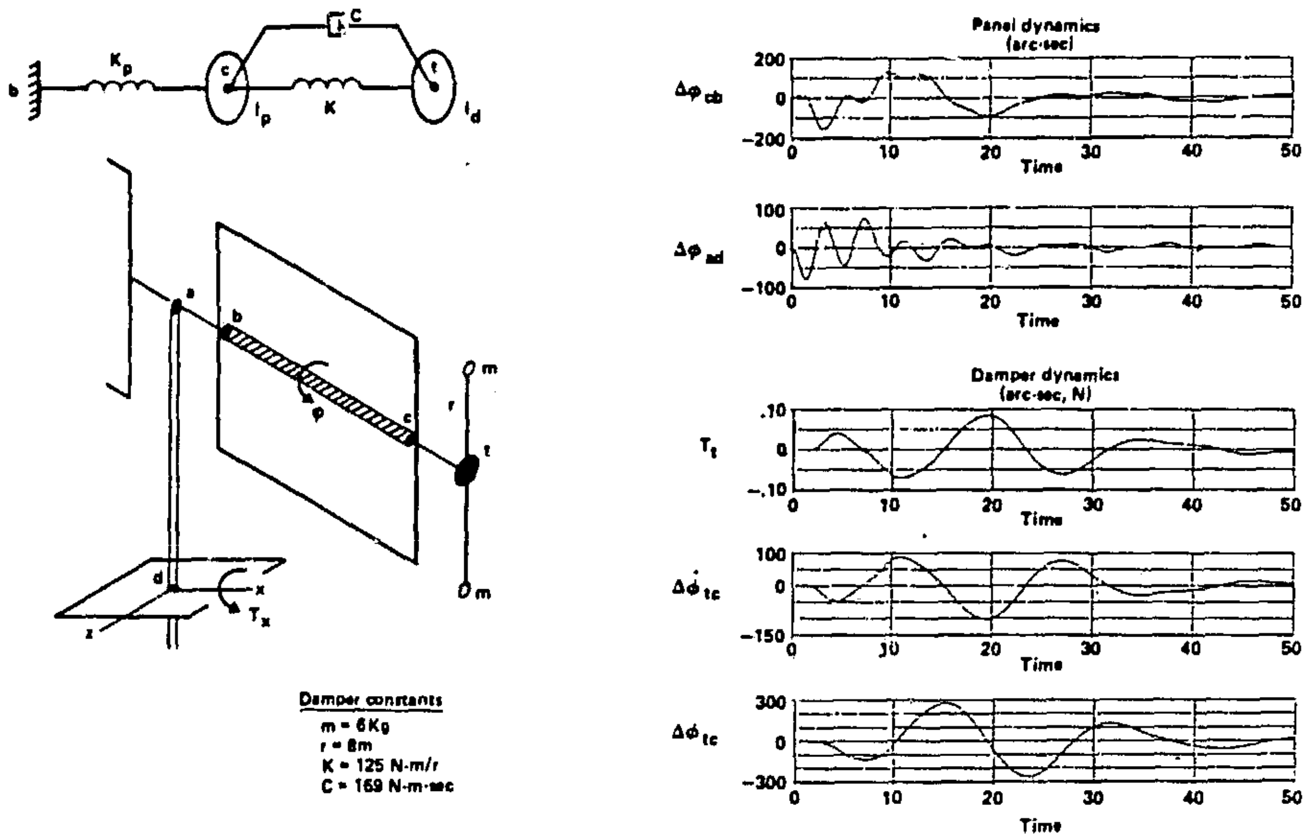


Figure 3.3–11. Response of a Tip Mounted Torsional Damper Tuned for 15% Damping Tilt Actuator Locked, T_x=1000 N-m

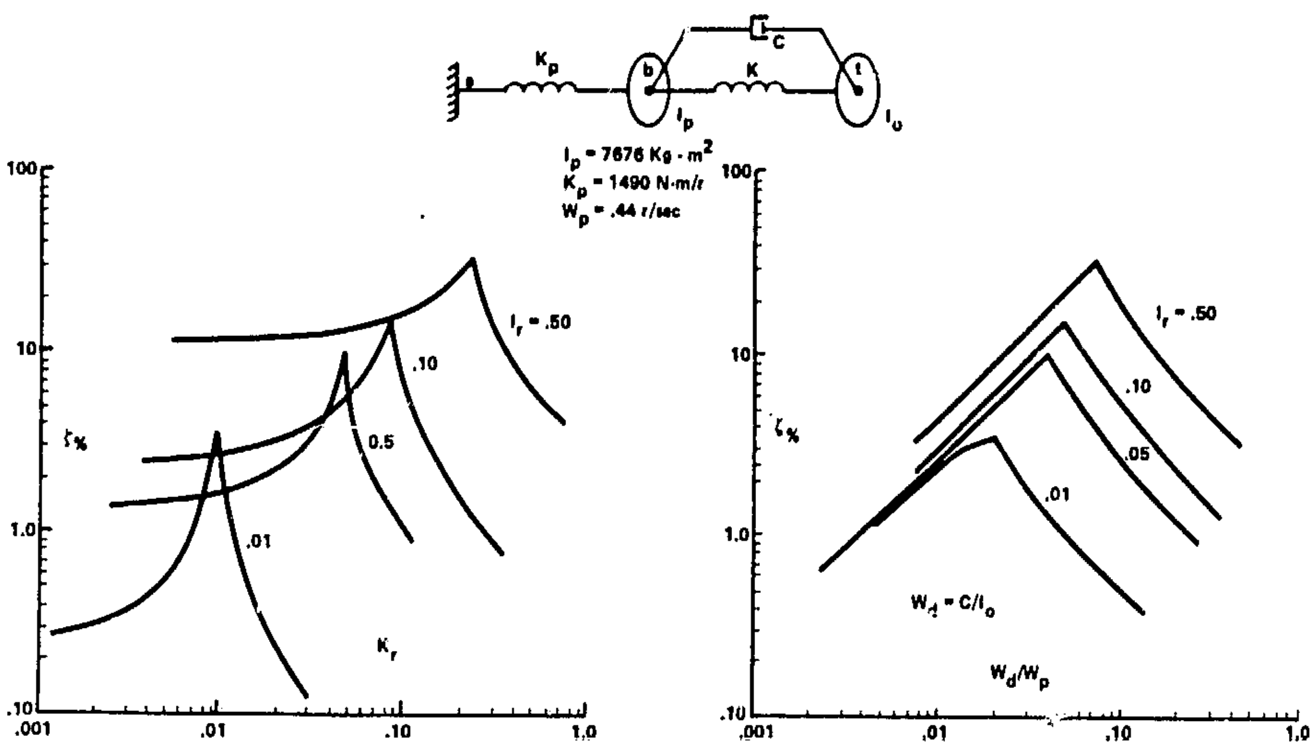
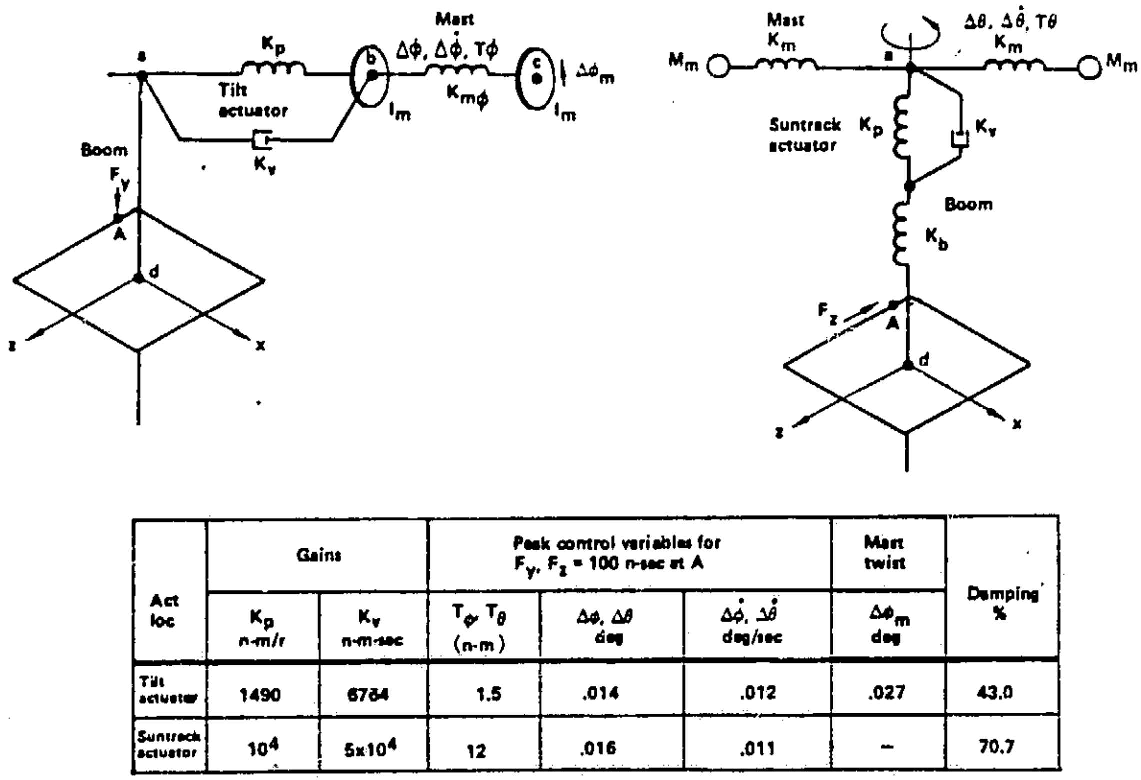


Figure 3.3—12. Performance Curves for a Tip Mounted Torsional Damper



Act loc	Gains		Peak control variables for F_y, F_z = 100 n-sec at A			Mast twist	Damping %
	K_p n-m/r	K_v n-m-sec	T_ϕ, T_θ (n-m)	$\Delta\phi$, $\Delta\theta$ deg	$\Delta\dot{\phi}$, $\Delta\dot{\theta}$ deg/sec	$\Delta\phi_m$ deg	
Tilt actuator	1490	6764	1.5	.014	.012	.027	43.0
Suntrack actuator	10^4	5×10^4	12	.016	.011	–	70.7

Figure 3.3—13. Torsional Vibration Suppression Performance with CMG's, Co-located Suntrack/Tilt Actuators

was designed to provide isolation between the boom and the mast. Tuning of parameters was not required and any level of damping can be achieved. The time histories for the impulse response and response to the crew motion profile for controller IV is shown in Figures 3.3-14 to 3.3-18.

3.3.5.2 Motions Analysis for Controller V

The objective here was to apply multivariable control methodology to the given flexible Space Station. Eigenstructure assignment using output feedback was selected for the following reasons. First, note that output feedback results in fixed gain controllers which do not contain frequency sensitive elements. Fixed gain controllers are easy to implement. Eigenstructure assignment implies that subsets of the modal frequencies and the closed loop eigenvectors can be arbitrarily specified. The size of the subsets depend upon the number of sensors and actuators comprising the controller. Eigenvalue assignment provides modal stability augmentation. Eigenvector assignment allows the closed loop specification of relative motions between various elements of the structure. Finally, eigenstructure assignment theory is a multivariable tool allowing the control system to be synthesized in a single run. However, the theory does not guarantee stability of the closed loop system.

The simulation results are shown in Figure 3.3-19. The eigenvector assignment feature was used to decouple core motion from solar panel motion. In this simulation the solar panels remain stationary with respect to the sun and are independent of disturbances within the core.

The results of the experiments with eigenstructure indicate that the control objectives are achieved when inertial measurements are implemented as previously mentioned. Although the sensors and actuators are pairwise collocated, crossfeed between sensors and actuators at different locations is permitted to satisfy the control objectives. Spatial separation between sensors and actuators on a flexible structure can lead to stability problems. However, the bandwidth of the controller was low enough to provide a stable core and all controllable flex modes were well damped.

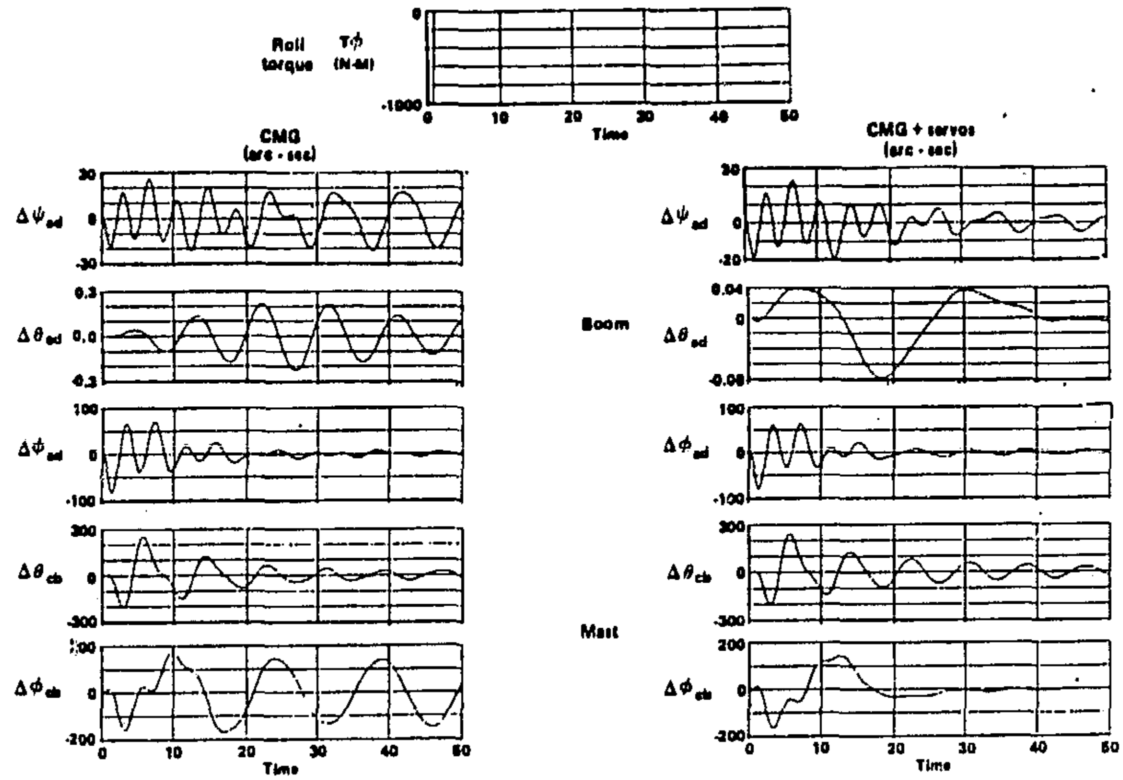


Figure 3.3–14. Comparison of Appendage Response with CMG and Suntrack/Tilt Actuators

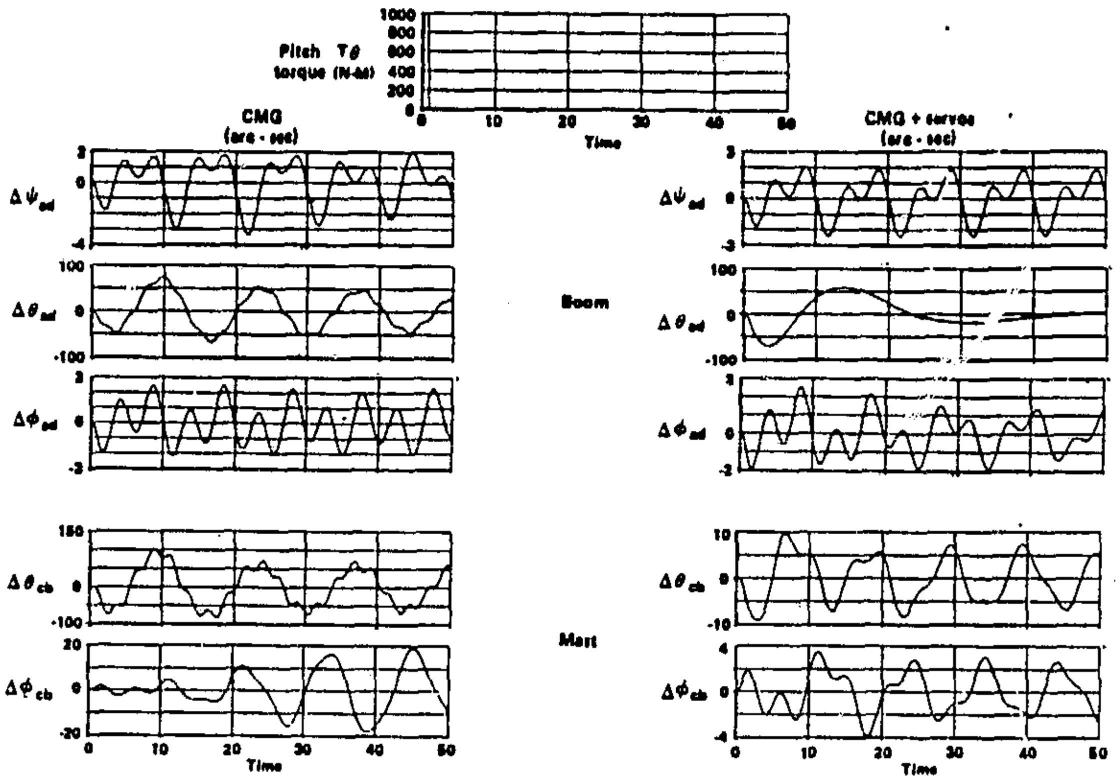


Figure 3.3–15. Comparison of Appendage Response with CMG and Suntrack/Tilt Actuators

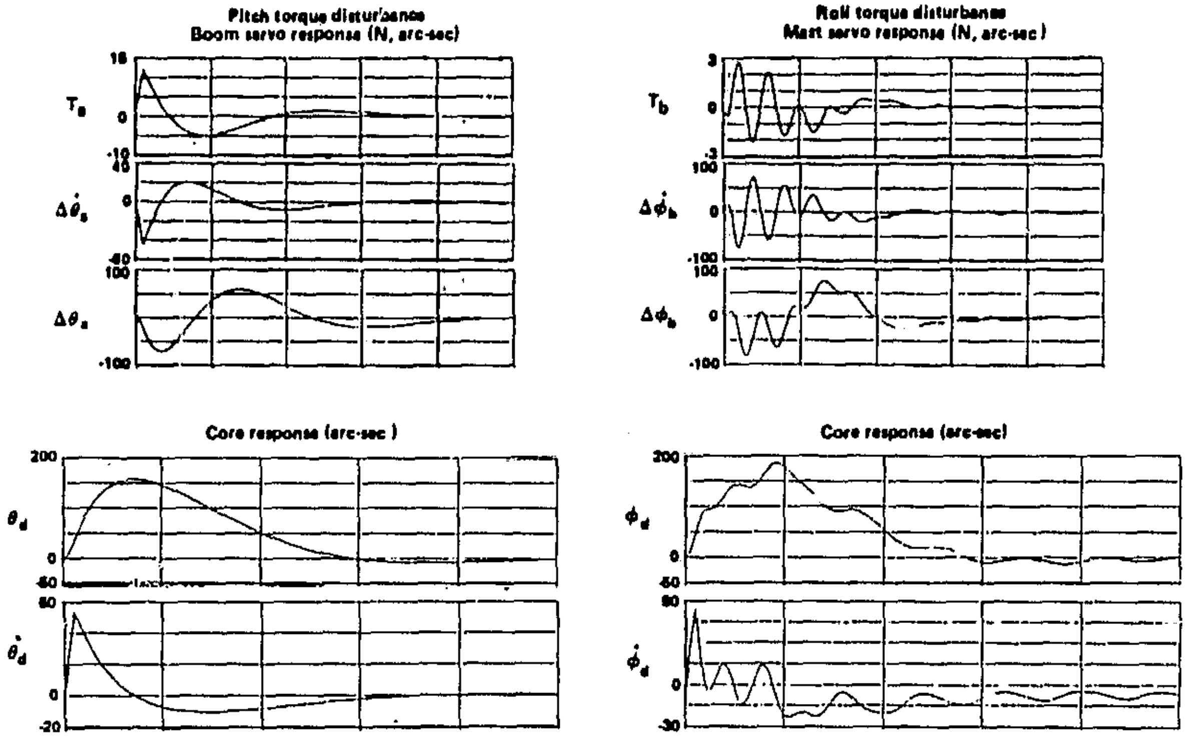


Figure 3.3–16. Control Response of SERVO Torquers

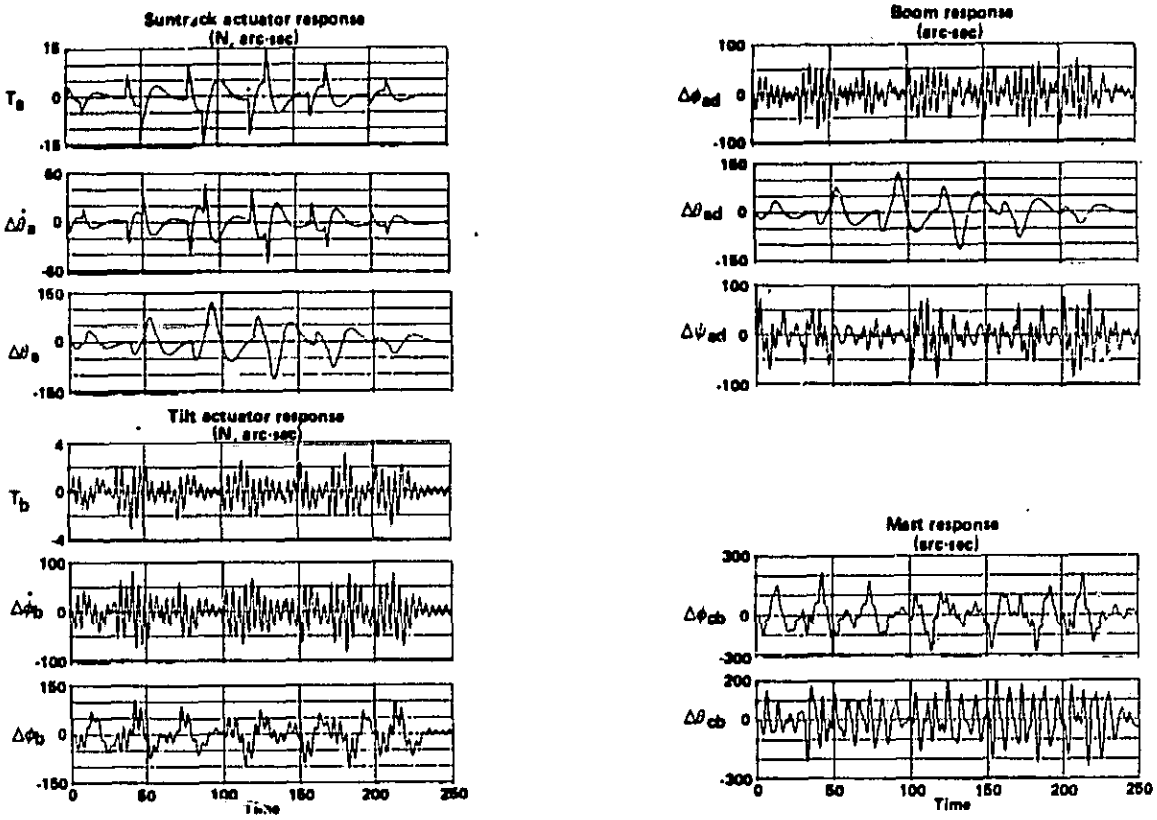


Figure 3.3–17. Appendage Response with CMG + Servo Controllers Crew Motion Profile Input

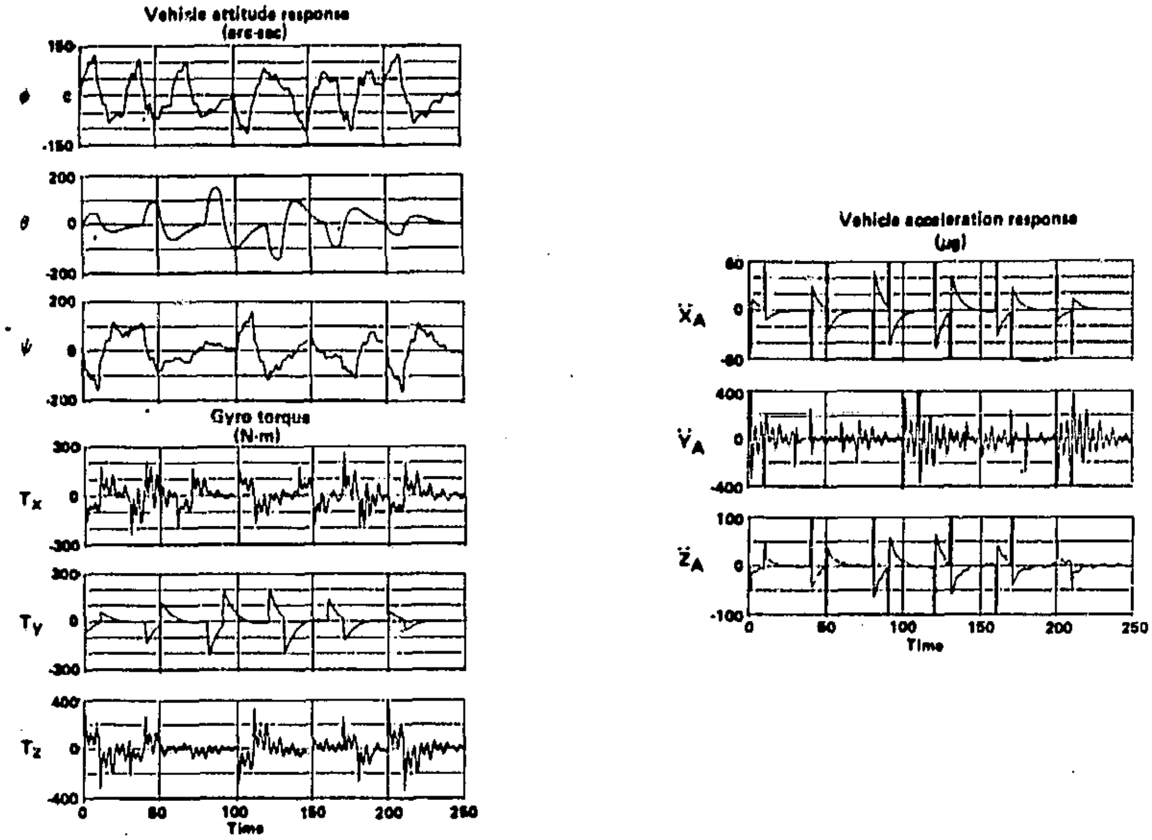
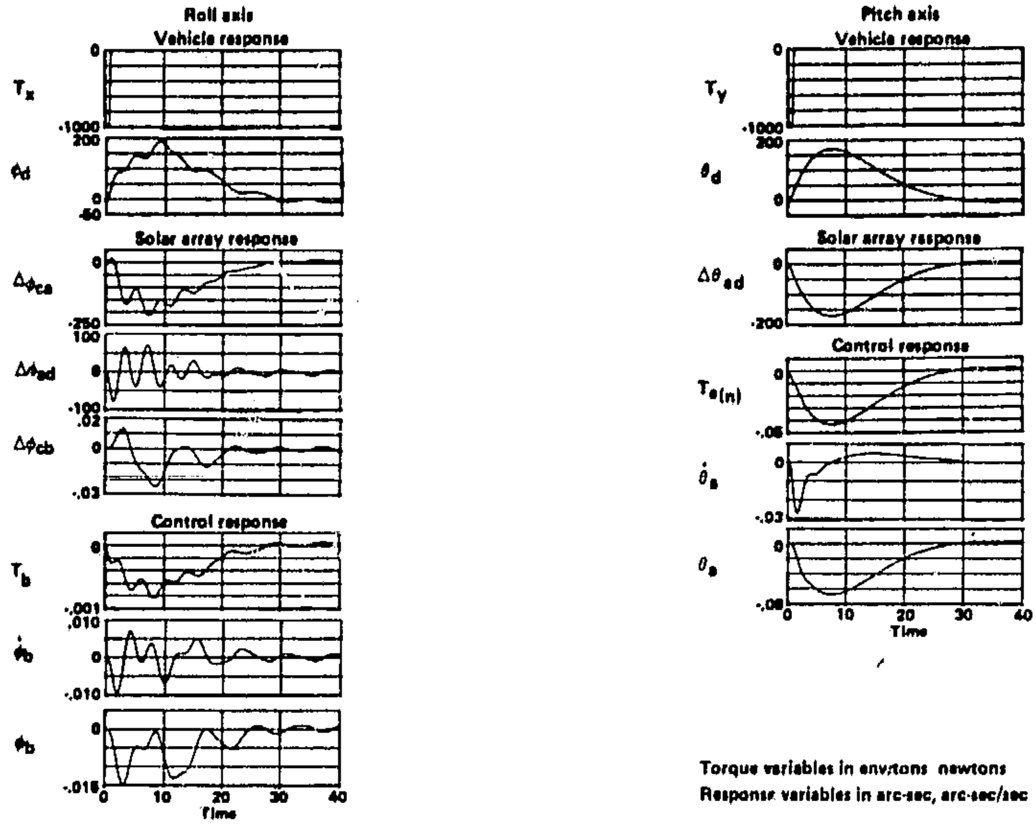


Figure 3.3–18. Station Response with CMG + Servo Controllers Crew Motion Profile Input



Torque variables in newtons newtons
Response variables in arc-sec, arc-sec/sec

Figure 3.3—19. Application of Eigenstructure Placement to Space Station Attitude Control, Absolute Positioning

3.3.6 Vibration Suppression of Symmetric Modes

The simulation data clearly indicates that appendage translational amplitudes due to symmetric mode excitation from impulse doublet forcing are negligible. However, docking and module berthing shocks could induce significant solar panel motions and attendant central core translation, especially for stations with large power requirements. Accordingly, the purpose of the task was to take a quick look at the feasibility of using a propulsion system comprised of resisto jet type thrusters driven by appropriate control logic to damp the translational (butterfly) modes. As mentioned previously, symmetric bending modes are not controllable using torquers unless the panel drives are such that each array can be independently controlled over the two degrees of freedom.

Figure 3.3-20 illustrates the basic simulation configuration used in the analysis of candidate control laws. The .13N force ionized gas thrusters were placed as shown at locations A, B, C, and D. There are two positive x-direction thrusters, locations C and D, and two negative x-direction thrusters, locations A and B. There are four positive and four negative z-direction thrusters. Angular rate and linear position sensors are located at the center of the station core and at the ends of the solar array booms, locations S0, S1 and S2, respectively. Symmetric bending occurs in both the x-y and y-z planes. Peak-to-peak amplitudes of the displacements and the rates are small, as mentioned previously. Peak values of rotational displacements and rates sensed at ends of the solar array booms in the x-y and z-y planes are about 4.5 arcsec and arcsec/sec.

3.3.6.1 RCS Control Logic

The RCS thruster control logic was implemented in the form of a rate damper. The angular rates sensed at locations S1 and S2 were chosen as rate feedback signals to the RCS control logic. Since the CMG's are quite effective in damping the other bending modes, it is desirable to use the RCS thrusters to damp primarily the transverse symmetric modes. An angular position check comparing the signs of deflection at locations S1 and S2 was implemented to filter out the symmetric modes.

3.3.6.2 Motions Analysis for RCS Controller

Figure 3.3-20 shows the effect of rate-damping the transverse symmetric modes with the use of RCS thrusters. The rotational rates about the z-axis shown in Figure 3.3-20

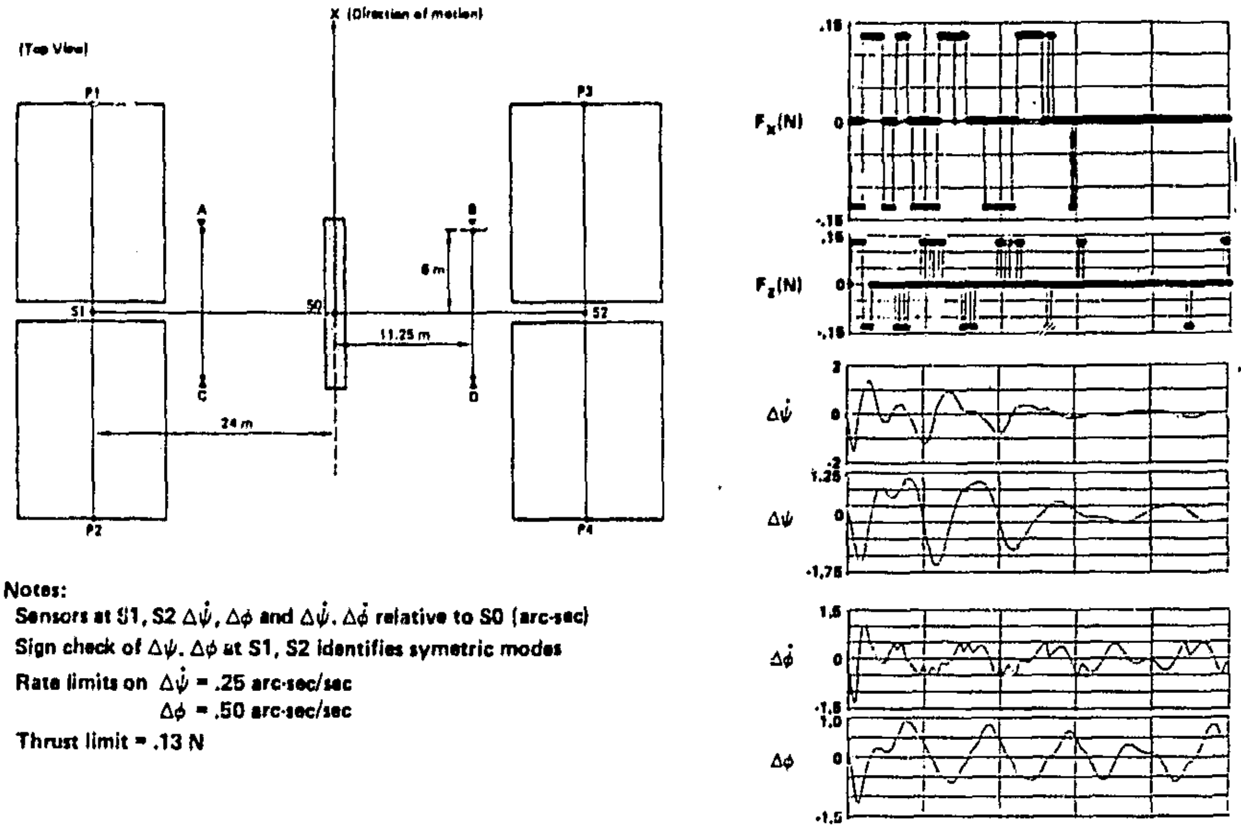


Figure 3.3–20. RCS (Resisto Jet) Control of Symmetric Bending Modes Response to 1000 N-m-sec Torque in Pitch

3.3.6 Vibration Suppression of Symmetric Modes

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Figure 3.3-20 shows the effect of rate-damping the transverse symmetric modes with the use of RCS thrusters. The rotational rates about the z-axis shown in Figure 3.3-20 were reduced from the undamped 4.5 arcsec/s to less than .4 arcsec/s peak-to-peak in 25 sec. Less desirable performance was observed in the y-z plane. The z-axis thruster firing and the rotational rates about the x-axis indicate a new disturbance and RCS thruster chattering. As the solar arrays were modelled as lying in the x-y plane, minimal excitation of the solar array bending modes occurred. However, in the y-z plane, the RCS thruster firings result in the excitation of the solar array symmetric bending modes. Although the rotational rates are reduced from the undamped rates of 4.5 arcsec/s to less than 1 arcsec/s peak-to-peak, the continuous RCS thruster firing may not be desirable.

As the Space Station solar arrays rotate 360° about y-axis to track the sun, it would be difficult to fire the RCS thrusters and not excite the solar array bending modes. However, if some RCS thruster chattering is permissible, then the thrusters can be used to effectively damp the transverse symmetric modes of the solar array boom.

3.3.7 Modeling of Stiffer Solar Array Structures

The preceding discussions clearly indicated that vibrations induced in very flexible solar array structures can be easily managed by employing simple techniques with component hardware currently in existence. However, the controllability of solar panels with improved stiffness must still be determined. The problem is to compare the structural motions of the SEPS type array with the stiffer arrays for controller I, viz., assuming the panel drive actuators are locked.

3.3.7.1 Waffle Grid Solar Panels

A solar panel design of current interest at Boeing is shown in Figure 3.3-21. The design features a substrate backed by a lightweight waffle grid structure. The waffle grid adds the required stiffness. The panel sections are foldable in accordion fashion with tapered thickness. The dynamic characteristics are improved due to the extent that the first bending mode is 1.05 Hz. Packaging is less efficient than the SEPs type array and the increase in mass required to obtain the given improvement in first mode frequency is about twice the SEPS array mass.

3.3.7.2 Motions Analysis for Controller I

The Space Station flexible model with the waffle grid solar panels included 21 flexible modes up to the first panel bending mode of 1.05 Hz. At control bandwidths of interest all significant bending and torsion is seen to occur in the supporting structure, the panels remaining essentially rigid.

The comparative response of the solar arrays and supporting structure is shown in Figure 3.3-22. The simulation results indicate that the most severe motion is in pitch. It is manifested primarily as symmetric boom twist and bending. Symmetric torsion in the boom is mildly augmented by CMG control, because some damping in pitch is required. Panel roll axis torsion and accompanying vibrations in the supporting structure were found to be negligible.

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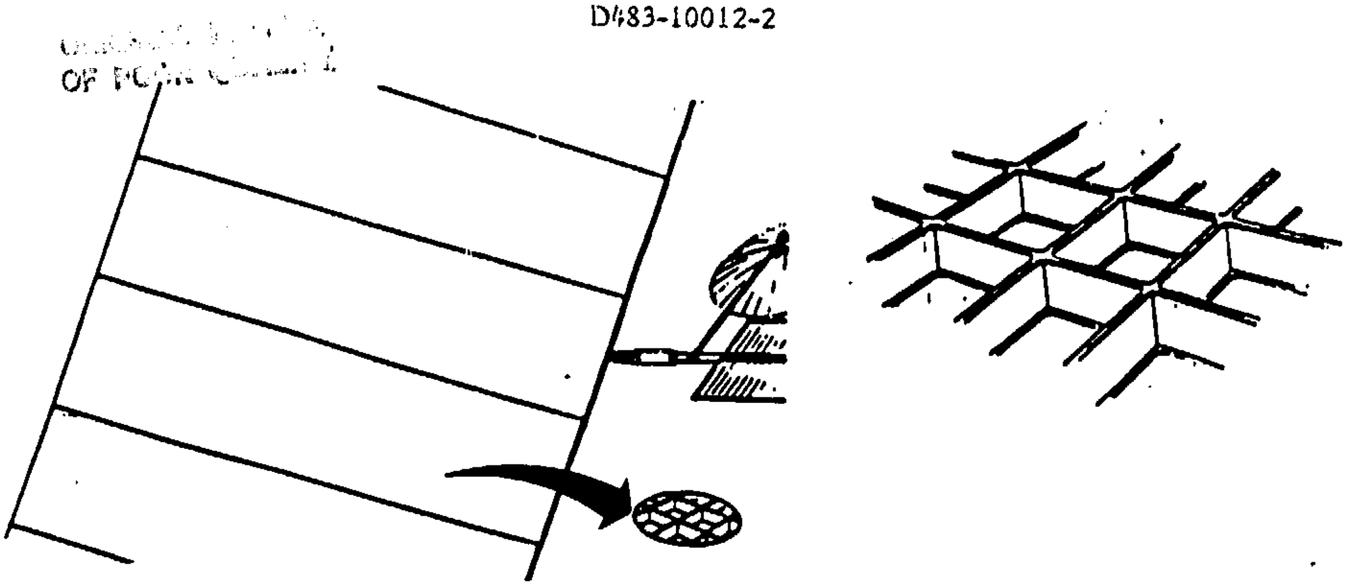

- Substrate backed by lightweight waffle grid structure
- Foldable panels with tapered thickness
- Improved dynamic characteristics (first mode frequency = 1.05 Hz)
- Packaging less efficient than SEPS type solar array
- Mass increase over SEPS type by 2.5

Figure 3.3–21. Waffle Grid Solar Panels

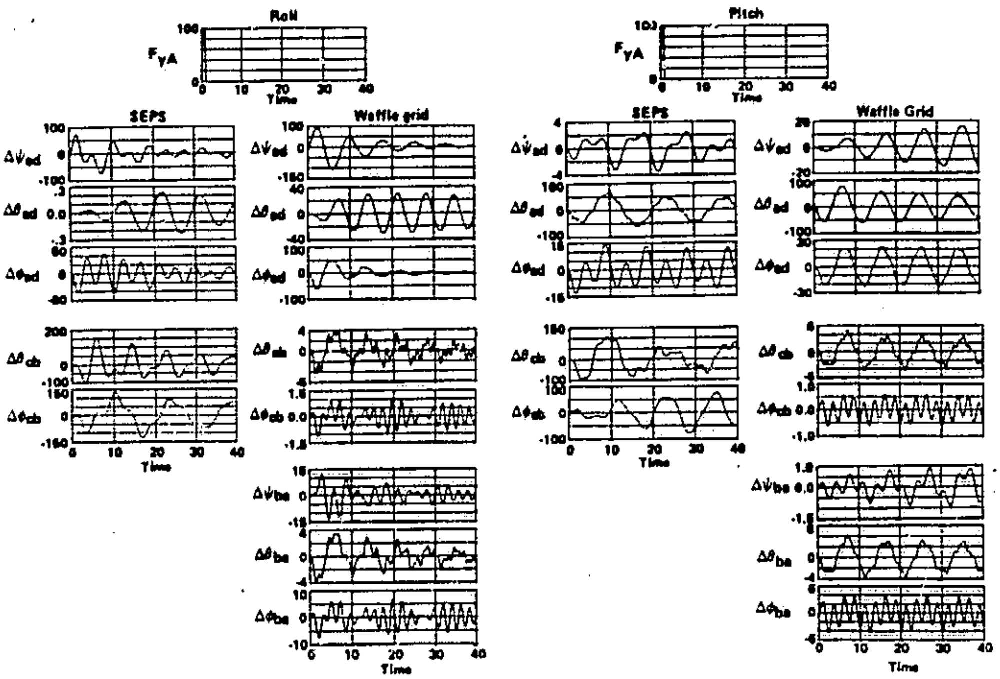

Figure 3.3–22. Appendage Response Comparison of SEPS with Waffle Grid Array CMG Controller, Panel Drive Actuators Locked (arc-sec)

3.4 SUMMARY OF RESULTS

The issues relating to attitude control impact from structural dynamic motions for a planar space station configuration have been addressed. The following statements summarize the findings of the study.

3.4.1 SEPS Arrays

3.4.1.1 Loads and Motions with Locked Panel Drives

- o Dedicated vibration suppression required for solar array torsional modes.
- o Results based on worse case ad hoc disturbance model.
- o Stability guaranteed at control bandwidths of interest.

3.4.1.2 Control Laws

- o Collocated (coordinated) control of station and solar panels provides both rigid body attitude regulation and vibration suppression.
- o Decoordinated control provides the added benefit of panel/station motion decoupling, introducing potential for instability.
- o Dedicated (RCS) control of symmetric bending modes not required for the planar balanced configuration.
- o Simple RCS symmetric bending mode damper with antisymmetric discriminator is effective and feasible.

3.4.1.3 Active Control

- o Use of panel drive servo actuators is effective and feasible.
- o Current SOA relative motion sensors are adequate.

3.4.1.4 Passive Control

- o Root mounted damper best choice for most isolation, least sensitive to parameter variations.
- o Mechanical design may be difficult to implement due to small motions.

3.4.2 Stiff Solar Arrays

3.4.2.1 Motions with Locked Panel Drives

- Use of waffle design (or equivalent) could eliminate need for dedicated vibration suppression controllers.
- Mass increase by 2.5.

3.5 CONCLUSIONS

The conclusions of the study can be summarized as follows. It is recognized that attitude performance requirements for a habitable space station in low earth orbit are lax. This study has clearly demonstrated that when the control bandwidth is small compared to the bandwidth of the sensors and actuators, all modes in the proximity and above the controller pass band are effectively gain stabilized. Thus robustness (stability with a margin) is guaranteed under these conditions and the fundamental issue becomes one of augmenting uncontrollable modes when such augmentation is necessary. The study has shown that coordinated control using collocated sensors and actuators will provide effective vibration suppression. In this particular application it was shown that CMG control of the central modular core, in conjunction with the panel positioning actuators, gives vibration suppression for all modes with the exception of the symmetric bending modes. Worse case amplitudes of appendage motion due to symmetric bending was found to be negligible. Based on these observations, attitude control development for a space station is not significantly influenced by flexibility. The need for a dedicated vibration suppression system is eliminated by collocated and coordinated regulation of modular core and solar array motion. However, preference toward a locked panel tilt actuator <u>may</u> require some passive damping to dissipate solar array torsional vibrations, especially in the case where SEPS type arrays and deployment are utilized. If a type of stiff substrate backed panel or equivalent is employed, then the severity of the vibration problem is mitigated, if not totally eliminated. In this case, insuring the stiffness of the supporting structure is adequate.

3.6 RECOMMENDATIONS

Continuing effort in attitude control for space station should concentrate on defining functional requirements for rigid body control of a dynamically evolving space station. The findings of this study, or equivalent, should be used to estimate the effects of flexibility and to assess the need for dedicated vibration suppression systems.

3.7 REFERENCES

1. "Space Station Systems Technology," Volume II, Final Report, D180-27935-2.

4.0 CONTROLS AND DISPLAYS FOR OMV, OTV & SPACECRAFT SERVICING, FLIGHT OPERATIONS & FUNCTIONAL OPERATION

This section presents the results of a study conducted to characterize a multifunction workstation on-board Space Station for the servicing and operation of spacecraft. This characterization could potentially fulfill all the workstation needs for Space Station which would incorporate a high degree of design commonality.

4.1 Introduction

The area of controls and displays is a new one to the Space Station Systems Technology Study. It was selected as an area of concern due to its inherent complexity, numerous interfaces and vital function to the safe operation of Space Station. It is an area that is rapidly advancing. Efforts to develop this technology could benefit the Space Station if they were conducted for its specific needs. This study will identify three areas of technology: (1) those items that will be available for an early Space Station of their own accord; (2) those items that would be available for an early Space Station if pushed; and (3) those items that would be available at a later time. A cost/benefit analysis of the various technologies was also part of the study.

The following paragraphs report on the approach, results, conclusions and recommendations resulting from this characterization study and also provide a technical discussion of the study elements.

4.2 Approach

The objective of this study was to define OMV workstation technology requirements in order to (1) determine any open technology issues unique to Space Station, (2) identify potential benefits and risks associated with the development and use of advanced technology, and (3) develop an implementation plan for advancing those technologies. The following paragraphs present the methodology used to define the workstation configuration and required technology. Summarily, an operational scenario was developed and a functional analysis of the individual tasks was performed. From this analysis, optimal solutions for task implementation in terms of workstation configuration were determined. Technology identification and cost/benefit trades were then performed. The methodology flow is illustrated in Figure 4.2-1.

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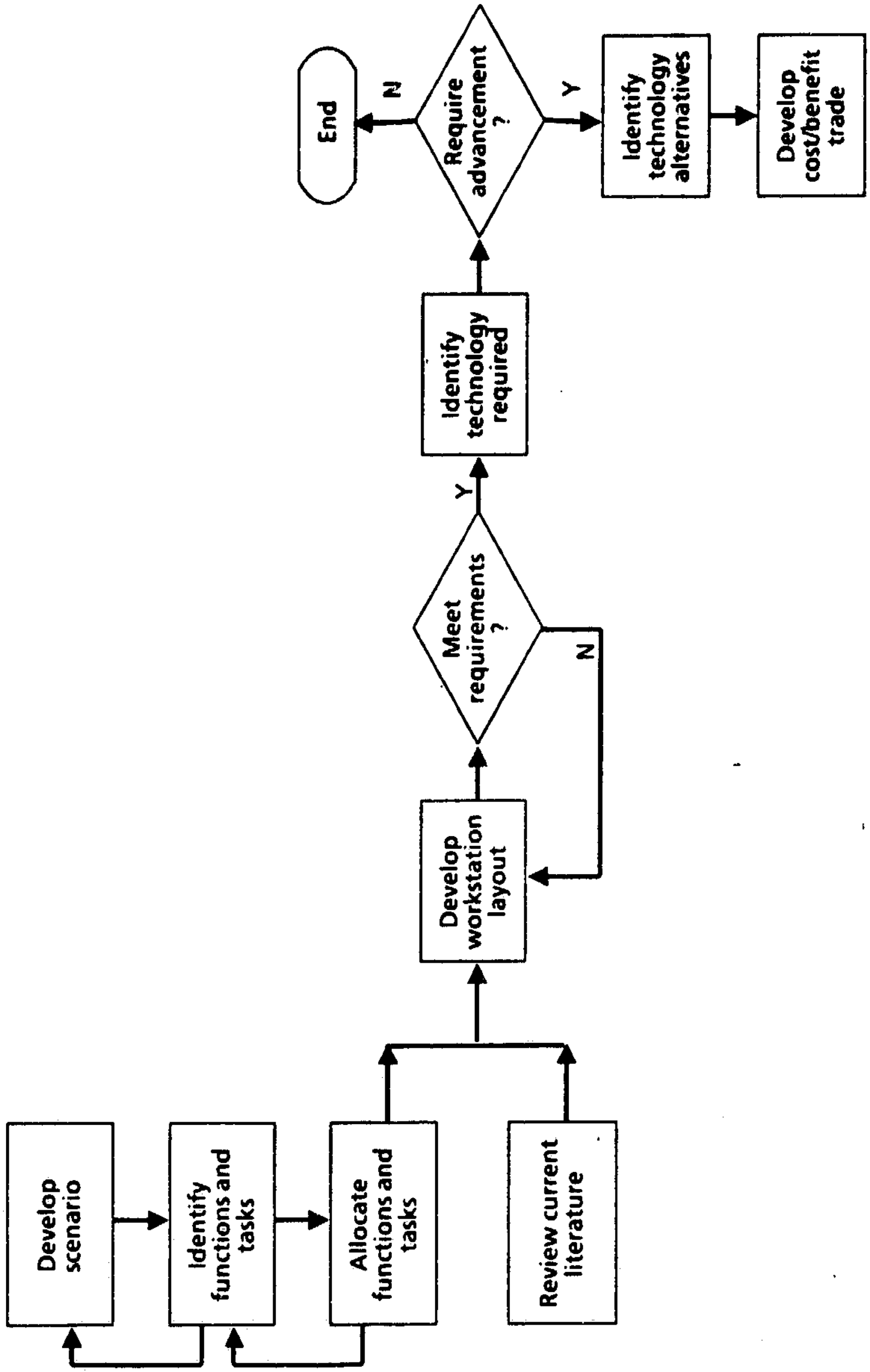

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Figure 4.2-1. Study Methodology Flow

4.2.1 Definition of Functional Requirements

Prior to designing the workstation, we had to understand the functions that will be accomplished through the controls and displays (C&D) suite. An operational scenario was developed for an OMV controlled from the Space Station and included checkout, launch, rendezvous, docking, return and retrieval mission phases. The scenario is presented in Figure 4.3-1 and Table 4.3-1.

The scenario was then used as the basis for a functional analysis of the required tasks. Through the functional analysis, we gained a solid understanding of what tasks needed to be accomplished simultaneously and what information was required to accomplish the tasks. Also, priorities were assigned to the data display requirements.

In developing the scenario, we drew on our recent OMV simulation experience. A real-time simulation was developed to study operator performance during a remote rendezvous and docking operation. A simple workstation was built for this purpose and is shown in Figure 4.2-2.

4.2.2 Review of Flight Deck Control and Display Technology

A literature review of past and current research on control and display technology and its implementation was conducted. The purpose of this review was to determine any potential benefits or problems with the various technologies and their implementation based on fellow researchers' experiences. The review included the research done for the Boeing 757/767 flight deck, B1-B aft control stations and Air Force Flight Dynamics Laboratories' Pictorial Format Displays contract (figures 4.2-3, 4.2-4, and 4.2-5).

4.2.3 Design of Conceptual Configurations

Based on the results of Tasks 4.2.1 and 4.2.2, two workstation configurations were developed that satisfied all the scenario functional requirements and operated efficiently. Hardware specification at this point was limited to equipment characterization, i.e., visual displays, full color, high resolution, 10-inch and 15-inch diagonal sizes. The configurations are illustrated in Figure 4.3-2. Software specification was also limited to characterization at this point.

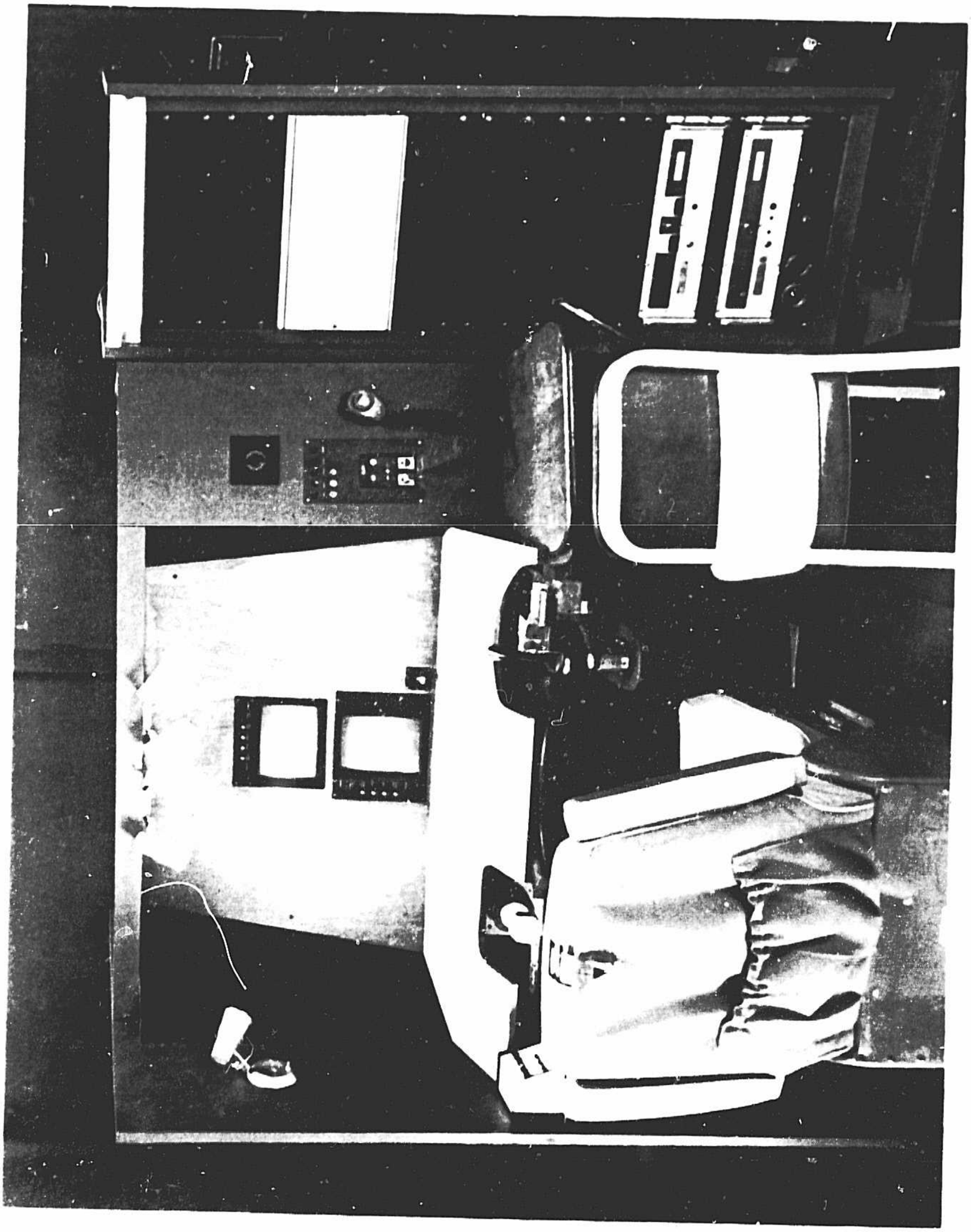

Figure 4.2-2. OMV Simulation Workstation

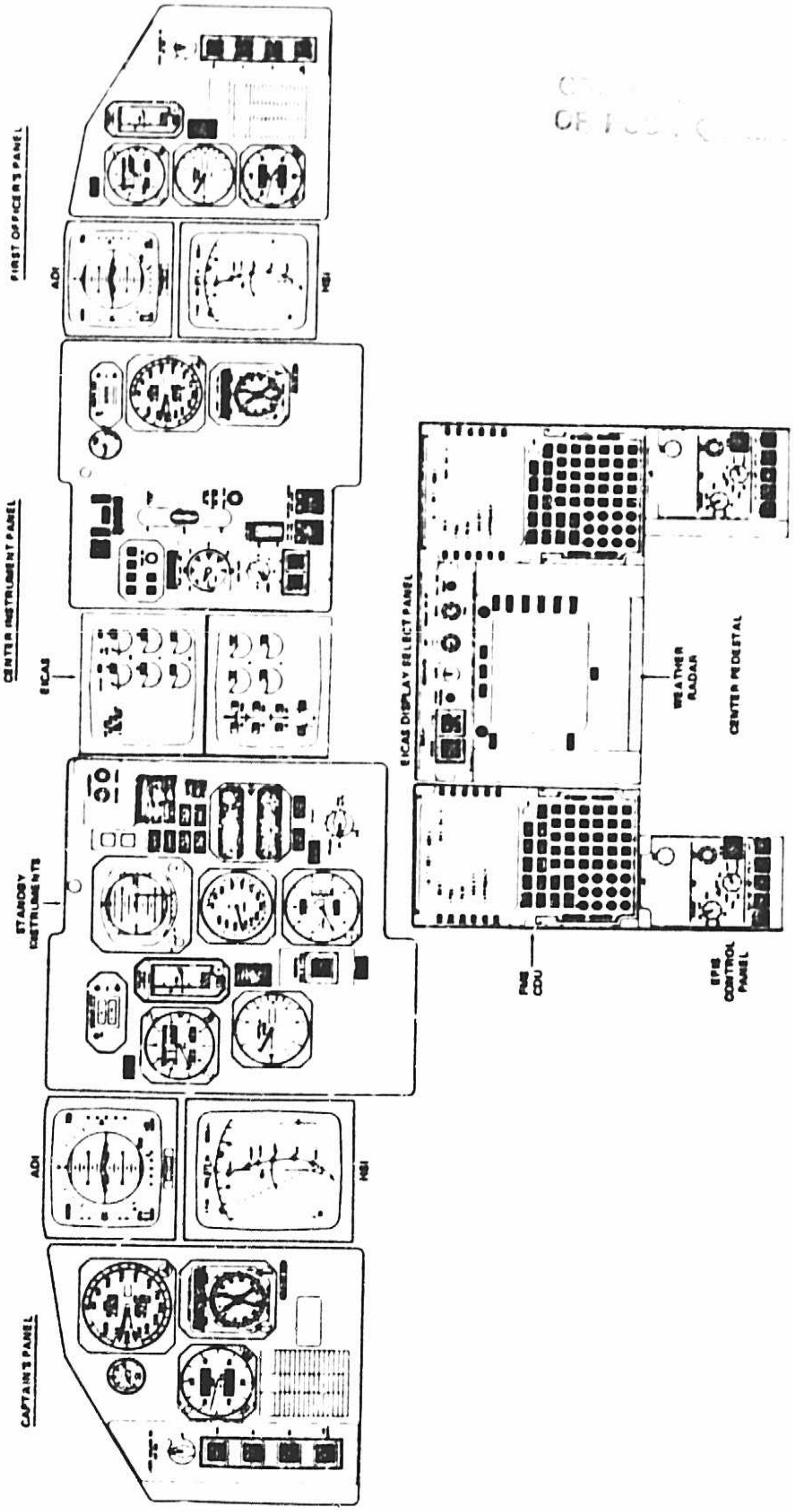

Figure 4.2-3. 757/767 Front Instrument Panel

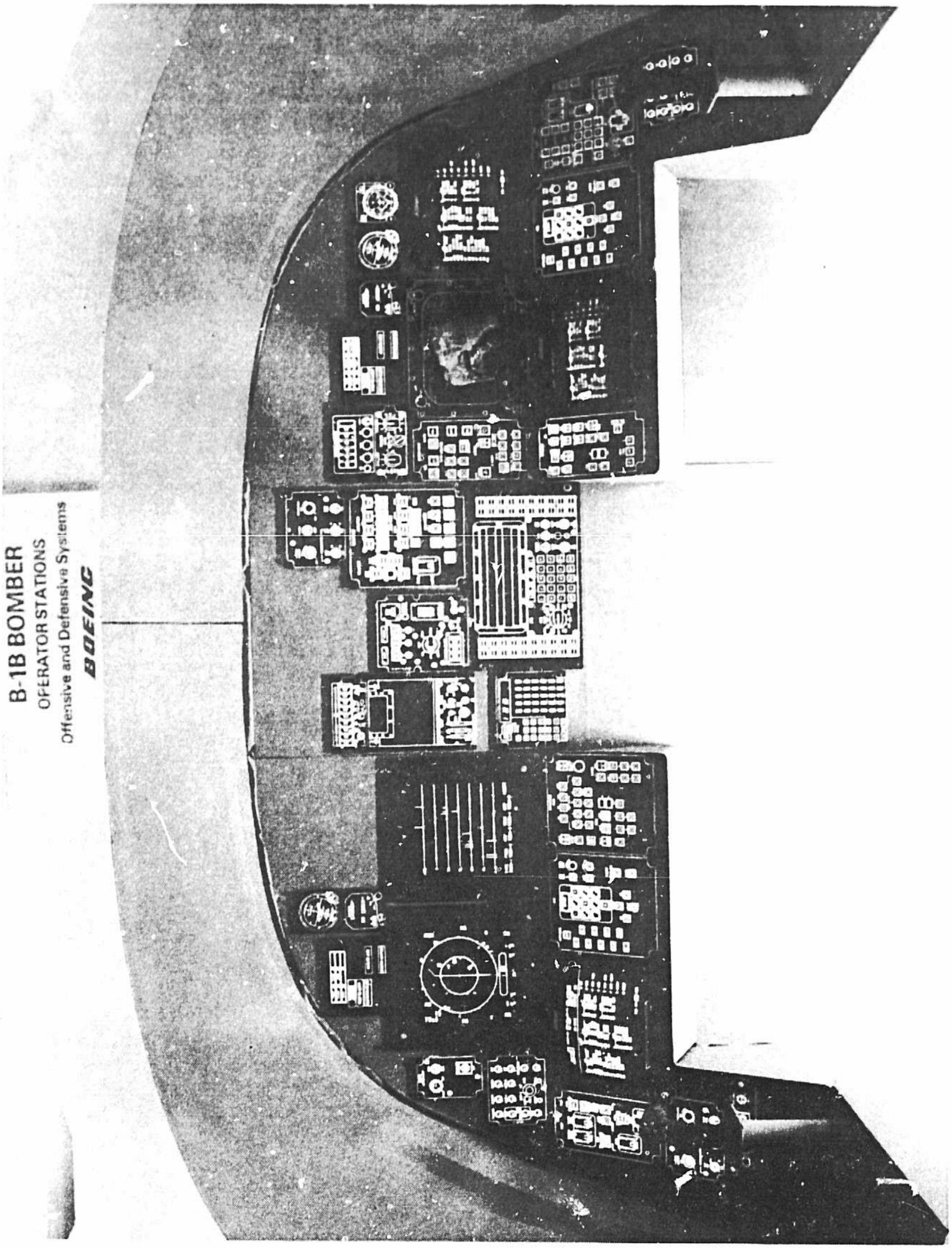

Figure 4.2-4. B1 B Aft Control Stations

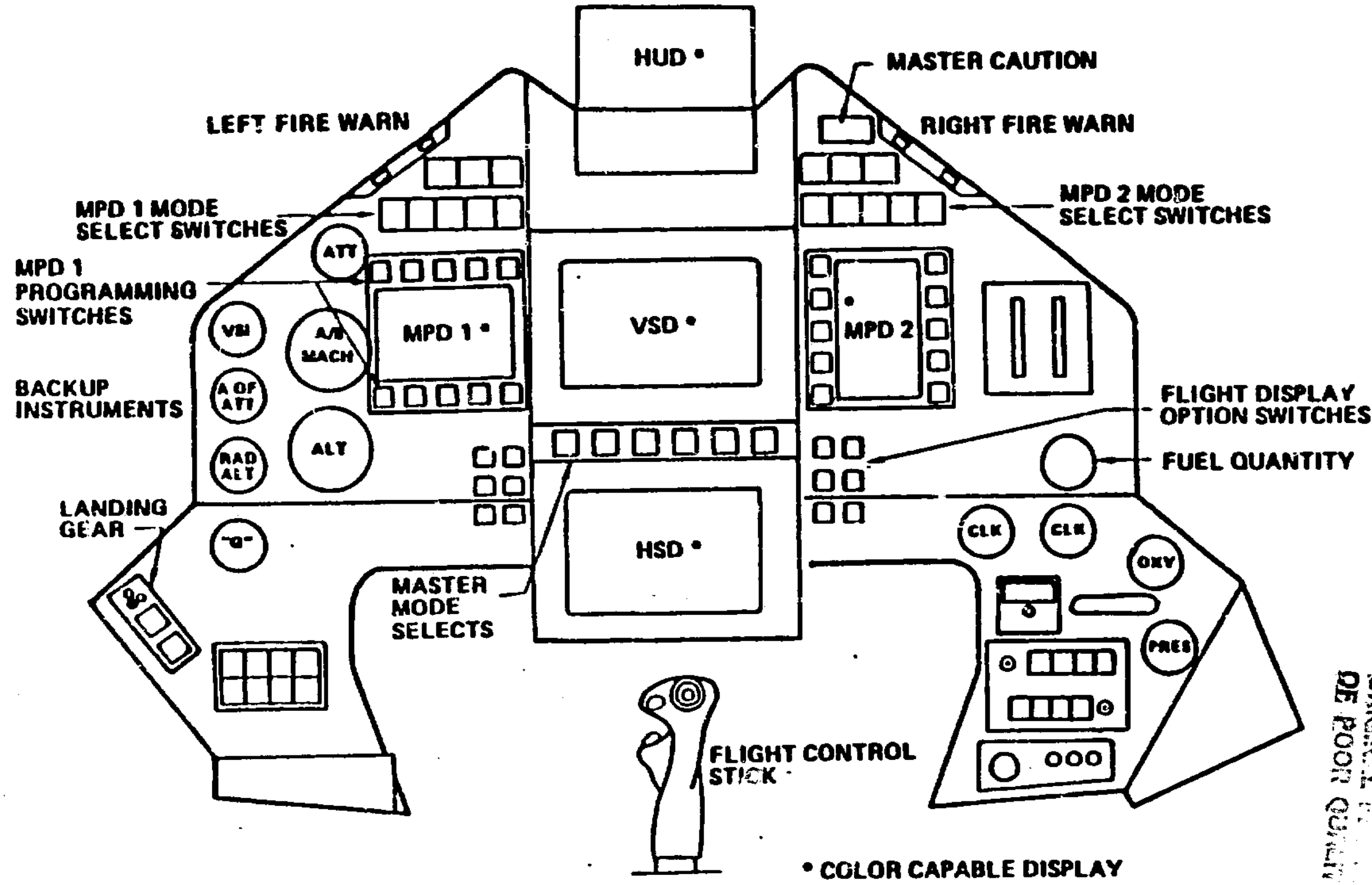

Figure 4.2-5. "Pictorial Format Displays" Front Instrument Panel

4.2.4 Identification of Technologies Required

Due to the unique conditions of Space Station, the hardware and software required to implement the workstations led to the examination of innovative technologies. These technologies included flat panel displays, programmable switches, hand controllers, voice recognition, voice synthesis and touch input devices. Various options within each technology were evaluated for compliance with Space Station restrictions.

4.2.5 Technology Trade Studies

Those technologies found to be most promising during Task 4.2.4 were evaluated further on a cost/benefit basis. The new technologies were compared to their existing respective counterparts in terms of power, weight, volume, crew time, recurring and nonrecurring costs.

4.3 Technical Discussion

The following sections include a detailed discussion of the study outputs with illustrations. The order follows the sequence of the Approach subtasks.

4.3.1 Definition of Functional Requirements

The next two subsections present the discussion of the mission scenario development and functional analysis upon which the conceptual workstation configurations were based.

4.3.1.1 Mission Scenario

The mission scenario defined the limit of operational tasks that would be considered and the order of those tasks. The development of the scenario drove out potential sequencing problems, manloading requirements and offered a preliminary look at the operational timeline. The development of the scenario was based on previous OMV experience.

The scenario was limited to the control of one OMV on a rendezvous and docking mission. It included checkout, launch and retrieval upon return to Space Station. The mission scenario was broken into phases as shown in Table 4.3-1. Below each major mission phase heading are listed some of the tasks at the gross level for that phase. This initial

Table 4.3-1. OMV Mission Scenario by Mission Phase

1.0 Prelaunch checkout requires C&D and EVA operators

- Power-up OMV (C&D)

  Check OMV subsystems using BIT through umbilical (C&D, EVA)
  - Power, fuel, thrusters, video docking, apparatus, radar, communications, computers, GN&C, etc.
- Complete OMV visual inspection (EVA)

2.0 Move to launch position requires C&D and EVA operators

- Disconnect umbilical (EVA)
- Grapple with RMS (C&D)
- Using RMS, move OMV to launch position (C&D)

  (*may want windows to check position*)
- Check thrusters if not done previously (C&D)
- Check any subsystem necessary (C&D)
  - Nav program loaded into computer
  - Select manual control
- Complete power-up sequence (C&D)

  (Radar, Star scanner, etc.)

3.0 Launch OMV (requires C&D operator)

- Fire GN_2 thrusters to move away from Space Station TBD ft
  - When at TBD ft switch to AUTONOMOUS CONTROL
  - Set up subsystem monitoring configuration

    (*may require two C&D operators to monitor functions*)

4.0 Rendezvous/dock/repair/retrieve (requires C&D operator)

For docking, repair and retrieving:

- Automatically stop at TBD ft from target spacecraft
- Select manual control, GN_2 RCS, cameras, lamps, range sensor, etc.
  - Locate target with cameras and focus, adjust aperture, etc.
- Close on target using GN_2 RCS
- Extend grapple fixture
- Dock with target and soft latch
- Complete hard latch

For repairing only:

- Extend Robotic arm, remove ORU from target and store on Free-Flyer
- Remove ORU replacement and position on target
- Stow arm

Table 4.3-1. OMV Mission Scenario by Mission Phase (Concluded)

5.0 Return to Space Station (requires C&D operator)

Without target spacecraft attached:

- Unlatch from target spacecraft
- Use GN_2 to back up from target

With target spacecraft attached:

- Turn off cameras, lamps, range sensor, and associated equipment
- Turn on ΔV and MMH RCS
- Set in return course
- Reset to AUTOMONOUS CONTROL
- Stop at TBD ft from Space Station
- Turn on/off pertinent subsystems
- Switch to GN_2 RCS and manual control
- Maneuver to RMS pick-up point and stop

6.0 Berth Free-Flyer (requires C&D and EVA operators)

Without target spacecraft attached:

- Grapple using RMS (C&D)
- Power down, turn off propulsion (C&D)
- Using RMS, move into Containment Area (C&D)
- Place in position and connect umbilical (EVA)
- Download computers (C&D)

With target spacecraft attached:

- Unlatch Free-Flyer from target spacecraft (C&D)
- Grapple target spacecraft wtih RMS and move into Containment Area (C&D)
- Grapple Free-Flyer with RMS and move into Containment Area (C&D)
- Place in position and connect Umbilical (EVA)
- Download computers (C&D)

step in the scenario development served as the basis for further refinement in the functional analysis.

Even at this gross level, some of the important features of the workstation were already evident. For example, a means of communication to the EVA operator was necessary; some means of controlling the OMV and RMS was required; status information must be presented and so on. The scenario basically served as an ideal pool for further development during the functional analysis. However, certain items listed in the scenario were not developed further: the EVA workstation was out of the scope of this study; and insufficient data was available to further detail the repair task.

4.3.1.2 Functional Analysis

During this subtask several aspects of the mission description were completed. The storyline of the scenario was filled out, including how each task could be accomplished. The division of labor between the crew and the system was determined. An idea of the crew workload level was obtained. Lastly, we were able to start defining the generic equipment required to successfully complete the tasks.

A summary flow diagram of the completed scenario is shown in Figure 4.3-1. It is keyed to the detailed listing of the functional analysis presented in Table 4.3-2. The numbers in the bottom of the boxes correspond to the numbering system in the functional analysis. The flow diagram provides an overview of the sequence of events while the analysis provides the details of how the tasks are accomplished.

Based on our recent experience with OMV and OTV we estimated that a ground crew of 10-20 was required to control such a vehicle remotely through an entire mission. Such manloading is not feasible for Space Station. In looking for alternatives, we decided that an expert system could greatly reduce the manpower requirements by handling the subsystem monitoring tasks. However, the remaining tasks still appeared to create too high a workload level for one operator. The division of labor became: one operator primarily responsible for the operation of the OMV, and the other operator primarily responsible for the operation of the RMS. Each operator would also serve as backup for one another during critical tasks, i.e. docking to a target spacecraft. The expert system would track subsystem status and monitor the OMV in transit.

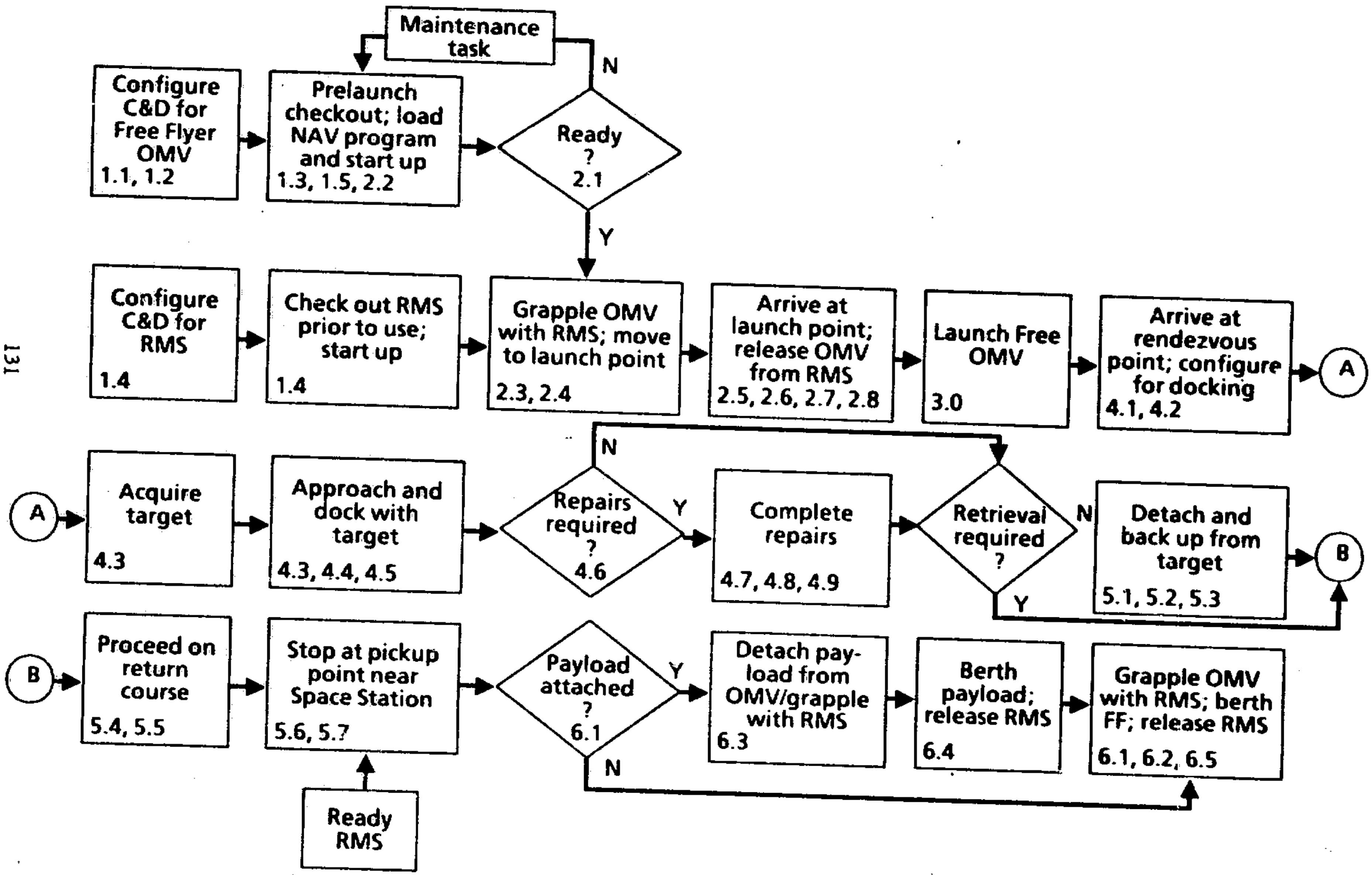

Figure 4.3-1. Mission Scenario Overview

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Table 4.3-2. OMV Mission Scenario Functional Analysis

Mission Phase: 1.0 Prelaunch

Event	Pilot	Copilot	Computer	Free-Flyer	Comment
1.1 Configure Controls and Displays (C&D) for OMV Operations (Ops)	Select OMV Ops		Main Function Menu on Display OMV menu up • Other C&D configure according to preset design • Menu allows selection of mission phase and access to appropriate pages		
1.2 Configure C&D for Checkout (C/O)	Select Prelaunch Checkout • Enter vehicle ID #		1st p. of Prelaunch (PRLCH) C/O • Appropriate C&D ready to configure for C/O • List of subsystems available for C/O on 1st p. • If there is a specific sequence to follow, system won't allow any other unless specifically overridden • First is visual inspection	– OMV connected to umbilical – Provides heater power and COMM link	Need alphanumeric pad, enter, clear, delete, etc. keys First action is visual inspection

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Table 4.3-2. OMV Mission Scenario Functional Analysis

Mission Phase: 1.0 Prelaunch

Event	Pilot	Copilot	Computer	Free-Flyer	Comment
1.3 Visual Inspection A. EVA B. Remote	Communicate with EVA crew on their activity Using Containment Area cameras, and controls and displays, inspect OMV exterior. Enter "COMPLETE" when done.		Acknowledges task completed		– EVA Crew necessary – Requires at least 2 cameras or 1 on a robot
1.4 Start up RMS Operations	* 'C/O COMPLETED'	– Configure C&D for RMS Ops – select from menu – Complete presented checklist – RMS and C&D ready for ops	– RMS ops selected – C&D configured – Check list presented		
1.5 Subsystem Checkout	Makes appropriate inputs to system as instructed on displays Completes C/O		Subsystem sequence is shown to operator and walked through operation. System suggests tolerance limits but pilot has final decision. Apply power to all systems at once or as you go along? Assuming done as you go along. * C/O COMPLETE PRELAUNCH GO/NO GO STATUS	Send status information to SS computer for all inquiries	Probably use graphics for subsystem C/O (easiest for operator to understand) with lists of pertinent tolerances or use color/pattern codes for quick status recognition

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Table 4.3-2. OMV Mission Scenario Functional Analysis

Mission Phase: 2.0 Move to Launch Position

Event	Pilot	Copilot	Computer	Free-Flyer	Comment
2.1 Disconnect Umbilical • EVA • Remote		Communicate to EVA crew to remove umbilical OR Activate Disconnect switch	– * 'UMBILICAL DISCONNECTED' (CP)		EVA crew removes umbilical Stiff umbilical that retracts

2.2 Configure for Manual Control	Start setting up C&D for OMV manual control
	– Select from main menu
	  – results of PRLCH C/O available if necessary
	If not previously done, load in NAV program
	– Select NAV
	  – Select program load
	  – Enter data
	  – C/O program load
			– Configure (P) C&D for OMV manual	– Power on for appropriate system	

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Table 4.3-2. OMV Mission Scenario Functional Analysis

Mission Phase: 2.0 Move to Launch Position

Event	Pilot	Copilot	Computer	Free-Flyer	Comment
2.3 Grapple OMV with RMS		Using hand controller(s) grapple OMV with RMS • Video plus pertinent information displayed • When aligned, engage snare wires	Video, range, range rate, etc. displayed * 'FF LATCHED'		
2.4 Move OMV to Launch Position • Direct Vision – Windows		Using same configuration move OMV to launch point with RMS – have HUD on on window	Has plasmavor such type display over window for HUD. Graphics include traffic info, predicted & programmed flight path, range and range rate, caution and warnings, etc.		Feasible that size of work area may require RMS to be on a rail and move along to get additional reach
• Indirect Vision – camera or imaging-type sensor	Help monitor traffic during transition (need to bring up on one of station monitors - unless use a panoramic display)	Must select cameras (RMS wrist camera blocked). Also select which displays video is shown on. Adjust cameras.	– Controls available to select cameras, etc. – Camera configuration selected is illustrated. Parameters selected are displayed		Movement along rail applies whether use direct or indirect vision.

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Table 4.3-2. OMV Mission Scenario Functional Analysis

Mission Phase: 2.0 Move to Launch Position

Event	Pilot	Copilot	Computer	Free-Flyer	Comment
2.4 Move OMV to Launch Position (Continued)		Select prime video and overlay graphics (as on HUD). Move RMS/FF using controller(s) to launch point.	– On the display selected prime, overlay similar graphics to what was on HUD * 'LAUNCH POINT ARRIVAL'		Feasible that size of work area may require RMS to be on a rail and move along to get additional reach Movement along rail applies whether use direct or indirect vision.
2.5 Check Launch Status	Check last minute details & recheck critical systems. – computer walks operator through checklist.		* 'LAUNCH STATUS' – rundown on various systems. Order is preset. Operator just pages through or calls a particular system up for C/O. * 'LAUNCH STATUS GO/NO GO'	Send status message to SS computer	Pilot now is prime If 'GO' continue
2.6 Unlatch OMV from RMS		Depress switch on hand controller to unlatch OMV from RMS	* 'UNLATCH OMV' (COMMAND SENT TO COPILOT) * 'OMV UNLATCHED'		Snare wires untwist & end effector retracts

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Table 4.3-2. OMV Mission Scenario Functional Analysis

Mission Phase: 2.0 Move to Launch Position

Event	Pilot	Copilot	Computer	Free-Flyer	Comment
2.7 Stow RMS		Using hand controller(s) plus direct or indirect viewing, stow arm	* 'RMS STOWED'		
2.8 Select Attitude Hold (need to do this prior RMS release)	Select attitude hold and GN_2 RCS		Access attitude control page – activate attitude hold mode – GN_2 RCS on	– in attitude (& translational hold) – GN2 RCS on – Onboard computers active.	

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Table 4.3-2. OMV Mission

Mission Phase: 3.0 Launch OMV Mission Scenario Functional Analysis

Event	Pilot	Copilot	Computer	Free-Flyer	Comment
3.1 Select Launch Sequence	Select launch program from main menu - Select cameras if necessary for viewing departure; or have direct viewing; or have CGI display		*Launch sequence Configure C&D for launch using manual control - must include hand-off to autonomous control If using direct vision, HUD would be great. Planned flight path, range and range rate, traffic (may need one for P and for CP (head-down)	- Systems are ready for launch - Communication system on and operational	
3.2 Monitor Traffic	Also has responsibility communications during this time	While pilot is maneuvering OMV out of SS proximity, monitor subsystem displays and traffic. Also handles communications if necessary.	Subsystem monitoring and display of pertinent infc (expert system required for processing and filtering data)		
3.3 Move to Launch Point	Using hand controller(s), move OMV TBD feet from SS				

Table 4.3-2. OMV Mission

Mission Phase: 3.0 Launch OMV Mission Scenario Functional Analysis

Event	Pilot	Copilot	Computer	Free-Flyer	Comment
3.4 Final Systems Check	- When at/near TBD feet (launch point) check with CP to make sure systems are go – IF GO –	Prior to release to autonomous control, check to make sure all necessary subsystems are on and operating	Present final checklist to CP before autonomous control command		
3.5 Launch OMV	Hit switch to autonomous control Relieved	Relieved	SS computers (expert systems) will monitor flight and subsystems. Will notify crew of problem (level of problem when crew notified must be decided). Status available on call by crew.	- Onboard computers will handle flight to rendezvous point. - In continuous communication with SS computers for monitoring and status checks (use of SS expert systems)	

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Table 4.3-2. OMV Mission Scenario Functional Analysis

Mission Phase: 4.0 Rendezvous/Dock

Event	Pilot	Copilot	Computer	Free-Flyer	Comment
4.1 Arrive at Rendezvous Point			– Signals crew OMV has arrived at rendezvous point	– When approaching rendezvous point, OMV starts slowing down so that it is station-keeping with target spacecraft – Stays in this mode until commanded otherwise by crew	
4.2 Configure Systems	Request C&D setup for controlling docking – Turn on cameras, lamps, docking sensor, etc. and locate target. Adjust equipment as necessary – Select GN_2 RCS	Request C&D setup to monitor systems – Monitor systems	– Configure C&D per requests – Display operational messages	– Continue feedback of status information – Cameras, etc. on and operational – GN_2 RCS on; MMH RCS off	
4.3 Close on Target	Using controller(s) approach target spacecraft. Video data, fuel, range and range rate, flight path, predictive display, etc. displayed.		– Display video and other data.	– Transmit video and flight status data	

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Table 4.3-2. OMV Mission Scenario Functional Analysis

Mission Phase: 4.0 Rendezvous/Dock

Event	Pilot	Copilot	Computer	Free-Flyer	Comment
4.4 Extend End Effector	– At 10 ft. from target, request extension of end effector to full-out position – Continue closing following flight plan		– Have graphics overlay of flight plan incorporated in display	– End effector moves to fully extended position	
4.5 Dock – Soft & hard latch	Align end effector over grapple fixture – When within docking distance hit snare wires switch to rotate wires – Activate hard latch mechanism – Turn off cameras, lamps,. etc. as necessary		* 'SOFT LATCH' * 'HARD LATCH'	– Snare wires rotate around grapple fixture and secure it. Jack screws then pull in target to soft latch – Target is hard latched to OMV – Cameras, etc. off as requested	
4.6 Configure System for Repair	Request repair mode	Monitor systems	Reconfigure C&D for repair. Hand controller(s) now control robotic arm. Menu up to select functions.	– Robotic arm activated	Assuming use of robot arm on OMV

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Table 4.3-2. OMV Mission Scenario Functional Analysis

Mission Phase: 4.0 Rendezvous/Dock

Event	Pilot	Copilot	Computer	Free-Flyer	Comment
4.6 Configure System for Repair (Continued)	– Turn on arm camera(s), etc. (Possible use of OMV cameras) – Adjust camera(s) as necessary	Monitor systems	– Send signal to turn arm on	– Arm camera(s), etc. on – Camera(s) adjusting	Need a control to open and close grip on arm. Maybe use a spring-loaded hand grip
4.7 Remove Target Spacecraft Orbit Replaceable Unit (ORU)	– Move arm to new ORU and using grip remove from OMV – Place new ORU in designated slot on target spacecraft; release grip; redo fasteners and connect cable	– Power up and checkout ORU	– Continue to display video, etc.	– Arm continues to respond	
4.8 Replace Target Spacecraft ORU	– Move arm to target ORU, undo fasteners and using grip remove ORU and disconnect cable – Place ORU in designated slot on OMV; release grip	– Power up and checkout ORU	– Continue to display video, etc.	– Arm continues to respond	
4.9 Stow Arm	– Move arm to stow position and secure – Turn off arm and appropriate systems		* 'ARM STOWED AND SECURED'	– Arm stowed and secured – Arm power off, camera(s), etc. off	

D006L-032/sec 4.0/pg 3

Table 4.3-2. OMV Mission Scenario Functional Analysis

Mission Phase: 5.0 Return To Space Station–Retrieval and Nonretrieval

Event	Pilot	Copilot	Computer	Free-Flyer	Comment
5.1 Configure C&D for return trip	Select Return from menu		– Display main menu and highligh selection – 1st page of Return up – C&D reconfigured		
5.2 Unlatch from target spacecraft	Unlatch OMV from target spacecraft		* 'UNLATCHED'	– Unlatched from target spacecraft	
5.3 Move away from target spacecraft	– Select GN_2 RCS – Turn on camera(s) radar, etc. so can keep track of progress – Using hand controller(s) back up TBD ft from target spacecraft		– Display video, range, range rate, etc.	– GN_2 RCS on – Camera(s), etc. on – OMV backs up from target spacecraft	Continues same as retrieval mission (on next sheet)
5.4 Turn equipment on/off	– Turn off camera(s) lamp(s), laser ranger, etc.; turn on V and MMH RCS, rendezvous radar	Continue monitoring systems	– C&D available to turn equipment on and off; display feedback status information	– Appropriate systems turn on or off	

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Table 4.3-2. OMV Mission Scenario Functional Analysis

Mission Phase: 5.0 Return To Space Station–Retrieval and Nonretrieval

Event	Pilot	Copilot	Computer	Free-Flyer	Comment
5.5 Program return course	Set in return course. (Expert system could determine what it is and have the course available or another crewmember may determine it and stored it.)		– Return course set in	– NAV information accepted and activated	
	– Select autonomous control		OMV is released from manual control	– Now under autonomous control of onboard computers	
	Relieved	Relieved	Expert systems will monitor OMV status and progress. Will also alert crew of problems.	– Will alert crew when approaching Space Station. Continue to send status information	

D006L-032/sec 5.0/pg 2

Table 4.3-2. OMV Mission Scenario Functional Analysis

Mission Phase: 5.0 Return To Space Station–Retrieval and Nonretrieval

Event	Pilot	Copilot	Computer	Free-Flyer	Comment
5.6 OMV with or without Payload (P/L) arrives at near stand-off point from Space Station	– Locate OMV visually either directly or by sensors (assuming SS has onboard sensors) – Select GN_2 RCS and manual control	– Monitor systems, traffic and P/L if there is one – Checklist complete	– Receives signal from OMV and alerts crew of its proximity C&D ready for ops. – Display systems checklist on appropriate switch panels	– Onboard sensors determine when at TBD ft from SS and thrusters come on to match SS velocity (stationkeeping) – ΔV & MMH CS off; GN_2 RCS on	
5.7 Maneuver OMV into RMS pickup point	– Using controller(s) maneuver OMV to RMS pickup point; monitor traffic and systems. – Stop OMV at pickup point; put in attitude and translational hold – Start some of the powering down sequence (cameras, radar, etc.)	– Prepare RMS for use – RMS checklist complete	– Configure CP C&D for RMS use – Monitor OMV systems & traffic – Provide for power-down sequence	– Moving to pickup point – Attitude and translational hold on – Systems shutting down	

Table 4.3-2. OMV Mission Scenario Functional Analysis

Mission Phase: 6.0 Berth OMV–No Payload

Event	Pilot	Copilot	Computer	Free-Flyer	Comment
6.1 Grapple OMV	– Monitor subsystems of OMV – Power down rest of system except computer and heater power	Commander now – C&D configured – using controller(s) and HUD (or other such display) move RMS to OVM and align end effector over grapple fixture – hit switch to engage snare wires	– RMS prime cameras, etc. on. – display video and other pertinent data – * 'FF LATCHED'	– in attitude and translational hold – OMV grapple fixture snared and vehicle latched	OMV now in direct vision
6.2 Move to containment area	– Download computers – Shut down	– Using RMS move to containment area and place in 'cradle' – Connect umbilical (provides power and communication link)	– Data transfer	– Quiescent	– Complete

Table 4.3-2. OMV Mission Scenario Functional Analysis

Mission Phase: 6.0 Berth OMV–No Payload

Event	Pilot	Copilot	Computer	Free-Flyer	Comment
6.3 Disengage OMV and Payload (P/L)	– Release latching mechanism between OMV and P/L. If necessary, back-up OMV from P/L – Put OMV in attitude and translational hold		– Pilot C&D configured for OMV and CP C&D configured for RMS – *'OMV and P/L DISENGAGED' – RMS up, C&D ready	– OMV and P/L disengaged	
6.4 Grapple P/L and move into containment area		– Using RMS, grapple P/L and move into containment area, placing in cradle. Connect umbilical if necessary			
6.5 Grapple OMV and move into containment area. (Proceed as on previous page)					

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From the functional analysis, several other facts became apparent. In order to control the vehicle, an operator requires visual data on vehicle attitude and location in addition to numeric data. However, some of the operations could only be handled by indirect vision such as video or sensor data. For other operations, direct vision might be desirable but it may also be difficult to accommodate and restrict Station operations. Advanced avionics and information presentation are also required in addition to the expert system, to handle the vast amounts of data generated during such a scenario.

4.3.2 Flight Controls and Displays Technology Literature Review

DoD, NASA and Boeing documentation was searched to locate related research topics. We were looking for new concepts and to discover problems with them or with the old concepts. The results of the searches are listed below.

One of the most promising ideas for information presentation is the use of pictorial formats. This concept relies on the use of graphics and object representation rather than columns and rows of numbers and characters to communicate information. Various pieces of related data are integrated into a single format that is readily comprehended by an operator. In this way, the operator can make better use of his decision-making capabilities rather using his time and energy in the data-gathering mode. This concept has been researched extensively at the Air Force Flight Dynamics Laboratories at Wright-Patterson AFB.

The use of voice both as a means of data input and output is another new promising area. Voice input or voice recognition can be used for many of the same types of tasks that are presently accomplished through a keyboard. By using voice however, the visual channel of the operator is offloaded as well as one or both hands. Similarly, with voice output or voice synthesis, the operator can listen to a message rather than have to read it. The use of voice is being studied at several military research bases as well as at Boeing for use in commercial cockpits.

The use of expert systems has already been mentioned. This also is a relatively new area that appears to be quite promising for use on Space Station. Since a previous section in this report addresses this topic, not much will be said here other than its use would seem to reduce crew manloading requirements and crew workload.

The use of multifunction displays and controls is not new but they still offer many advantages. A multifunction display or control is one that is not dedicated to one particular function. The display may present navigation data at one point, then when requested by the operator, change to a logistics display or any other desired display. The same concept is true for multifunction controls. The underlying idea is that only the information necessary or desired at any one time is what is displayed and no more. For example: if an operator is controlling an OMV, information on the supply module is unnecessary so it should not be cluttering up the panel.

The last concept to be discussed is eye-gaze control. With this method, an operator's eyes are monitored to determine where they are gazing. The operator's gaze activates or deactivates the control as the case may be. As such, this technology was not pursued any further.

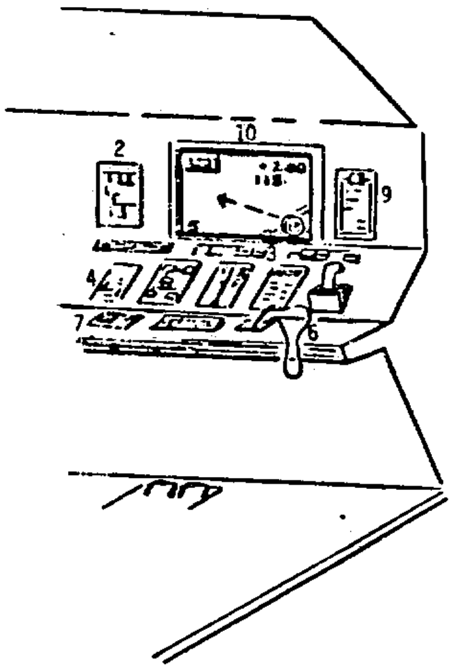
4.3.3 Conceptual Workstation Configurations

Based on the results of the functional analysis plus the research review and mission scenario, two workstation configurations were designed. The configurations are shown in Figure 4.3-2. The primary difference between the two configurations is that the first has a window for direct viewing of proximity operations, and the second has no window using indirect or remote vision only. The configurations served to define the number and type of displays and controls, i.e., high resolution, full color graphics displays, 10-inch and 15-inch on the diagonal, are required. The following discussion presents the general features of the workstations.

As mentioned earlier, one configuration uses a window while the other does not. Direct vision is usually the preferred means of viewing an operation. Depth perception, relative rates, resolution and color detection are usually better with direct vision. The window size was conceived to fill a visual angle of 60-degrees. This is the size of the normal binocular vision cone without eye or head movement.

However, an operator's field of view and line of sight are limited by the size and location of the window. Requiring a window at the workstation further restricts the operator since the operator can no longer move to another window or workstation to perform the task.

With Window



Unique Features
(10) Head-up Display

Common Features
(1) Multifunction Displays
(2) Programmable Switches
(3) Caution & Warning Panel
(4) Dedicated Switch Panels
(5) 6-Axes Hand Controller
(6) Touch Input Device
(7) Voice Synthesis and Recognition
(8) Keyboard
(9) Clipboard

Without Window

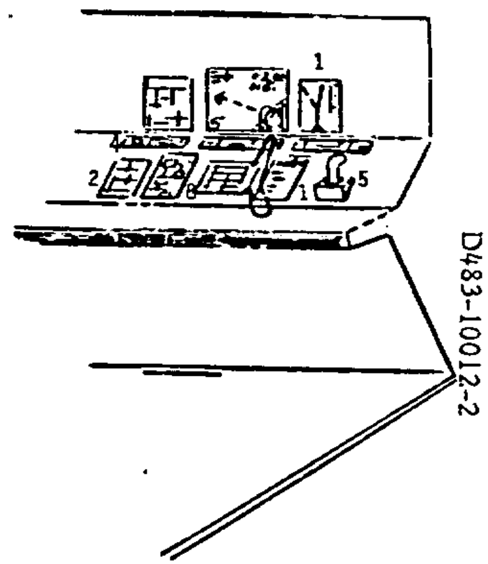


Figure 4.3-2. Conceptual Workstation Configurations

While remote vision is not as desirable due to loss in resolution, color and lack of depth, it does offer other advantages. If the sensor is mounted on a pan/tilt platform and has zoom capability, the field of view can be changed dramatically while the line of sight can be virtually limitless. Operationally, remote vision is used for critical OMV operations such as docking to a target spacecraft or payload and repairing another spacecraft by using a robotic arm. Grappling a spacecraft with the RMS also requires remote vision.

The geometry of the workstation is based on zero-g posture, line of sight and reach envelopes for the 95-percentile male to the 5-percentile female. It was assumed that adjustable foot restraints were either not available or not functional so that all crewmembers' feet would be basically at the same height above the floor.

The following paragraphs discuss the specific features of the workstations. The number preceeding each feature is keyed to Figure 4.3-2.

(1) The displays must all be high-resolution, full color graphic displays with a short rise-fall time for dynamic scene presentation. The center display is a 15-inch diagonal screen, primarily used for the presentation of sensor and graphic data directly related to the control of OMV or RMS. The three other displays are 10-inch diagonal screens, also high-resolution, full-color graphic type. These displays are primarily used for subsystem data presentation, one subsystem per display. An alternative method is to use larger screens, reduce the total number of displays and partition the screens for the simultaneous display of various system and subsystem information on the same screen. This screen partitioning method has been used successfully in many ground control situations.

Any display should be capable of presenting any type of information on any system or subsystem that is requested by the operator. Hence, they are called multifunction displays. The information can be presented in several different types of formats, including pictorial, graphic, analog or video, in color or monochrome. Examples of some format concepts are shown in Figure 4.3-3.

(2)&(3) Programmable switches offer many advantages over dedicated switches for a number of applications. Most switches at a workstation are used a very small percentage of the time during a mission. As a result, much of the panel real estate is occupied by many switches that may only be used once during an entire mission. A few dedicated programmable switches can replace many switches. Alphanumeric as well as graphic

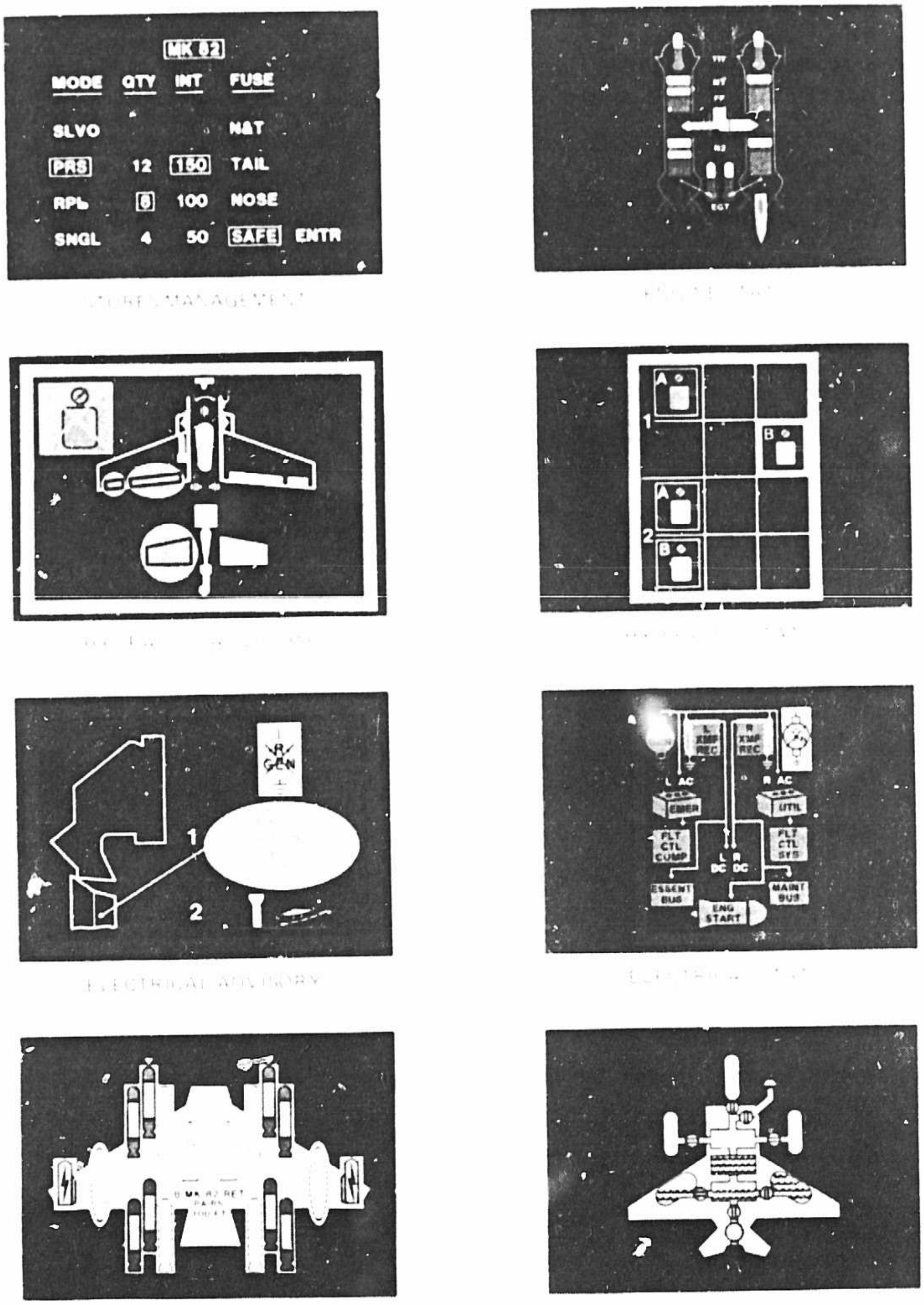


Figure 4.3-3. Multifunction Display Format Examples

data can be displayed to match the programmable switches and changed as desired. These switches can be used to lead an operator through a checklist or present status information. They can include caution and warning messages in addition to simple on/off indications. Most important, only the data, controls or checklists required need be displayed at any one time. Programmable switches can reduce operator error rate, workload level and training requirements.

(4) Certain functions, however, do require a dedicated switch. Specifically, any function that is life-sustaining (Environmental Control/Life Support System) or perhaps critical to the safe operation of Space Station (Communications) should have a dedicated switch that is hardwired rather than tied to the data bus. Many types of dedicated switches exist and can be suited to the needs of this workstation.

(5) Some means of rotational and translational input is necessary for the control of OMV and RMS. Traditionally, two three-axes hand controllers have been used, one for translation and one for rotation. When an operator is responsible for additional tasks other than vehicle control and has both hands occupied, real problems can result. One six-axes controller offers the advantage of freeing one hand while putting all the motion axes in the other, potentially increasing the accuracy of control. Some preliminary studies using the six-axes controller thus far have not indicated any training problems nor any cross-control problems.

(6) Touch input devices allow display screens to make control inputs. Highlighted areas or objects can be touched on the screen for convenient control. Touch input devices are relatively new devices but have had high user-acceptance thus far. They could be used to make display selections, move a cursor or possibly draw graphics. Touch screens are the most common but are not very well suited for Space Station use. While the resolution of touch screens has improved from the early versions, accidental activation can still occur. In a free-floating zero-g environment, the likelihood of accidental activation may be higher, which would be hazardous. Touch pens are an alternative that use a stylus to activate a statically charged screen. The screen is only activated when touched by the stylus thereby reducing the accidental activation problem. While using a stylus is very natural, it may pose some reactionary problems in the zero-g environment.

(7) Research has indicated that 90% of the information we process is received through the visual channel. As such, that channel usually tends to be overloaded. Voice recognition and synthesis offer alternative means of operator input and system output.

By using voice recognition, an operator does not have to divert his attention from the task at hand to locate the keyboard and type in the data. Addressing the computer and saying the data would be a convenient alternative. Similarly, using voice synthesis allows an operator to continue working at the task without having to again divert the operator's attention to look at a screen for the computer output. A synthesized voice could just tell the operator the results. This is also an excellent means of getting the operator's attention for a caution or warning message.

A voice recognition system has been characterized for this purpose. The characteristics include: (1) capable of recognizing connected speech at least but would prefer continuous speech recognition; (2) at least 500 words and phrases in the stored vocabulary with 100 to 150 words and phrases available at any one time; (3) capacity for a minimum of 70 vocabulary subdivisions; (4) require 2 or less training passes per word or phrase; (5) recognition accuracy of at least 99% and a combined substitution and false acceptance error rate of less than 0.05%; response time of 0.1 sec; and (6) capable of speaker identification and adaptability.

A voice synthesis system also has been characterized for the workstation. Its features include: (1) speech generated by using phonemes rather than a prerecorded digitized voice; (2) a minimum vocabulary of 20,000 words; (3) generate speech that is distinctive, intelligible and coarticulated; and (4) generated speech that is capable of intonation, inflection and is speed-variable.

(8) A keyboard is also provided for data entry, so an operator may have the choice of data entry method - keyboard, voice recognition or touch input device. The keyboard at this workstation was conceived to use programmable switches. This implementation allows the keyboard to be configured in standard QWERTY fashion or in special configurations specifically suited to the task at hand.

(9) A clipboard is provided at the workstations for the operator to use as desired.

(10) A Head-Up Display (HUD) was incorporated into the windowed workstation as a unique feature. A HUD is an instrument where relevant computer-generated dynamic symbology is projected onto a clear combining surface mounted in the operator's field of view, thereby overlaying the symbology on the viewed scene. The operator then has all necessary information in his immediate field of view, lessening eye accommodation and attention-diversion problems. An example of a HUD developed for commercial aircraft

is shown in Figure 4.3-4. The symbology includes an airplane, flight path angle, horizon and pitch ladder representation. The symbology is overlaid on a runway scene.

The HUD for Space Station application would be used to present control and status information graphically while directly viewing an OMV or RMS operation. When the operation was not in the line of sight, the HUD would display sensor information overlaid with control and status information graphics. The HUD should be fairly large so that the operator's head does not have to maintain a fixed position which could be quite difficult in zero gravity. If the display was not large enough, the operator could lose the symbology with head movement. Here, the HUD was conceived to fill the same visual angle as the window.

Two other technologies were identified as part of the workstation but are not represented in the figure. These include computer-generated imagery and artificial intelligence/expert systems; both are software-based technologies. They are discussed in the following paragraphs.

Computer-generated imagery (CGI) can include various forms of data representation from simple graphics through detailed dynamic scenery. The entire range of CGI types would be used at this workstation. The workstation computer hardware and software must be capable of generating the full line of CGI, both in real-time and in nonreal-time. Nonreal-time generation requires additional storage and retrieval capabilities. In addition to the stored or canned graphics, the software should allow the operator to compose unique displays easily.

As mentioned earlier, an expert system is required to monitor the OMV subsystems and in transit progress. This expert system is necessary to maintain an appropriate level of operator workload. The expert system would also interact with the caution and warning system and the voice synthesis/recognition system. Since expert systems were studied in a parallel effort with the controls and displays and were discussed earlier in this report, no further discussion will be found in this section.

4.3.4 Technology Identification

The following subsections present the pros and cons on the various options for the technology items presented in the previous section.

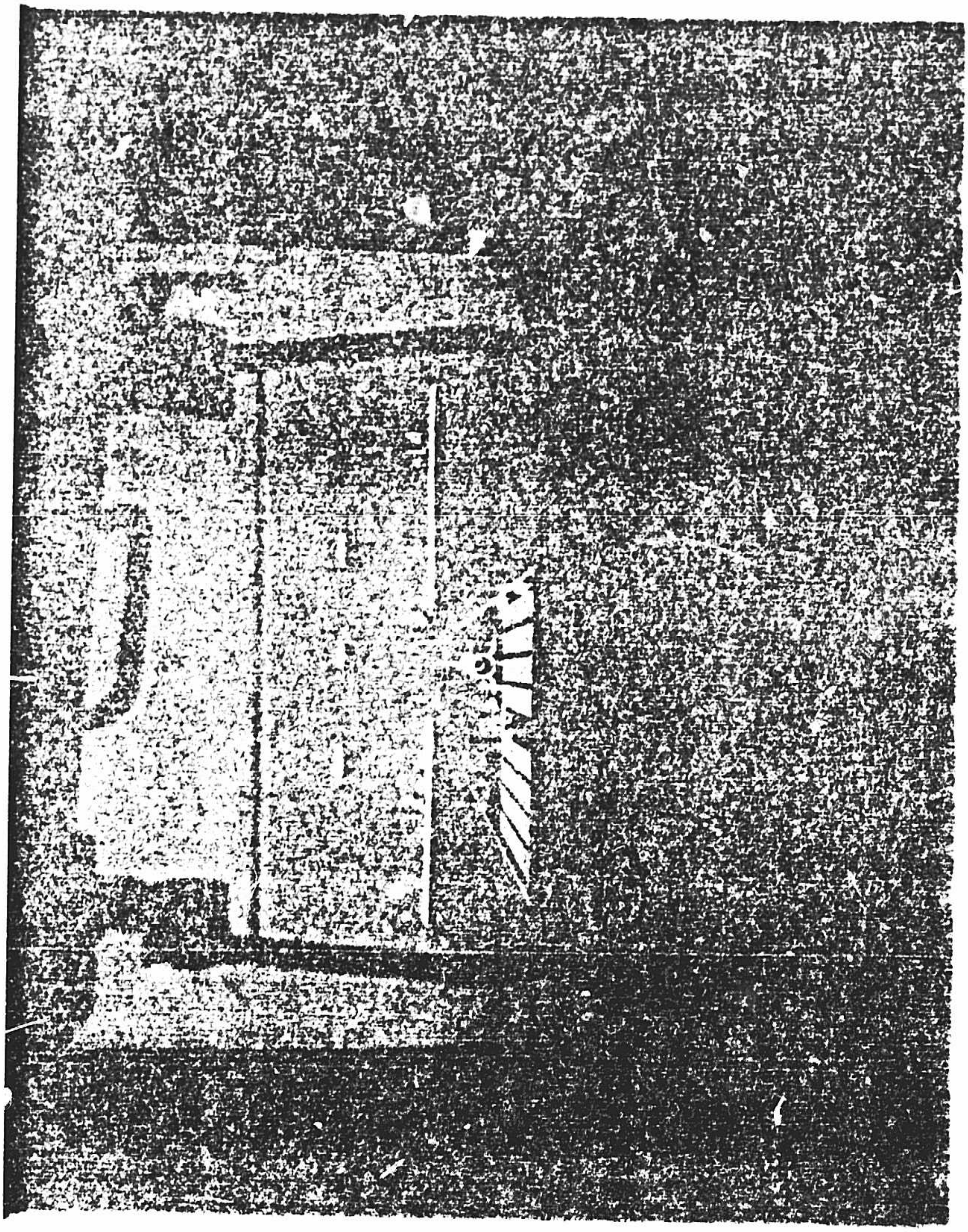


Figure 4.3-4. Commercial Aircraft Head-Up Display for Landing

4.3.4.1 Displays

The standard for display comparison is the cathode ray tube (CRT). CRT's are readily available in many sizes, with low-, medium-, or high-resolution, and with full color or monochrome screens. The rise-fall time of CRT's is very short (approximately 0.1 millisecond) making it ideal for the presentation of dynamic imagery. However, CRT's are also very heavy, bulky, consume much power and as a result dissipate much heat requiring forced-air cooling. These drawbacks could have a serious effect on Space Station consumables. Potential source: Hitachi, Mitsubishi, Tektronix.

Flat panel technology is the current replacement for CRT's. Typically, these displays are quite shallow in depth, 1-2 inches versus 12-14 inches. They are usually lighter in weight and have low power consumption. Due to the low power requirements, they have a longer life and higher reliability. Three flat panel technologies seemed to warrant further investigation for use a a multifunction display: liquid crystal displays (LCD), plasma displays and thin-film electroluminescent (TFEL) displays. These technologies are discussed below.

For comparison purposes only, the display information in Table 4.3-3 is provided. This information was compiled from a report done at VPI&SU (ref. 1). Note that the display technology field has advanced significantly since the report was published.

Liquid crystal display technology is probably the most promising of all the flat panel technologies. LCD's are among the lowest power consumers, do not require forced-air cooling and have few inherent limitations. They are much lighter in weight than CRT's and are much smaller in volume, typically only one to two inches in depth. LCD's have some drawbacks however. Currently, the majority of displays are monochrome with tricolor and full color displays just being developed. The resolution is no greater than medium for the best monochrome and low for color displays. Only small sizes are available. The rise-fall times have been shortened from what is reported in the table. Potential source: PanelVision, Seiko.

Plasma displays are also thinner and lighter than CRT's but their power consumption is not substantially lower. They do not require forced-air cooling. The resolution of plasma monochrome displays tends to fall in the medium to high category. They are available in many sizes, from small to very large. Color displays do exist but are

	Voltage	Power	Colors	Display size	Display depth	Rise time	Fall time	Inherent memory
Cathode ray tube (CRT)	up to 15kv	≦ 100w	<20	.75m diag.	1.2 x diag	1μs-1ms	1μs-100ms	No
Plasma	115	400-500 mw/cm^2	<20	2m diag	12mm	100ns	2μs	Yes
Electroluminescent (EL)	30-650	2-6mw $/cm^2$	<20	$(1.63m)^2$	5mm	1ms	10μs-1.5ms	No
Liquid crystal display (LCD)	1-8	$1mw/cm^2$	<20	$(30cm)^2$	1-2mm	50-300ms	100-400ms	Yes
Light-emitting diode (LED)	1.5 to 5.0	1.5mw /elem	3	$(.26m)^2$	10mm	10ns	10ns	No

Table 4.3-3. Display Technology Comparison

0022L-003/R1

small, have low resolution and luminance. Their availability is limited. Potential source: Hitachi, NHK Labs.

TFEL displays have similar power, weight and volume characteristics as plasma displays and are typically available in the smaller sizes. Neither tricolor nor full color displays have been demonstrated and some color shift problems have been reported with the monochrome displays as they age. Potential source: Texas Instruments.

4.3.4.2 Programmable Switches

Flat panel technology is also being used in programmable switches. Light-emitting diode (LED), thin-film electroluminescent (TFEL) and liquid crystal display (LCD) technologies are being incorporated into various switch housings for this purpose. The most mature of these is the LED switch which is being developed for both military and commercial aircraft application.

LED's are available in tricolor units. They produce red and green colors separately. Combined, the two produce amber as the perceived color. The resolution of these switches is sufficient to present good-quality graphics as well as legible alphanumerics. They are heavy power consumers, however, and require either forced-air cooling or a cold plate to remove excess heat. The LED's can be packaged into a switch size (1.0 x .75 inches) or into a larger display area (2 x 3 inches) with one-inch units edge-abutted. Potential source: Microswitch, Litton Systems.

TFEL light bars have also been incorporated into switch housings using a touch screen for activation. Currently, they are only available in monochrome units in green and amber. Other colors are certainly feasible using different dyes. Tricolor units are not commercially available. Again, these are heavy power consumers and require a cold plate for cooling. The resolution is comparable to the best LED switch. Potential source: Microswitch, and FarWest Manufacturing.

The incorporation of LCD's into a switch housing is a very recent development and is quite immature as a technology. It will certainly benefit from the research going on in the display area. Tricolor switches are feasible but are not yet commercially available. As with the larger LCD displays, the switches are lower power consumers and do not require cooling. Potential source: Litton Systems.

4.3.4.3 Dedicated Switches

As stated in the previous section, many types of dedicated switches are currently available. Some of the types include toggles, pushbuttons, discrete and continuous rotaries, lever locks, etc., all of which can be guarded or unguarded. Potential source: Korry, Microswitch.

4.3.4.4 Hand Controller

These are two methods of implementation for hand controllers. The first is the displacement type where the grip alone or the grip and shaft can move an appreciable distance, usually up to 0.25 to 0.50 inch. The second method is a force-feel type where the grip and shaft move a very small distance but the force input is actually detected by pressure transducers. A displacement type controller is in the prototype stage and the results from preliminary testing have been good. A force-feel type is in the design stages. Potential source: CAE Electronics, Lear Siegler.

4.3.4.5 Touch Input Device

The most common touch input device presently is the touch screen. There are two basic methods of implementation: beam-interrupt and pressure-sensitive overlay which is implemented in different ways. Pressure-sensitive screens usually have better resolution than the beam-interrupt and are less prone to accidental activation. With either implementation, the screen surface tends to smudge from fingerprints. Potential source: Hewlett-Packard, MicroSwitch.

The touch pen is an alternative to the touch screen. It uses a stylus to activate a statically-charged mesh overlay which also serves as a contrast enhancement filter. Since the stylus is needed to activate the screen, the chance of accidental activation is less. The resolution of this device is also fairly high. Potential source: Sun-Flex Co.

4.3.4.6 Voice Recognition and Synthesis

Much research is being done in the area of voice recognition, spurred on by military and commercial applications. The current systems are speaker-dependent and recognize isolated or connected speech. The stored vocabulary size is less than 500 words with approximately 50-75 words available at one time. Training the systems requires three to four passes on each word. Speaker adaptation and identification is limited. Potential source: Texas Instruments, ITT.

Voice synthesis is much further advanced than voice recognition. Stored vocabularies can be 10,000 words with some degree of inflection and intonation. Some systems use digitized voice whereas others use phoneme-based speech. Some systems also allow a choice of voice types. Potential source: Digital Equipment Corp., SpeechPlus.

4.3.4.7 Head-Up Display

The current technology of head-up displays has achieved a maximum horizontal field-of-view (FOV) of 30°. The combining surface for such a FOV is usually 4-8 inches from the operator's eyes. The operator must maintain his eyes in a fixed position in space in order to view the entire display. These features are unacceptable for this workstation.

However, research is continuing on the development of a HUD projected onto the cockpit windscreen. This technique may be applicable to the Space Station needs. Potential source: Svena.

4.3.4.8 Computer-Generated Imagery

Real-time graphics and high-resolution dynamic imagery is feasible with current technology and it is continually advancing. Potential areas of concern with current technology include: the size of the machine necessary to generate the displays, its power, volume and weight specifications. However, until the display formats are at least superficially defined, any estimate on machine capacity requirements would be unrealistic. Potential source: Lexidata, ADAGE.

4.3.5 Technology Trade Studies

The previous section presented various technology alternatives or described what state-of-the-art systems could do. This section will describe the technology option that appears most promising and evaluate it further on a cost/benefit basis. The qualitative and quantitative results are shown in Tables 4.3-4 and 4.3-5.

Technology	Cost	Benefit	Comment
• Flat panel	H	H	Cost is high relative to CRT; great savings in power, weight, and volume; helped by consumer market
• Voice recognition and synthesis	L	H	Cost low due to development for commercial and military markets; great boon to operators
• Programmable switch	L	H	Exist presently; relieve panel space
• Hand controller	L	M	Prototypes exist presently; relieves panel space and one hand
• Input devices (touchpen)	L	M	Exist presently; reduces operator error rate, workload, and time
• Head-up display	H	H	Wide field-of-view would drive cost up; reduces operator workload

Table 4.3-4. Qualitative Cost/Benefits of Techncloqy

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Item	Cost Δ(%)		Δ (%)			Development Risks	Benefits
	Development	Production	Power	Weight	Volume		
Multifunction display							
CRT							
LCD	+3* mil	−80	−67	−93	−83	Color saturation, resolution, update rates, luminance	Reduced power, weight, volume and production cost. Higher MTBF
Multifunction switch							
LED							
TFEL	+35	−12	−83	0	0	Color shift with aging, tricolor panel	Reduced power and production costs. Higher MTBF.
LCD	*	−86	−90	0	0	Color saturation, luminance	Weight and volume savings insignificant due to switch actuator mechanism

* Complementary development costs

Table 4-3.5. Quantitative Costs/Benefits/Risks of Technology

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Item	Cost Δ(%) Development	Cost Δ(%) Production	Δ (%) Power	Δ (%) Weight	Δ (%) Volume	Development Risks	Benefits
<u>3-Axes Controller</u>							
6 Axes Controller	0	+ 25	0	− 50	− 50	Already developed but requires zero-g test	Fewer components; frees one hand
<u>Touch Screen</u>							
Touch Pen	0	+ 25	- 25	0	0	Already developed but required zero-g test	Reduced accidental activation. Increased accuracy
<u>Voice I/O</u>							
Advanced Voice I/0	+ 1.5 mil	+ 90	0	0	0	Memory requirements and signal processing speed	Reduced training requirements and visual workload. Increased operator performances
<u>30°-FOV HUD</u>							
60°-FOV HUD	?					Technology feasibility	Reduce operator workload and eye fatigue

Table 4-3.5. Quantitative Costs/Benefits/Risks of Technologies (Concluded)

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4.3.5.1 Liquid Crystal Display

Of the flat panel display technologies, LCD appears to be the most promising. In addition to the technical market, LCD technology is receiving much support from the consumer market. Some problems still have to be resolved however. The major problem is a full-color display. Such displays have been demonstrated but they have their shortcomings[2]. One method is to use some type of backlighting, either TFEL or a lamp source and produce the color by field-sequential techniques. Using either of these techniques requires a high power illumination source thereby reducing the low-power advantage. The other method involves using various dye deposits in the crystal matrix. The colors thus far have not been as saturated as CRT colors and the luminance level is quite low when compared to CRTs. Resolution is quite low also. However, this technique does allow a color display while maintaining a low power profile and seems to offer the greater advantage for Space Station. This technique is actively being developed in Japan.

When LCD's are compared to CRT's over the life of Space Station, the benefits could be significant. Even though the development costs will be high ($3 million, not 3 million percent), the savings in power, weight and volume in addition to the increased reliability and reduced production costs could prove to be quite advantageous.

4.3.5.2 Programmable Switches

At present, the LED technology is the most promising for use on Space Station. It is already developed, tested and used in various applications. The switches can be heavy power consumers when all of them are lighted. However, the duty cycle of the individual LED's per switch and the duty cycle of the switch bank as a whole must be evaluated before a determination of real power consumption can be made.

As LCD color technology progresses, the application of this technology to programmable switches would again prove beneficial to Space Station. As shown in the table, the production costs and power savings are significant when compared to the LED's. There will not be any savings in weight or volume since the major factors in those two parameters are the switch housing and mechanism. They will be basically the same regardless of the flat panel technology used.

Currently the TFEL technology does not appear promising for a tricolor display. Manufacturers have quoted a development time of approximately 10 years. There does not seem to be much of a push on this technology.

4.3.5.3 Dedicated Switches

No required new development indicated. Present equipment is satisfactory.

4.3.5.4 Hand Controller

The displacement six-axes controller seems to be the most promising new technology for this application. The table may be misleading in reporting no development costs however. Since this item is not yet in production, some of the nonrecurring costs are rolled into the production costs for the units. Since there is only one controller per station, there is a reduction in weight and volume as compared to using two three-axes controllers. The power consumption will probably be the same since the total number of axes is the same and the number of input/output signals is the same.

4.3.5.5 Touch Input Device

The touch pen appears to meet the needs of this workstation the best. Since it is an item already developed, the only risk is the space qualification of the item. The production cost does appear to be higher than the touch screen costs. However, the advantages mentioned in the previous section may outweigh the slightly higher costs.

4.3.5.6 Voice Recognition and Synthesis

The costs for a system that will meet the requirements described earlier is rather high when compared to the current systems. However, such a system does not exist and the current systems could do the job but not as efficiently. A significant cost factor that is not reflected in the table is the cost per hour of the operator's time. The reduction in crew time required for an operation could be significant and may be great enough to offset the initial high costs of procuring the system.

4.3.5.7 Head-Up Display

At this time it is rather difficult to assess the costs of developing a HUD that would meet our requirements. First, the need for a HUD needs to be established. If there is a need, the field of view requirements need to be evaluated. At present, no such technology exists for such a wide field of view display and it is not clear how it could be implemented.

4.3.5.8 Computer-Generated Imagery

At this time, it is difficult to assess a need for further development of CGI hardware or software. Until such time as the formats are defined, no trade studies can be made on this topic since no requirements as yet exist.

4.4 SUMMARY OF RESULTS

An OMV rendezvous and docking scenario was developed. The premise for the scenario was controlling the OMV from the Space Station with no ground control intervention. A functional analysis was performed on the scenario to determine division of labor between the operator and the computer system, the number of operators required and to characterize the workstation. Two workstation configurations were designed, one with a window for direct viewing and one without a window using remote viewing. The technology required to complete the workstations was evaluated based on the goals of low power consumption, low weight and volume, high reliability and favorable human interface characteristics such as sufficient luminance, good color saturation, safe and easy operation. The promising technologies were then evaluated for recurring and nonrecurring costs and compared to existing technology costs.

4.5 CONCLUSIONS

Based on the developed mission scenario and functional analysis, a minimum of two operators is required to successfully complete the mission. To assist the operators, an expert system is also required to monitor subsystem status of the OMV and RMS, monitor enroute progress of the OMV on its mission, and control the caution and warning system.

The following technologies were found to best satisfy Space Station workstation requirements but require further advancement:

- o Liquid crystal display technology for use in both multifunction displays and programmable switches. Beside the Space Station benefits already discussed, this technology would also benefit the consumer market and high-technology areas.

- o Six-axes hand controller. This technology requires further testing, especially in a zero-gravity environment.

- o Voice recognition and synthesis technology. There is a potential benefits interaction with military and commercial development. It may become the favored means of computer interface.

- o Wide field of view head-up display. A need must be established yet.

The following technologies were found to satisfy Space Station workstation requirements and do not require further advancement but do require zero-gravity testing:

- o Touch pen or screen
- o Dedicated switches
- o LED programmable switches

4.6 RECOMMENDATIONS

Some issues discussed in this study are recommended for further research. These issues include:

- o Establish the need for a window at the OMV workstation. If a need is established, the requirements for the window need to be determined such as size and location at the workstation as well as in the module.

- o If a window is found to be required, a Head-Up Display for that window should be developed. Again, the requirements for the HUD need to be determined such as size, location at the workstation, presentation of sensor data, illumination and transmissivity.

- o Development of display formats for vehicle control, system and subsystem information, caution and warning messages and other pertinent data presentation requirements.

4.7 REFERENCES

1. Snyder, Harry L. Human Visual Performance and Flat Panel Display Image Quality. Office of Naval Research, Code 455, Department of the Navy, Arlington, VA. July 1980. ONR-80-1.

2. Society for Information Display Digest of Technical Papers, SID International Symposium 1984, San Francisco. Paper 13.4. Palisades Institute for Research Services, Inc., New York. June, 1984.