TELEOPERATOR SYSTEM MAN-MACHINE INTERFACE REQUIREMENTS FOR SATELLITE RETRIEVAL AND SERVICING

VOLUME I: REQUIREMENTS

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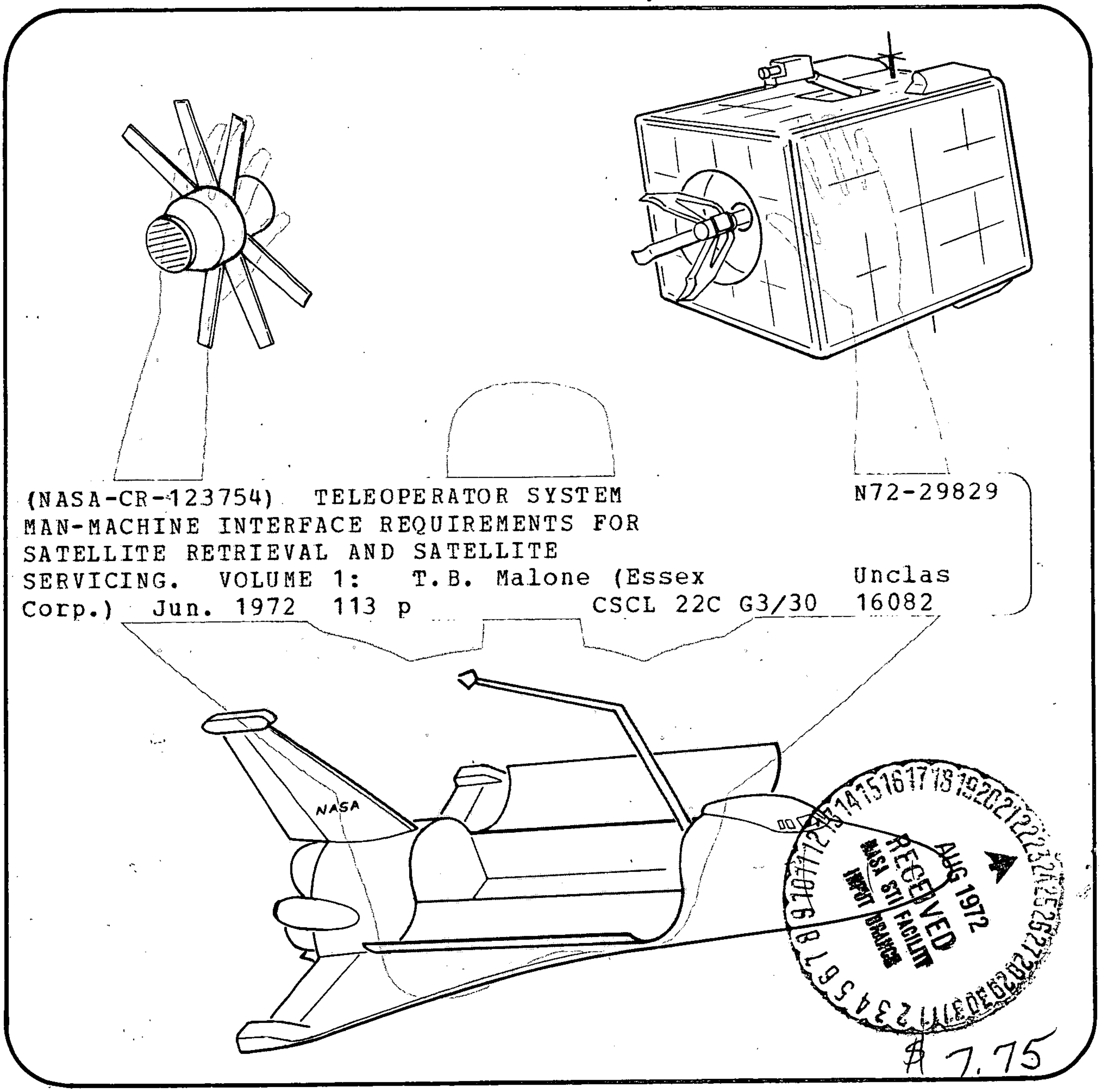

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JUNE 1972

ESSEX CORPORATION
ALEXANDRIA, VIRGINIA

Final Report

TELEOPERATOR SYSTEM MAN-MACHINE INTERFACE REQUIREMENTS FOR SATELLITE RETRIEVAL AND SATELLITE SERVICING

Volume I - Requirements

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and quantitatively described performance requirements. The best approach to design a system to do what must be done is to first of all define in precise terms what must be done, i.e., the performance requirements. These requirements identify the capability which the system must possess. They must be reliable, accurate, quantitative, and unambiguous. Developing such requirements is the first order of business of personnel engaged in developing teleoperator systems technology. The URS/Matrix Corporation is currently performing a study for MSFC to establish such requirements.

When system requirements have been identified and analyzed, they must be integrated. This process assures that priorities are considered and that incompatibilities and inconsistencies existing among different requirements are eliminated.

The next step was then to develop guidelines for allocating system functions to man or machine performance, for each mission. This tradeoff was based on the integration of requirements and the relationship between these requirements and human capabilities and limitations on the one hand, and between the requirements and engineering considerations on the other (complexity, state-of-the-art technology, reliability, etc.). The allocation developed in this study were such that the satellite servicing system is basically a manual system, the free flyer satellite retrieval system is primarily machine-aided (computer aided or supervisory control).

Again based on the results of the requirements analysis, a series of other operational tradeoffs were performed. The results of these trades were as follows:

Number of operators	- all systems and missions - one
Location of operator	- Free Flyer - sortie module - Attached - shuttle
Free Flyer ranging	- provision of range and rate sensor
Measurement of satellite rotational parameters	- video aids and special sensors

Free Flyer tracking of satellite attach point	- unresolved between manual or automatic and between grappler tracking vs whole vehicle tracking
Free Flyer station keeping	- unresolved between manual and automatic control
Satellite contact	- single point contact
Attached manipulator position monitoring	- direct view and video
Attached manipulator number of arms	- one for satellite contact - one for satellite emplacement into bay
Mode of emplacement	- automatic or computer assist
Type of servicing manipulators	- unresolved between special and general purpose
Number of servicing manipulators	- one
Type of modules to be serviced	- standardized
Stabilization at the worksite during servicing	- additional arm(s)

Design criteria were then developed for the control system of the teleoperator. These criteria were in three basic areas: controllers; control sharing for mobility and manipulative activities; and video control.

The essential capabilities and limitations of seven different controller configurations were identified and analyzed. This process led to the elimination of three concepts: the switch box; the exoskeleton; and a separate joystick and switchbox. The remaining concepts included an integrated joystick/switch arrangement, a pivoted joystick, the MIT isometric controller, and the Martin Mechanical Analog. An attempt was made to further reduce this list of competing candidates for each system/mission combination by comparing the performance requirements with the capabilities of each configuration. However, based on the inadequacy of existing information concerning the relative importance of the separate requirements and the specific capabilities of the concepts, in quantitative terms, no such selection was possible. All that can be said at present is that the selection of a controller must be made within the framework of the requirements associated with the specific mission, and must be based on man-in-the-loop simulation of that mission.

In terms of mobility unit-manipulator control sharing, no problems were identified for the attached system. For the free flyer satellite retrieval, it is recommended that techniques of computer assisted control be investigated to reduce the workload on a single operator controlling both functions simultaneously. It can be stated that if a computer assist capability is not provided, serious consideration must then be given to increasing the crew size from one to two men for the free flyer satellite retrieval mission.

No requirements for head aimed or eye aimed TV were evidenced for the subject missions. The recommended mode of video control is therefore manual control.

In the display area specific design requirements were developed for the primary display system - the visual system. These requirements can be summarized as follows:

- Use of four 11-inch 525 2D monitors with two receiving video from the teleoperator, one receiving video from the shuttle, and one dedicated for computer generated display
- Use of a single 44° field of view or a selectable 44° and 10° field
- Video size resolution - 5 arc minutes
- Video motion resolution - 5 arc minutes/sec
- Depth of view - two 2D cameras to provide three axis orientation
- Frame rate - at least 30 frames per second
- Lighting - adjustable up to 100 ft. lamberts on the screen. Requires 50,000 ft. candles at 20 feet from the target.

RC

- No specific requirements for force feedback have been identified
- Manipulator position - video of arm and computer generated display and advisory indicators.

In terms of operator workload it was determined that the free flyer satellite retrieval mission was the most demanding with the satellite servicing mission requiring the smallest load. In terms of skill requirements, the most important skill areas, in order of importance, are as follows:

- manipulator operation
- docking control
- image interpretation
- data handling and integration
- troubleshooting - fault isolation

The last task in this study was to identify requirements for additional research and technology development. Much research is needed to resolve unanswered questions concerning operator capabilities and system requirements. In technology development, additional effort is needed in manipulator and effector development and evaluation, display integration, controller design, computer assisted control techniques, special sensors and display aids, and methods for quantifying operator workload.

The conclusions of the study can be summarized as follows:

- Human operators can effectively participate in satellite retrieval and servicing missions using teleoperators providing that adequate attention is given to the design of the man-machine interface.
- Use of a single operator in orbit should be a design goal for reasons of space requirements, control integration and continuity, and demands of operator selection and training. This will necessitate investigation of computer assisted control techniques primarily for satellite retrieval missions.
- Man-machine interface design must be based on a careful and complete understanding of system performance requirements for the specific mission.

- No requirements are apparent, based on existing evidence, for inclusion of stereo TV, head or eye aimed TV, dual field of view, and kinesthetic feedback of arm position (exoskeleton controller).

- A range and range rate sensor will be needed in the free flyer system primarily to reduce operator workload and to ensure mission success.

- For satellite capture, single point contact is recommended based on man-machine considerations.

- A single manipulator arm is sufficient for satellite servicing.

- Spacecraft modules to be serviced should be standardized in terms of attach point design and location and markings.

- A good deal of work remains to be done before the precise design requirements for the man-machine interface of a teleoperator system can be specified. This work will essentially involve the conduct of man-in-the-loop simulations of selected sequences of each mission.

This report of work conducted in this study is organized into two separate volumes. Volume I presents the results of the analysis of requirements. Volume II is concerned with the descriptions of design criteria and requirements for additional research.

B

Executive Summary

A good deal of interest has been developing within NASA in providing the shuttle with a capability for retrieving and servicing automated satellites. In fact, a sizeable degree of the economic justification for the shuttle itself has been based on this specific capability. Investigations are proceeding to determine the impact of providing a retrieval and in orbit servicing capability to the shuttle on the economic and performance requirements of the satellites themselves. With the shuttle, satellites can be emplaced in orbit without requiring an expendable and dedicated boost vehicle. Satellites can also be replaced in orbit or a failed or obsolete spacecraft can be retrieved and returned to earth for refurbishment. Having the shuttle in orbit also enables the repair, maintenance, update, resupply, and refurbishment of satellites on orbit, all of which functions have been included in the generic term, satellite servicing.

The likely candidate system to perform satellite retrieval to the shuttle and satellite servicing on orbit is the teleoperator. This system basically entails a remotely controlled mobility unit with manipulators and sensors to perform the required mission operations. The system includes man in the control loop either serving as the primary source of control input or as a supervisor of computer control. Finally, the system includes a communication and data link between the manipulators, effectors, and sensors at the worksite, and the man at a remote location.

The rationale for considering the use of a teleoperator for satellite retrieval and servicing missions is basically that it is the most effective means of successfully completing the missions. Satellite mass and astronaut safety considerations obviate the use of EVA for satellite retrieval. Astronaut safety considerations and required workload make EVA for satellite servicing less attractive. Requirements for adaptive control and degree of

system complexity reduce the effectiveness of completely automated systems for both retrieval and servicing. The teleoperator, however, has the basic advantages of the EVA approach (use of man's adaptive intelligence and sensory capabilities) while ensuring astronaut safety and requiring less complexity than an automated approach.

With its heavy reliance on the capabilities of the human operator in the control system, the teleoperator has been described as a system which serves to extend and enhance the natural sensory, manipulative, locomotive, and cognitive capabilities of man. If this is a valid description, it necessarily follows that one of the more important considerations in the definition of a teleoperator system is the man-machine interface. This interface includes the aspects of the hardware and software design which interact with the man as well as the aspects of the man himself which impact his ability to interact with the machine (skills and skill levels, and workload). Specification of requirements for the man-machine interface entails the development of system requirements, the integration of these requirements with relevant capabilities and limitations of the human operator, and the determination of methods to satisfy the requirements taking full advantage of man's capabilities and within the constraints imposed by his limitations.

The objective of this investigation was to analytically develop requirements for the man-machine interface for a teleoperator system performing on-orbit satellite retrieval and satellite servicing. Requirements are basically of two types: mission/system requirements, and design requirements or design criteria.

Two types of teleoperator systems were considered in the study: a free flying vehicle; and a shuttle attached manipulator. The free flyer comprised a separate vehicle deployed by the shuttle carrying its own propulsion, power, manipulators, and sensors. The shuttle attached manipulator system included one or two long (up to 50 feet) boom manipulators with sensors and end effector devices attached. Throughout the study no attempt was made to evaluate the relative effectiveness or efficiency of these two system concepts. It was assumed at the outset that one or both could be incorporated in any specific shuttle mission and, therefore, requirements and design criteria for both will be needed.

The methodology used in the study entailed an application of the Essex Man-Systems analysis technique as well as a complete familiarization with relevant work being performed at government agencies (notably NASA) and by private industry. While the investigation was analytic and did not result in the acquisition of any additional data through experimentation, it did rely heavily on the findings and conclusions of past and on-going empirical studies of remote manipulator system requirements. The investigation of teleoperaotr man-machine interface requirements for satellite retrieval and servicing also logically proceeded from an earlier effort performed by the author for NASA (Malone, 1971). This earlier study was concerned with specifying requirements for additional human factors research and advanced man-machine interface technology development for space teleoperator applications.

The present study initially identified satellite retrieval and satellite servicing mission requirements and identified five satellites selected as being representative of the population of spacecraft projected for the period 1973-1985. The next step entailed developing system requirements for three system/mission combinations (free flyer satellite retrieval, attached manipulator satellite retrieval, and free flyer or attached manipulator satellite servicing). Identification of system requirements began with a development of functional requirements. For the satellite retrieval mission a total of 14 basic functions were identified which were further analyzed to about 180 subfunctions or tasks. In the analysis of the satellite servicing mission, three basic functions were identified which were further resolved into a total of 37 tasks.

Specific requirements were then generated for each task in each mission. These requirements included:

Information Requirements	- information needed by the system to perform the task
Performance Requirements	- capabilities required of the system to successfully complete the task
Support Requirements	- capabilities required of other systems
Interface Requirements	- physical, procedural, and environmental interfaces required

The identification of specific requirements relied heavily on the results of earlier investigations, notably the Bell Aerospace MSFC studies, the GE MSC and ARC investigations, the North American Rockwell ATS-V study, the Grumman MSFC Docking study, the Martin and MBA attached manipulator work, the MDAC Shuttle Orbital Applications and Requirements (SOAR), the MIT control studies for MSFC, the Lockheed Payload Effects Analysis, General Dynamics studies for the Office of Naval Research, and in house study efforts performed at MSFC and MSC. Where available and relevant, performance requirements for the retrieval and servicing missions were obtained from these sources. Due to variations in the subject missions and system techniques, these requirements are not meant to isolate the precise capabilities required of a teleoperator. Rather they are indicative of the range of required values which might be encountered in typical retrieval or servicing missions.

The above discussion serves to point up an immediate and critical problem in the development and integration of technology for teleoperator systems. Maximum levels of effectiveness and economy in design are realized when the design efforts are focussed and directed by clearly defined and

CHAPTER 1 INTRODUCTION

A teleoperator, as its name implies, is a device operated at a distance. A teleoperator system includes the remote device, a control station and a link between the device and the station. The general purpose of a teleoperator system is to augment and extend man's capabilities beyond his physical presence. These capabilities include sensory, manipulative, locomotion and cognitive abilities. A teleoperator system, therefore, includes provisions for sensing the remote environment, remotely manipulating objects in that environment, moving to the environment and within the environment, and, to some degree, local logic or data processing.

The sophistication and complexity of subsystems developed to provide these capabilities can vary over a wide range. Sensor subsystems can include video, force feedback sensors, tactile sensors, position and rate sensors, and environment sensors. Manipulators can vary in the degree to which they represent the human arm, in their degrees of freedom, in their articulation and dexterity, in the type of arm drive, electromechanical or hydraulic. Locomotion systems can comprise self contained free flying vehicles or booms attached to spacecraft. Cognitive subsystems can range from a minimal automatic capability with maximum use of the man, to use of preprogrammed subroutines, to systems capable of learning, adapting to changes in the environment, pattern recognition and problem solving.

Although teleoperators or manipulator systems have been widely used in radiation hot cells for some years, and have been receiving greater interest for undersea applications, their utility for space missions has been recognized only in the recent past. NASA has established a committee to study teleoperator technology development requirements and to develop the NASA wide program of teleoperator technology research and development.

Since man plays a prominent role in the teleoperator system, a good deal of consideration must be given to human operator requirements and capabilities in the development and integration of teleoperator technology. These requirements can be expressed in terms of requirements on the man (skills and workloads) and requirements on the man-machine interface (controls and displays).

The objectives of this study are:

- To develop and define the role of man in shuttle teleoperator satellite retrieval and satellite servicing missions.
- To develop design criteria for the shuttle teleoperator man machine interface
- To develop workload criteria and to identify operator skill requirements
- To identify requirements for additional research and technology development

The scope of the study is limited to human factors considerations; two classes of shuttle teleoperator systems: the free flying teleoperator and the attached manipulator; and two specific missions: satellite retrieval and satellite servicing. In being limited to human factors considerations, the study focused on man/system requirements, and was concerned with the design of only those aspects of equipment which interface with man. The engineering design requirements of manipulators, sensors, propulsion systems, etc., were considered out of the scope of this study. Satellites selected for study were low earth orbit systems, however, some consideration was given to satellite retrieval and servicing in geosynchronous orbit. Satellite dynamic states investigated in this study ranged from completely stable and stationary with respect to motions about rotational axis, to spinning, tumbling, and wobbling.

The methodology used in the present study comprised an application of the Essex Man/Systems Integration Approach. This approach is characterized by its orientation to and emphasis on requirements and their identification, analysis and integration. A second feature of the Man/Systems Integration Approach is that it stresses the comprehensive understanding of system requirements in terms of what the system must do and what capabilities it must have prior to giving consideration to how the system will be configured and designed to satisfy the requirements.

Thus, requirements serve as the starting point for the development of man-machine interface design criteria. Requirements provide the framework for further analysis and refinement of other requirements. They serve as the basis for tradeoff criteria used to select the best compromise from among the candidate concepts, and they form the basis for performance evaluations during system verification.

System requirements generally reflect the capabilities which the system must possess in order to achieve its assigned objectives within limitations imposed by system constraints. At one level, requirements describe the general objectives and phases of the mission (mission requirements). At a more specific level, they describe the activities and the relationships among activities to be accomplished by the system (functional requirements). At another still more specific level, requirements describe the capabilities required by the system to perform each function (system requirements). One important type of system requirement defines the level of proficiency or accuracy and the limits to be imposed on the system in performing each functions and each functional sequence (performance requirements). At this level, requirements also define what the system must know to perform each function (information requirements), what interfaces must be established to enable the system to effectively coordinate its activities with other systems (interface requirements) and what provisions are required for support of system activities (support requirements). Finally, requirements detail the characteristics of the system design in terms of hardware and software design features and approaches (design requirements or design criteria).

The outputs from this study will include the following:

- An understanding of teleoperator system requirements for satellite retrieval and satellite servicing missions
- Identification of the roles, responsibilities and requirements of man in the teleoperator system
- Teleoperator control station/control/display design criteria and design concept
- Teleoperator system operator position descriptions including tasks, skills, and workload criteria
- Guidelines for integrating teleoperator system activities and man-machine interface design with other shuttle systems
- Requirements for additional research and technology development to resolve design problems, provide performance evaluation data and advance system capabilities beyond the current state-of-the-art in manipulator design.

The work steps undertaken to develop these outputs, and the relationships among work steps are illustrated in Figure 1. These worksteps were accomplished primarily for the satellite retrieval mission which was judged to be the more difficult and critical of the two missions (satellite retrieval and satellite servicing). Due to this judgment and the fact that operationally the two missions differ only after docking and satellite stabilization, reduced emphasis was given to the satellite servicing mission.

The organization of this report is such that Volume I deals with requirements, system requirements, and control-display requirements, while Volume II presents results of tradeoffs and identifies control-display design criteria which can be established based on existing data. Where existing data are not sufficient, requirements for additional research are presented.

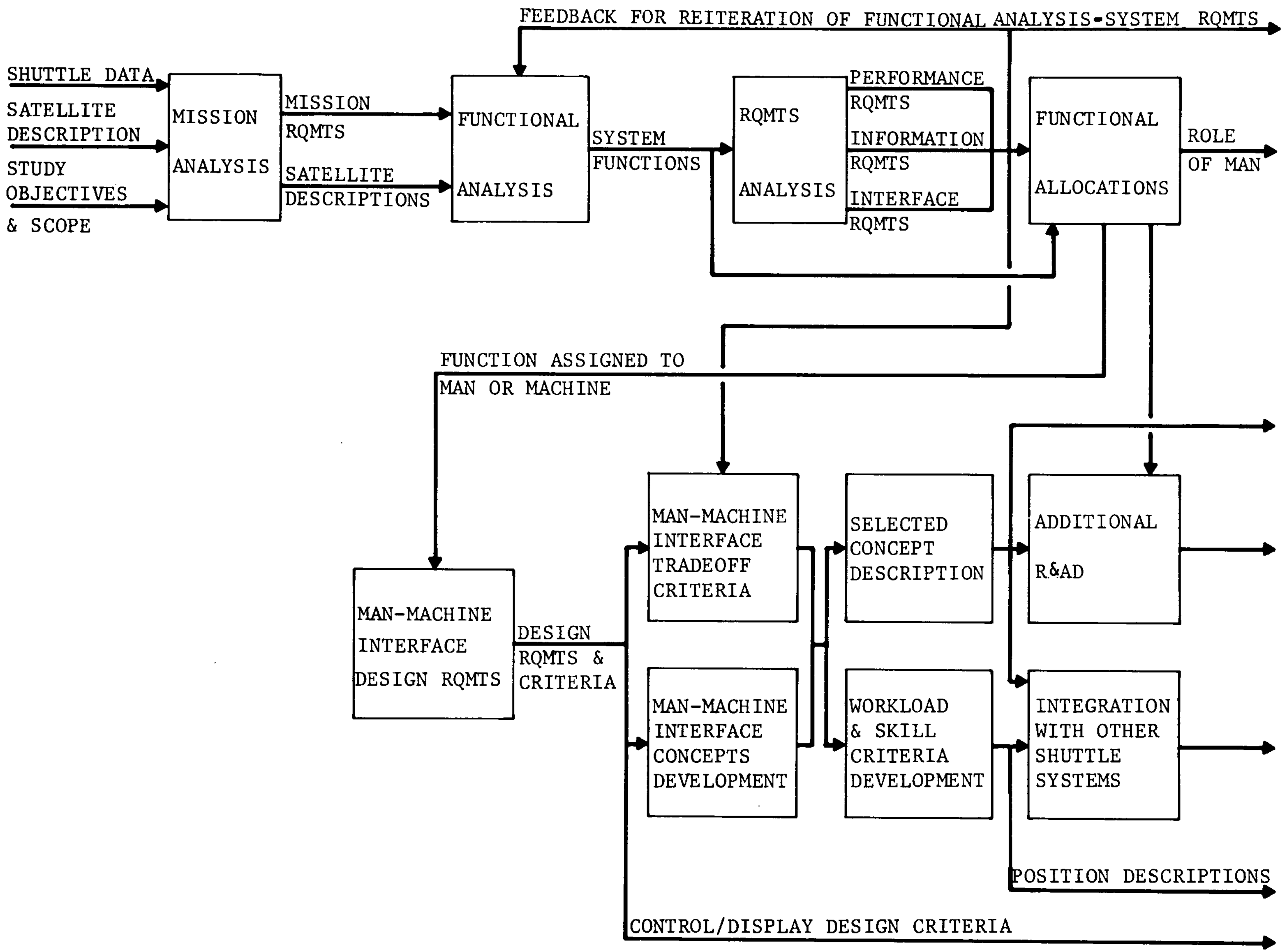

FIGURE 1 Study Activities and Outputs

CHAPTER 2 MISSION REQUIREMENTS

This chapter will discuss and describe the two shuttle teleoperator missions of interest: satellite retrieval and satellite servicing. Mission descriptions will entail identification of objectives, constraints, mission requirements and mission phases. The mission phases, which constitute the overall mission profile for each mission, will form the framework for later identification of functional requirements.

The objectives of the satellite retrieval mission is the capture and return of satellites to the shuttle and the recovery of the satellite in the shuttle cargo bay. Mission constraints for satellites in a shuttle-compatible orbit include performing retrieval operations on the sun side of the orbit and the maintenance of a line of sight from shuttle to satellite. Constraints for retrieval of geosynchronous orbit satellites include satellite mass vs. free flyer propulsion capability and the likely requirement to control retrieval activities from the ground rather than from the shuttle which is in a circular orbit. Constraints on retrieval for either type of satellite orbit generally include shuttle capabilities and limitations. Shuttle characteristics assumed for this study include those identified in Table 1.

Satellite retrieval mission requirements include the following:

- capability of retrieving satellites in low earth shuttle compatible orbit, in low earth non-shuttle compatible orbit (inclination of 0°) and in geosynchronous orbit

- capability of recovering satellites of a size and mass up to the limits imposed by cargo bay constraints

TABLE 1

Shuttle Characteristics Assumed for the Study

Characteristics	Quantity/Requirement	Source
Payload capacity	65,000 lbs.	MSC
Cargo bay dimensions	60 ft. length by 15 ft. width	MSC
Miss distance	± 6 inches	MSC
Miss angle	± 3°	MSC
Longitudinal velocity	± .4 fps	MSC
Lateral velocity	.15 fps	MSC
Angular velocity	.1 degree/second	MSC
Payload access	Internal sealable tunnel	NAR*
Shuttle crew	4 man crew Commander Pilot Mission operator Mission observer	NAR
Mission Duration	7 day total - 5 days on orbit or 30 day mission	HQ.

* NAR - North American Rockwell

- capability of recovering satellites which are either prepared or unprepared. Prepared satellites will have one or more of the following features: dedicated docking port/attach point, visual aids for docking, transponders or beacons, running and marker lights

- capability of recovering satellites of varying dynamic state, ranging from stable and stationary with respect to motion about a rotational axis, stable and spinning, unstable and spinning and/or tumbling, and unstable spinning, tumbling and nutating (wobbling).

The satellite retrieval mission for a remote control manipulator system begins subsequent to deployment of the system from the shuttle and ends with emplacement of the satellite in the shuttle cargo bay. In the case of the free flying manipulator system, it will be assumed that a mechanism is incorporated into the shuttle which will perform the actual deployment of the free flyer and the emplacement of the satellite and manipulator system into the cargo bay. The attached manipulator system could interface with such a mechanism for satellite emplacement in the bay or it could emplace the satellite itself. (The attached system could also deploy the free flyer.)

Three specific phases of a satellite retrieval mission have been delineated. These include the approach or rendezvous phase, the capture phase and the recovery phase. In the approach or rendezvous phase, the manipulator will proceed from the vicinity of the shuttle to the vicinity of the satellite. This phase will include such operations as transfer or translation, station keeping and satellite inspection. The phase will terminate with the free flyer at a distance of 10 to 20 feet from the satellite for an end-on approach or up to 50 feet away for a side approach, and with the attached system at a distance of about 10 feet from the satellite. It will be assumed that, with the attached system, some portion of the approach to the satellite can be performed by shuttle translation maneuvers.

The satellite capture phase entails achieving and maintaining contact with the satellite by means of docking or grappling, and stabilization of satellites which are in an unstable state.

The recovery phase includes the activities required to transfer the satellite from its position in space at capture to a position either at the shuttle cargo bay or within the bay itself.

A number of shuttle based missions have been identified which potentially require retrieval of satellite payloads to the shuttle bay. These include stabilized, normally operating satellites which require periodic servicing or refurbishment. These satellites could be spin stabilized, (i.e., the orbiting solar observatory or OSO) or could be actively stabilized by reaction jets (with a limit cycle) or by control moment gyros. Freely tumbling and/or spinning satellites might also be retrieved. For example, the Micrometeorite Exposure Module (MEM) is currently conceived as a non-stabilized passive satellite and close inspection and retrieval of this satellite to the shuttle may be a requirement.

Another category of satellites which may require retrieval includes those which have malfunctioned. The nature of the malfunction may be such that the satellite is in an unstabilized condition, i.e., it may be spinning or tumbling or have three axes motion.

Satellites typical of those which might be launched in the 1973-1985 time-frame are listed in Table 2. These satellites represent candidates for which retrieval might be required. The criteria used in selecting satellites for study are presented in Table 3. Satellite characteristics on each criterion are presented in Table 4 and selection of satellites for study is presented in Table 5. From the list of satellites in Table 2, five representative satellites were chosen for analysis in this study. These are:

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TABLE 2

Planned Satellites 1973-1985

Space Physics

Satellite	Launch Dates	Launch Vehicle	Orbit Miles	Incl.	Dimensions Length Width - (feet)	Wt.	ΔV 100 mile Orbit to Final (fps)	Payload (lbs.)
Relatively Experim.	1981	Shuttle/	300	90°	7' x 5'	1500	690	
Explorers (3)	73-C 74-D 75-E							
(26)	75-(2) 76-83(3)	/scout	350	90°	10' x 4'	1000		
(5)	79-83(1)	Shuttle	350	90°	10' x 4'	1000	896	
Plasma Physics		Centaur	19300	0°	20' x15'	5000	14070	
H.Energy Cosmic lab(1)	1983(?)	Shuttle	270	28°	35' x15'	30000	592	
ISIS	71							
IMP	73	Delta						
Dual Air Density (2)	74	Scout						
SSS	71							
Sorties (5)	81(1) 81(1) 82(2) 83(1)	Shuttle						

Astronomy

Satellite	Launch Dates	Launch Vehicle	Orbit Miles	Incl.	Dimensions Length Width - (feet)	Wt.	ΔV 100 mile Orbit to Final (fps)	Payload (lbs.)
LST	1981	Shuttle-Tug	400	30°	60' x15'	30000	1018	46.6K
Orb.Obs	OAO C 1972	ATL/cent						
	SAS D 1975							
	SAS E 1978							
Solar Orbit Pair	1984	Shuttle	19300	30°	12' x10'	1000	AGena 12927	46.6K
LSO	1983	Shuttle	350	30°	60' x15'	22000	896	46.6K
OSO	73,74,76,78,80	Delta						
	83	Shuttle						
HEAO	A-75	T-111C	230	15°	60 x15	25000	794	7000
	B-76	T-111C	230	15°	60 x15	23000	794	7000
	C-79	Shuttle	230	15°	60 x15	23000	794	7000
	D-82	Shuttle			60 x15			
Radio inter	1982	Shuttle/ centaur	40000	30°	60 x15	10K	14K	46.6K
LRO	1985	Shuttle/ centaur	19300	30°	50 x15	28K	13K	46 K
Explorers (18)	75- 83	/scout	350	90°	10 x 4	1000	896	23.6K
(5)	79-83	Shuttle						
Sorties (11)	79-80 81(2)82(3)83(4)	Shuttle						
KWRT		Shuttle-Centaur	40000	30°	60 x15	2K	14K	46.6K
Optical Support		Shuttle	350	90°	12 x10	5K	236	23.6K

TABLE 2 (cont'd)

Space Applications

Satellite	Launch Dates	Launch Vehicle	Orbit Miles	Incl.	Dimensions Length Width - (feet)	Wt.	ΔV	Payload (lbs.)
Comm & NAV R&D								
ATS	73-F,75-G,77,78,79	T111C/cent.	19300	0°	21x12	4K	14K	47K
	81 83	Shuttle						
CAS	74 77	/scout	19300	0°	12x6.5	700	14K	47K
	79 82	Shuttle						
SATS	75,76-83(2)	/scout or A	19300	0°	12x6.5	600	14K	47K
	80 -83	Shuttle						
Sorties	81 82	Shuttle						
labs & modules	83	Shuttle						
Earth Obs R&D								
Nimbus	72, 74	Delta						
ERTS	72, 73	Delta	19300	0°	12x6.5	1000	14K	47K
EOS	75 -79	Delta						
	80 -83	Shuttle						
SEOS	78	Delta						
	82, 82	Shuttle						
EPS	81,82,83	Shuttle						
Sorties	80,81-83(2)	Shuttle						
Comm & NAV - Syst Dem								
Data relay	76 (2)	T111D-cent						
Planet relay	78 (2)	Delta						
Med. Network	79	Shuttle						
Ed broadcast	80	Shuttle						
Follow on Comm	81-83	Shuttle						
Earth Obs - Sys Dem								
SMS	72, 79	Delta						
	82, 83	Shuttle						
Tirus	76,77(2),78	T111C						
Synch & RS	81 82 83	Shuttle						

TABLE 3

Selection Criteria

- Shuttle Compatible Orbit (Low earth orbit)
- Availability of Satellite Design Data
- Planned Shuttle Interface (for deployment or recovery)
- Development Stage
- Weight
- Next Launch and Number of Launches (1973-85)
- Characteristics Common to Other Satellites

TABLE 4

Satellite Characteristics

			shuttle interface					
	Orbit	Avail. of Data	Planned Recovery	Planned Deploy	Develop Stage	Weight	Next Launch & No.	Common Character.
Relativity Expmt.	300-90°			Yes	Pre-A	1,500	'81-1	
Explorer	350-90°	Good		Yes	D	100 - 1,000	'73-57	OSO
Cosmic Ray Lab	270-28°			Yes	Pre-A	30,000	'83-1	
Sorties - RAM	Shuttle	Mod.	Yes	Yes	B	20,000	'79-23	
LST	400-30°	Mod.		Yes	A	30,000	'81-1	LSO, HEAO
OAO	480-35°	Good		No	D	3,900	'72-1	
SAS		Good		No	D	180	'75-2	
LSO	350-30°			Yes		22,000	'83-1	
HEAO-C	230-15°	Mod.		Yes	B	23,000	'79-2	LSO, LST
Tiros	350-58°	Good		Yes	D	18,500	'76-2	ERS
SMS				Yes			4	
OSO	350-33°	Good		Yes	D	547	'73-6	Explorer
ERS	500-100°	Mod.		Yes		19,000	'76-4	Tiros
MEM	300-28.5°	Mod.	Yes	Yes		5,000	'78-	
Op Sat. Support	350-90°			Yes		1,000		

TABLE 5

Satellite Selection

Criteria	Satellites		
Weight	Small (<1000 lb)	Medium (1000-20000 lb)	Large (>20000 lb)
	OSO SAS Explorer Relativity BRM	MEM Tiros Optical Sat. Support ERS	Cosmic Ray Lab RAM LST LSO HEAO-C
Develop Stage (Phase B or more)	OSO SAS Explorer BRM	MEM Tiros Optical Sat. Support ERS	RAM HEAO-C
Shuttle Interface	OSO Explorer BRM	MEM Tiros Optical Sat. Support ERS	RAM HEAO-C
Data Availability Next Launch - No.	OSO Explorer BRM	MEM Tiros ERS	RAM HEAO-C
Less Commonalities	OSO BRM	MEM ERS	RAM HEAO-C
Data Available	OSO BRM	MEM	HEAO-C RAM
Selected Satellites	OSO BRM	MEM	HEAO-C RAM

1) The Large Space Telescope research applications module (RAM)

2) The High Energy Astronomical Observatory (HEAO)

3) The Orbiting Solar Observatory (OSO)

4) The Meteoroid Exposure Module (MEM)

5) The Bioresearch module (BRM)

The MEM was treated by similarity to the HEAO and RAM. The characteristics of the selected satellites are presented in Figures 2, 3, 4, 5 and 6. Major reasons for the selection of these satellites were that they were representative of the class of satellites that might be launched in the 1978-1985 time-frame and they encompass a wide range of satellite shapes, sizes and possible motion characteristics. In addition, data regarding the characteristics of these satellites were readily available.

In an ongoing effort to define requirements for a Free Flying Teleoperator Flight Experiment, Bell Aerospace has investigated potential retrieval and servicing missions associated with the first 10 shuttle flights. These missions are basically satellite deployment and retrieval missions and include MEM deployment on flight one, MEM retrieval on flight number four, and BRM deployment and retrieval on flight seven.

In recent investigations of satellite retrieval conducted at Bell and at MSFC, the following dynamic conditions were assumed for each of the selected satellites:

BRM - can range from stabilized and stationary to a stabilized spin rate of up to 6 rad/sec (about 60 RPM) with little nutation

MEM - probably will contain attitude stabilization

LST and HEAO - spin rates up to 10 rad/sec (100 RPM), coning rates up to 1 rad/sec (10 RPM) nutation angles up to 45^{o}

OSO - stabilized spin at 30 RPM - little nutation

These targets, therefore, represent a wide variety of satellite mass, size, and dynamic conditions. These conditions were investigated in this study only to the extent that they would affect the design decisions for the man-machine interface. In every case, it will be assumed that the satellites are prepared for capture. This preparation includes some or all of the following items:

- attach point or points located along principle axes of rotation
- Docking aids for ranging and alignment
- Acquisition beacon or transponder
- Markings, identification coding, running lights, etc.
- Capability for remote deactivation of attitude control systems, purging of tanks, jettison of solar panels and extended booms, etc.

Engineering tradeoffs will be required to determine the degree to which satellite preparation is feasible and required. To the extent that such preparation is not provided, more of the load for satellite capture will be borne by the teleoperator.

The objective of the satellite servicing mission is to perform on-orbit satellite maintenance, repair and resupply to return the satellite to operational status. Mission constraints are the same as those identified for the satellite retrieval mission. The main mission requirement for satellite servicing is that the capability be provided of performing all activities required for satellite retrieval missions in addition to satellite maintenance, repair and resupply activities.

The basic issue in satellite servicing missions is the degree to which the satellite is designed for servicing along standardized design approaches common to a variety of satellites. To the extent that standardized modules are employed, servicing can be accomplished using special purpose manipulators designed specifically to interface with the modules. To the extent that satellite design for servicing is not standardized, general purpose, versatile and flexible manipulator systems will be required.

CHAPTER 3 TELEOPERATOR SYSTEM REQUIREMENTS

In this section, function requirements and system requirements are described for each teleoperator mission. System requirements include performance requirements, information requirements, interface requirements and support requirements. These requirements were developed for two classes of shuttle teleoperator systems: attached boom and free flying vehicle.

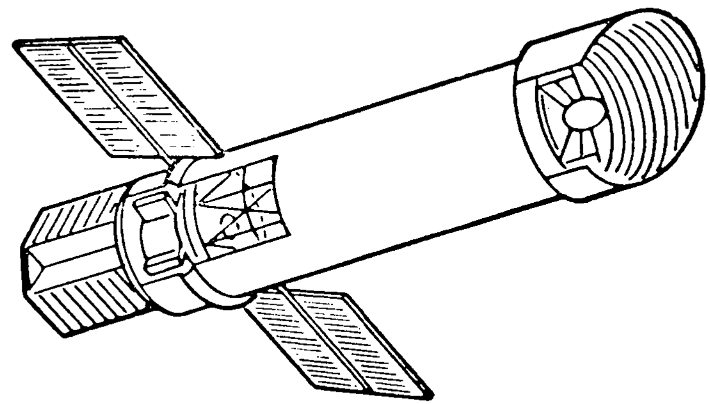
A. Satellite Retrieval

The overall functional flow for the satellite retrieval mission is presented in Figure 7. This flow depicts the functions which must be accomplished by either a free flying or attached teleoperator to successfully complete the satellite retrieval mission. Second level flow diagrams depicting mission tasks for each function shown in Figure 7 are presented in Figures 8 through 20.

The numerous tasks identified in these flow diagrams can be reduced to a smaller number of significant tasks for each function. These tasks are listed in Table 6 for the rendezvous mission phase, in Table 7 for the capture phase and in Table 8 for the recovery phase. These tasks identify the major operations to be completed in each mission phase. They apply equally to use of an attached teleoperator or to a free flier.

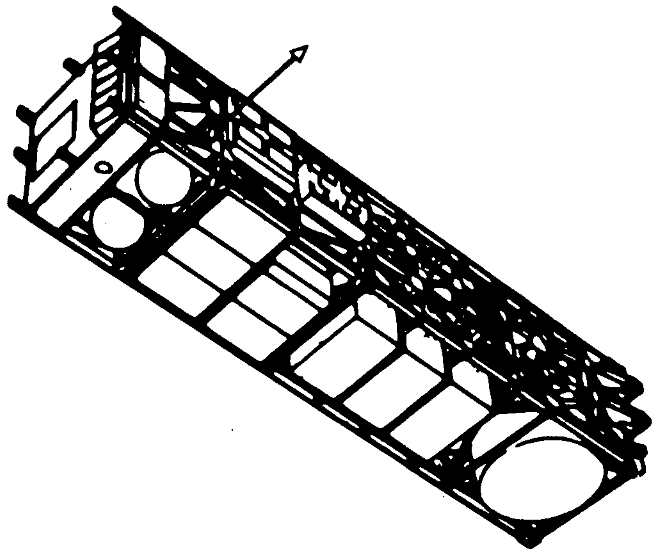
The next step in the analysis was to identify system requirements associated with each task. The information sources contacted to establish requirements were as follows:

Shuttle interface data	MSC MSFC NASA Headquarters Grumman Aerospace North American Rockwell



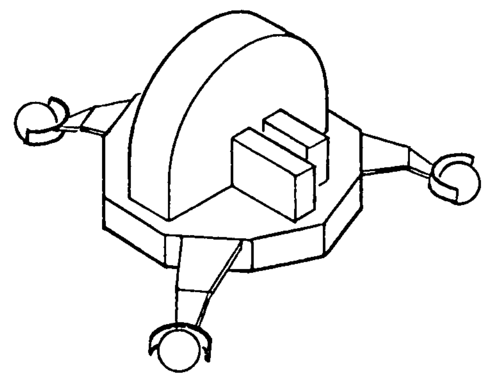
LENGTH	45 ft
DIAMETER	13 ft
WEIGHT	20,000 lbs
ORBITAL ALTITUDE	350 mi $\pm$100 mi
INCLINATION	28.5° to 30°
NORMAL STATE	Stable

FIGURE 2 - LST Description



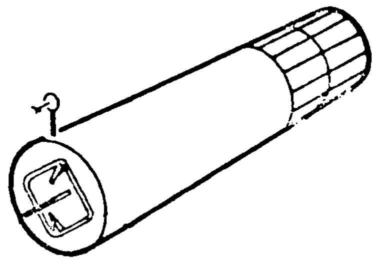
LENGTH	60 feet
DIAMETER	15 feet
WEIGHT	23,000 lbs
ORBITAL ALTITUDE	230 miles
INCLINATION	15°
NORMAL STATE	Stable

FIGURE 3 -- HEAO Description



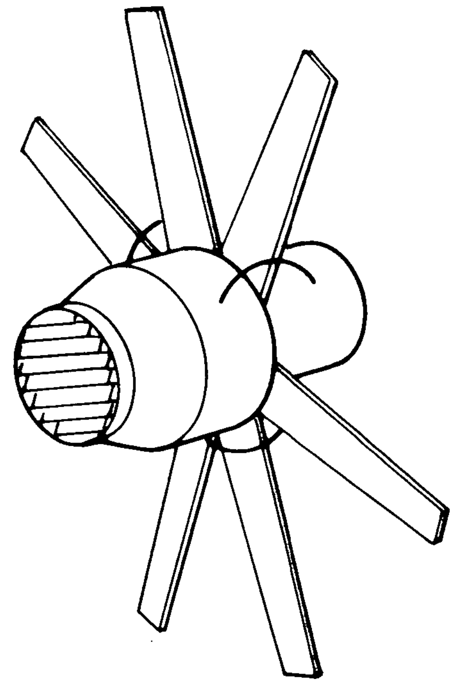
LENGTH	37 inches
DIAMETER	44 inches
WEIGHT	600 lbs
ORBITAL ALTITUDE	350 miles
INCLINATION	33°
NORMAL STATE	Spinning at 26 to 30 RPM

FIGURE 4 - OSO Description



LENGTH	60 ft
DIAMETER	13.5 ft
WEIGHT	5000 lbs
ORBITAL ALTITUDE	300 miles
INCLINATION	28.5°
NORMAL STATE	Attitude stabilization

FIGURE 5 - MEM Description



LENGTH	8 ft
DIAMETER	3 ft
WEIGHT	300-600 lbs
ORBITAL ALTITUDE	200-300 miles
NORMAL STATE	Spinning at 6 rad/sec

FIGURE 6 - BRM Description

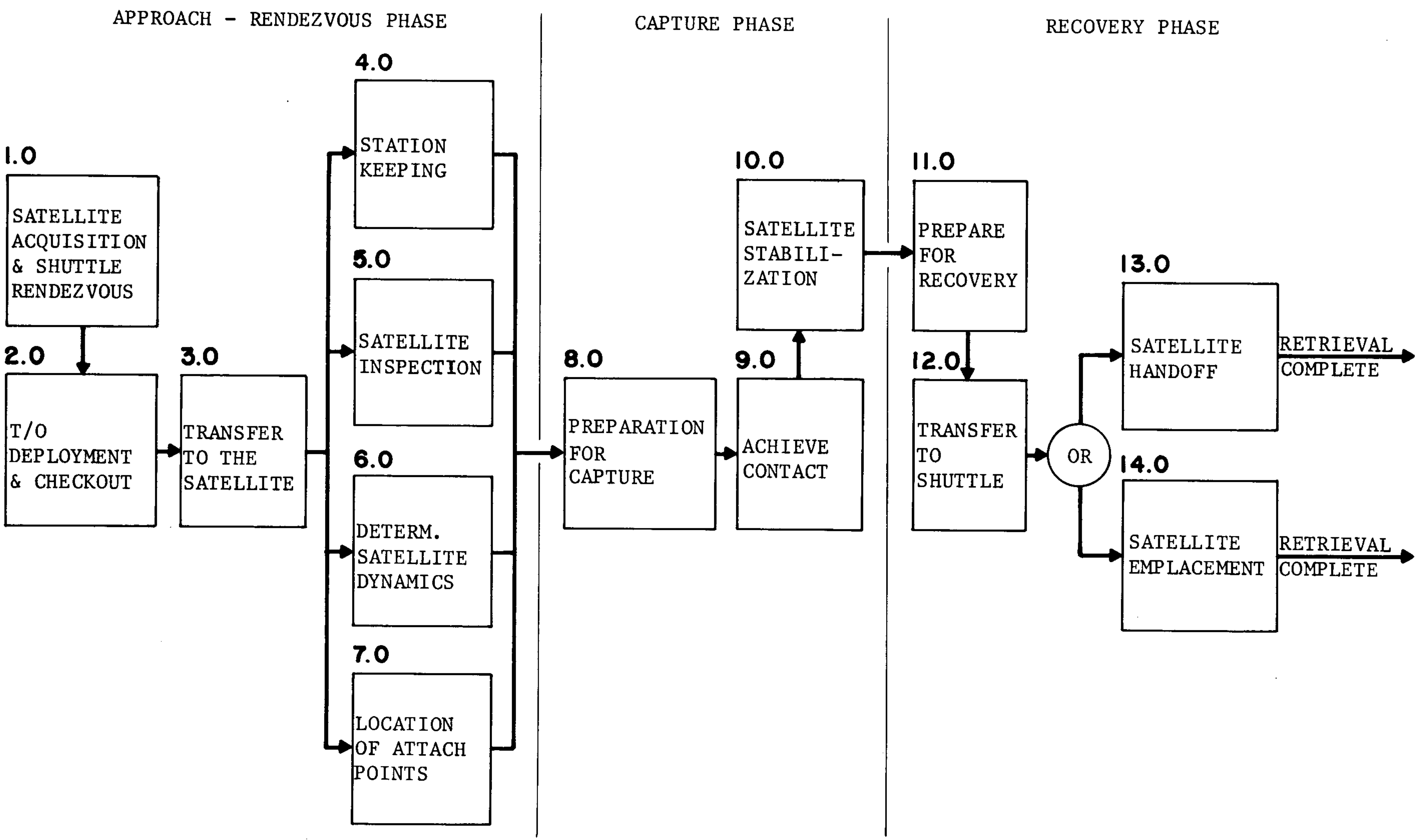


FIGURE 7 Satellite Retrieval Mission Function

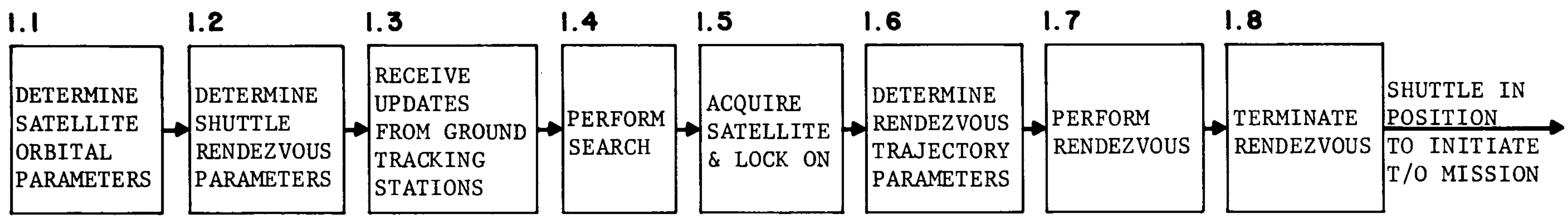


FIGURE 8 2nd Level Flow for Function 1.0 - Satellite Acquisition and Shuttle Rendezvous

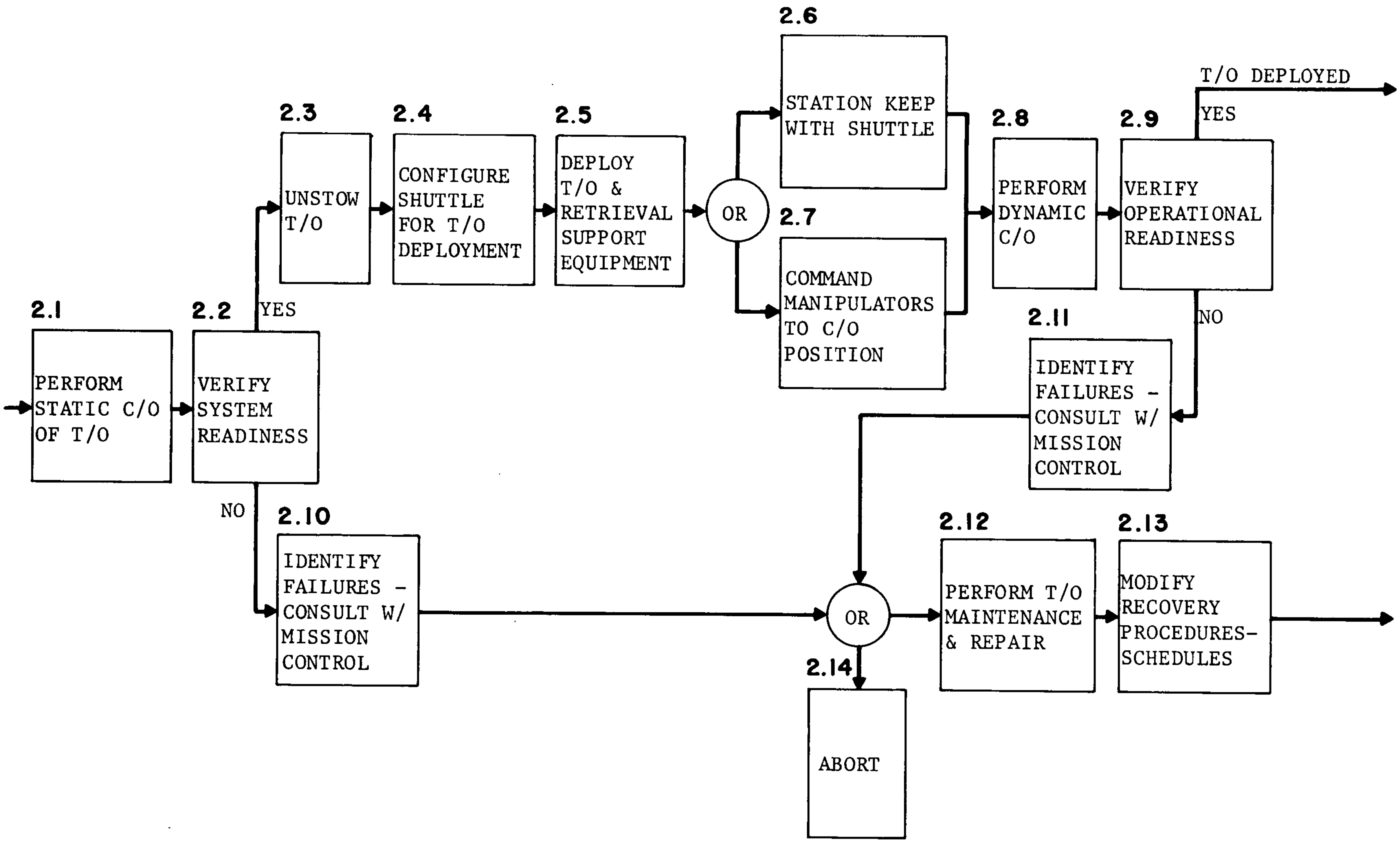


FIGURE 9 2nd Level Flow for Function 2.0 - T/O Deployment and Checkout

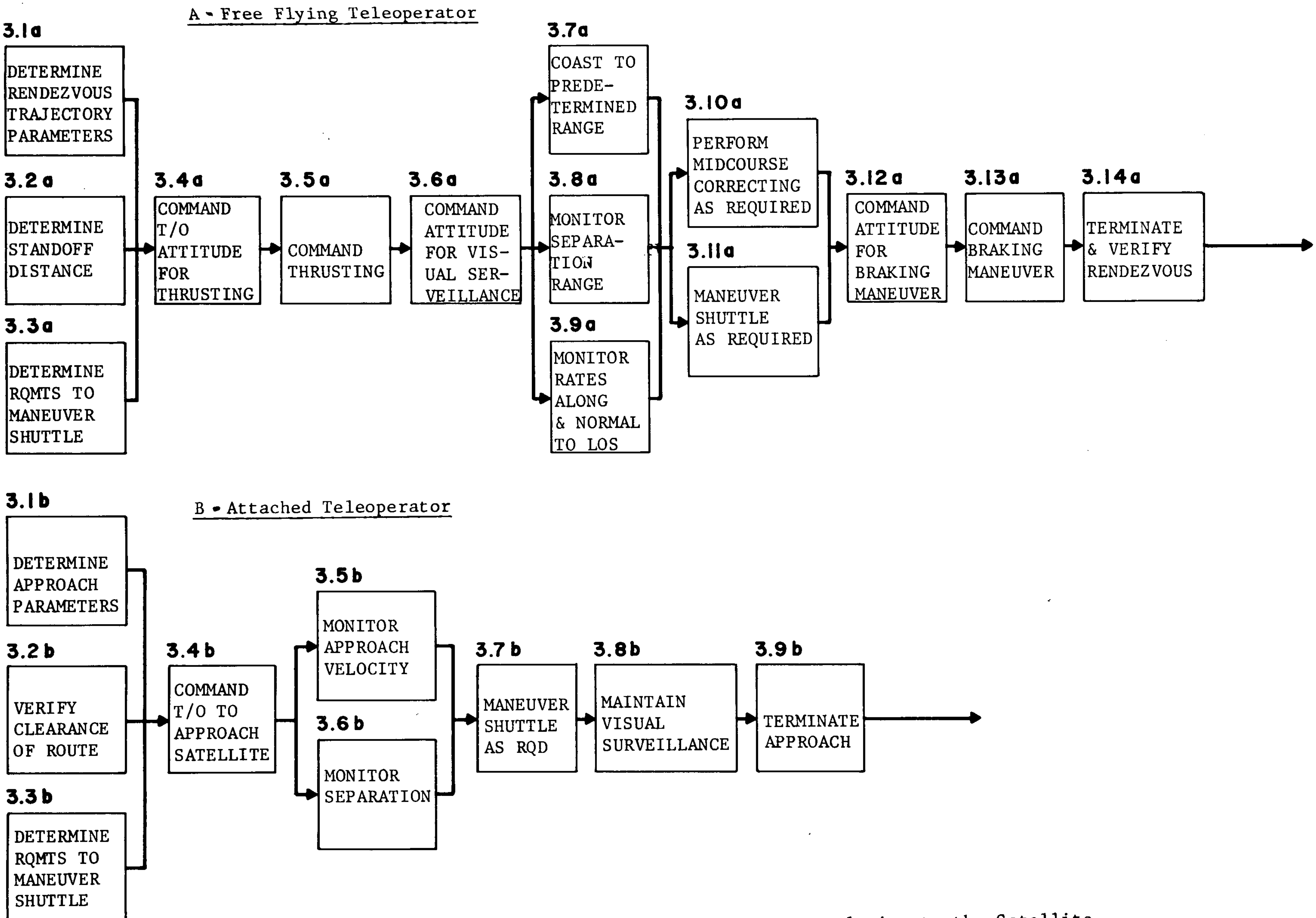


FIGURE 10 2nd Level Flor for Function 3.0 - Translation to the Satellite

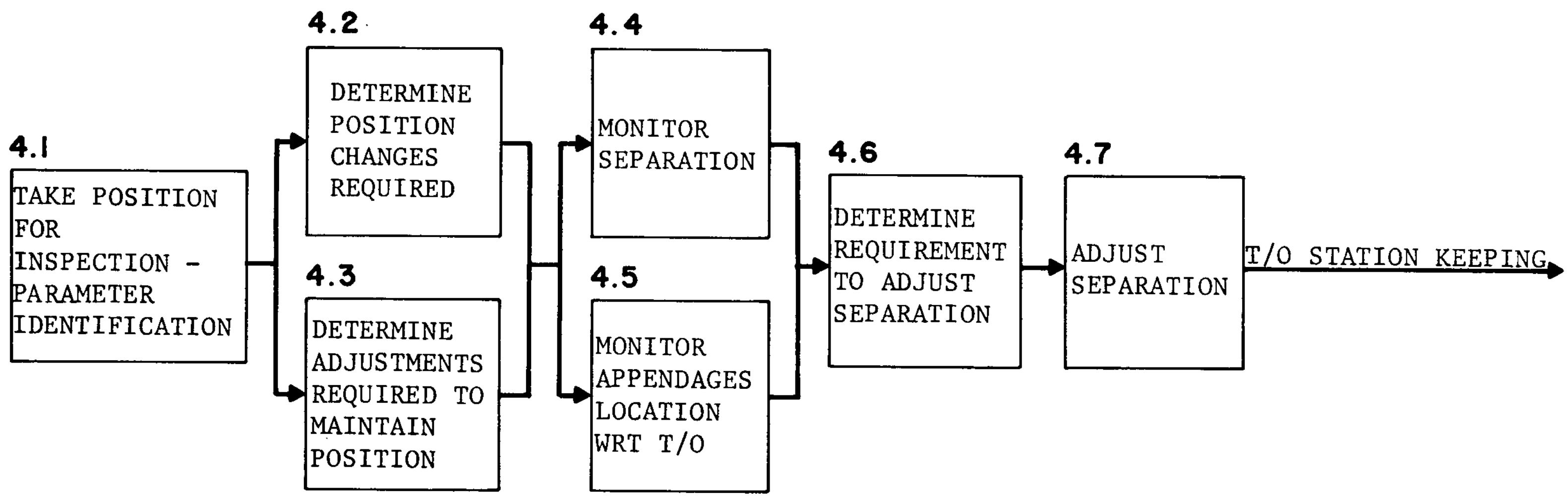


FIGURE 11 2nd Level Flow for Function 4.0 - Station Keeping - Position Maintenance

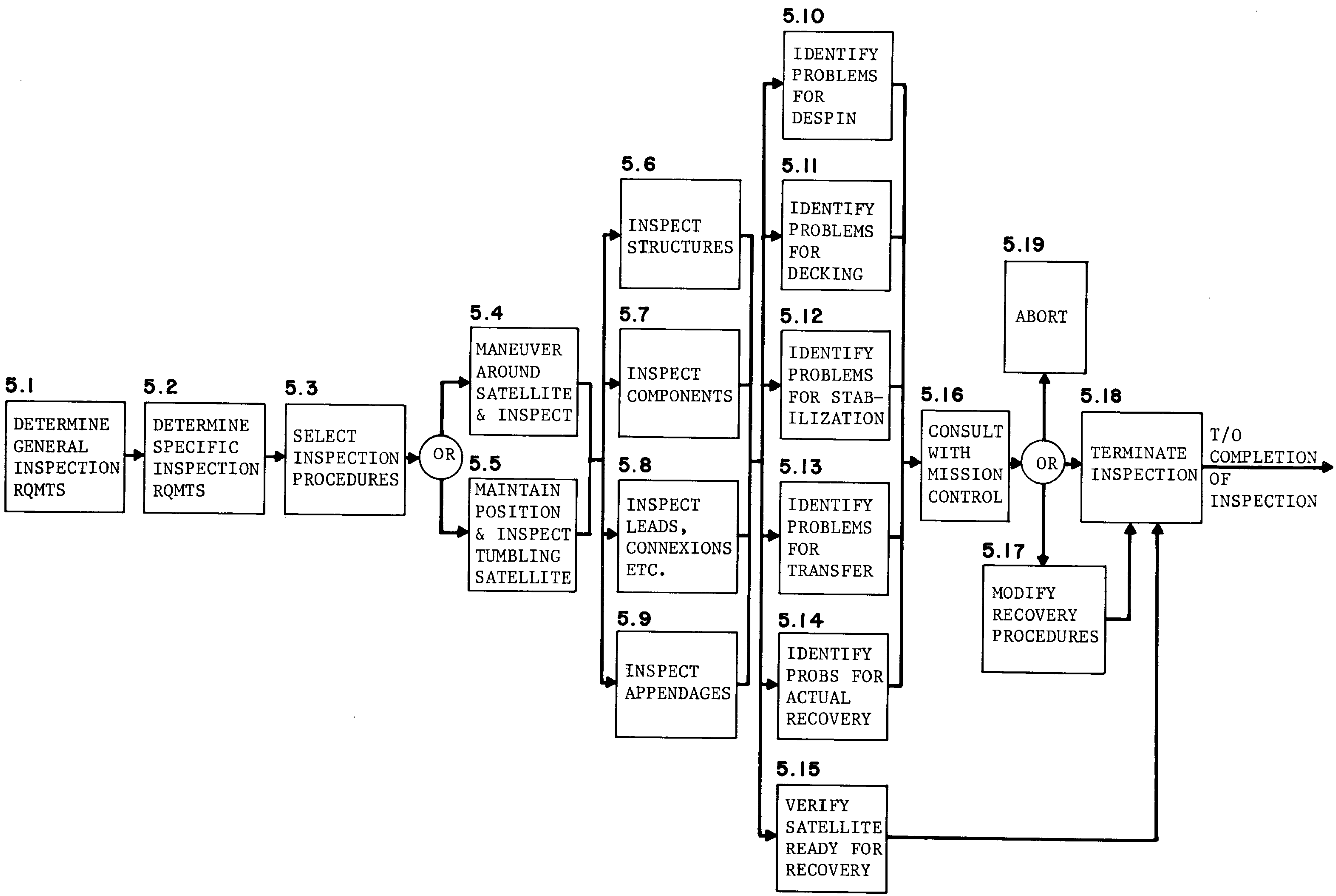


FIGURE 12 2nd Level Flow for Function 5.0 - Satellite Inspection

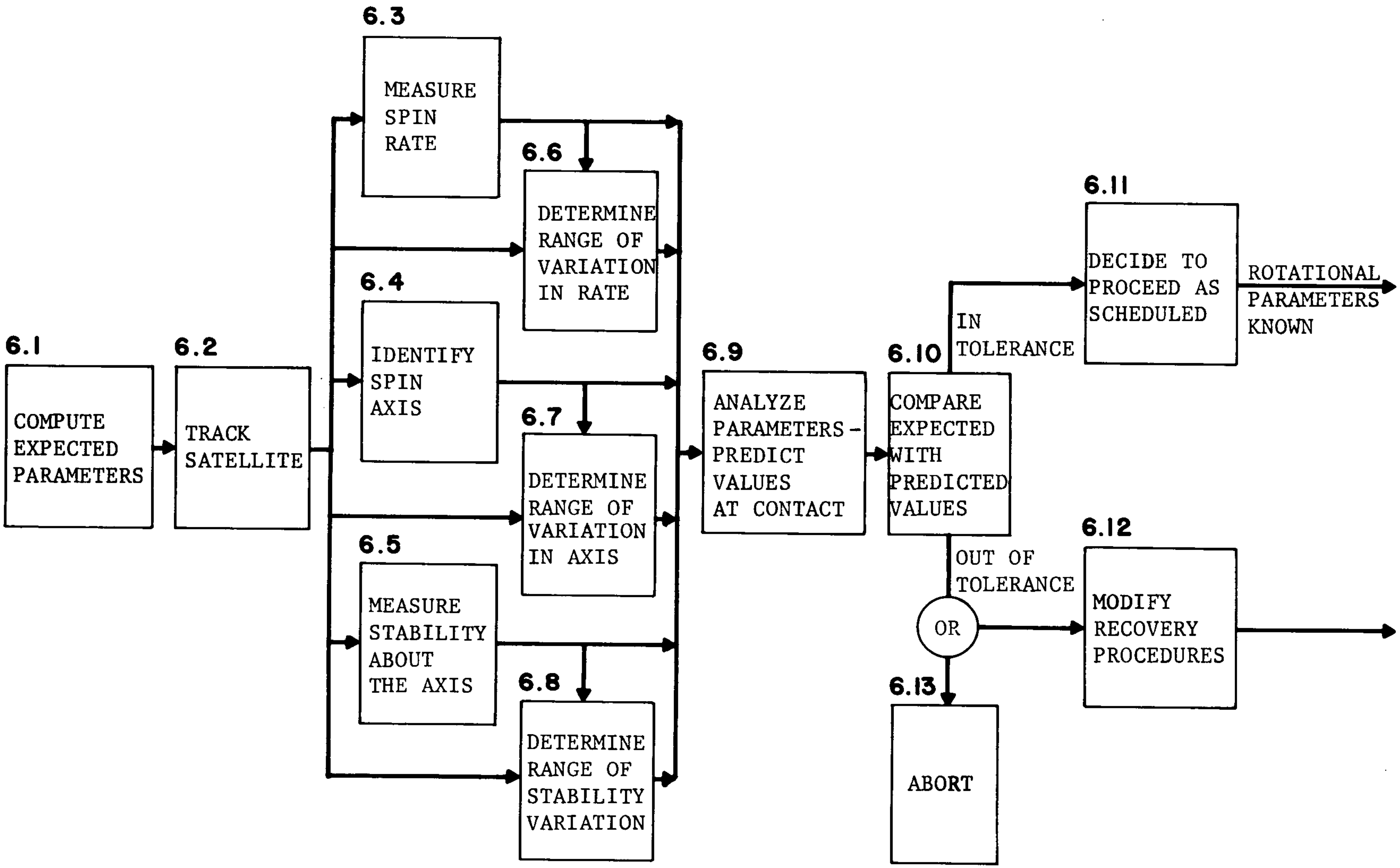


FIGURE 13 2nd Level Flow for Function 6.0 - Determination of Rotational Parameters

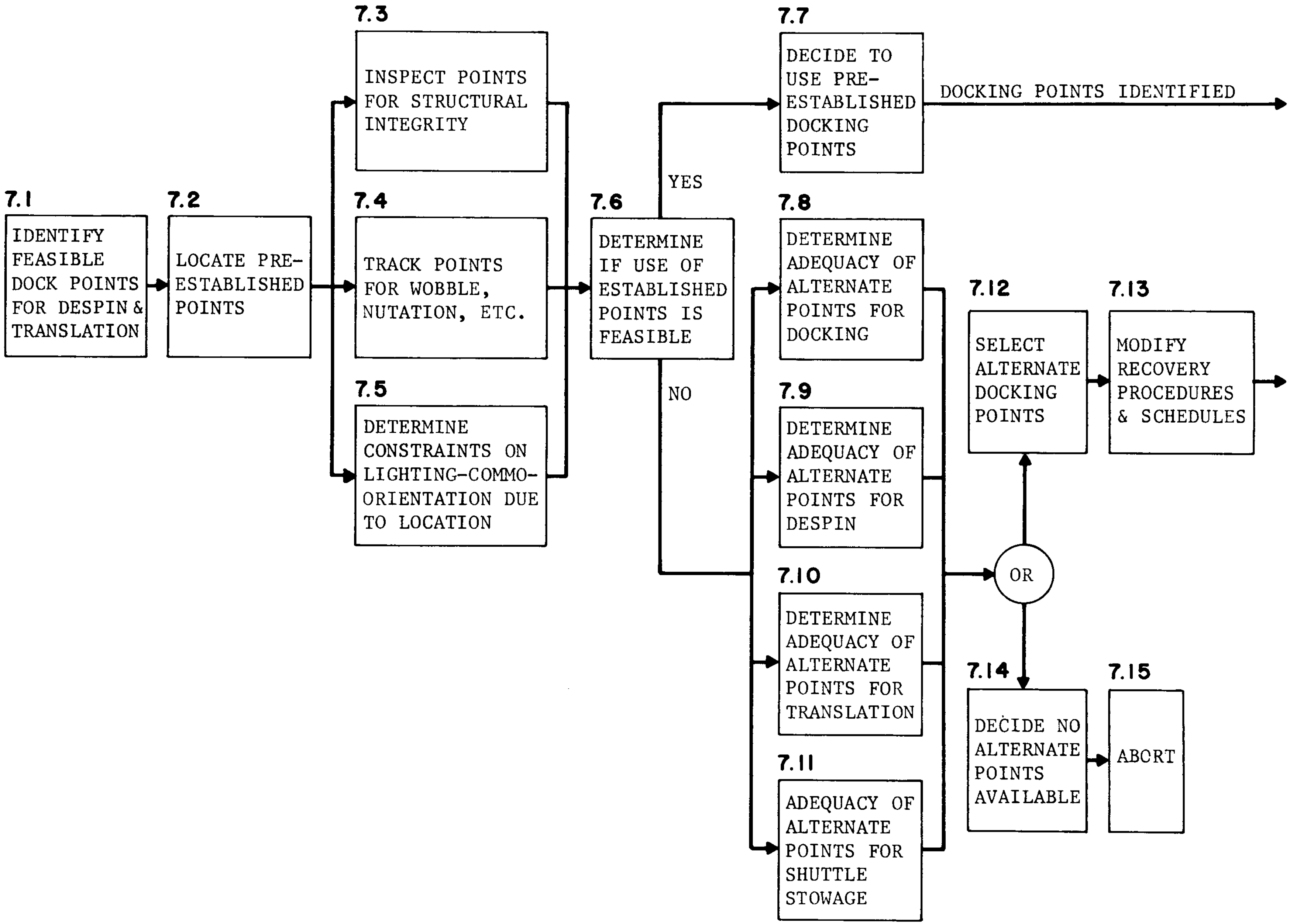


FIGURE 14 2nd Level Flow for Function 7.0 - Identification of Attach Points

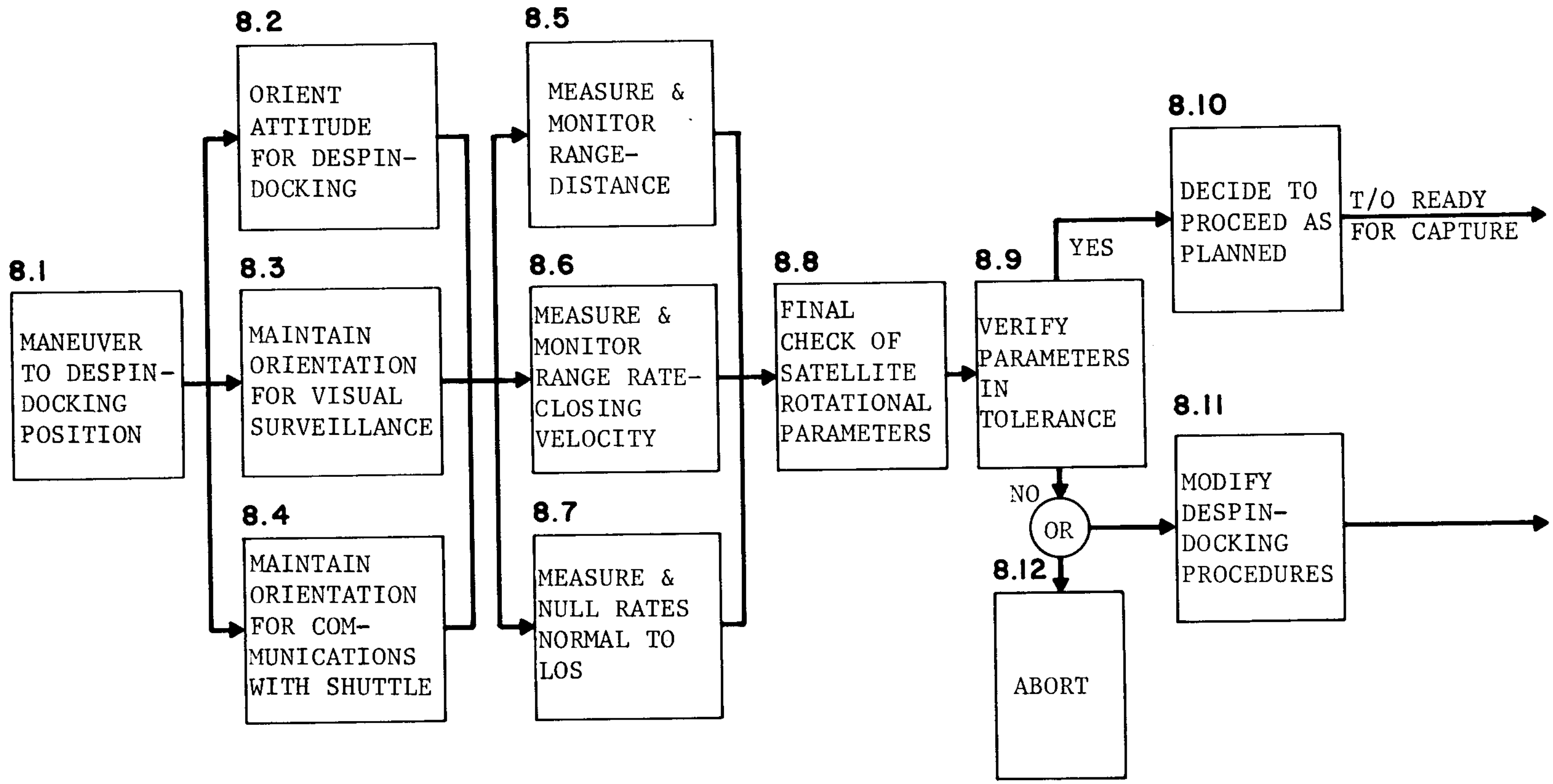


FIGURE 15 2nd Level Flow for Function 8.0 - Preparation for Capture

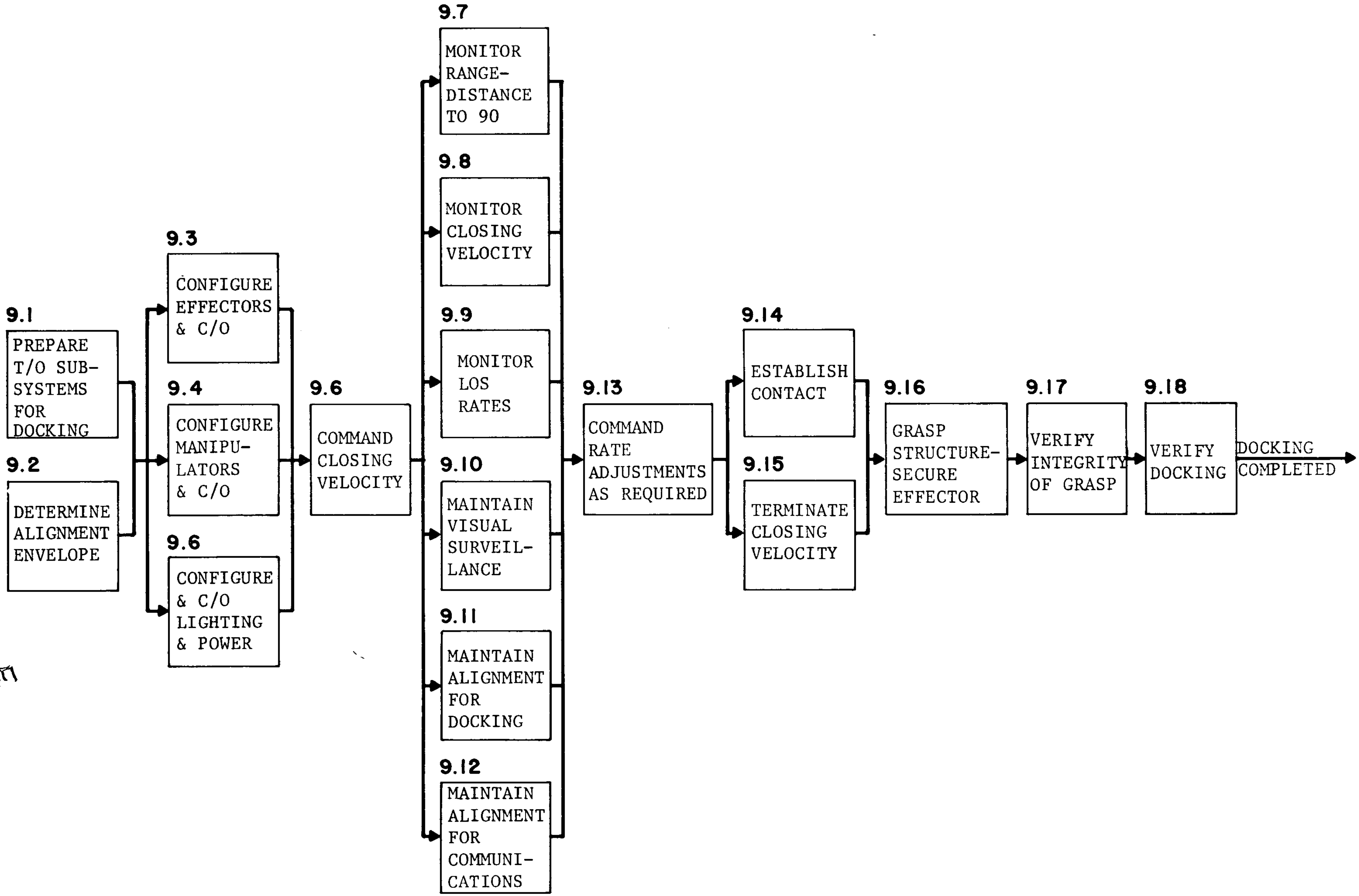


FIGURE 16 2nd Level Flow for Function 9.0 - Contact - Dock with Satellite

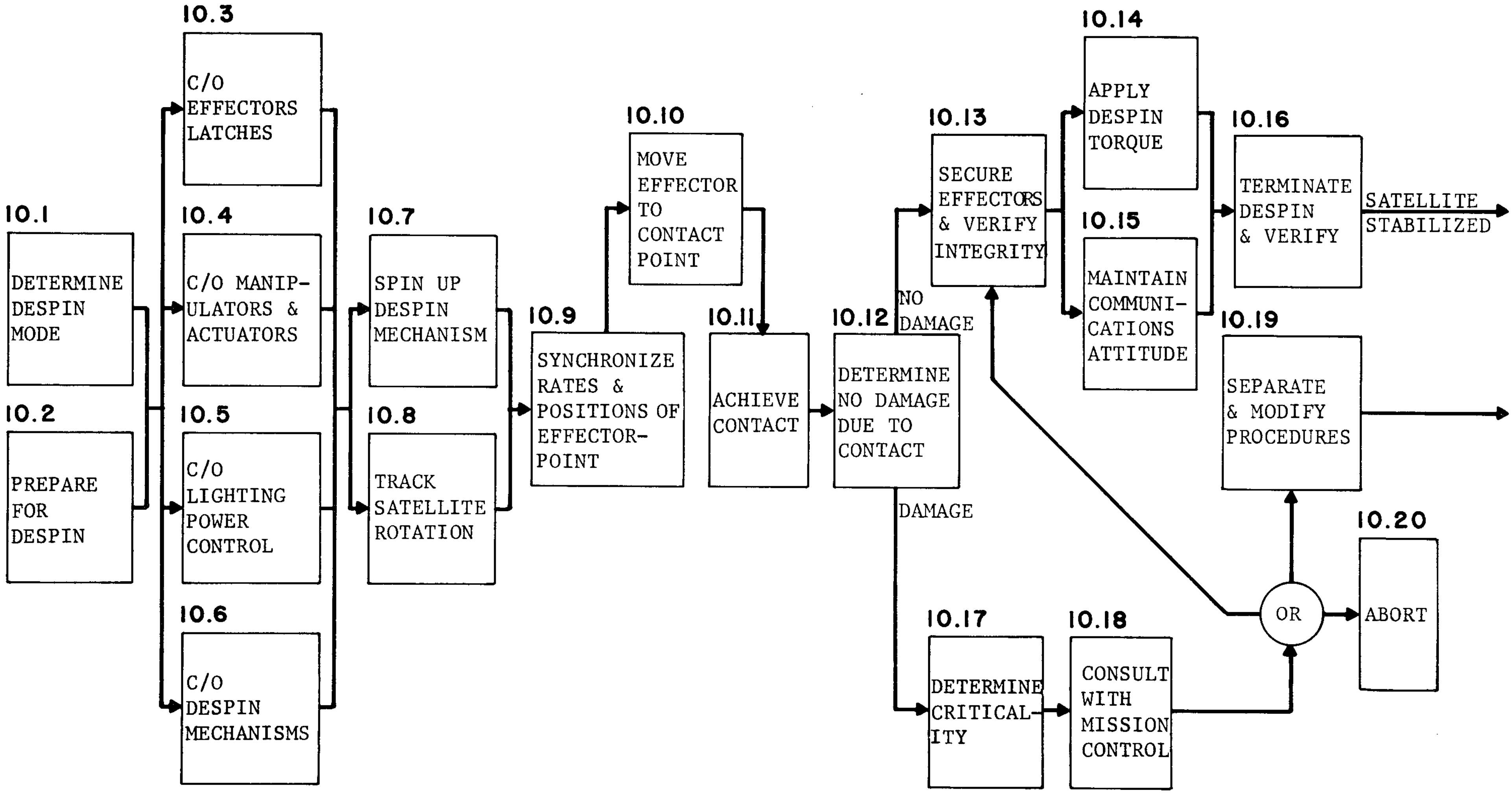


FIGURE 17 2nd Level Flow for Function 10 - Satellite Stabilization

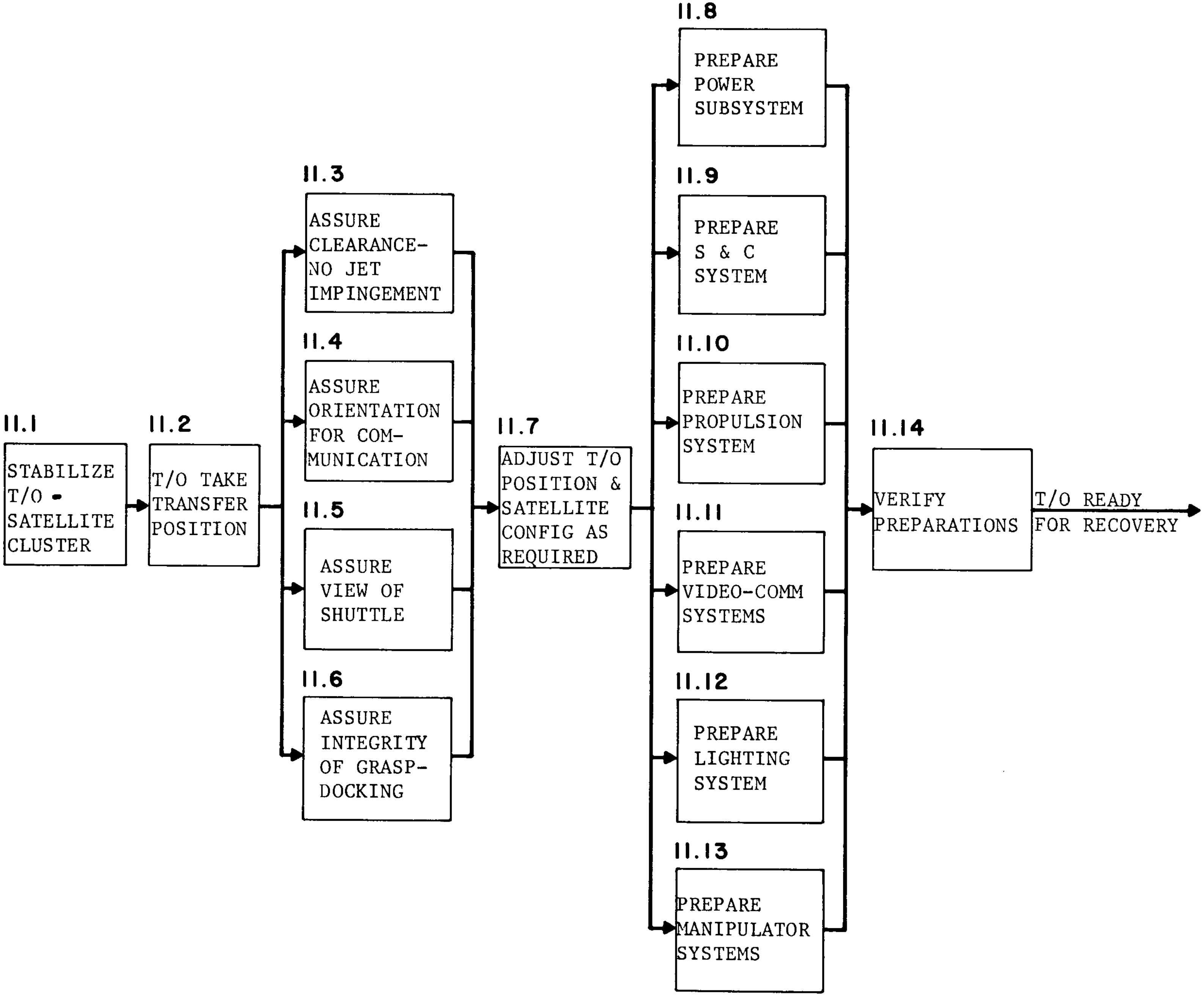


FIGURE 18 2nd Level Flow for Function 11 - Prepare for Recovery

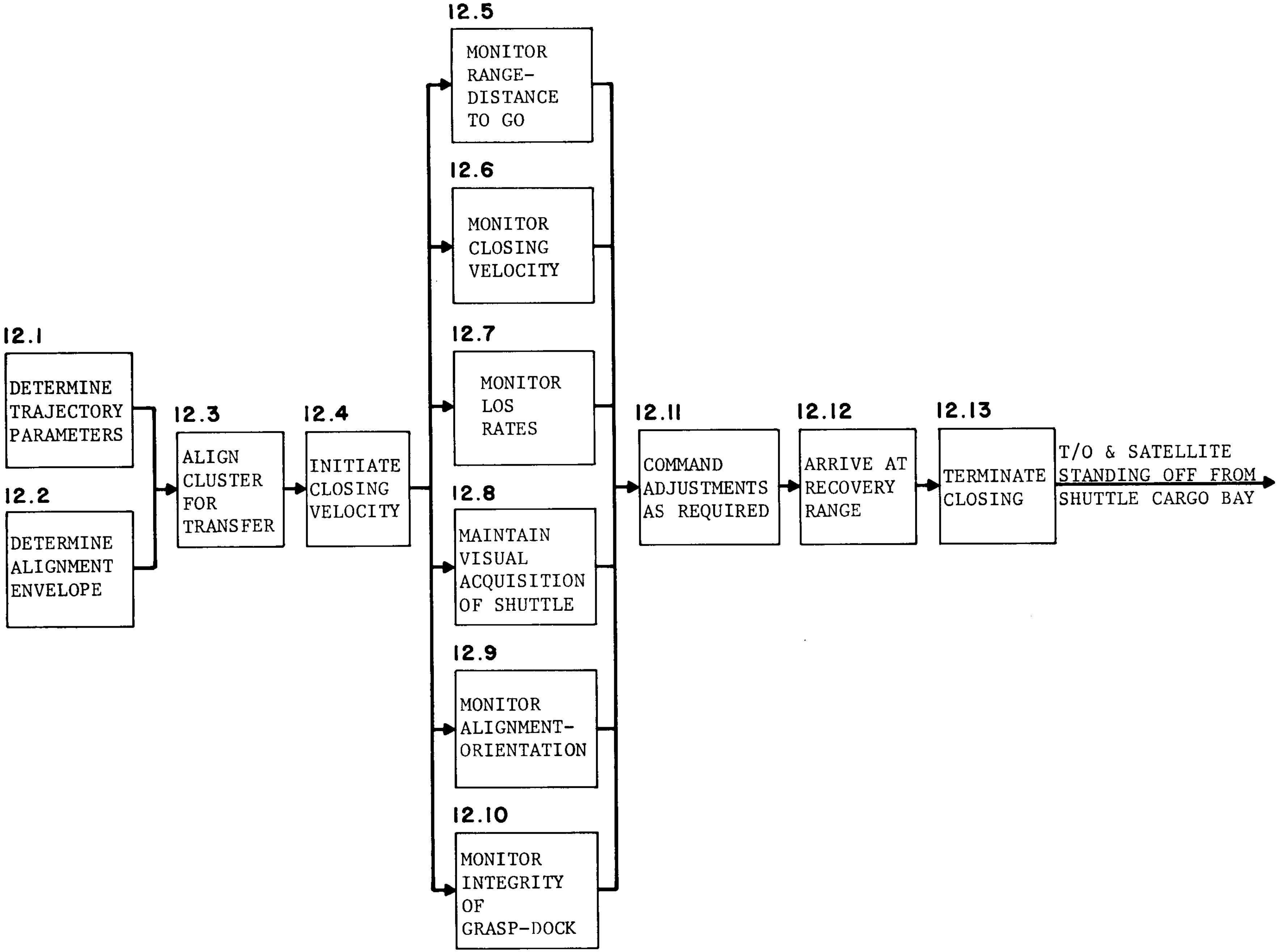


FIGURE 19 2nd Level Flow for Function 12 - Transfer to Shuttle

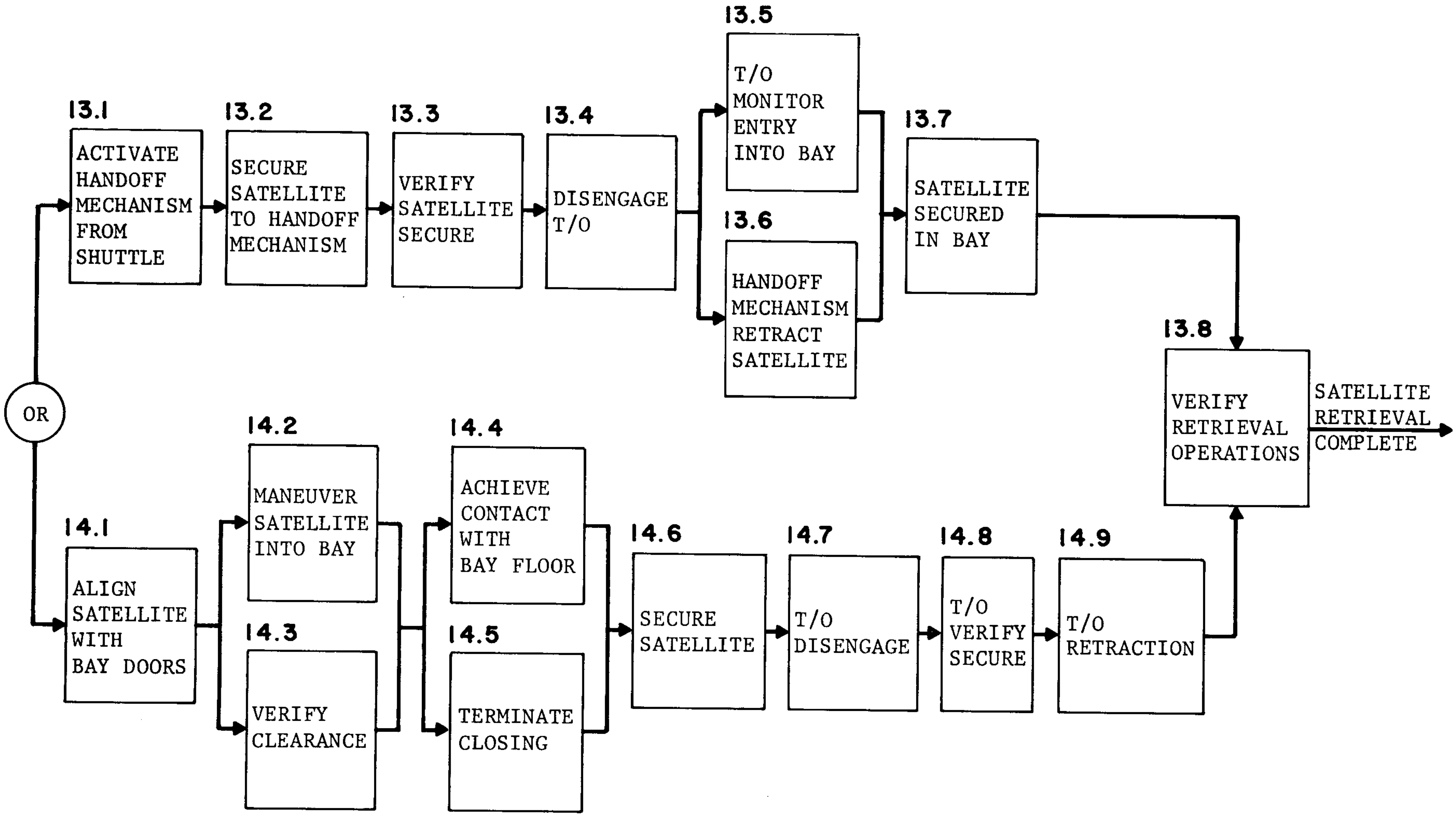


FIGURE 20 2nd Level Flow for Function 13 - Satellite Handoff and Function 14 - Satellite Emplacement in Cargo Bay

Free Flier Performance requirements	North American Rockwell MSFC Bell Aerospace GE
Attached manipulator requirements	MSC Grumman Aerospace Martin Marietta MB Associates North American Rockwell
Satellite characteristics	Goddard Space Flight Center Langley Research Center General Dynamics MSFC Bell Aerospace GE
Telecommunications requirements	JPL Bell Aerospace MSFC
Control system requirements	MSFC MSC Bell Aerospace Grumman Aerospace North American Rockwell
Manipulator requirements	NASA Headquarters MSFC MSC Bell Aerospace

Requirements in the form of information, performance, support and interface requirements were developed for each function within each mission phase. A sample data sheet for these requirements for the function "transfer to the satellite" is presented in Table 9. Rather than present all identified requirements for each task in each function, it was decided to select only those requirements judged to have an impact on man-machine interface design decisions. These requirements are presented in Table 10 and 11 for the rendezvous phase for the free flier and attached boom, and Tables 12 and 13 for the capture and recovery mission phases respectively. The quantitative values of requirements presented in these Tables are not meant to

TABLE 6

Mission Tasks for the Rendezvous Phase

Functions	Tasks
Transfer to the Satellite	Command closing velocity Maintain visual surveillance attitude Maintain attitude to assure communications Monitor range Monitor rates Perform corrections Maneuver shuttle as required Command braking
Station Keeping	Assume position for station keeping Align attitude angles Determine position changes required Maintain position with respect to satellite Monitor location of obstacles - obstructions
Satellite Inspection	Maneuver around the satellite Inspect structures, components, subsystems Identify problems - detect off nominal conditions
Determination of Satellite Dynamics	Track entire satellite Identify axis of rotation Align attitude and body axis for measurement Measure rotation rates Measure stability about the axis Measure oscillation - wobble rates Decide if parameters are within acceptable range
Location of Attach Points	Identify attach points Inspect attach points Track attach point motions Decide if attach points are acceptable

TABLE 7

Mission Tasks for the Capture Phase

Function	Tasks
System preparation for capture	Position mobility unit or boom for capture Position and orient manipulators/effectors Synchronize rate of effector - despin device motion with satellite rotational rate
Achieve and maintain contact	Impart closing velocity Maintain alignment of docking axis Maintain attitude alignment Achieve contact of attach points Secure effector grasp of attach points Monitor rates, forces and torques Decide to stabilize the satellite or disengage
Satellite stabilization	Impart despin force Monitor spin rate reduction Monitor rates about other axes Monitor cluster stability Verify completion of despin

TABLE 8

Mission Tasks for the Recovery Phase

Function	Tasks
Preparation for Recovery	Move mobility unit or manipulators to recovery position Prepare manipulators - effectors for recovery Activate shuttle aids
Satellite Transfer	Impart a closing velocity Monitor range and rates Monitor free flyer - satellite orientation Begin braking Assure attitude for emplacement into bay Complete braking Verify position and orientation of satellite
Satellite Handoff	Maneuver satellite to recovery mechanism Verify connection to recovery mechanism Verify orientation, position and rates Disengage from the satellite
Satellite Emplacement in the Bay	Verify that path is clear Impart closing velocity Monitor clearances through bay access Begin braking Achieve interface with satellite secure mechanism Disengage and retract manipulator

E

TABLE 9
Example Requirements
Analysis

Function - 3.0 Transfer to the Satellite (Free Flying)

TASKS	TASK CONSTRAINTS	INFORMATION REQUIREMENTS	PERFORMANCE REQUIREMENTS	SUPPORT REQUIREMENTS	INTERFACE REQUIREMENTS
3.4a Command Attitude for Thrust	Communication Envelope	Actual & Required Attitude	Attitude Control accuracies	Communications	
3.5a Command Thrusting		Duration of burn, when to fire	Maintain attitude within ± .5° Impart 1/2 fps ΔV for each 100' range	Ranging	Shuttle Ranging
3.6a Command Attitude for visual surveillance	Shuttle - T/O-Satellite - sun geometry constraints	Acceptable envelope within constraints	Command Attitude for view of satellite from T/O - Possibly maneuver shuttle		Shuttle Attitude Control
3.7a Coast	Time to complete		Min time to close is 200 sec.		
3.8a Monitor range	Accuracies required	Range to go	Determine range to ± 10% accuracy	Ranging aids	Shuttle ranging -to T/O -to target
3.9a Monitor rates	Accuracies required	Actual closing Rate & rates along axis normal to LOS	Range rate ± 2 fps to 100' range, .2 fps within 100'	Ranging aids	Shuttle ranging
3.10a Perform Midcourse Corrections	Propellant budget time	Range Check Points 100' 20'	Null rates at 100' range Impart a closing velocity of 2fps. Null rates at 20' range	Ranging aids	Shuttle ranging
3.11a Maneuver shuttle	Shuttle position - Attitude constraints	Required Attitude position	Maneuver shuttle for visual LOS, communication envelope		Shuttle control

TABLE 9 - cont'd

Function - 3.0 Transfer to the Satellite (Free Flying)

TASKS	TASK CONSTRAINTS	INFORMATION REQUIREMENTS	PERFORMANCE REQUIREMENTS	SUPPORT REQUIREMENTS	INTERFACE REQUIREMENTS
3.12a Command braking Attitude	Attitude envelope for communications - visual LOS	Attitude required Present Attitude	Command pitch and yaw for for braking at 100' and 20'	Attitude control Handling qualities	
3.13a Command braking	Accuracy limits	Duration of burn - when to fire	Max attitude misalingment ± .5°, Δv of 2fps at 20' range	Ranging aids	Shuttle Ranging

TABLE 10

Important Requirements by Tasks for the Rendezvous Phase - Free Flier

Task	Requirements	
Command closing velocity	Command .5 fps for each 100 ft. range	
Maintain visual surveillance attitude	Video field of view 60° (subtends 60 ft. RAM at 35 ft.)	
Maintain attitude to assure communications	Antenna always oriented toward the shuttle or ground tracking station	
Monitor range	Accuracy requirements	10% beyond 100 ft. ±2 ft. within 100 ft.
Monitor rates	Range rate accuracy	±1 fps beyond 100 ft. ±.2 fps within 100 ft.
	LOS rate accuracy	+.5 feet/sec beyond 100 ft. ±.1 feet/sec within 100 ft.
Perform corrections	At 100 ft. range null LOS rates and Range rate Command ±.2 fps closing velocity (Minimum of 400 sec. to reach 20 ft. range)	
Maneuver shuttle as required	Maintain visual contact from shuttle	
Command braking	At terminal range - null range rate ±.1 fps Terminal ranges 35 ft. for RAM from the side 20 ft. for all other conditions	
Assume position for station keeping	Maneuver to station keeping position	
Align attitude angles	Attitude alignment accuracy ±3° High accuracy attitude hold - limit cycle of less than .5° or CMG's	
Determine position changes required	Correct positional and rate errors	
Monitor position	Ranging aids Hold rates within ±.1 fps in all axes Hold position within ±2 feet in all axes	

Table 10 - continued

Task	Requirements
Monitor location of obstacles	Full field of view of satellite
Maneuver around satellite	Circumnavigate in 2 orthogonal planes maintaining station keeping distance and position in plane
Inspect structures - components	Minimum of 4:1 zoom
Identify problems	Decision criteria
Track entire satellite	Field of view of 60°
Identify axis of rotation	Accuracy requirements TBD*
Align attitude and body axis	Accuracy of alignment TBD*
Measure rotation rates	Accuracies of .1 to 2 RPM depending on satellite structures
Measure stability about the axis	Measure wobble to an accuracy of TBD*
Measure oscillation or wobble rates	Accuracy TBD*
Decide if rotational parameters are acceptable	Decision criteria Consultation with mission control
Identify attach points	Lighting - 15° cone directed
Inspect attach points	Size resolution 5 arc min.
Track attach points	Motion resolution 5 arc min/sec

*TBD - To be determined

C2

TABLE 11

Important Requirements by Tasks for the Rendezvous Phase - Attached

Task	Requirements
Command closing velocity	Command .4 fps Resolve approach velocity to ± .1 fps
Maintain visual surveillance attitude	Arm orientation to assure visual access and minimal interference of visual field
Maintain attitude to assure communications	Command link and sensor (video) links to and from boom probably hard wired
Monitor range	Accuracy - ± 2 feet into 10 foot range, ± 2 inches within 10 feet
Monitor rates	Range rate accuracy ± .1 fps Tip positional accuracy ± 2 inches Maximum rate - unloaded - 1.5 fps
Perform corrections	Adjust joint angles and limb orientations as required
Maneuver shuttle as required	Maintain direct view of satellite
Command braking	Tip deceleration - no load - stop in 1.5 ft. Begin braking at 12 feet range
Assume position for station keeping	Range - 10 feet
Determine position changes required	Correct errors
Monitor position	Hold rates ± .1 fps in all axes Hold tip position within 2 inches Hold range at 10 feet

Remaining requirements same as those listed in Table 10 for free flier

[redacted]

[redacted]

TABLE 12

Important Requirements by Tasks - Capture Phase - Free Flier and Attached

Task	System Performance Requirements
Position vehicle for capture	Attitude alignment accuracy ±3° Inertial axis alignment accuracy ± TBD
Position and orient manipulators and effectors	Effector orientation TBD Manipulator positioning accuracy TBD
Synchronize effector rate with satellite rotation rate	Accuracy .1 to 2 RPM
Commence final closing	Closing velocity between .05 and .2 fps (Duration from 400 to 100 seconds from 20 ft. 200 to 50 seconds from 10 ft.)
Maintain inertial axis alignment	Keep LOS aligned with X axis within ± .2 ft.
Maintain attitude alignment	Accuracy of ±3°
Achieve contact	Signal to operator number of effectors contacting Adjust attitude to contact all effectors - all points
Secure effector to attach point	Forces TBD (Dependent on post docking dynamics of the cluster)
Monitor rates, forces, torques	Sensors to measure cluster motions
Decide to stabilize or disengage	Decision criteria
Impart despin force - torque	Forces TBD
Monitor rate reduction	Rate measurement aids
Monitor rates about other axes	Rate measurement aids
Monitor cluster stability	Stability envelope TBD
Verify completion of despin	Decision criteria

TABLE 13

Important Requirements by Tasks - Recovery Phase

Tasks	System Performance Requirements
Position for recovery	Position mobility unit - manipulators
Prepare manipulators	Assume recovery configuration - orientation
Impart closing velocity	Apply .5 fps closing velocity for each 100 ft. in range - free flier
	Apply .174 fps ± .05 fps - attached
Monitor range and rates	Accuracies 10% - free flier
	Tip velocity accuracy - .05 fps - attached
Monitor orientation	View from shuttle with 10X zoom
Begin braking	At 2000 ft. range adjust range rate to 100 fps ± 1 fps (Free Flier)
	At 1000 ft. null range rate ± 1 fps; null Los rates (Free Flier)
	Impart velocity of 2.5 fps (Free Flier)
	At 500 ft. null range rate ± .1 fps (Free Flier)
	Tip deceleration loaded - 15 ft., begin braking at 25 ft. - attached
Assume emplacement attitude	Orient satellite for emplacement
Complete braking	At 100 ft. null all rates ± .1 fps - free flier
Verify satellite position - orientation	View from shuttle with 60° field of view
Maneuver satellite to recovery position	Develop .5 fps translational rate
Verify connection to mechanism	Feedback from recovery mechanism
Disengage from satellite	Release forces TBD

represent finalized performance limits but rather comprise indications of the order of magnitude of parameters associated with the tasks. The quantified values have been selected based on analysis or from published studies of teleoperator performance requirements which include the General Electric studies for Ames Research Center and MSC, the North American Rockwell ATS-V despin study, the Martin Marietta study of attached teleoperator requirements for MSC, and the Bell Aerospace study of free flying teleoperator requirements for MSFC.

B. Satellite Servicing

The requirements to be imposed on a teleoperator system performing a servicing mission rather than a retrieval mission which are different from the requirements for the satellite retrieval mission apply only to mission activities after docking and stabilization of the satellite. Thus, for this mission, all requirements developed for the approach/rendezvous and capture phases of the satellite retrieval mission apply equally to the satellite servicing mission.

It will be assumed that satellite servicing will be conducted with the manipulators of the teleoperator system in contact with the satellite. These manipulators may or may not comprise the devices used for capturing and could include two types of manipulators, one for attachment during servicing activities and one for performance of the servicing activities.

The requirements for satellite servicing developed in this section will apply to the missions where satellites are serviced in free space. If satellites are retrieved to the shuttle bay for servicing there, the servicing mission is identical with the retrieval mission since the teleoperator is not expected to perform servicing activities for a satellite located in the cargo bay.

Satellite servicing is a generic term used to include all missions where satellite or satellite systems and components are repaired, resupplied, maintained, refurbished, updated or otherwise modified. The range of different operation included in such missions includes the following:

Removal/replacement of modules and components

Maintenance, including cleaning, tightening, aligning, calibrating, inspecting and attaching

Repair, including mending, bonding, welding, patching, deforming, sealing, cutting

Deployment, including installation, assembly, extension

Updating including adding, removing and modifying

One of the most comprehensive investigations of requirements for teleoperator servicing of satellites was conducted for NASA - Ames Research Center by the General Electric Company in 1969. This study entailed a failure modes and effects analysis for five satellites, the OAO-A1, OSO-D, Direct Broadcast Satellite (DBS), Nimbus A-C and Nimbus D-E. Repair and refurbishment requirements were developed which included design requirements for the (free flying) teleoperator system and design criteria for the satellite to enable on-orbit maintenance and repair.

Although design requirements developed by GE (1969) for the teleoperator system generally remain to be verified, the study effectively demonstrated the importance of considering the satellite design and the satellite - teleoperator interface in the conceptual design of a teleoperator system for an orbit maintenance and repair. The study identified no less than 97 design requirements for satellites to enable or facilitate maintenance and repair. Each requirement was rated on a three point scale in terms of the degree to which it was needed and its impact on the satellite system. The scale contained three levels of need and impact - minor, moderate and major. No requirements were noted to have both major need and major impact. Only one was cited as having a major need with moderate impact, and this was the need to evaluate satellite design for maintainability with respect to ease of manipulation and interpretation. Two requirements were noted to have moderate need and major impact. These included:

Standardization of equipment bays and mounting areas

Commonality and standardization of components, connectors, grips, fasteners and tools

Of the remaining requirements, 12 had a moderate need and a moderate impact and 82 had a minor need and/or a minor impact.

The importance of satellite commonality and standardization of design for on-orbit repair and maintenance was further developed by Lockheed in a 1971 study for MSFC (Payload Effects Analysis Study, June 30, 1971). The objective of this study was to develop a low cost version of representative payloads. As stated in the Lockheed study the single most important cost driver in the unmanned payload cost reduction effort is the capability of repair, refurbishment and servicing of payloads. The low cost payload repair/refurbishment approach developed in the study has the following characteristics:

- modular design
- segregation of low quality from high quality components
- simple functional and mechanical interfaces
- ease of access to and removal and installation of modules without requirements for special tools
- on-board spares for module replacement
- return of failed modules to earth for component repair
- on-orbit checkout to increase probability of mission success and allow lower payload design reliability

In their study, Lockheed constantly cited the need for common and standardized satellite design and demonstrated the technical feasibility of a standard spacecraft.

In the Lockheed study, on-orbit repair and maintenance essentially involves one major servicing operation - removal and replacement of modules.

In the GE (1969) study, it was stated that from 75 to 80% of the total of maintenance activities involves maintenance at the module level, and, furthermore, that such maintenance involves the removal and replacement of nuts, bolts, and connectors. Therefore, the major satellite servicing operation is removal/replacement. In this report, it will be the only operation analyzed since requirements for removal/replacement cover most of the requirements for on-orbit servicing, since many requirements for other operations (maintenance, repair, update, etc.) are the same as those for removal/replacement, and since the specific requirements and constraints associated with these other operations are at best uncertain at this time.

A functional analysis of a generic removal/replacement operation resulted in the identification of the functions and tasks listed in Table 14. In order to identify requirements associated with these tasks, some consideration must be given to satellite design parameters and the range of variation of these parameters. Dimensions of important satellite and teleoperator parameters associated with each task are presented in Table 16 and removal/replacement requirements and complexity levels are presented in Table 17.

Table 14 Remove/Replace Functions and Tasks

Function	Task
Prepare for removal	
	Search for module
	Locate module
	Ingress work site
	Stabilize mobility unit (clamps or jets)
	Inspect work site (detect obstacles, damage)
	Orient for removal (spatial alignment)
	Configure work site for removal (deactivate systems, move obstacles)
	Configure manipulator for removal (take precautions, orient lights, cameras)
Removal	
	Uncover module (thermal blanket, super insulation, door)
	Stow stabilize cover - door
	Remove obstructions
	Inspect module
	Configure lighting/camera
	Attach safety tether
	Break connections
	Stow connections
	Break hold down/lock
	Contact module
	Free module
	Remove module
	Handle module
	Stow module
	Detach safety tether
Replacement	
	Attach safety tether
	Retrieve fresh module
	Inspect fresh module
	Inspect work site
	Orient for replacement
	Align module
	Install module
	Adjust module
	Make hold down
	Unstow connections
	Make connections
	Detach safety tether
	Verify seating

Table 15

Dimensions of Satellite Parameters for Removal/Replacement of Modules

Module clearance from surrounding structures

- tight clearance
- clear

Obstructions

- none
- limited visual access
- limited effector access
- limited visual and effector access

Module connections - type

- structural
- electrical
- fluid line
- mechanical linkage
- optical train
- two or more of the above

Module connections - number

- one
- two to five
- six to ten
- greater than 10

Connection complexity

- simple alignment/simple actuation - lock and track, quick release
- complex alignment/simple actuation - plug in
- simple alignment/complex activation - bolts, fasteners
- complex alignment/complex actuation - assembly/disassembly

Number of modules to be removed/replaced

- one
- two to 10
- more than 10

Module location

- Satellite interior
    - shallow - 0 to 3 inches deep
    - deep - greater than 3 inches deep

Table 15 - cont'd

Satellite exterior

Module access

exposed
covered

flexible cover - superinsulation, thermal blanket
rigid cover - structure

Module - effector interface (prepared)

none
grip hold

Module attachment to satellite

lock-latch
bolted
welded - riveted

Module seating on satellite

end attachment
inserted into structures

Module alignment

visual - unaided
tactile - unaided
aided

Worksite clearance

unconfined
semi-confined
confined

Precautions required

none
module special handling - retention
contamination
thermal effects
photic effects
nuclear radiation
stellar radiation

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Table 15 - cont'd

Direction of module removal/replacement (with respect to manipulator)

- any
- along fore-aft axis
- along up-down axis
- along right-left axis
- off axis

Module replacement verification

- no direct, positive feedback
- system feedback
- visual feedback
- tactile/force feedback

Module markings

- none
- identification
- labelling - instructions

Table 16 Satellite and Teleoperator System

Parameters Associated with Each Removal/Replacement Task

TASK	SATELLITE PARAMETERS	TELEOPERATOR PARAMETERS
search	markings	video field of view
locate	markings	video resolution
ingress work area	worksite clearance	reach capability
stabilize mobility unit	attach points	attach devices
inspect work area	skin reflectivity	lighting, video zoom
orient for removal	attach points	reach
	worksite clearance	
configure manipulator	precautions	video - lighting - manipulator
	access	
uncover	type of access	type of effector/tool
stow cover	stowage area	stowage provisions
remove obstructions	obstruction movability	tools
inspect module	markings	video
	location	
attach tether	attach point on module	tool fastener
break connections	type, number, complexity	tools
stow connections	stow area	stowage aids
break hold down/lock	type attachment	tools
contact module	effector interface	module interface
free module	type attachment	effector
remove module	direction	manipulator reach
	size	
handle module	precautions	effector
	size	
stow module	stow area	tools - aids
detach tether		fastener
retrieve fresh module		stowage
inspect fresh module		video
inspect work site	clearance	
orient for replacement	clearance	reach envelope
align module	module alignment	effector orientation
		visual system
install module	seating	effector orientation
	attachment	
adjust module	attachment	tools
	alignment	
make hold down	attachment	tools
	location	
	seating	
instow connections	number - type	tools
make connections	number - type - complexity	tools
detach tether		fasteners
verify seating	verification	visual - force
retrieve cover	stow area	stowage
replace cover	access	tools

Table 17 Removal/Replacement Requirements and Complexity Levels for Operations

Function/ Task	Requirements: Information	Requirements: Performance	Complexity: Level*	Complexity: Factors Affecting
Prepare				
Search	General location	Systematic search	L	Area to be searched
Locate	Specific location	Recognition	L to M	Identification markings
Ingress site	General orientation	Maneuver into position	M to H	Degree to which site is constrained
Stabilize	Attach points and location	Make attachment Verify attachment	L to M	Attach point configuration
Orient lights/ cameras	Recovered angles	Adjust lights/ cameras	L	
Inspect	View of obstacles, structures, locks, bolts, etc.	View from different aspects	L	Lighting, skin reflectivity
Orient	Required arm position	Configure arm - tool	L	Clearances
Configure site	Structures to be moved Precautions	Move structures Take precautions	H	Degree of preparation Extent of precautions
Uncover	Procedures Precautions	Cut-strip insulation Unlock - open doors, accesses	M to H	Requirements for special handling
Stow-Stabilize Cover-door	Procedures	Move cover to stow location Stow cover	L	Number of arms required
Remove obstructions	View of access	Displace-removal obstruction to reach	L	Type and density of obstructions Method for removal
Inspect module	View	Vary aspect	L	Depth of view
Configure lighting/ camera	View	3 axis control	L	
Attach safety tether	Location of fastener	Fasten	L to M	Visual clearance
Break connections	Location, type, method	Acquire connections Demate	M to H	Type and number of connections
Stow connections	Stow area	Bundle and stow	L	Restraining device
Break hold down/lock	Location Method	Unlatch, remove bolts pins, fasteners	H	Type hold down Number of operations

* Complexity Levels
L - Low Little demand placed on teleoperator system.
M - Moderate Demand placed on teleoperator system.
H - High Demand placed on teleoperator system.

Table 17- cont'd

Function/ Task	Requirements: Information	Requirements: Performance	Complexity: Level	Complexity: Factors Affecting
Stow bolts, etc.	Stow location	Place elements in stowage	L to M	Degree to which fasteners become free of structures
Contact module	Contact point Effector orientation Contact rates	Maneuver effector to contact point and attach	M	Visual clearance Contact point design Reach requirements
Free module	Feedback	Apply force to free	M	Level of force Type of feedback
Remove module	Alignment during	Retract - Pull off module	M to H	Reach Special handling Clearances

CHAPTER 4 MAN-MACHINE ALLOCATIONS

Once requirements have been identified, the next step in the analysis is to allocate functions and tasks to man performance or machine performance. However, due to uncertainties in teleoperator system design such as provisions for ranging and degree of computer control, and also since certain of the requirements listed in Tables 10 through 13 cannot be quantified based on existing information, this allocation must, at this stage, remain preliminary. In order to assure that an allocation approach is meaningful over the wide range of possible and varied system configurations, not one but several allocations will be made based on certain assumptions. These allocations will attempt to cover the range of possible system configurations from completely manual to completely automatic. Four classes of allocations will be used which include:

manual - man has primary responsibility

manual aided - man has responsibility but is aided by machine

machine aided - machine performs the task with man aid

machine - automatic performance with man monitoring

A. Satellite Retrieval

Required capabilities for each allocation for each task for the rendezvous phase are presented in Table 18, for the capture phase in Table 19, and for the recovery phase in Table 20.

The primary attributes of a system developed following the manual allocation approach is that the primary control input is from the man and the primary display media is direct view and/or TV. This approach offers the least complex system configuration but places maximum workload on the man who must perform all information processing and decision activities based on raw visual data alone.

In the man-aided allocation approach, man still provides the basic control input, however, he is aided by computer generated data display, computer integration of data and sensor data. In this approach, ranging is performed by the man, as in the manual allocation, using video data and display aids such as reticles, range circles, etc., or by means of a ranging sensor. The man could be provided with additional information in this approach for the ranging task such as computer integration of ΔV applications to compute range of the free flier from the target, and computer resolution of tip displacement to estimate range for the attached teleoperator. This approach, then, is of an order of magnitude more complex than the manual allocation since the display side of the control station will require additional display devices, computer software and computer-display interfaces.

The machine aided approach has the computer process sensor range and alignment data for display to the man with updates in position and alignment coming from the man. The computer will also share in some of the control activities such as the computation of which joints of the attached boom should rotate, how much and when. These computations would be displayed to the man for his input or for his approval prior to input by the computer. The distinguishing characteristic of the machine aided allocation, then, is use of the computer for actual control input with man serving to update and refine the control activities based on visual information.

In the machine allocation approach, virtually all control input is from the computer with the man serving a supervisory and monitoring role. This approach makes maximum use of supervisory control where man gives the "go" signal and the computer controls each activity in the sequence either in a preprogrammed fashion or by selecting alternate routes based on solutions provided by sensor data.

The command/control system to be actually implemented for shuttle satellite retrieval will probably entail some combination of the capabilities afforded by these four allocation approaches for different tasks. In addition, a selection of operating modes from among the allocation approaches will probably also be available. In all likelihood, the manual allocation approach will always be available at least as a backup mode when failures or off nominal-condition obviate the use of a more sophisticated approach or mode. Therefore, control and display requirements will be required for this allocation approach in any case. It is difficult at the present time to trade off the allocation approaches for each task in order to select the optimal approach for that task since the current research literature is inadequate to support such decisions. An evaluation was conducted of the degree to which each allocation approach can satisfy the specific requirements which have been quantified. The results of this analysis are presented in Table 21 for free flier ranging requirements, 22 for free flier control requirements, 23 for attached teleoperator ranging requirements, 24 for attached control requirements and 25 for free flier and attached information processing and decision making requirements. As can be seen from these tables, different orders of magnitude of system complexity and capability can be conceived for the teleoperator system depending on the allocation approach selected. These different orders of magnitude can apply to the initial system configuration and to the course of teleoperator technology development where a less complex approach is selected initially and the systems become increasingly more complex and sophisticated as a function of the development of advanced technology and the conduct of additional research over time.

Within the guidelines of selecting the simplest system which can provide full capability to meet all retrieval requirements and which requires minimum advanced technology development, a selection of allocation approaches was made for the free flier and the attached manipulator. The results of this allocation based on requirements are presented in Table 26.

As indicated in this Table, the recommended system for the free flier is basically a manual system with computer assistance in such intricate control tasks as rate synchronization and despin and computer generated displays for monitoring systems status and geometry of bodies, identifying the axis of rotation of the satellite, measuring rotational rates and wobble rates and performing inspection.

The attached manipulator system is basically a machine aided system with computer assisted control of boom position and rates and computer generated display of those parameters cited for the free flier for computer display.

In selecting these allocations, certain assumptions were made. It was assumed that ranging would be conducted primarily in a manual mode due to uncertainties of the availability and feasibility of high accuracy ranging sensors. If the state-of-the-art is such that such sensors are available when required (approximately 1975-76) then their use should be considered since they do provide an additional order of magnitude in system capability. The use of automated control, as included in the machine allocation was not selected for any requirement since such control requires additional complexity and also since it removes man from the control loop in situations where his rapid intervention might be required to resolve unexpected problems.

TABLE 18

Required Capabilities for Each of Four Allocations for Each Task - Rendezvous Phase (Free Flier and Attached)

Task	Allocation classes: Manual	Man Aided	Machine Aided	Machine
Command closing velocity	Man commands attitudes and firing based on telemetry	Man commands based on computer generated data	Computer commands attitude - man commands firing computer controls duration of burn	Computer controls attitude and firing with man monitoring via telemetry
Maintain attitude	Man adjusts attitude based on envelope data	Man adjusts attitude based on generated envelope data	Computer adjusts attitude based on manual input of envelope data	Computer adjusts attitude based on sensed range and orientation data
Monitor range	Man judges range to target via video and video aids	Man judges range using target mounted aids, comm link, computer integration of ΔV burns and video	Ranging sensor displays range to man	Ranging sensor inputs range to control loop and displays to man
Monitor rates	Man with video and video aids	Man with computer generated rate data and video	Ranging sensor	Ranging sensor
Perform corrections	Man input with video	Man input with display and video	Computer input on man command	Computer input with feedback to man
Maneuver shuttle as required	Man control of shuttle			
Command braking	Man command based on video	Man command based on video and computer generated data	Man initiated based on sensor data - machine control of duration of burn	Machine controlled based on sensor data

TABLE 18 - cont'd

Task	Allocation classes Manual	Man Aided	Machine Aided	Machine
Assume station keeping position	Man control based on video	Man control based on video and computer generated data		Machine control based on sensor data
Align attitude angles	Man control based on telemetry and video	Man using computer generated data and aids on the satellite	Machine computes required angles and man inputs commands	Machine control based on sensor data
Determine position changes required	Man sensing of offsets - input corrections	Computer generation of inspection sequence - display to man	Computer command inspection maneuvers based on inputs from man	Computer command inspection sequence based on sensor data and man input
Monitor position	Man - video	Man with video and computer integration of range input data	Display to man of sensor data	Computer display to man based on sensor data
Monitor location of obstacles	Man - video	Man - computer aided display	Man - ranging sensor input to computer	Computer monitor based on ranging data
Maneuver around satellite	Man based on video input	Man based on video and computer generated display	Man based on sensor data	Computer control based on sensor data
Inspect structures	Man - video			
Identify problems	Man - video			

TABLE 18 - cont'd

Task	Allocation classes Manual	Man Aided	Machine Aided	Machine
Identify axis of rotation	Man - video		Computer based on sensor data - display to man	
Align attitude and body axes	Man - video			
Measure rotational rates	Man - video	Man - video and computer data	Man - video and sensor data	Computer - sensor data
Measure stability about the axes	Man - video	Man - video and computer data	Man - video and sensor data	Computer - sensor data
Measure wobble	Man - video		Man - video and sensor data	Computer - sensor data
Identify attach points	Man - video			
Inspect - track attach points	Man - video			

TABLE 19

Required Capabilities of Each of Four Allocations for Each Task - Capture Phase

Task	Allocation classes			
	Manual	Man-aided	Machine aided	Machine
Position for capture	Man - video	Man - computer display and video	Man - sensor data	Computer - sensor data
Position/orient manipulators	Man control	Man control - computer display	Computer control man input	Computer control
Synchronize rates	Man - video and aids	Man - video and satellite data	Computer - satellite data - based on man input	Computer - sensor data
Commence final closing	Man - video	Man - video satellite aids	Computer - sensor data - man input	Computer - sensor data
Maintain alignment	Man - video	Man - video and satellite aids	Computer - sensor data - man input	Computer - sensor data
Achieve contact	Man - contact sensor			Computer - contact sensor
Secure effector	Man - video and force data		Computer - force data display and man input	Computer - force data input
Monitor rates and forces	Man - video and force data		Computer with man input	Computer - force sensors
Decide to stabilize	Man - video and force data		Computer - force sensors with man override	
Impart despin force	Man - force data	Man - computer integration of force data	Computer - man input	Computer controlled - force sensors

TABLE 19 - cont'd

Task	Allocation classes Manual	Man-aided	Machine-aided	Machine
Monitor rates	Man - force data and video	Man - integration of force data		Computer - display
Monitor stability	Man - force data and stability sensors	Man - integration of force data and stability sensors		Computer - display to man

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TABLE 20

Required Capabilities for Each of Four Allocations
For Each Task - Recovery Phase

Task	Allocation classes: Manual	Man-aided	Machine-aided	Machine
Position for recovery	Man - video data	Man - computer display		
Prepare manipulators	Man - manipulator position data	Man - computer integration and display		Computer - joint position sensors
Impart closing velocity	Man - video and shuttle ranging	Man - computer integration and display	Computer - man input	Computer - sensor input
Monitor range and rates	Man - video and shuttle ranging	Man - computer integration and display		Computer - sensor input
Monitor orientation	Man - video and shuttle view			
Begin braking	Man - video and shuttle ranging		Computer - man input based on sensor data	Computer - sensor data
Assume emplacement	Man - video and direct view		Computer - man input	
Complete braking	Man control		Computer termination of burn based on man input	Computer control of burn
Verify satellite orientation	Man - video and direct view			
Maneuver satellite to recovery position	Man - video and direct view		Computer control based on man input	Computer based on sensor input

TABLE 20 - cont'd

Task	Allocation classes Manual	Man-aided	Machine-aided	Machine
Verify connection to mechanism	Man - contact sensor			
Disengage from satellite	Man - video			Computer - sensor data
Monitor status and performance of all systems	Man - video and fault sensors	Man with computer generated data		Computer built in test

Table 21

Performance of each allocation approach for ranging requirements - Free Flier

Requirement	Manual	Man-aided	Machine-aided	Machine
Range accuracy of 10% beyond 100 feet	Probably capable given adequate aids but increases operator workload	Capable - Problem of resolving conflicts between video data and computer integrations of ΔV firings	Capable but requires a ranging sensor to skin track rotating non-cooperative targets	Too complex
Range accuracy of ±2 feet within 100 ft.	Probably capable given adequate aids on monitor and/or satellite	Probably not capable due to error magnitude	Capable - requires high accuracy sensor	Capable but may not allow sufficient time for man to intervene in off nominal conditions
Range accuracy ±2 fps beyond 100 ft.	Probably capable - requires research	Probably not capable based on integration of Δ V burns	Capable with ranging sensor	Capable
Range rate accuracy ±2 fps within 100 ft.	Probably capable - requires research	Probably not capable due to errors	Capable given high accuracy sensor	Capable but tight time-frame for man intervention
LOS rate accuracy .5 fps beyond 100 ft.	Probably not capable of detecting. .4 mrad/sec rate at 100 ft. range	Probably not capable due to alignment errors at thrusting	Capable given ranging sensor	Capable
LOS rate accuracy ±.1 fps within 100 feet	Probably not capable of detection .08 mrad/sec at 100 ft. range	Not capable	Capable given high accuracy sensor	Capable but complex

Table 22

Performance of each allocation approach for control requirements - Free Flier

Requirement	Manual	Man-Aided	Machine-Aided	Machine
Command .5 fps closing velocity each 100 ft. range	Capable	Capable	Capable	Capable but complex
Null rates at 100 ft and again at 20 ft ±.1 fps	Capable of ±.2 fps	Not capable	Capable supervisory control	Capable but complex
Align attitude	Capable with CMG system	Capable	Capable but complex - depends on sensing target attitude	Capable but highly complex
Maneuver around satellite	Capable with adequate aids and lighting	No additional capability	Capable but complex	Capable but complex
Maintain position for station keeping range ±2 ft. rates ±.1 fps	Probably capable	No additional capability	Capable with high accuracy sensors	Capable but complex
Synchronize effector rate with satellite rate to .1 to 2 RPM	Probably capable based on ATS-V data	Probably capable based on input from satellite	Probably capable and high accuracy control	Probably capable and high accuracy
Maintain docking axes alignment ±.2 ft.	Capable based on Bell Aerospace simulation	No additional capability	Probably capable with high accuracy sensor - complex	Capable but complex and little time for man intervention
Achieve contact - max closing rate .2 fps	Capable - Apollo	No additional capability	Capable but complex sensor	Capable but highly complex
Despin satellite	Capable - ATS-V	Capable - satellite rate input	Capable - high accuracy	Capable - complex

Table 23

Performance of each allocation approach
for ranging requirements - attached teleoperator

Requirement	Manual	Man-aided	Machine-aided	Machine
Range accuracy ±2 ft. into 10 ft. range	Capable	Capable provided position of target is known WRT the shuttle	Capable given a ranging sensor	Capable given a ranging sensor
Range accuracy ±2 inch within 10 ft.	Probably not capable - requires research	Same as above	Same as above	Same as above
Rate accuracy ± .1 fps	Probably not capable - requires research	Same as above	Same as above	Same as above

Table 24

Performance of each allocation approach for control requirements - attached

Requirement	Manual	Man-aided	Machine-aided	Machine
Command .4fps closing velocity	Capable	Capable	Capable - high accuracy	Capable - high accuracy
Maintain surveillance orientation	Capable	Capable - computer resolution based on man input	Capable with man input	Not capable
Perform corrections	Capable but complex - requires research	Capable with computer resolution, predictive display, display of arm orientation	Capable with computer resolution and control - with man input - supervisory control	Capable if all parameters are known and software is available
Maneuver around satellite	Capable but probably limited due to boom constraints	Not capable	Capable with high resolution ranging	Capable but limits man intervention time
Command braking	Capable with adequate ranging aids	Capable with known satellite location	Capable and high accuracy with man input	Capable but limits man intervention time
Assume station keeping position at 10 ft. range	Capable	Same as above	Same as above	Capable given high accuracy sensors
Maintain rates at .1 fps, tip position ± 2 in.	Probably capable	Capable with high resolution satellite location WRT shuttle	Capable with ranging sensors and man input	Capable with ranging sensors
Final closing rates .05 to 2 fps	Capable	Same as above	Capable - high accuracy ranging	Capable - limits man intervention time
Contact with rates ± .2 fps maximum	Capable	Same as above	Same as above	Same as above
Despin satellite	Capable but complex	Capable with satellite rate input - computer solution	Capable with high accuracy - computer assisted control	Same as above

Table 25

Performance of each allocation approach for information processing and decision making requirements - free flier and attached

Requirement	Manual	Man-aided	Machine-aided	Machine
Monitor location of obstacles	Capable	Capable with known satellite characteristics	Not capable	
Inspect structures	Capable - video	Capable - computer scheduling of inspection routines	No added capability	No added capability
Monitor orientation of satellite - teleoperator, shuttle and sun	Capable but demanding	Capable - situation display of geometry	No added capability	No added capability
Identify axes of rotation	Capable - gross	Capable with shuttle expected dynamics data	Capable with special sensors	No added capability
Measure rotation rates	Capable - point tracking and display aids	Capable - predictive display on satellite data as in ATS-V mission	Capable with special sensors and man input	Capable but complex
Measure axes stability	Capable - gross	Same as above	Same as above	Same as above
Measure wobble rates	Capable - gross	Same as above	Same as above	Same as above
Identify attach points	Capable - pattern recognition	Capable - computer aided search	No added capability	No added capability
Track and inspect points 5 ARC min. resolution, 5 ARC min./sec. resolution	Capable with good video	No added capability	Not capable	Not capable
Monitor forces at contact	Capable with sensors	Capable with sensor integration	No added capability	No added capability

Table 25 - Cont'd.

Requirement	Manual	Man-aided	Machine-aided	Machine
Decide to latch or disengage	Capable - high workload	Capable with data integration	No added capability	Capable but complex
Monitor systems status	Capable with sensors	Capable with sensors and data integration for trouble shooting	No added capability	Automatic test and checkout

Table 26

Selected allocation for each class of requirements - free flier and attached

Requirement	Selected Allocation	Rationale
Ranging - free flier	Manual with display aids and satellite markings and ranging aids	Simplicity plus the uncertainty that ranging sensors are available for short distance, high accuracy skin tracking-ranging allows continuity of manual control in short response situations (failure modes)
- attached	Man-aided - computer assisted ranging if satellite position WRT the shuttle is known. Otherwise manual	Added precision with man still in the loop
Control of velocity - free flier	Manual	Full capability, simplicity and continuity of control
- attached	Machine-aided - computer solution of joint angles and rates - computer assisted control	Complexity of joint control and rate accuracy requirements
Control of orientation - free flier	Manual	Simplicity and full capability
- attached	Man-aided - computer solution of angle requirements	Complexity of joint control
Control of position - free flier	Manual	Simplicity - no additional sensors required beyond TV
- attached	Man-aided - computer generated display	Complexity of joint control
Control of inspection maneuvers - free flier	Manual	Simplicity
- attached	Machine aided	Complexity of joint control

Table 26, Cont'd.

Requirement	Selected Allocation	Rationale
Rate synchronization		
- free flier	Machine aided	Resolution and workload requirements
- attached	Machine aided	Same as above
Control final closure		
- free flier	Manual	Simplicity and continuity
- attached	Man-aided - readouts or display of joint control requirements	Simplicity and continuity with complexity of joint control
Control docking		
- free flier	Manual	Simplicity and continuity
- attached	Man-aided	Simplicity, continuity and complexity of joint control
Control despin		
- free flier	Machine aided	High accuracy control
- attached	Machine aided	High accuracy control
Monitor location of obstacles		
- free flier and attached	Manual	Simplicity and continuity
Inspect*	Man-aided	Man with computer support
Monitor geometry of bodies	Man-aided	Reduced workload and integrated display
Identify axes of rotation	Machine aided	Provides required accuracies given special sensors
Measure rotation rates	Man-aided	Reduced workload - high accuracy
Measure stability about an axis	Man-aided	High accuracy
Measure wobble rates	Man-aided	High accuracy

*Remaining requirements in this Table apply equally to the free flier and to the attached teleoperator.

Table 26, Cont'd.

Requirement	Selected Allocation	Rationale
Identify attach points	Man-aided	Computer assisted search an added advantage over manual
Track and inspect points	Manual	Sufficient capability
Decide to latch	Man-aided	Reduced workload with computer integration of data
Monitor systems status	Man-aided	Simplicity and computer data integration

B. Satellite Servicing

In determining the allocation of removal/replacement operations to man or machine, an evaluation was made of each of the four allocation approaches identified in the satellite retrieval section (manual, man-aided, machine-aided and machine). The results of this evaluation are presented in Table 27. Based on the evaluation, it was decided that at least the early systems developed for satellite servicing should be manual systems. The primary advantages of this approach are simplicity, flexibility, continuity of control and minimum impact on satellite design. This latter consideration is critical to this decision. If a strong move suddenly develops within NASA to significantly increase the commonality and standardization of satellite and payload systems, as recommended by GE (1969) and Lockheed (1971), then the more sophisticated and complex automated allocation approaches become more feasible. At the present time, NASA has made no such move. Therefore, the safest approach seems to be to ensure a maximum of flexibility and simplicity of teleoperator design, and a minimum impact on satellite design at the cost of efficiency and workload.

Some investigations of satellite servicing requirements have moved toward the machine allocation or use of automated systems. The STAR (Shuttle for Telescope Activation and Resupply) concept developed at Goddard for servicing the Large Stellar Telescope (LST) postulates a strong-back rigid manipulator system deployed from the shuttle cargo bay which docks with the LST and automically removes and replaces modules. In this approach, the man controls the dock and monitors the automatic resupply sequence. The primary drawback to this approach is that it represents a special purpose system and is not intended for servicing of satellites other than the LST.

A second drawback is that no capability is provided for contingency modes of removal/replacement such as automatic system failure, module hangup in a rack, etc. However, with the work progressing at Lockheed on requirements and design criteria for standard spacecraft design, the machine and machine-aided allocations will gain in applicability and feasibility.

Given that, at this time, the manual allocation of removal/replacement tasks is preferred, the next step is to develop control/display requirements for these tasks.

TABLE 27

Evaluation of Allocation Approaches for Removal/Replacement

Allocation Approach	Advantages	Disadvantages
Manual	Simplicity of design within current state-of-the-art Minimum impact on satellite design Continuity of man-in-the-loop Required as a backup mode therefore must be available Maximum flexibility - adaptability	Higher workload placed on man Somewhat limited to anthropomorphic manipulator Greater control/display requirements Greater reliance on ground resources Probably the most inefficient approach
Man Aided	Computer support of trouble-shooting activities Computer generated displays of arm position and orientation	Complex software and computer interfaces Uncertain requirements for computer display
Machine Aided	High accuracy Good for rote, routine, repetitive, long duration tasks and sequences Order of magnitude additional information available on satellite via special sensors Computer assisted control of manipulator position and rates	Requires standard satellite design or special purpose teleoperator system Complex hardware and software reduced reliability and increased maintainability of teleoperator system Reduced time for man to intervene in contingencies
Machine	Lowest workload on man Computer control of manipulator position and rates	Maximum impact on satellite Maximum complexity and cost Requires advanced technology Minimum man intervention capability

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CHAPTER 5 CONTROL/DISPLAY REQUIREMENTS

Based on system requirements for each mission, and the allocation of functions to man or machine, control and display requirements were developed for each satellite retrieval and satellite servicing task. In addition, for the satellite retrieval mission, computer support requirements were also generated in Table 28 for free flyer satellite retrieval, Table 29 for attached manipulator satellite retrieval, and Table 30 for satellite servicing with either a free flyer or an attached manipulator.

The relative importance in terms of frequency and use of controls and displays was derived by computing for each mission the percentage of the tasks which placed requirements on each type of control or display. The results of this analysis are presented in Table 31. As indicated by this table, the most important display for all three mission/system combinations was video. The most frequently used controls were attitude and translation for free flyer satellite retrieval, manipulator control for attached satellite retrieval, and manipulator-effector control for satellite servicing.

Table 28

Control/Display Requirements by Tasks - Free Flier

		REQUIREMENTS	
PHASE/TASK	CONTROL	DISPLAY	COMPUTER SUPPORT
Rendezvous Phase			
Command closing rate	•Translation controller	•Attitude angles and rates •ΔV required ±.1 fps •ΔV applied ±.1 fps	•Generation of ΔV required and attitude angles required
Maintain visual surveillance attitude	•Attitude controller .Video control	•Attitude angles and rates •Surveillance envelope •T/O, shuttle, target and sun geometry	•Generation of geometry display and envelope display
Maintain comm. envelope attitude	•Attitude controller	•Attitude angles and rates •Communication envelope •Body geometry	•Same as above
Monitor range	•Video controls - field of view, zoom, pan and tilt .Sensor controls	•Video •Video ranging aids •Satellite aids •Envelope aids •Range display	•Range envelope
Monitor rates	•Same as above	•Same as above	•Rate envelope
Perform corrections	•Attitude and translation controllers	•Video	•Range and rate envelopes
Maneuver shuttle	•Shuttle control	•Shuttle display •Video	.Shuttle flight control data
Command braking	•Attitude and translation controllers	•Video •Actual attitude angles •Required angles •Required Δ V •Applied ΔV	•Computation of angles and ΔV required based on man input of range and rates

Table 28, cont'd.

PHASE/TASK	CONTROL	DISPLAY	COMPUTER SUPPORT
	REQUIREMENTS		
Rendezvous cont'd.			
Assume station keeping position	•Attitude and translation controllers •Lighting control	•Video •Video aids	
Align attitude angles	•Attitude and translation controllers •Zoom control	•Video of satellite •Alignment aids on satellite and video	
Determine position changes required	•Lighting control	•Video	
Monitor position	•Lighting control	•Video •Video aids	
Monitor location of obstacles	•Video pan, tilt and zoom control •Lighting control	•Video •Pan, tilt and zoom values	
Maneuver around satellite	•Attitude and translation-light control	•Video	
Inspect	•Lighting control •Pan, tilt, zoom	•Video-resolution 5 arc min. (2 TV lines) •Aids •Pan, tilt, zoom •Display of inspection routine	•Generation of inspection routine
Track satellite	•Controllers and video control - field of view	•Video - resolution 5 arc min/sec	
Identify axis of rotation	•Position control	•Aided display accuracy TBD	•Computer generated display based on satellite dynamic data and special sensors
Align docking axis	•Position control	•Video-accuracy TBD •View and satellite aids	

Table 28, cont'd.

PHASE/TASK	CONTROL	DISPLAY	COMPUTER SUPPORT
	REQUIREMENTS		
Rendezvous cont'd			
Measure satellite rates	•Sensor control	•Video •Aided display Accuracy .05 to 2.0 RPM	•Computer generated display based on satellite dynamic data and special sensors
Measure stability about axes		•Video •Aided display accuracy TBD	•Computer generated display
Identify attach points	•Positioning of lighting	•Video - 5 arc min. •Search cues	•Computer generated search assist cues
Inspect attach points	•Zoom control	•Video - 5 arc min.	
Track points	•Pan and tilt •Controllers	•Video - 5 arc min/sec.	
Capture Phase			
Position for capture	•Controllers	•Video	
Orient manipulators/ effectors	•Manipulator/capture device control	•Video •Arm position and rate feedback	•Computer generated display of arm orientation
Synchronize rates	•Computer control based on measured rates •Adjustment controls or •Arm rotation control (depending on accuracy requirements)	•Rate display - arm and satellite •Video •Video aids	•Computer generated synchronization rate commands and display of rates
Commence final closing	•Arm position and rate control •Vehicle attitude and translation control	•Video for: -Arm position -Effector position -Effector orientation -Effector rates -Vehicle rates .Ranging	

Table 28, cont'd.

PHASE/TASK	CONTROL	DISPLAY	COMPUTER SUPPORT
Capture cont'd.			
Maintain alignment	•Manipulator control •Vehicle control	•Video •Alignment aids accuracy TBD	
Achieve contact		•Contact display •Rate display •Force display •Video	
Secure effector	•Effector grip control	•Forces and torques •Video	
Decide to latch or disengage		•Decision display	•Computer resolution of force/torque data
Despin	•Manipulator control	•Manipulator rates •Forces/torques •Vehicle stability •Video •Decision display	•Computer resolution of force/torque data
Monitor rates, forces, torques		•Same as above	•Same as above
Recovery Phase			
Prepare for recovery	•Manipulation - vehicle control	•Video •Stability display	
Prepare satellite for recovery	•Control of manipulators	•Satellite preparation requirements display (purge, etc.) •Manipulator position and rates	
Impart closing velocity	•Translation control •Attitude control	•ΔV display •Angles and rates	•Generation of ΔV requirements and cluster angles for burn
Monitor range and rates		•Range and rate data from shuttle ranging sensors or •Video	

Table 28, cont'd.

PHASE/TASK	REQUIREMENTS CONTROL	 DISPLAY	 COMPUTER SUPPORT
Recovery cont'd.			
Monitor orientation		•Angles and rates •Video of shuttle	
Begin braking	•Attitude control •Translation control	•Attitude angles • Δ V display	•Same as above
Complete braking	•Same as above	•Same as above	•Same as above
Verify position - orientation		•Video from T/O •Video from shuttle •Direct view from shuttle	
Maneuver to recovery position	•Same as above	•Same as above	
Disengage from satellite	•Arm control •Translation control	•Effector status • Δ V •Video	
Monitor systems status		•Computer display	•Computer interpretation of checkout data

Table 29

Control/Display Requirements by Tasks - Attached

PHASE/TASK	CONTROL	DISPLAY (REQUIREMENTS)	COMPUTER SUPPORT
Approach Phase			
Command closing velocity	•Supervisory	•Video - entire arm •Rate display accuracy ±.1 fps •Computed miss distance and envelope	•Computer resolution of joint angles and rates •Computed miss distance and envelope
Maintain orientation	•Override control of joint angles and rates •Video control	•Orientation envelope •Video pan, tilt, zoom and field of video	•Computation of envelope
Monitor range	•Range accuracy 2 inches within 10 feet - computer assisted controlled	•Computer generated if satellite location is known, otherwise video with aids	•Computation of range from satellite location inputs
Monitor rates	•Rate accuracy ±.1 fps computer assisted controlled	•Rate display •Closing velocity display if location is known	•Computation of closing velocity - control of all rates
Perform corrections	•Override control •Computer assisted control	•Boom angles, rates and torques •Miss distance display	•Generation of miss distance display
Command braking	•Supervisory control	•Video ranging or •Computer generated ranging display •Rate display	•Generation of rate display and ranging display
Assume station keeping position	•Supervisory control •Computer assisted control •Lighting control	•Same as above - direct view of satellite	•Same as above
Determine position changes required		•Video •Direct view	

Table 29 cont'd.

PHASE/TASK	REQUIREMENTS CONTROL	 DISPLAY	 COMPUTER SUPPORT
Approach, cont'd.			
Monitor position		•Computer generated graphic display of boom position and orientation WRT satellite and shuttle	•Generation of orientation display
Monitor location of obstacles	•Video control	•Video •Direct view	
Maneuver around satellite	•Manual control with computer input for joint angles and rates	•Sequence of joint activation •Video •Direct view	•Solution of angles, rates and activation sequence
Inspect	•Lighting control •Video control	•Inspection routine •Pan, tilt and zoom •Video	•Generation of inspection routine
Track satellite	•Video control	•Video •Direct view	
Identify Axis of rotation	•Position control	•Aided display accuracy TBD	•Computer generated display based on satellite dynamics data and special sensors
Align docking axis	•Manual control based on computer generated data	•Computer display of joint angles and rates	•Display generation
Measure satellite rates	•Sensor control	•Video •Aided display accuracy .05 to 2 RPM	•Computer generated display based on satellite data and special sensor data
Measure stability about axis		•Video •Aided display accuracy TBD	•Computer generated display

Table 29 - Cont'd

PHASE/TASK	REQUIREMENTS CONTROL	 DISPLAY	 COMPUTER SUPPORT
Approach, cont'd.			
Identify attach points	•Lighting control .Video control	•Video •Search cues	•Computer generated search cues
Inspect attach points	•Zoom control	•Video - 5 arc min. resolution	
Track points	•Pan and tilt •Manual controller	•Pan and tilt •Video - 5 arc min/sec resolution	
Capture Phase			
Position for capture	•Manipulator control	•Computer display of angles and rates	•Computer generated display
Orient effectors	•Effector control	•Effector orientation .Video •Direct view	
Synchronize rates	•Computer control based on measured rates	•Rate display .Video	•Computer assisted control
Commence final closing	•Boom controller	•Video •Rate display	
Maintain alignment	•Boom-effector controller	•Video and aids	
Achieve contact		•Contact sensors •Rate display •Force display	
Secure effector	•Grip control	•Forces and torques •Effector orientation •Video	
Decide to latch or disengage		•Decision display	•Computer generation of decision display

Table 29, cont'd.

	REQUIREMENTS		
PHASE/TASK	CONTROL	DISPLAY	COMPUTER SUPPORT
Capture cont'd.			
Despin	•Effector control	•Rotation rates - effector and satellite •Stability display •Load on boom display •Despin sequence	•Solution of despin sequence
Monitor rates and forces	•Effector control	.Rates •Forces at effector •Loads on boom •Decision display	•Integration of force-rate data Generation of decision display
Recovery Phase			
Prepare recovery	•Effector control	•Video •Direct view	
Prepare satellite for recovery	•Effector control	•Display of preparation/ configuration requirements •Video	
Impart closing velocity	•Supervisory	•Video •Direct view •Boom angles, rates and torques	•Computer control of recovery trajectory and rate for 1 or 2 arm recovery under supervisory control
Monitor range, rates, orientation		•Video •Range display •Rate display •Joint torque display	•Same as above
Brake	•Supervisory	•Same as above	•Same as above
Verify position - orientation		•Video •Direct view •Joint angles •Display of final recovery sequence	•Computer solution of final recovery

Table 29 , cont'd.

PHASE/TASK	REQUIREMENTS CONTROL	DISPLAY	COMPUTER SUPPORT
Recovery cont'd.			
Maneuver to recovery position	•Supervisory	•Video •Direct view	•Computer control
Emplace satellite into cargo bay	•Computer control man override	•Feedback display	•Control
Monitor systems status	•Computer I/O	•Computer trouble-shooting display	•Automated checkout

TABLE 30

Control/Display Requirements for Removal/Replacement Tasks

Task	Requirements: Control	Requirements: Display
Search for module	. video, pan, tilt, zoom . lighting control	. video . pan, tilt, zoom
Locate module		. video . module markings
Ingress worksite	. control of manipulators and end effectors	. obstacle sensing . situation display
Stabilize mobility unit	. control of stabilization devices	. video . contact sensors
Inspect site	. lighting control . pan, tilt, zoom . camera control	. video . pan, tilt, zoom
Orient for removal	. manipulator control	. video aids . satellite aids
Configure worksite	. manipulator control . tool control	. full site field of view
Configure manipulators	. attach tools . point cameras	. tool feedback . video . manipulator status sensors
Uncover module	. control of arms . control of tools	. view of cover . view of tools . arm position and rates
Stow cover	. restraint control . arm-tool control	. directed field of view
Remove obstructions	. arm-tool control . lighting control	. video . contact-force feedback

TABLE 30 - cont'd

Task	Control (Requirements)	Display (Requirements)
Inspect module	. lighting control	. video
Configure lighting/ camera	. pointing control	. variable brightness video . glare reduction filters
Attach tether to module	. arm-hand control	. positive feedback of attachment
Break connections	. arm-hand control	. view of leads, lines, etc. . verification of disconnect
Stow connections	. arm-hand control . control of stow device - tape, velcro, etc.	. video . forces applied to wires, leads, lines, etc.
Break lock	. arm-hand control	. positive feedback
Contact module	. hand control	. grip integrity display
Free module	. arm-hand control	. forces at hand - axis rotational and translational
Remove module	. arm-hand control	. view of removal . forces - 6 axis . contact sensor display
Handle module	. arm-hand control . multiarm coordination	. view of module . arm joint antles and rates . arm joint torques
Stow module	. arm-hand control . control of stow device	. view of stowage . feedback of connection
Detach tether	. arm-hand control	. feedback
Attach tether to fresh module	. arm-hand control . tether control	. view of fresh module . feedback of connection
Retrieve fresh module	. arm-hand control	. view of retrieval route

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TABLE 30 - cont'd

Task	Requirements: Control	Requirements: Display
Inspect module	. multi-arm coordination	. verify identification of module . view of all module surfaces
Inspect worksite	. camera control . lighting control	. view of worksite from several aspects
Orient module	. arm-hand control	. view of module and module receptacle
Align module	. arm-hand control	. view of alignment aids
Install module	. arm-hand control	. view of installation . forces in 6 axis applied to the module
Adjust module	. hand control	. view of module as installed . view of alignment aids
Make hold down	. hand control	. positive feedback
Unstow connections	. hand control	. view of connections
Make connections	. hand control	. view of connections . positive feedback
Detach tether	. hand control . tether control	. view of disconnect
Verify module seating	. arm-hand control	. force/torque in 6 axis . view of module
Retrieve/replace cover	. arm-hand control	. view of cover operations

TABLE 31

Percentage of Total Tasks for Each Mission/System Requiring Specific Control/Display

Control/Display	Free Flyer Satellite Retrieval	Attached Satellite Retrieval	Satellite Servicing
Vehicle Translation Control	48		
Vehicle Attitude Control	40		
Manipulator Control or Grappler	22	50	65
Effector Control	7	20	75
Video Control	20	16	14
Lighting Control	20	8	14
Sensor Control	5	3	14
Stabilization Device Control (Computer Assisted-Supervisory Control)		30	
Video Display	86	92	81
Video Aids	24	14	3
Satellite-module aids			14
Attitude Display	17		
Range and Rates	14	30	
ΔV	14		
Grappler-Manipulator Display	17	25	8
Effector Display	7	8	20
Force Display	5	14	35
Direct View		27	