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Space Station Automation Study — Satellite Servicing

Volume II
Technical Report

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PREFACE

This study, performed by the TRW Space and Technology Group under contract NAS8-35081 for the NASA Marshall Space Flight Center, Alabama, addressed the definition of the technology requirements for automated satellite servicing operations aboard the forthcoming (early 1990s) NASA Space Station. It was one of several parallel studies performed by a team of NASA contractors investigating various facets of Space Station automation.

This study was conducted by TRW over the six month time frame from early June through November 1984. Three major tasks were completed: Servicing Requirements (Satellite and Space Station Elements) and the Role of Automation; Assessment of Automation Technology; and Conceptual Design of Servicing Facilities on the Space Station. It was found that many servicing functions could benefit from automation support; that certain research and development activities on automation technologies for servicing should start as soon as possible; and some advanced automation developments for orbital servicing could be effectively applied to U.S. industrial ground based operations.

The study final report consists of two volumes:

Volume I - Executive Summary

Volume II - Technical Report

This is Volume II - Technical Report

For the reader's convenience we have used essentially the same table of contents for both of these volumes, except as warranted by major addition of information or coverage of new subject matter in some of the subsections of Volume II.

Requests for additional information, relating to this study, should be directed to the TRW Study Manager: Mr. Hans Meissinger, Telephone Number (213) 536-2995.

Dr. Victor Anselmo of NASA Headquarters (Code S) and Mr. Jon Haussler of the NASA/Marshall Space Flight Center (Code PM01) were the NASA managers of this study. TRW, with appreciation, acknowledges the excellent coordination and direction they provided during this effort.

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DEFINITIONS

AUTONOMY: The ability to function as an independent unit or element, over an extended period of time, performing a variety of actions necessary to achieve pre-designated objectives, while responding to stimuli produced by integrally-contained sensors.

AUTOMATION: Automation is the use of machines to effect initiation, control, modification, or termination of system/subsystem processes in a predefined or modeled set of circumstances. The implication is that little or no further human intervention is needed in performing the operation. The terms hard automation and flexible automation define subsets of automation.

TELEOPERATION ("REMOTE OPERATION"): Use of remotely controlled sensors and actuators allowing a human to operate equipment even though the human presence is removed from the work site. Refers to controlling the motion of a complex piece of equipment such as a mechanical arm, rather than simply turning a device on or off from a distance. The human is provided with some information feedback (visual display or voice) that enables him to safely and effectively operate the equipment by remote control.

AUGMENTED TELEOPERATOR: A teleoperator with sensing and computation capability that can carry out portions of a desired operation without requiring detailed operator control. The terms "teleautomation" and "tele-robotics" have been used here.

TELEPRESENCE ("REMOTE PRESENCE"): The ability to transfer a human's sensory perceptions, e.g., visual, tactile, to a remote site for the purpose of improved teleoperation performance. At the worksite, the manipulators have the dexterity to allow the operator to perform normal human functions. At the control station, the operator receives sufficient quantity and quality of sensory feedback to provide a feeling of actual presence at the worksite.

ROBOT: A generic term, connoting many of the following ideas: A mechanism capable of manipulation of objects and/or movement having enough internal control, sensing, and computer analysis so as to carry out a more or less sophisticated task. The term usually connotes a certain degree of autonomy, and an ability to react appropriately to changing conditions in its environment. Robotics is a specialized discipline within the broader fields of autonomy and automation.

ARTIFICIAL INTELLIGENCE: That branch of computer science concerned with the design and implementation of programs which make complicated decisions, learn or become more adept at making decisions, interact with humans in a way natural to humans, and in general, behave in a manner typically considered the mark of intelligence.

EXPERT SYSTEM: An expert or knowledge-based system is one that stores, processes, and utilizes a significant amount of information about a particular domain of knowledge to solve problems or answer questions pertaining to that domain. The system is able to perform at the level of an experienced human practitioner working in that domain of knowledge.

LIST OF ABBREVIATIONS AND ACRONYMS

AXAF Advanced X-Ray Astrophysical Facility
AFSD U.S. Air Force Space Division
AI Artificial Intelligence
CCTV Closed Circuit Television
COR Contracting Officer's Representative
CSI California Space Institute
DoD U.S. Department of Defense
DS (Space Station) Data System
EVA Extra-Vehicular Activity
FSS Flight Support System
GE General Electric Company
GEO Geosynchronous Earth Orbit
GM General Motors, Inc.
GRO Gamma Ray Observatory
GSFC Goddard Space Flight Center
HAC Hughes Aircraft Company
HO Human Operator
HQ NASA Headquarters
IOC Initial Operational Capability
IR&D Independent Research and Development
IVA Intra-Vehicular Activity
HPA Handling and Positioning Aid
JSC Johnson Space Center
LEO Low Earth Orbit
LOS Line of Sight
MM Martin Marietta Aerospace Company
MIT Massachusetts Institute of Technology
MMS Multi-Mission Modular Spacecraft
MMU Manned Maneuvering Unit
MPF Materials Processing Facility (Free Flying)
MSFC Marshall Space Flight Center
NASA National Aeronautics & Space Administration
OMV Orbital Maneuvering Vehicle
ORU Orbital Replacement Unit
OTV Orbital Transfer Vehicle
PFR Portable Foot Restraint
RMS Remote Manipulator System
S/C Spacecraft
SRI SRI International, Menlo Park, CA
SS Space Station
SMM Solar Maximum Mission (Spacecraft)
STS Space Transportation System (Shuttle)
T/M Telemetry
T/O Teleoperator
TDM Technology Demonstration Mission

1.0 INTRODUCTION AND BACKGROUND

The use of automation and robotic capabilities in space for on-orbit servicing of satellites is gaining increasing importance as the technology evolves and mission requirements will call for frequent applications of this capability.

This study was undertaken

- to determine the benefits that will accrue from using automated systems onboard the Space Station in support of satellite servicing
- to define methods for increasing the capacity for, and effectiveness of satellite servicing while reducing demands on crew time and effort and on ground support
- to find optimum combinations of men/machine activities in the performance of servicing functions.
- to project the evolution of automation technology needed to enhance or enable satellite servicing capabilities to match the evolutionary growth of the Space Station

The study, being performed concurrently with those by other aerospace contractors under the Space Station Automation Study Project (see below), had the general objective of defining a plan for advancing the state of automation and robotics technology as an integral part of the U.S. Space Station development effort. The intent, as mandated by Congress early in 1984, is to benefit the national economy by providing a stimulus to accelerated growth and utilization of robotics in terrestrial applications, as a spin-off from the Space Station Program.

1.1 Servicing by the Space Shuttle

The Space Shuttle having reached operational status in the early 1980s has ushered in the era of on-orbit satellite servicing. An important first milestone was passed in April 1984 as the crew of Shuttle Mission 41-C undertook and successfully completed the planned servicing of the Solar Maximum Spacecraft (SMM) by replacing the malfunctioning attitude control system module and performing several other needed repair and refurbishment tasks. From a standpoint of servicing and repair feasibility, the essential prerequisite in this exercise had been the fact that the spacecraft was specifically designed to permit and facilitate module exchange.

Numerous spacecraft system engineering and design studies and related mission analyses have been performed during the past decade to establish principal requirements, constraints and technology needs of on-orbit servicing. The driving considerations have been: 1) cost economy attainable through extension of spacecraft life by correcting unexpected malfunctions, exchanging defective units, and resupply of depleted consumables (notably propellants), and 2) mission flexibility by on-orbit payload changeout.

1.2 Automated Servicing On-board the Space Station

The manned Space Station (SS), now entering the active preliminary design phase and projected to be in initial operation in the early 1990s, will greatly extend on-orbit servicing capabilities by virtue of (1) constituting a permanent operations base in low earth orbit, (2) its greater and more highly developed resources and (3) the presence of crew members operating without the time constraints inherent in all Shuttle missions. Of particular relevance are man's unique cognitive, sensing, and manipulative skills, and especially, his ability to react to new and unforeseen situations. Given appropriate tools, resources and operating facilities, the crew can perform on-orbit operations, such as satellite servicing, of greater scope and complexity than would be feasible on board the Shuttle orbiter. However, certain man-assigned satellite servicing functions can be automated such that the best of man's abilities and automation capabilities can be combined to achieve the highest degree of productivity in satisfying user needs.

1.3 Parallel Studies of Space Station Automation Issues

Concurrent studies performed by five NASA aerospace contractors, Figure 1, addressed various facets of Space Station automation, including (1) SS system and subsystem operation autonomously from ground control (Hughes Aircraft), (2) automated commercial activities and manufacturing on the SS or on a co-orbiting platform (General Electric), (3) automated assembly of large structures (Martin Marietta), (4) satellite servicing (TRW) and (5) human operator interfaces with automated systems on board the SS (Boeing). SRI International provided technology assessment and forecasting, supporting the aerospace contractors' work. California Space Institute at UCSD had the responsiblity of guiding the joint

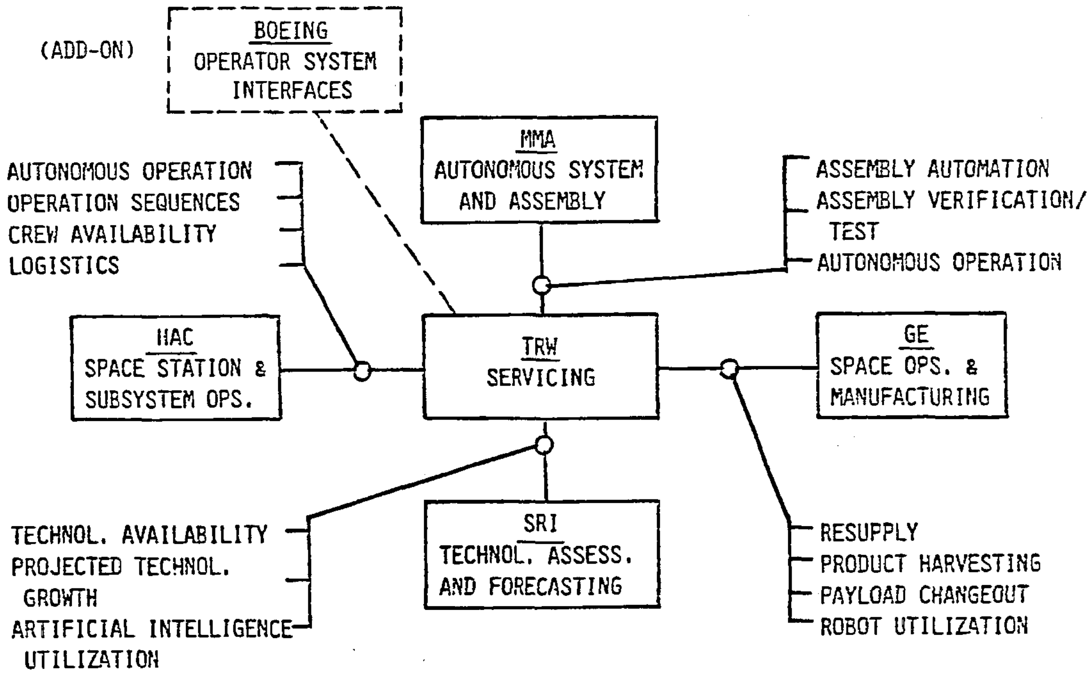

Figure 1. TRW Automated Servicing Study Interaction with Parallel Studies (Callouts in the figure indicate subjects involving interaction between the respective study teams)

activities on behalf of NASA and, based on the overall study results, preparing a Space Station Automation Technology planning document and recommendations to NASA prior to the start of Space Station definition phase studies in April 1985.

2.0 STUDY OBJECTIVE, GUIDELINES AND APPROACH

2.1 Objectives

Our study objectives were twofold:

1) Determine the current and potential capabilities of telepresence, robotics and artificial intelligence, and their role in supporting on-orbit servicing of satellites as well as SS components.

2) Define a generic servicing facility for the IOC Space Station that incorporates automation technologies for supporting and/or relieving the crew in servicing tasks. The potential for significant growth to accommodate projected future requirements was to be taken into account.

2.2 Study Ground Rules and Guidelines

Study ground rules included the following:

- Applicable data from recent Space Station servicing technology and automation studies and other related government sponsored studies provided input data to the study tasks

- The IOC Space Station will be operational in calendar year 1992. A reference Space Station configuration defined by NASA was assumed as baseline configuration

- Orbital Maneuvering Vehicles (OMV) and Orbital Transfer Vehicles (OTV) will be available to support orbital servicing operations

- The opportunity for flying precursor automation technology experiments or demonstrations will be available on STS 1986-1990 flights.

The principal concern with autonomous and automatic SS operations is summarized by a set of general guidelines, as follows:

- Develop high degree of Space Station autonomy

- Automate subsystems to fullest extent practical

- Use flight crew if cost effective alternative to automation
- Minimize crew involvement for routine monitoring functions
- Allow for implementation of artificial intelligence, as state of technology permits
- Support rapid assimilation of new technology without major redesign
- Largely automate data system resource management, allocation and scheduling
- Automate fault detection, isolation and redundant element switching
- Automate management and control functions but provide accessibility to the crew for manual override.

2.3 Study Approach

Figure 2 shows the three study tasks: (1) servicing requirements analysis, (2) technology assessment and (3) conceptual design of a generic servicing facility, and their respective subtasks. Figure 3 shows the study schedule, starting in June and extending to the end of November 1984. After November continued support is to be provided to California Space Institute, until March 1985, during preparation of the automation technology planning document.

TRW's study approach involved, as a first step, a review of the NASA mission model of the 1980s and 1990s and an assessment of likely servicing requirements. However, rather than to provide an exhaustive coverage of the many projected missions, we found it more appropriate to concentrate on a set of four representative mission scenarios which encompassed the most relevant aspects of servicing functions to be performed either on board the SS itself or remotely (in situ), at the orbital position of the target satellites (Task 1). By this case study approach we identified the servicing requirements and technology needs, operational modes, sequences and timelines that characterize each of the specific missions under investigation.

The reference mission scenarios were:

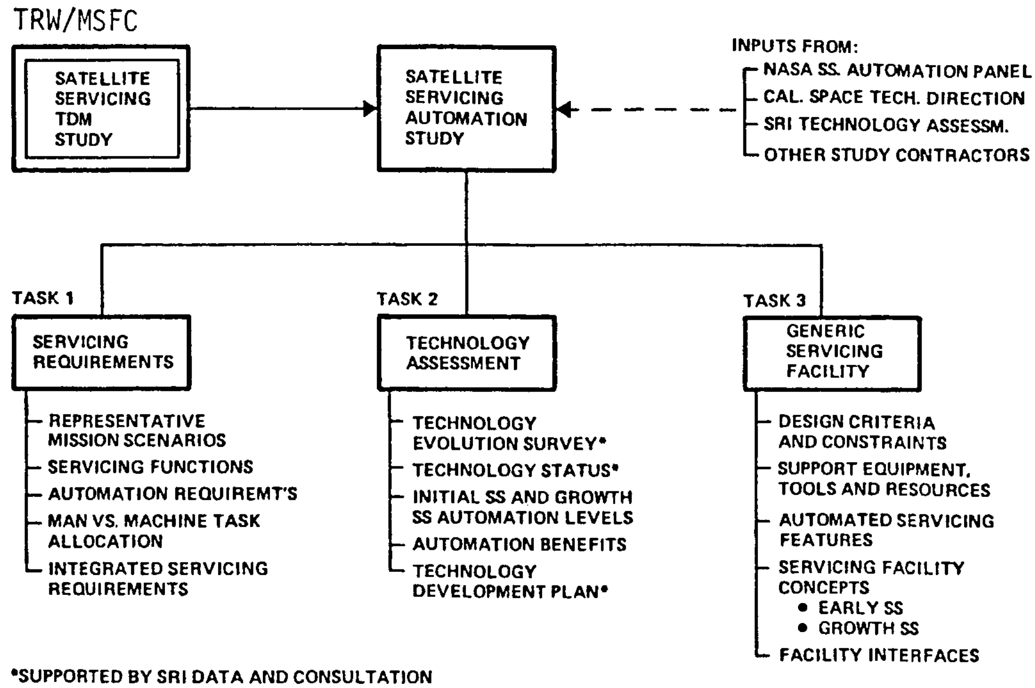

Figure 2. Automation Study Task Breakdown

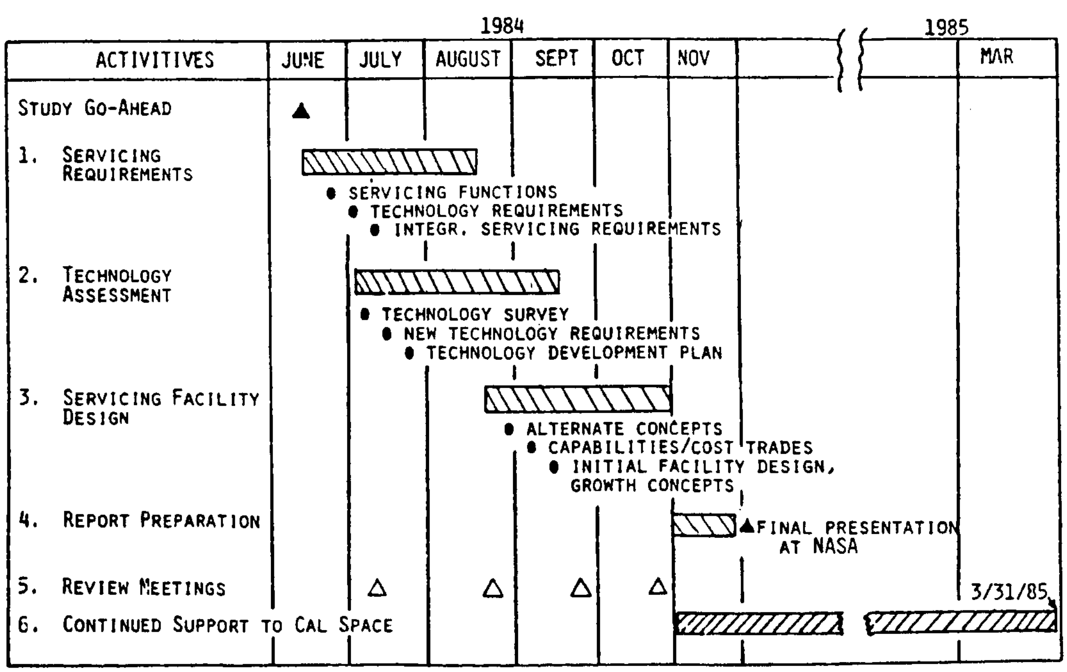

Figure 3. Task Elements and Schedule

1. Servicing of a low-earth-orbit (LEO) satellite, e.g., the Gamma Ray Observatory (GRO), at the Space Station with orbit transfer by an Orbital Maneuvering Vehicle.

2. Servicing of a free-flying, co-orbiting materials processing facility, in situ, including periodic resupply and harvesting of finished products.

3. Repair/refurbishment or changeout of Space-Station-attached payloads or subsystems.

4. Servicing of a geostationary satellite, in situ, by using a recoverable Orbital Transfer Vehicle to perform the ascent and descent to/from synchronous orbit, carrying supplies, replacement parts, tools and support equipment such as a remote/robotic servicer.

These reference missions are derived from a set of servicing technology development missions (TDMs) previously studied by TRW under NASA/MSFC contract NAS 8-35081 to which this automation study task was subsequently added. The reference mission scenarios, and their servicing and automation requirements are discussed in Section 3.

As a next step, we analyzed the potential application of automation technology -- teleoperation, robotics and artificial intelligence -- and the utilization of the Space Station data system in support of servicing activities, in general. Drawing on information supplied by SRI, on data from the literature, and on the results from the prior TRW study, we assessed the status of the technology available for satellite servicing; defined relative priorities; and determined benefits that accrue from utilization of automated systems. This analysis led to defining technology development needs (Task 2).

The study approach for Task 3 involved definition of design criteria and constraints, resource requirements, listing of tools and support equipment, and identification of robotic and other automation attributes required by a generic servicing facility. This was followed by an investigation of design concepts of servicing facilities and facility elements and selection of a specific layout and implementation of the main work station at which satellites will be placed for refurbishment, repair, module exchange and other servicing functions. The baseline adopted by us for this part of the study was the reference IOC Space Station configuration defined by NASA, also known as the "Power Tower".

The study also included analyses of operating issues and problems involved in performing the servicing missions and in using automated support equipment (see Section 3.9). Some of the results obtained have major implications on feasibility and cost effectiveness of the intended servicing functions, on satellite accessibility for retrieval or servicing and on communication modes to be used in remote control of in-situ servicing tasks.

Evolution of servicing capabilities of the Space Station in its growth from the IOC configuration in the early 1990s to the all-up configuration beyond the year 2000 was a major issue addressed in our study. (See Section 3.8.) This includes the projected growth of automation technology as applied to servicing functions.

We also addressed (Section 4.0) the important question of how Space Station automation developments can provide a potential technology transfer beneficial to ground-based automation needs in research and development, manufacturing, laboratory work and other applications.

3.0 RESULTS

3.1 Servicing Activity Requirements Based on NASA Mission Model

The growth of satellite servicing activity in the years 1987 through 2000 projected from the current NASA space mission model was analyzed, and estimates of servicing events per year (75 on the average) and crew hours expended in servicing tasks were obtained. As a conservative estimate, average satellite servicing activities by the crew amounted to 2500 hours per year of which about two-thirds are for IVA and one-third for EVA tasks. Potential time savings due to automation are not reflected in this figure.

The demand for satellite servicing to be performed by the Shuttle orbiter will continue in the years beyond 1992. Although considerably less frequent than SS-based servicing events, Shuttle servicing will cover satellites inaccessible to the low-inclination Space Station, e.g., those in (1) polar orbits and (2) low-inclination orbits too far from coplanar condition because of nodal misalignment. With the advent of a high energy Reusable Orbital Transfer Vehicle (ROTV) in the late 1990s, the accessibility range from the Space Station will increase rapidly, and in-situ geostationary satellite servicing will become feasible.

3.2 Reference Mission Scenarios

The previously-mentioned four reference servicing missions are outlined in Figures 4 through 7. Each figure shows a sketch of the mission concept and lists scenario highlights and key automation requirements. Also shown are estimated hours of crew activity required, with and without automated servicing support, and the hours saved by automation. (Not accounted for are time intervals that are not relevant to the comparison, such as the time elapsed during orbit transfer to and from the Space Station.) It was found that in the activities accounted for, 40 to 60 percent of crew time can be saved by automation support, often eliminating time-consuming preparation for and completion of EVA tasks.

Detailed event sequences and automation requirements are given in Tables 1 through 4 for the respective reference scenarios. Corresponding event flow charts are shown in Figures 8 through 11, with an indication of those activities where manual (M), automated (A), semi-automated (SA), or teleoperation (T) functions are assumed. The designation SSDS refers to support by the SS integrated data system.

3.3 Automation Requirements

One of the major objectives of the study was to determine effective combinations of the strongest capabilities of automated functions and of man's functions in performing satellite servicing tasks. Table 5 summarizes man-machine partitioning considerations listing principal criteria of the strength of machine operations versus human operations.* The automated system is capable of performing repetitive operations under predictable conditions and is utilized most effectively where it enhances true productivity and safety (e.g., in tasks which would otherwise require EVA). Man's unique cognitive, sensing and manipulative skills and his ability to react to unforeseen situations were the criteria for assigning certain tasks to the crew rather than the automated system. Related experience on Shuttle missions in 1984 highlights this fact: 1) the retrieval and repair by astronauts of the Solar Max Mission (SMM) spacecraft in April 1984 and the recovery of two communications satellites, Palapa and Westar in November 1984.

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*See also Appendix A.

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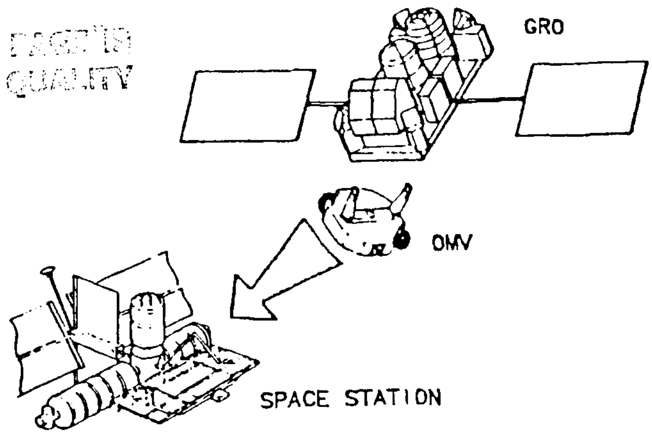
1. SCENARIO HIGHLIGHTS

- OMV RETRIEVES GRO FROM 400 KM ORBIT
- RENDEZVOUS AND BERTHING AT SS
- COMPREHENSIVE GRO STATUS TESTS
- REPLACEMENT OF FAILED UNIT(S)
- PROPELLANT REFILL
- GRO CHECKOUT AND REDEPLOYMENT

2. AUTOMATION REQUIREMENTS

- REMOTE CONTROL OF GRO RETRIEVAL
- AUTOMATED RENDEZVOUS AND DOCKING AT SS
- LOAD HANDLING AND TRANSFER BY TELEOPERATION
- PROPELLANT REFILL
- AUTOMATED TESTS, CHECKOUT, COUNTDOWN
- DATA SYSTEM SUPPORT (DATA DISPLAY, DIAGNOSTICS, TROUBLE SHOOTING)



3. CREW ACTIVITY COUNT

- ESTIMATED ELAPSED TIME 10.5 HR WITH AUTOMATION, (20.5 HR WITHOUT AUTOMATION)
- ESTIMATED TIME SAVING THROUGH AUTOMATION 10 HR

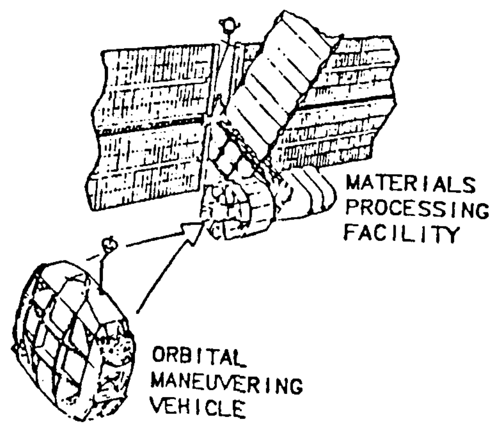
Figure 4. Reference Mission No. 1
Servicing GRO Satellite on Space Station

1. SCENARIO HIGHLIGHTS

- OMV ATTACHED TO SERVICING MODULE CARRYING FRESH SAMPLE MATERIAL
- OMV TRANSFERS TO AND PERFORMS RENDEZVOUS, BERTHING AT MPF
- SERVICER EXCHANGES SAMPLE MAGAZINES AT MPF UNDER REMOTE CONTROL
- OMV PERFORMS MPF ORBIT REBOOST
- RETURNS TO SS, DELIVERS FINISHED SAMPLES
- OMV REFURBISHED FOR NEXT USE

2. AUTOMATION REQUIREMENTS

- LOAD HANDLING AND TRANSFER AT SS BY TELEOPERATION
- RENDEZVOUS, DOCKING/BERTHING
- SAMPLE MAGAZINE CHANGEOUT
- MPF ORBIT REBOOST BY OMV
- AUTOMATED CHECKOUT, COUNTDOWN



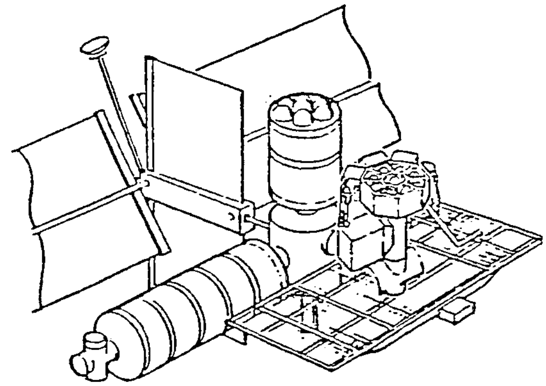
3. CREW ACTIVITY COUNT

- ESTIMATED ELAPSED TIME 4.8 HR WITH AUTOMATION, (11.8 HR WITHOUT AUTOMATION)
- ESTIMATED TIME SAVING THROUGH AUTOMATION 7.0 HR

Figure 5. Reference Mission No. 2
Servicing Free-Flying Materials
Processing Facility (MPF)

1. SCENARIO HIGHLIGHTS

- INSPECT PAYLOAD/SUBSYSTEM TO BE SERVICED
- CALL FOR AND RECEIVE REQUIRED PARTS OR SUPPLIES VIA ORBITER
- TRANSFER SERVICING OBJECT TO AND FROM WORK STATION
- PERFORM REPAIR, REFURBISHMENT MODULE REPLACEMENT
- CHECKOUT AND RESTORE TO NORMAL OPERATION



2. AUTOMATION REQUIREMENTS

- LOAD HANDLING AND TRANSFER
- AUTOMATED TESTS, DIAGNOSTICS, CHECKOUT
- MODULE REPLACEMENT BY TELEOPERATION

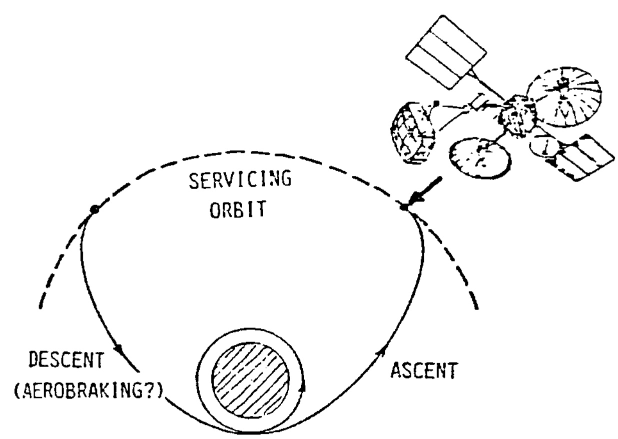
3. CREW ACTIVITY COUNT

- ESTIMATED ELAPSED TIME 2.9 HR WITH AUTOMATION, (6.5 HR WITHOUT AUTOMATION)
- ESTIMATED TIME SAVING THROUGH AUTOMATION 3.6 HR

Figure 6. Reference Mission No. 3
Servicing of Space Station-
Attached Payload or Subsystems

1. SCENARIO HIGHLIGHTS

- CALL FOR AND RECEIVE NEEDED SUPPLIES VIA ORBITER
- ATTACH SERVICING MODULE TO OTV
- TRANSFER TO SYNCHRONOUS ORBIT, RENDEZVOUS AND DOCK WITH TARGET SATELLITE
- CHECKOUT, REPLACE FAILED MODULE AND/OR REFUEL SATELLITE
- RETURN TO SS (POSSIBLY BY AEROBRAKING MANEUVER)



2. AUTOMATION REQUIREMENTS

- LOAD HANDLING AND TRANSFER ON SS
- ASSEMBLE SERVICING VEHICLE WITH OTV
- AUTOMATED CHECKOUT, COUNTDOWN
- ORBIT TRANSFER, RENDEZVOUS, DOCKING/ BERTHING
- INSPECTION
- MODULE REPLACEMENT
- REFUELING

3. CREW ACTIVITY COUNT

- ESTIMATED ELPASED TIME 11.1 TO 13.1 HR WITH AUTO- MATION (17.2 TO 19.2 HR WITHOUT AUTOMATION)
- ESTIMATED TIME SAVING THROUGH AUTOMATION 6.1 HR

Figure 7. Reference Mission No. 4
Servicing Geostationary Satellite
In-Situ

Table 1. Top Level Reference Mission Scenario
Reference Mission 1 - Servicing
GRO Satellite on Space Station

ACTIVITY/FUNCTION	CREW TASK	AUTOMATION REQUIREMENT	EST. TIME (MINUTES) WITH/WITHOUT AUTOMATION	
1 Schedule GRO servicing		DS support		
2 Determine required support equipment and supplies		DS support		
3 Receive needed equipment and supplies from ground via STS	EVA	Automated unloading and stowage	30	60
4 Determine optimal GRO retrieval mission profile by OMV		DS support		
5 Prepare OMV for retrieval mission (incl. propellant addition if required)	EVA	Automated handling of new propellant tanks if required	60	120
6 Launch OMV from SS and perform orbital transfer to GRO vicinity	IVA	DS support and automated command sequence		
7 Deactivate GRO				
8 Perform OMV rendezvous and docking to GRO	IVA	Remotely controlled by crew/ automated sequence	20	60
9 Orbital transfer of GRO to SS by OMV		Automated command sequence		
10 Perform rendezvous and docking of GRO/OMV at SS with aid of SS manipulator arm (RMS)	IVA	Remotely controlled or supervised by crew (automated sequence)	20	60
11 Secure GRO to SS berthing port and connect umbilical(s)	IVA/ EVA	RMS, teleoperation	20	140
12 Detach and stow OMV	EVA	Teleoperation	15	60
13 Inspect GRO and perform comprehensive checkout	EVA	DS support	20	60
14 Determine source of malfunctions if any	IVA	Expert system support from DS		
15 Transfer replacement units (ORU) from storage area	EVA	Teleoperation, automated handling and transfer	15	45
16 Replace failed units on GRO	EVA	Automated handling	15	45
17 Check out GRO for proper functioning with new units	IVA/ EVA	DS support		
18 Connect propellant transfer line	EVA		15	15
19 Perform propellant transfer to GRO	IVA	Automated sequence	300	300
20 Disconnect and stow propellant line	EVA		15	15
21 Checkout and prepare GRO for departure in operational configuration	IVA/ EVA	DS support, automated sequence	60	120
22 Disconnect umbilical(s)	IVA/ EVA	Teleoperation	15	115
23 Deploy GRO by RMS and release	IVA	Teleoperation, automated sequence	15	15
24 GRO transfers to operational altitude and resumes operation		Remotely controlled, automated sequence		
25 Verify normal operation of GRO		Monitoring sequence, supported by DS		
		Total of activities accounted for	635 (10.5 hr.)	1230 (20.5 hr.)

Table 2. Top Level Reference Mission Scenario Reference Mission 2 - Servicing Free-Flying Materials Processing Facility

ACTIVITY/FUNCTION	CREW TASK	AUTOMATION REQUIREMENT	EST. TIME (MINUTES) WITH/WITHOUT AUTOMATION	
1 Plan detailed mission sequence including transfer trajectories to and from MPF		DS support		
2 Transfer servicer kit from storage and attach to OMV front end	IVA/ EVA	Automated handling and transfer; teleoperation	30	120
3 Transfer magazines containing new specimens (raw materials) to OMV and attach as cargo	IVA/ EVA	Automated handling and transfer; teleoperation	15	45
4 Check out OMV and servicer system	EVA	DS support	20	60
5 Prepare OMV for departure	IVA	Automated sequence with DS support		
6 Unberth and deploy OMV	IVA	Teleoperation	20	20
7 Perform orbital transfer to MPF		Automated command sequence		
8 Perform rendezvous and docking of OMV with MPF		Remotely controlled or supervised by crew	20	60
9 Deactivate MPF for servicing				
10 Remove finished products (magazines) from MPF and replace with new-specimen magazines		Automated on MPF, teleoperation by OMV servicer	60	60
11 Checkout MPF for operation and reactivate		Automated checkout sequence, DS support		
12 Unberth OMV from MPF and initiate departure*		Teleoperation	10	10
13 Return OMV to SS vicinity		Automated command sequence		
14 Perform rendezvous and docking at SS, OMV placed in berthing port	IVA	Remotely controlled or supervised by crew, automated sequence	20	60
15 Remove finished-product magazines from OMV and transfer to storage area	IVA/ EVA	Teleoperation, automated handling and transfer	15	45
16 Remove MPF servicer from OMV and transfer to storage area	IVA/ EVA	Teleoperation, automated handling and transfer	30	120
17 At next orbiter visit, receive fresh specimen magazines and transfer to storage area	IVA	Teleoperation, automated handling and transfer	30	60
18 Retrieve finished product magazines from storage and load on carrier in orbiter cargo bay for return to ground	IVA/ EVA	Teleoperation, automated handling and transfer	15	45
12A Prior to OMV departure from MPF, perform orbit-raising maneuver, if necessary		Automated or remotely controlled		
		Total of activities accounted for	285 (4.8 hr.)	705 (11.8 hr.)

Table 3. Top Level Reference Mission Scenario Reference Mission 3 - Servicing of SS-Attached Payload or Subsystem

	ACTIVITY/FUNCTION	CREW TASK	AUTOMATION REQUIREMENT	EST. TIME (MINUTES) WITH/WITHOUT AUTOMATION	
1	Receive alert of equipment malfunction on attached payload or SS subsystem		DS support		
1A	or receive instruction to perform changeout of a payload subunit		DS support		
2	Check malfunction and determine failure source	IVA/ EVA	Automated sequence; expert system support (DS)		
3	Plan servicing task and determine needed replacement part		DS support		
4	Call for and receive STS delivery of needed equipment from ground	IVA	Teleoperation, automated handling	30	60
5	Transfer support equipment and replacement unit(s) to station where service is to be performed	IVA/ EVA	Teleoperation, automated handling and transfer	20	60
5A	or remove unit in need of servicing and transfer to servicing work station (hangar)	IVA/ EVA	Teleoperations, automated handling and transfer		
6	Perform repair service or replace unit by new unit	IVA/ EVA	Teleoperation, automated handling	60	120
7	Test repaired/refurbished system and verify normal functioning		DS supported sequence	45	90
8	Transfer repaired system back to operating location, turn on and verify normal operation	IVA/ EVA	Automated handling and transfer; DS supported sequence	20	60
			Total of activities accounted for	175 (2.9 hr.)	390 (6.5 hr.)

Table 4. Top Level Reference Mission Scenario
Reference Mission 4 - Servicing a Geostationary Satellite

ACTIVITY/FUNCTION	CREW TASK	AUTOMATION REQUIREMENT	EST. TIME (MINUTES) WITH/WITHOUT AUTOMATION	
1 Determine required servicing functions (e.g., refueling, replacement of failed units others) for mission		DS support		
2 Determine needed support equipment and supplies (request STS delivery)		DS support		
3 Determine optimal mission profile to and from geosynch. orbit and determine propellant requirements (e.g., is another satellite to be brought back to SS on same return trip?)		DS support		
4 Receive needed equipment and supplies via STS	IVA	Teleoperation, automated handling	40	100
5 Transfer equipment etc. to assembly platform	IVA	Teleoperation, automated transfer	10	30
6 Assemble servicing module, including support equipment	IVA/EVA	Teleoperation	30	90
7 Transfer servicing module to OTV berthing location	IVA	Teleoperation, automated transfer	10	30
8 Mate servicing module to OTV	IVA/EVA	Teleoperation	30	90
9 Add propellant tanks for target satellite refueling if required	IVA/EVA	Teleoperation, automated handling	30	60
10 Fill OTV propellant tanks	IVA	Teleoperation	240	240
11 Fill add-on propellant tanks, if carried for satellite refueling	IVA	Teleoperation	60	60
12 Checkout assembled and loaded geosynch. servicing vehicle	IVA/EVA	Automated sequence, DS support	30	90
13 Countdown to launch from SS	IVA	Automated sequence		
14 Separate from OTV berthing port	IVA	Teleoperation	15	15
15 Launch and perform orbital transfer to target satellite		Automated command sequence		
16 Deactivate target satellite				
17 Perform rendezvous and docking with target satellite		Remotely controlled or supervised by crew	20	60

Table 4. Top Level Reference Mission Scenario Reference Mission 4 - Servicing a Geostationary Satellite (continued)

ACTIVITY/FUNCTION	CREW TASK	AUTOMATION REQUIREMENT	EST. TIME (MINUTES) WITH/WITHOUT AUTOMATION	
18 Perform diagnostic tests		DS support, automated command sequence		
19 Determine servicing sequence		DS support		
20 Perform servicing tasks - refueling - module exchange - other		Teleoperation	60 to 180	60 to 180
21 Checkout repaired/refurbished satellite and reactivate		DS support		
22 Prepare and checkout servicing vehicle for return trip to SS		DS support, automated sequence by command	60	60
23 Countdown to separation and launch		Automated command sequence		
24 Launch servicing vehicle and perform orbit transfer to SS		Automated command sequence		
25 Perform rendezvous and docking with SS	IVA	Remotely controlled or supervised by crew	20	60
26 Place servicing vehicle in OTV berthing port, using RMS	IVA	Teleoperation	20	40
27 Deactivate OTV	IVA			
28 Demate servicing module and transfer to storage location	IVA/ EVA	Teleoperation, automated handling and transfer	30	75
29 Demate retrieved satellite (or equipment) and transfer to storage location	IVA/ EVA	Teleoperation, automated handling and transfer	20	60
30 Load retrieved satellite or equipment on orbiter, at next visit, for return to ground	IVA	Teleoperation, automated handling and transfer	30	60
31 Checkout and refurbish OTV as required for next use (e.g., aerobrake replacement, if appropriate). Verify operability.	IVA/ EVA	Teleoperation, automated task sequence (DS support)		
		Total of activities accounted for	665 to 785	1030 to 1150
			(11.1 to 13.1 hr.)	(17.2 to 19.2 hr.)

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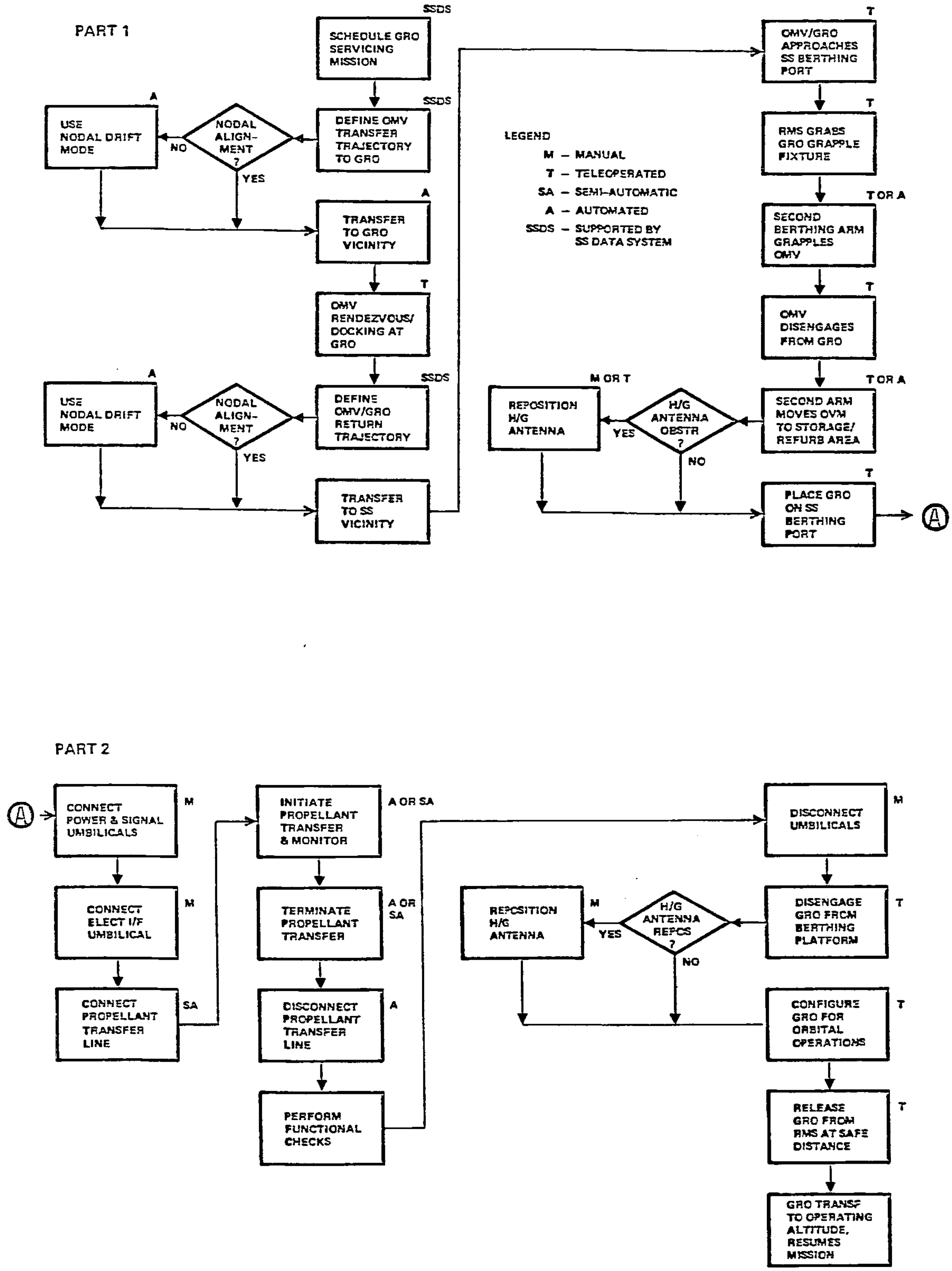

Figure 8. Event Flow - Reference Mission No. 1
GRO Refueling

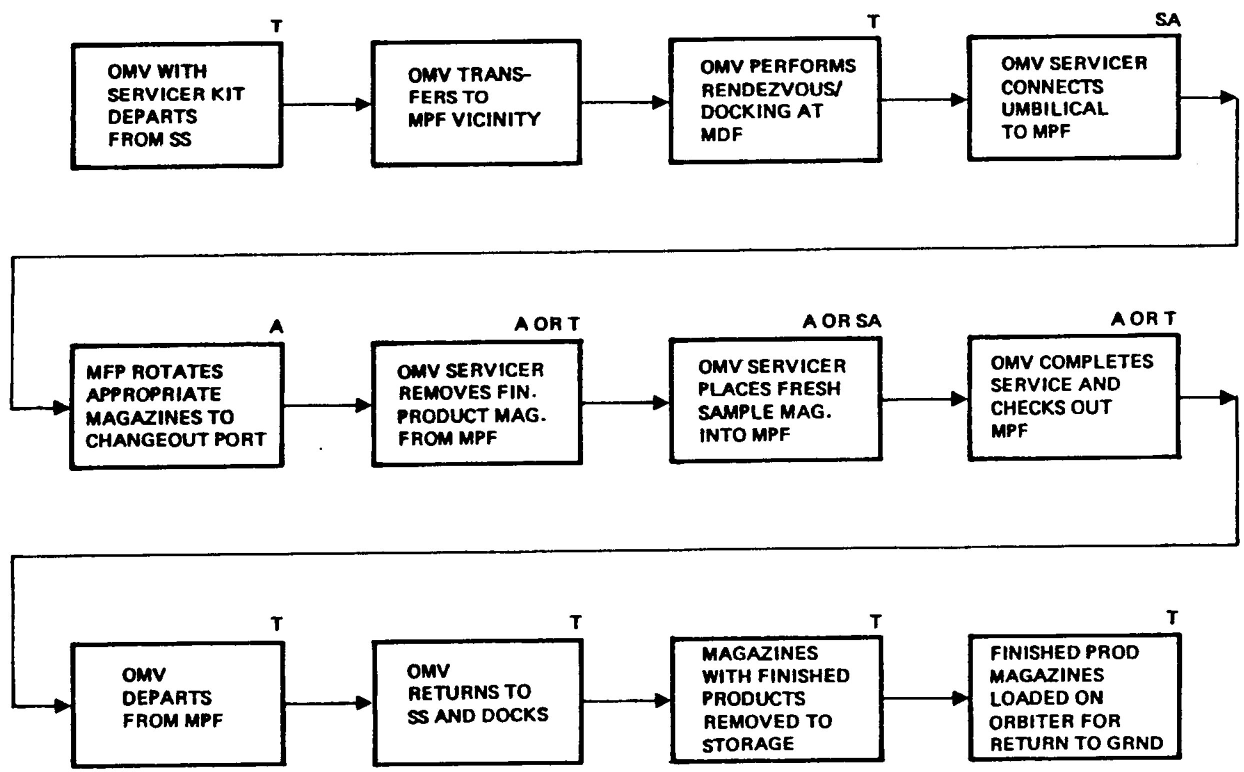

Figure 9. Event Flow - Reference Mission No. 2
Servicing Materials Processing Facility (MPF)

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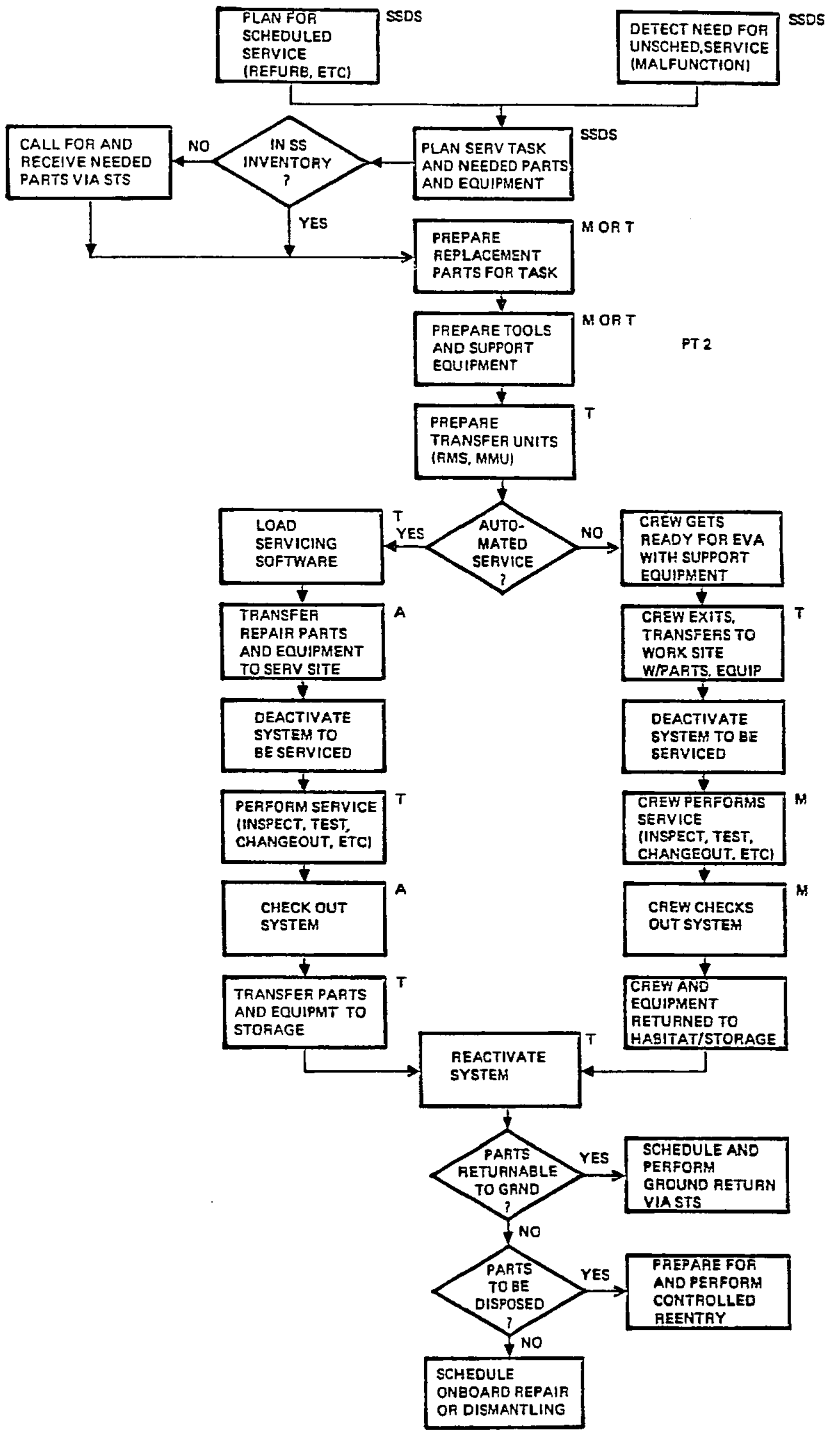


Figure 10. Event Flow - Reference Mission No. 3
Servicing SS-Attached Payload

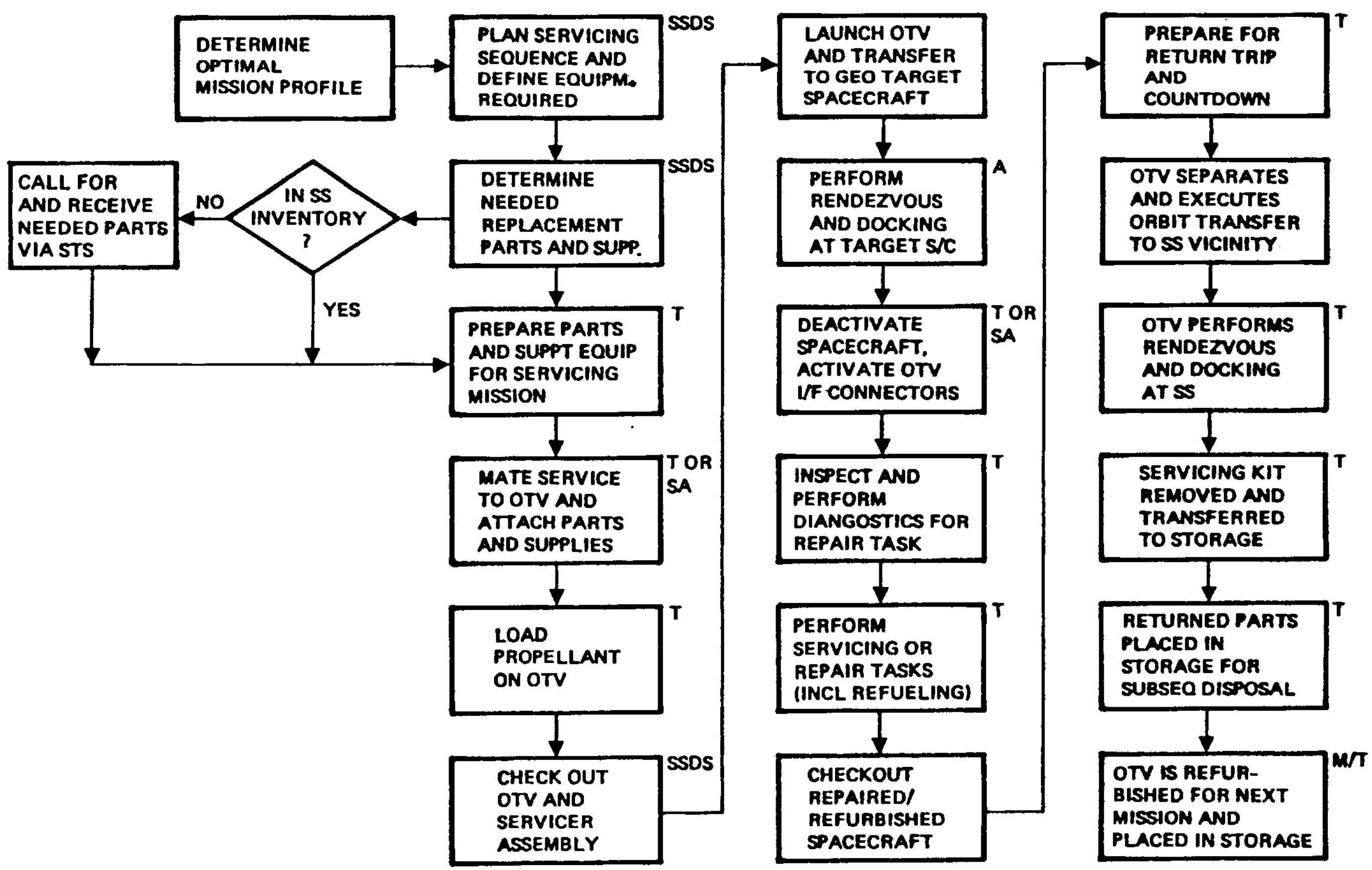


Figure 11. Event Flow - Reference Mission No. 4 Servicing GEO Satellite in situ

Table 5. Man-Machine Partitioning Considerations

MACHINE CRITERIA	MAN CRITERIA
• TIME CRITICAL	• TIME EFFECTIVENESS
• REPETITIVE/PREDICTABLE	• UNPREDICTABLE
• PRECISION	• MOTOR SKILLS
• PRODUCTIVITY ENHANCEMENT	• COGNITIVE ABILITY
• SAFETY ENHANCEMENT	• PATTERN RECOGNITION
• REMOTE LOCATION	• SEQUENCING COMPLEXITY

Basic questions addressed by the study include the following: What type of automation or robotics is needed and how will it be used? How much does automation facilitate crew tasks and enhance productivity? How much time saving is achieved? What is the impact on operational safety and what satellite design, standardization and operational requirements are imposed by automated servicing?

Figure 12 shows a logic diagram which defines interrelations between the three principal automation technologies or disciplines used in supporting satellite servicing, and their role in relation to man's functions and tasks. The shaded overlapping areas represent applications that involve joint utilization of more than one of the three technologies, as for example in situations where a remote manipulator is controlled either by teleoperation, with the "man in the loop", or autonomously as robot (usually man-supervised). Teleoperation may be a backup option where robotic use of the manipulator is unable to handle unforeseen aspects of a specific task.

Our use of the terminology and distinctions between automation disciplines conforms with the definitions listed in front of this volume.

Although not shown in the figure, the Space Station data system plays a major role in providing a critically important link or infrastructure to most or all automated activities.

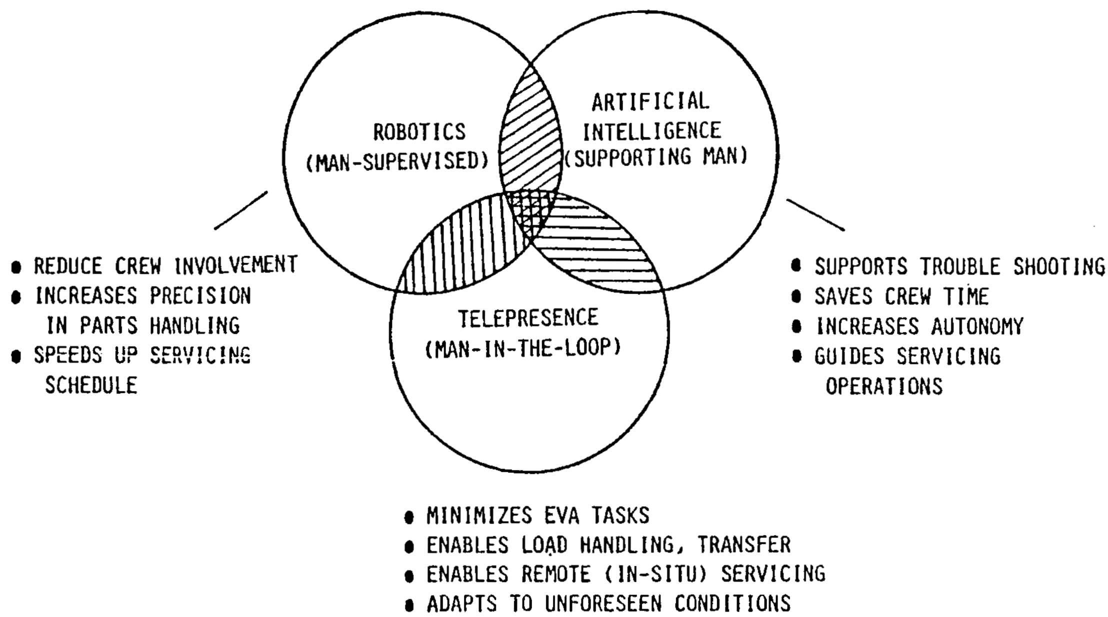


Figure 12. Automation Disciplines Applied to Satellite Servicing

A summary of the projected automation requirements for servicing support in the selected reference missions is shown in Table 6. Levels and modes of automation to be utilized for servicing will depend on the nature of the tasks, the location where the service is being performed (on the Space Station or in-situ), and on the state of technology evolution at the time of the mission.

The chart summarizes the use of teleoperation (T), robotics (R) and artificial intelligence/knowledge-based system support (A) in the four missions investigated, and the use of multiple-purpose data system support (D) other than for artificial intelligence. Mixed entries (T/R, D/A) indicate that both modes will be utilized depending on the specifics of the task, or in some instances, a preference for the more advanced technology (robotics, artificial intelligence) if it is available at the time of the mission. Consider, for example, the entries for mating/demating in the fifth row under teleoperation or robotics. In Mission 1 (GRO refueling) the mating and demating functions are performed at the Space Station and utilize teleoperation. In Mission 2 (Materials Processing Service in-situ) some of the functions are performed onboard the Space Station (T) and some in-situ (T or R). In Mission 4 (geostationary servicing) the in-situ functions are primarily performed in the robotic mode. (See also Appendix B.)

On the whole, it is apparent that teleoperation requirements are more numerous than robotics requirements, at least in the early Space Station operations phase. Also during this phase there will be a need for data system support across the entire mission spectrum and for most of the functions indicated, while artificial intelligence support requirements increase with Space Station evolution.

The greater dependence on teleoperation than robotics is explained by the diversified, "one-of-a-kind," tasks typically required in satellite servicing activities. It also concurs with quantitative results obtained by McDonnell Douglas in their recent NASA-sponsored study of the human role in space (THURIS). The analysis indicated that higher levels of automation technology only become cost-effective if a task is to be repeated many times (100, 1000, ...), depending on the number of different functions included in the activity.

Table 7 summarizes automated functions and characteristics utilized in servicing, highlighting automation requirements that are different from those of other automated Space Station activities such as large structure assembly or space manufacturing.

Table 6. Automation Requirements in Selected Reference Missions

SATELLITE SERVICING FAUNCTIONS/TASK AND TYPE OF AUTOMATION	SERVICING REFERENCE MISSION			
	1. GRO REFUELING ON SS	2. MAT. PROC. SERVICE IN SITU	3. P/L or S/S CHANGEOUT ON SS	4. GEO-SAT. SERVICE IN SITU
TELEOPERATION (T) OR ROBOTIC CONTROL (R)				
• EQUIPMENT LOADING/UNLOADING, HANDLING	T	T/R (1)	T	T/R
• SATELLITE BERTHING, RELEASING	T	T	T	T
• LOAD TRANSFER BY RMS OR RAIL SYSTEM	T	T	T	T
• MODULE CHANGEOUT (LOCAL, REMOTE)	T	T/R	T	R
• MATING/DEMATING UNITS OR UMBILICALS	T	T/R	T	T/R
• PROPELLANT, FLUID TRANSFER	T	T	-	T/R
• OMV, OTV MANEUVER CONTROL	T/R	T	-	T/R
• VISUAL INSPECTION	T	T/R	T	T/R
DATA SYSTEM SUPPORT (D) OR ART. INTELL. (A)				
• MISSION AND TASK PLANNING, SEQUENCING	D/A (2)	D/A	D/A	D/A
• ORBIT TRANSFER, MANEUVER OPTIMIZATION	D	D	-	D
• DATA PROCESSING, RETRIEVAL, DISPLAY	D	D	D	D
• AUTOMATED TESTS AND CHECKOUT	D	D/A	D	D/A
• DIAGNOSTICS, TROUBLE SHOOTING ASSISTANCE	A	A	A	A
• LOGISTICS PLANNING	D/A	D/A	D/A	D/A
• COMMUNICATION, TRAFFIC CONTROL	D/A	D/A	-	D/A

(1) T/R - TELEOPERATION (EARLY MISSIONS) OR ROBOTICS (LATER MISSIONS) OR BOTH MODES
(2) D/A - DATA SYST. SUPPORT AND/OR ARTIFICIAL INTELLIGENCE SUPPORT (LATER MISSIONS)

Table 7. Automated System Utilization

FUNCTION/CHARACTERISTIC	AUTOMATED SYSTEM UTILIZATION
• DIVERSITY OF SERVICING TASKS • DIVERSITY OF EQUIPMENT OR DESIGNS • UNKNOWN FAILURE SOURCE	- EMPHASIS ON TELEOPERATION, EVA FUNCTIONS - MAJOR DATA SYSTEM REQUIRED - TOOL AND SUPPORT EQUIPMENT DIVERSITY - DEPENDENCE ON AUTOMATED TESTS, AI-DIAGNOSTICS
• WIDELY DISPERSED FACILITY ELEMENTS • INHERENTLY HEAVY TRAFFIC FLOW - EQUIPMENT - PARTS AND SUPPLIES - CREW MEMBERS	- DEPENDENCE ON AUTOMATED LOAD HANDLING AND TRANSFER - DEPENDENCE ON AI PLANNING AND SEQUENCING - DEPENDENCE ON AUTOMATED LOAD HANDLING AND TRANSFER
• MAJOR LOGISTICS SUPPORT REQUIREMENTS - SHUTTLE TRAFFIC - GROUND SUPPORT	- NEEDS LOGISTICS PLANNING BY AI - DEPENDENCE ON DATA RETRIEVAL, AUTOMATED INVENTORY TAKING, RECORD KEEPING
• SERVICING REMOTE FROM SS - OMV OR OTV UTILIZATION - REFUELING NEEDS - TRAFFIC CONTROL/COMMUNICATION	- NEEDS MISSION PLANNING/OPTIMIZATION BY AI - NEEDS FREQUENT, AUTOMATED REFUELING - NEEDS ROUTINE AUTOMATED RENDEZVOUS
• HAZARD POTENTIAL (E.G., FREQUENT TRAFFIC, MAJOR LOADS, REFUELING)	- NEEDS CAREFUL INSPECTION, MONITORING, CAUTION/WARNING, ACTIVITY PLANNING (AI)

Table 8 lists key automation technologies used in support of servicing activities and defines the types of benefit, such as speeding up task performance and reduction of crew task loading, enhancement of crew safety, and enabling of remote servicing missions. The last column indicates that most or all of the four reference missions benefit from these automated functions, i.e., there exists a high degree of commonality in automated equipment requirements. This has favorable implications as to the cost-economy of automated servicing technology developments.

3.4 Automation Technology Assessment

A preliminary assessment of the servicing automation technology status was performed. Table 9 addresses the question of which features of currently available terrestrial robotics may be directly applicable or adaptable to use on the Space Station (left hand column).

The highly developed industrial robot technology provides many features also needed on the Space Station and in satellite servicing such as electromechanical design and articulation, computer control, versatility, and programming/teaching principles.

The right hand column lists those issues where major adptations or modifications are required for robots to work in the new and hostile space environment. Environmental concerns are primarily those of materials selection, thermal protection, and lubrication techniques. Terrestrial robots generally are designed to work within and exploit the gravity effects that exist on the ground. The design will require modification to operate in zero gravity. Additional development also will be necessary to adapt terrestrial robots to the weight and volume constraints imposed by the Shuttle as launch vehicle.

The key issue will be flexibility and adaptability to a great variety of operating conditions and tasks to meet the diversity of satellite servicing functions. Robot applications in space-based manufacturing or structural assembly typically are repetitive in character and therefore would require less flexible designs.

Table 10 is a first cut at assessing the current state of development of the twelve items previously listed as key technologies for the support of satellite servicing. Those required in the earliest servicing missions on the IOC Space Station are expected to be available in the near-term. Many of the

Table 8. Key Automation Technologies Used on Servicing Facility

TECHNOLOGY/AUTOMATED FUNCTION	PRINCIPAL BENEFITS	APPLIES TO REF. MISSIONS
1. DEXTEROUS MANIPULATOR, INCLUDING SPECIAL PURPOSE END EFFECTORS	• HANDLES DELICATE TASKS • USED IN T/O OR ROBOTIC MODE (SEE ITEM 3)	ALL
2. SERVICING-COMPATIBLE SPACECRAFT	• ENABLES AUTOMATED SERVICING	ALL
3. SPACE-QUALIFIED ROBOT, ROBOTIC SERVICING	• SAVES CREW TIME • ENHANCES CREW SAFETY • ENABLES REMOTE SERVICING	ALL
4. DATA SYSTEM SERVICING SUPPORT	• ENHANCES CREW PRODUCTIVITY • SAVES TIME	ALL
5. ADVANCED MAN-MACHINE INTERFACES (INCLUDING VOICE RECOGNITION, VOICE RESPONSE, HEADS-UP DISPLAY TECHNOLOGY)	• ENHANCES CREW PRODUCTIVITY • SAVES TIME • REDUCES CREW ERRORS	ALL
6. ADVANCED FLUID TRANSFER SYSTEM	• SAVES TIME • ENHANCES CREW SAFETY • ENABLES OTV SUPPORTED MISSIONS	1,2,4
7. ROBOT VISION SYSTEM	• ENABLES AUTONOMOUS REMOTE SERVICING • ENABLES ROBOTIC ASSEMBLY, MODULE EXCHANGE	ALL
8. AUTOMATED LOAD HANDLING AND TRANSFER	• SAVES CREW INVOLVEMENT • SPEEDS UP SERVICING	ALL
9. AUTOMATED RENDEZVOUS/DOCKING (PRECISION RANGE, RANGE RATE AND ATTITUDE DETERMINATION)	• ENHANCES REMOTE SERVICING • SAVES TIME, REDUCES CREW TASK LOAD	1,2,4
10. SMART FRONT END ON OMV, OTV	• ENABLES AUTONOMOUS REMOTE SERVICING	1,2,4
11. KNOWLEDGE-BASED SYSTEMS SUPPORTED SERVICING	• ENHANCES DIAGNOSTIC CAPABILITY • STREAMLINES SERVICING OPERATIONS • ENHANCES SS SERVICING AUTONOMY	ALL
12. REUSABLE OTV	• ENABLES REMOTE SERVICING AT MEO AND GEO ALTITUDES	4

Table 9. Robot Technology Adaptation to Space Station Use

APPLICABLE KEY FEATURES	ADAPTATION REQUIREMENTS
• ELECTRO-MECHANICAL DESIGN AND ARTICULATION • COMPUTER CONTROL CHANNELS • SENSING TECHNIQUES • DYNAMIC RESPONSE • DEXTERITY • PRECISION • EXCHANGEABLE END EFFECTORS • PROGRAMMING/TEACHING ROUTINES	• WEIGHT REDUCTION • COMPACT LAUNCH CONFIGURATION • PROTECTION AGAINST SPACE ENVIRONMENT: - MATERIALS - THERMAL - LUBRICATION • ZERO-g COMPATIBILITY • ADDED SAFEGUARDS • OPERATION FLEXIBILITY • MOBILITY

Table 10. Automated Servicing Technology Assessment

KEY TECHNOLOGY	STATE OF TECHNOLOGY: NEAR TERM	STATE OF TECHNOLOGY: INTERMEDIATE	STATE OF TECHNOLOGY: LONGER TERM	ENABLING TECHNOLOGY	ENHANCING TECHNOLOGY	PRIORITY RANKING
1. DEXTEROUS MANIPULATORS, INC. SPECIAL END EFFECTORS	X			X		1
2. SERVICING/AUTOM. SERVICING COMPATIBLE SATELLITES AND PAYLOAD UNITS	X			X		1
3. SPACE-QUALIFIED ROBOTS, ROBOTIC SERVICING		X		X		1
4. DATA SYSTEM SERVICING SUPPORT	X				X	1
5. ADVANCED MAN-MACHINE INTERFACES		X			X	1
6. ADVANCED FLUID TRANSFER SYSTEMS		X		X		1
7. ROBOT-VISION CONTROLLED SERVICING		X		X		1
8. AUTOMATED LOAD HANDLING/TRANSFER			X		X	2
9. AUTOMATED RENDEZVOUS/BERTHING AND PROXIMITY OPERATIONS		X			X	2
10. OMV WITH SMART FRONT END		X		X		2
11. KNOWLEDGE-BASED SYSTEM SUPPORT (TROUBLE SHOOTING, PLANNING, CONTINGENCY RESPONSE			X		X	3
12. REUSABLE OTV			X	X		3

technologies for more advanced missions fall in the intermediate category. Longer-term development is needed for items 8, 11, and 12. Knowledge-based systems (or expert systems) will be required to support autonomous, fully robotic servicing functions including automated diagnostics and trouble shooting, and response to contingencies. The reusable orbital transfer vehicle (OTV) will require technology advances to enable in-situ servicing missions to geostationary satellites, not expected to occur before the late 1990s.

The table identifies the listed items as "enabling" or "enhancing" technologies, and ranks priorities on a scale of 1 to 3. Seven of the 12 key technologies have top priority ranking.*

With regard to the data system state of technology, Items 4 and 11 in Table 10, we differentiate between a broad range of servicing support functions, including data retrieval and computational support such as orbital transfer optimization (Item 4), on one hand, and artificial intelligence support (Item 11), on the other. The latter includes functions such as automated failure detection and isolation, operational planning and control resource allocation and logistics, as well as response to contingencies. These functions require knowledge-based system development with a longer-term evolution than those under Item 4. Our findings reflect technology assessment by SRI and, also, initial results obtained in TRW's concurrent Space Station Data System Architecture and Analysis Study being performed under NASA Johnson Space Center contract (NAS 9-17132).

3.5 Technology Evolution

3.5.1 Road Map for Servicing Technology Growth

Figure 13 presents some milestones that relate growth in servicing capabilities to the evolution of automation technology. Three major stages of expansion in servicing capability, in the mid '80s, the early '90s and the late '90s, are depicted.

The first stage is limited to Shuttle-based servicing, having been initiated with the repair of the Solar Max Mission spacecraft (SMM) in April 1984 on Shuttle Flight 41C. In addition to actual servicing tasks, the Shuttle also will perform early Technology Development Missions (TDMs).

*Cost-benefit issues associated with automated servicing are discussed in Appendix C.

The second stage starting in 1992 on the early Space Station includes more numerous and more complex servicing missions plus advanced TDMs.

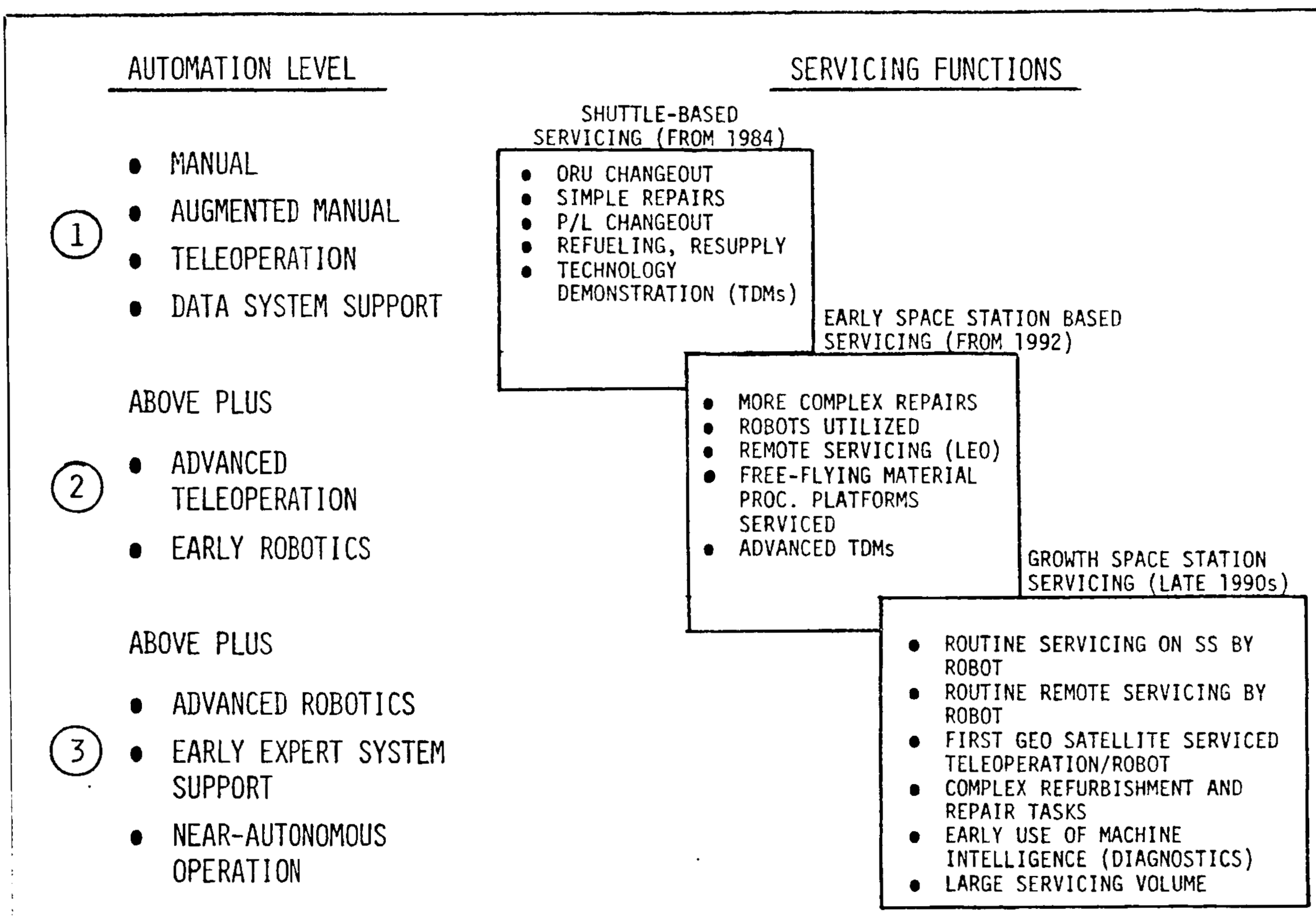


Figure 13. Road Map for Servicing Technology Growth

During the third stage, starting in the late 1990s, servicing tasks on or near the Space Station will be performed in a routine manner, repair task complexity will further increase and even geostationary servicing missions may be performed provided the OTV is available with the requisite payload delivery and return capability.

Levels of automation advance from early manual/augmented manual and teleoperation modes through early and advanced robotic modes to near-autonomous modes. The latter incorporate machine intelligence support in diagnostics, troubleshooting, fault isolation and correction, and some levels of decision making.

The earliest milestones in servicing were achieved in three 1984 Shuttle missions, i.e., repair of the SMM spacecraft, fluid transfer demonstration, and retrieval of two communication satellites for repair/refurbishment on the ground. Manual, augmented manual and teleoperation modes were employed with the Shuttle data system providing significant support functions.

As in these pioneering missions any future evolution of servicing technology will require initial phases with men playing a key role in demonstrating and verifying new capabilities.

3.5.2 Evolution in Manipulation Technology

Figure 14 illustrates the projected evolution from hands-on teleoperated servicing and finally to robotic servicing methods and implementation. Teleoperation, which uses the human operator's sensing, cognitive and decision making abilities, may in many instances be the best approach, particularly for servicing functions that involve unforeseen task elements and require impromptu responses. On the other hand, evolution to fully automatic operation by robot, including the use of machine intelligence, will be required to enable servicing missions where remote control by teleoperation would entail excessive feedback signal transmission time delays, e.g., those to geostationary satellites.

Dexterous manipulators are the common element in teleoperation and fully robotic handling of delicate servicing tasks. For maximum servicing flexibility, we project utilization of such manipulators in either the teleoperated or the robotic mode, i.e., with or without man-in-the-loop control. Figure 15

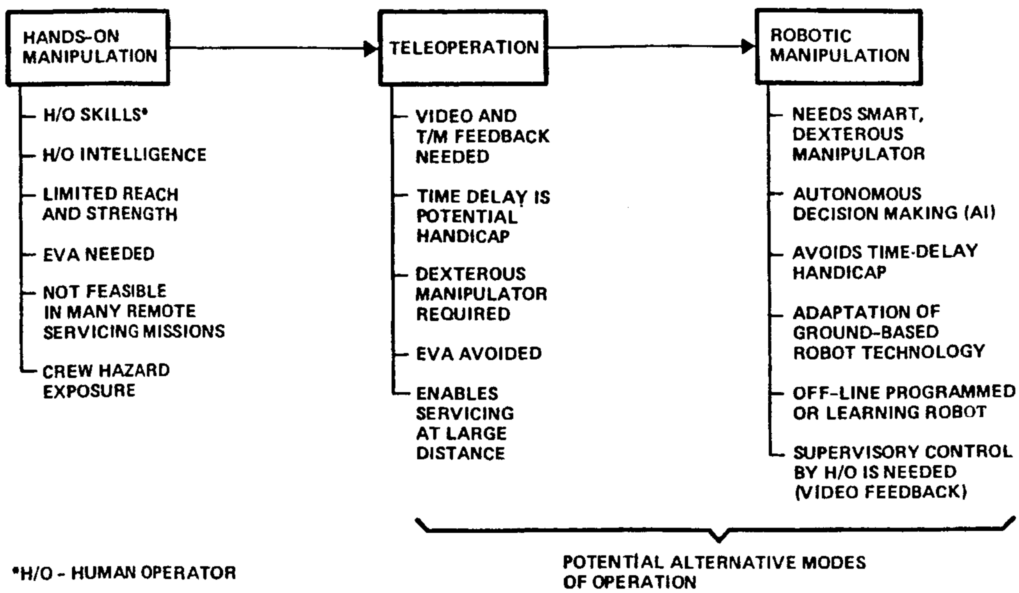


Figure 14. Evolution of Manipulation Modes in Satellite Servicing

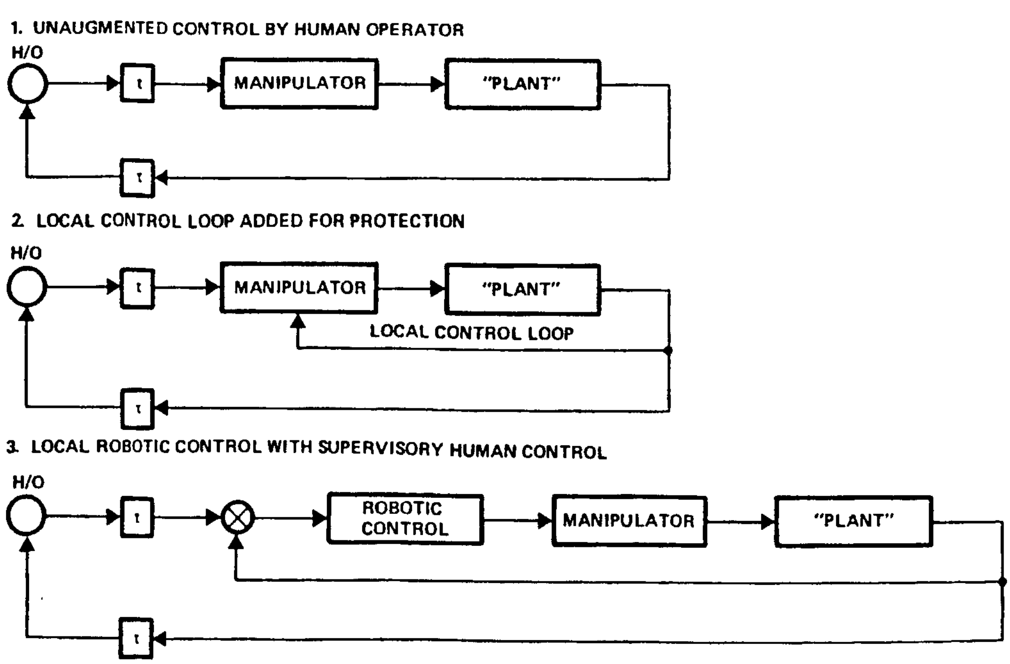


Figure 15. Alternatives of Remote Manipulation With Major Time Delay

illustrates three stages of evolution from fully teleoperated to fully robotic manipulation of an object or "plant." Supervisory control by the human operator is foreseen even in an otherwise fully robotic application, especially when the risk of potentially unrecognized and uncorrected errors by the automatic system would be unacceptable. An example is the servicer or "smart front end" to be used in conjunction with the Orbital Maneuvering Vehicle (OMV). With teleoperation available as back-up option to fully robotic action, the probability of successfully completing a difficult remote servicing task is greatly enhanced.

The presence of a significant time dealy (τ) in the command and feedback link used in a remotely controlled (teleoperated) servicing mission can interfere with the successful execution of sensitive tasks. In some missions this will be the principal driver toward fully robotic servicing, even though supervisory control by a human operator will still be required (see also Section 3.9).

Considerations regarding the use of teleoperation vs. fully robotic operation in satellite servicing and the technology evolution required to support the transition from the former to the latter are summarized in Figure 16.

3.5.3 Projected Evolution Time Table

A preliminary projection of key servicing automation technology evolution in the next two decades is shown in Figure 17. The stages shown include technology demonstration, early and advanced automation and, in some instances, future growth capabilities. Availability of six of the key technologies listed, at least in an early stage of development, will be essential for servicing functions required at the time of initial Space Station operations (1992) or soon thereafter.

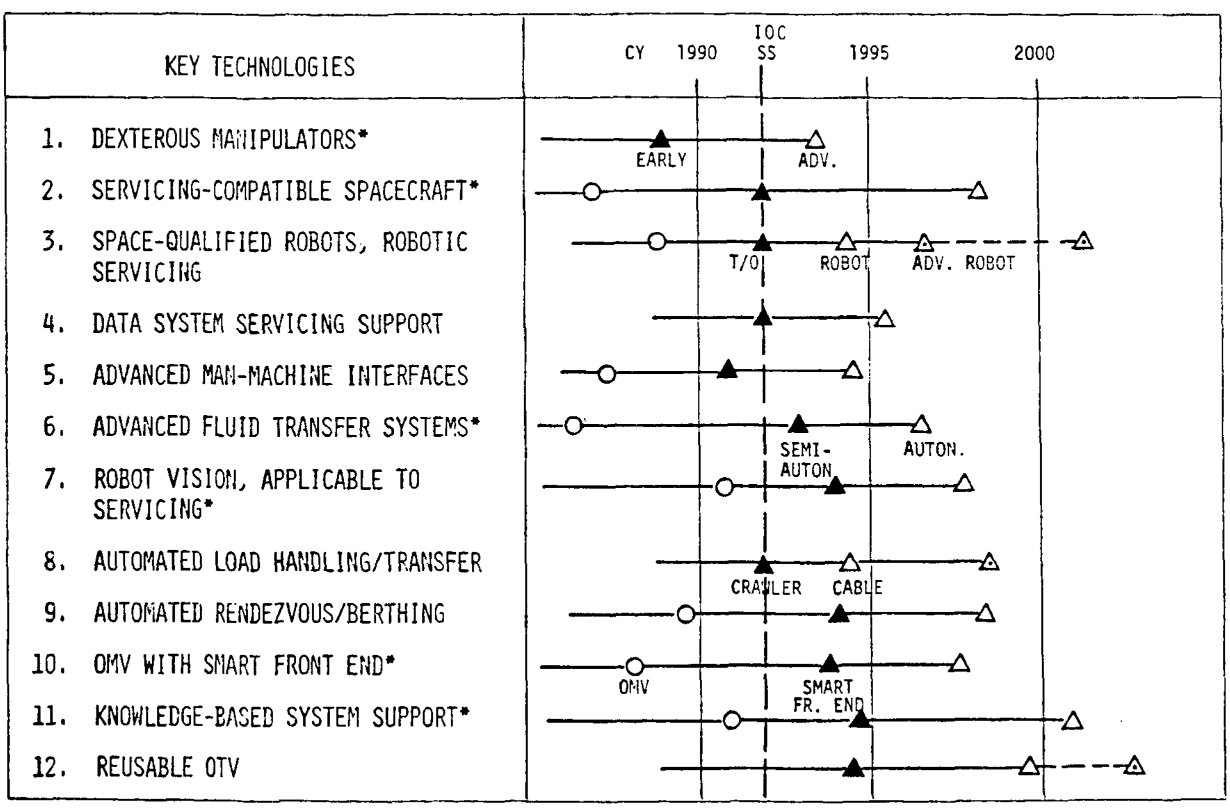
3.5.4 Servicing Technology Drivers

Figures 18 a and b summarize Space Station operating conditions and requirements related to servicing objectives that will become "drivers" for servicing technology development.

Items listed on the left are elements that characterize, in each case, the conditions that call for technology advancement and/or other approaches to meeting growing demands on the Space Station.

- FLEXIBLE UTILIZATION OF T/O AND ROBOTIC CAPABILITY DEMANDED BY
  - SATELLITE DESIGN DIVERSITY
  - SERVICING/REPAIR TASK DIVERSITY
  - UNFORESEEN TASKS
- DEVELOP MANIPULATORS THAT MAY BE USED ALTERNATELY IN T/O OR FULLY ROBOTIC MODE, DEPENDING ON TASK
- DEVELOP SERVICING TOOLS USABLE IN T/O OR ROBOTIC MODE
- DEVELOP VISION SYSTEMS THAT ENHANCE ROBOTIC MODE
- DEVELOP MACHINE INTELLIGENCE TO OPERATE MANIPULATOR IN ROBOTIC MODE IF APPROPRIATE
- EVOLUTION OF REMOTE (IN-SITU) SATELLITE SERVICING FROM T/O MODE TO ROBOTIC MODE (SMART SERVICING KITS)
- DEPENDENCE ON ROBOTIC MODE WHEN FEEDBACK TIME DELAY IS EXCESSIVE

Figure 16. Teleoperation vs. Robotics in Satellite Servicing



*ASSUMES MAJOR R&D FUNDING FOR SS AUTOMATION, STARTING FY 1986

○ - DEMONSTRATION ▲ - EARLY △ - ADVANCED △ - FUTURE GROWTH CAPABILITY

Figure 17. Automated Servicing Technology Development Forecast

1. TRAFFIC FLOW ON BOARD SPACE STATION

ITEMS

- STS CARGO
- SUPPORT EQUIPMENT, TOOLS AND SUPPLIES
- MANIPULATORS, ROBOTS
- SATELLITES
- SUBSYSTEMS, ORUs, PAYLOADS
- OMV AND OTV
- CREW AND CREW SUPPORT

IMPLICATIONS/GROWTH ISSUES

- FAST TRANSFER SYSTEM, AUTOMATED
- DATA SYSTEM SUPPORT (FLOW MONITORING/ CONTROL, LOGISTICS SUPPORT, SEQUENCING)

2. TRAFFIC FLOW NEAR SPACE STATION

- SHUTTLE VISITS
- SATELLITES RETRIEVED, DEPLOYED (INCL. OMV, OTV TRAFFIC)
- SATELLITES FLYING IN FORMATION
- RENDEZVOUS/DOCKING EVENTS
- CREW MOVEMENT ON MMU

- INTEGRATED TRAFFIC PLANNING, MONITORING AND CONTROL (DATA SYSTEM)
- AUTOMATED RENDEZVOUS/DOCKING MODE
- SAFETY MEASURES (DATA SYSTEM)
- HUMAN CONTROL INTERVENTION, AS REQUIRED

3. FREQUENT REFUELING (OMV, OTV, SATELLITES)

ITEMS

- PROPELLANT DEPOT
  - STORABLE
  - CRYOGENIC
- LARGE VOLUME
- DEPOT LOCATION, ACCESS
- PROPELLANT TRANSFER, EQUIPMENT
- TANK TRANSFER, EQUIPMENT
- SHUTTLE PROPELLANT DELIVERY
- PROPELLANT LINE HANDLING
- CONTAMINATION, HAZARD AVOIDANCE

IMPLICATIONS/GROWTH ISSUES

- CREW INVOLVEMENT (EVA, IVA)
- AUTOMATED AND T/O HANDLING AND CONTROL
- SAFETY MEASURES, RESPONSE TO EMERGENCIES

4. HARDWARE HANDLING (ASSEMBLY/DISASSEMBLY, ORU REPLACEMENT, ETC)

- MANIPULATION (GROSS, DEXTEROUS)
- LOAD TRANSFER
- VISION SYSTEMS
- TOOLS, SUPPORT EQUIPMENT
- SEQUENCING
- PLANNING
- LOGISTICS

- CREW INVOLVEMENT (EVA, IVA)
- CONTROL STATION
- WORK STATION ARRANGEMENT
- SAFETY MEASURES
- DATA SYSTEM SUPPORT

Figure 18a. Servicing Technology Drivers

5. SATELLITE REPAIR (ON STATION, IN SITU)

ITEMS	IMPLICATIONS/GROWTH ISSUES
- TEST, DIAGNOSITCS, FAILURE DETECTION - ACCESS TO SUBSYSTEMS - TOOLS, PARTS, SUPPORT EQUIPMENT - REPAIR MODES • AT WORK STATION • IN WORKSHOP (SHIRT-SLEEVE) - MACHINING, ETC.	- DEXTEROUS MANIPULATOR - PRESSURIZED WORKSHOP - AUTOMATED TEST EQUIPMENT - EXPERT SYSTEM SUPPORTS DIAGNOSTICS, FAILURE DETECTION - GROWTH IN REPAIR CAPABILITY BEYOND MODULE REPLACEMENT

6. LOGISTICS FLOW AND CONTROL

- INVENTORY CONTROL: TOOLS, SUPPLIES, PARTS, FUEL, ETC. - STS CARGO DELIVERY, FERRYING OF CREWS - GROUND SUPPORT IN SPACE STATION RESUPPLY	- LOGISTICS PLANNING - RESUPPLY SCHEDULING - TRAFFIC CONTROL } DATA SYSTEM SUPPORT

7. COMMUNICATION AND DATA MANAGEMENT

ITEMS	IMPLICATIONS/GROWTH ISSUES
- COMM. LINK ACCESS (SS-TO-EARTH, SS-TO-OMV/TARGET SATELLITE) - ADEQUATE CHANNEL CAPACITY (VIDEO RETURN) - DATA COMPRESSION, REDUCED FRAME RATES - INTEGRATED DATA SYSTEM UTILIZATION CONCEPTS - HIGH LEVEL AND NATURAL LANGUAGES	- COMPREHENSIVE DATA STORAGE, RETRIEVAL - DISTRIBUTED DISPLAY/CONTROL ACCESS - PLANNING AND MISSION/TASK SEQUENCING - ARTIFICIAL INTELLIGENCE SUPPORT TO AUTOMATED SERVICING

8. CREW INTERFACES

- CENTRAL AND SUBSIDIARY CONTROL STATIONS - DISPLAY/CONTROL FUNCTIONS - DATA SYSTEM ACCESS - CREW SUPPORT EQUIPMENT - CREW PROTECTION PROVISIONS (EVA, IVA)	- CREW TASK PLANNING, SEQUENCING - PROBLEM SOLVING (TROUBLESHOOTING) } AI SUPPORT EVOLUTION - MOVABLE WORK STATION (ENCLOSED CHERRY PICKER) FOR ON SITE TELEOPERATION

Figure 18b. Servicing Technology Drivers (continued)

Items listed on the right are principal implications relating to Space Station design and operation and specifically, to servicing technology and its evolution. Data System support is a key issue among most of the implications and growth issues identified. This support may take the form of increased data processing, data storage and retrieval, and computational activity or advanced machine intelligence for tasks such as planning, sequencing, troubleshooting, problem solving and handling of emergencies.

3.6 Design Requirements for Automated Servicing

Design requirements for automated satellite servicing, either on board the SS or in situ, encompass those pertaining to the satellite, the SS and the entire spectrum of support equipment. The latter also include the OMV and OTV and any manipulators, tools and supplies plus the control systems and machine intelligence needed for automated operation. Figure 19 summarizes design requirements and constraints of these systems. A more detailed listing of teleoperation/robotic functions and attributes required by the servicing facility is presented in Figures 20 and 21.

3.7 Generic Servicing Facility

3.7.1 Servicing Facility Design and Operation Criteria

3.7.1.1 Work and Storage Areas

The Space Station should provide large, uncrowded work and storage areas for berthing, servicing, and refueling of spacecraft to permit efficient performance of servicing tasks either by EVA crewmen or by teleoperated or robotically controlled equipment. Servicing tasks to be accomplished include berthing, dry servicing (i.e., ORU changeout), refueling, fluid/cryogenic resupply, checkout, storage, and launch/redeployment of unmanned (or possibly some day, manned) spacecraft. These areas should have growth capability in size, and automation level. In addition the servicing facilities should provide:

- Electrical/fluid attachments (umbilicals)
- Electrical power
- Thermal interfaces (heat transfer)
- Data interface
- Handling accommodations (RMS, dexterous manipulators and HPAs)
- Any fluid or cryogenic services
- Rendezvous accommodations (e.g., OMV)
- Transfer vehicle servicing/docking bay
- Convenient and safe access for EVA

1. SPACE STATION - PROVIDE:

- BERTHING/SERVICING FACILITIES FOR SATELLITES, OMV, OTV
- INTEGRATED AUTOMATION SUPPORT CAPABILITY BY SPACE STATION DATA SYSTEM WITH DISTRIBUTED ACCESS POINTS FOR
  - COMMANDS
  - DISPLAYS
  - SERVICING TASK SEQUENCING
  - TEST AND CHECKOUT SEQUENCES
- RMS AND RAIL SYSTEM FOR FULL COVERAGE/REACH OF ALL SS AREAS
- DIRECT LINE-OF-SIGHT COMMUNICATION LINK FOR TELEOPERATION COMMANDS AND TELEMETRY/VIDEO FEEDBACK IN REMOTE SERVICING TASKS
- ADVANCED TDRSS DIRECT-LINK SS-TO-SATELLITE COMMUNICATION FOR REMOTE SERVICING TASKS

2. OMV/OTV - PROVIDE:

- SERVICING KITS FOR TELEOPERATED OR AUTOMATED REMOTE SERVICING
- MULTIPLE TV CAMERAS AND LIGHTING
- CONVENIENT MATING INTERFACES BETWEEN OMV/OTV AND CARGO
- AUTOMATED RENDEZVOUS/DOCKING/BERTHING CAPABILITY

3. SATELLITES - PROVIDE:

- READY TELEOPERATOR ACCESS TO UNITS EXPECTED TO BE SERVICED
- CONVENIENT REMOVAL/REATTACHMENT OF THERMAL COVERS TO FACILITATE SERVICING ACCESS
- FIXED OR PORTABLE GRAPPLE FIXTURES ON REMOVABLE UNITS (ORU'S)

- STANDARDIZED ELECTRICAL AND MECHANICAL INTERFACES ON REPLACEABLE UNITS
- STANDARDIZED FLUID INTERFACES
- REFUELING CAPABILITY

- ASSEMBLY AND DEPLOYMENT CAPABILITY FOR LARGE SATELLITES
- TELEOPERATOR ACCESS FOR REPOSITIONING (TO AVOID BERTHING OBSTRUCTION) AND FOR DEPLOYMENT/RETRACTION OF APPENDAGES
- EXTERNAL TERMINALS FOR DIAGNOSTICS IN SERVICING AND CHECKOUT

Figure 19. Automated Servicing Design Requirements

1. GROSS MANIPULATION
   - LOAD HANDLING AND TRANSFER
   - STOWAGE
2. DEXTEROUS MANIPULATION
   - SMALL LOAD HANDLING
   - SMALL-CLEARANCE MANIPULATION
   - TOOL MANIPULATION
   - UMBILICAL HOOKUP/DEMATE
   - FLEXIBLE AUTOMATION CAPABILITY
3. MODULE EXCHANGE
   - BY RMS
   - BY SPECIALIZED KITS
4. ORIENTING, POSITIONING
   - GROSS
   - FINE
5. EXECUTING PROGRAMMED OR LEARNED SEQUENCES
6. MULTI-ARM HANDLING (COOPERATIVE MANIPULATION)
7. FLUID TRANSFER
   - FLUID LINE HANDLING
   - VOLUME, PRESSURE, TEMPERATURE CONTROL
   - MONITORING, CHECKING, SEALING, ETC.
8. TOOL SELECTION AND HANDLING
9. INSPECTION, GAUGING, MEASURING
10. MANIPULATE UMBILICALS
    - POWER
    - SIGNALS
    - FLUID LINES
    - GAS LINES
11. INTERFACE WITH AND UTILIZE COMPUTER/DATA SYSTEM, ARTIFICIAL INTELLIGENCE
12. INTERFACE WITH HUMAN CONTROL OPERATOR (DIRECT, SUPERVISORY)
13. PROVIDE SENSOR AND TELEMETRY FEEDBACK AND RECORDING
14. USE OF PRESENT AND NEW GENERATION TELEOPERATOR CONTROLS
15. DOCKING AND BERTHING PROCEDURES
16. GROWTH OF TELEOPERATED EQUIPMENT TO AUTOMATED TASKS
17. SERVICE SPACE STATION SYSTEMS/SUBSYSTEMS

Figure 20. Robotic and Teleoperation Functions in Satellite Servicing

1. MANIPULATION MODES AND SKILLS

- GRASPING, HOLDING
- LOADING/UNLOADING/TRANSFERRING
- STOWING/UNSTOWING
- MATING/DEMATING
- ASSEMBLING (LARGE, SMALL)
- INSERTION
- OPENING/CLOSING (COVERS, ENCLOSURES), WRAPPING/UNWRAPPING
- ALIGNING, INDEXING
- LOCKING/UNLOCKING
- SCREWING/UNSCREWING, BOLTING/UNBOLTING
- POINTING, ORIENTING
- CLAMPING, FASTENING, SECURING
- WINDING/UNWINDING, COILING/UNCOILING

2. VISION SYSTEM ATTRIBUTES

- CONTOUR RECOGNITION
- SELECTION, SORTING
- LOCATING OBJECTS, TARGET POINTS
- ILLUMINATION SOURCE SELECTION
- ILLUMINATION CONTROL
- CONTRAST ADJUSTMENT
- INSPECTION ALONG SELECTED PATHS
- OBSTACLE RECOGNITION, AVOIDANCE
- FOCUS ADJUSTMENT
- SENSITIVITY ADJUSTMENT
- PATTERN RECOGNITION

3. END EFFECTORS

- GRIPPERS, FINGERS, TONGS
- SPECIAL TOOLS
- SCREW DRIVERS, WRENCHES
- SPINDLES
- CUTTERS, SHEARS
- GRINDERS
- HEATING TOOLS
- WELDING TOOLS
- CHISELS
- OPENERS
- TV CAMERAS

4. RETENTION DEVICES

- CLAMPS, CLASPS
- STRAPS, BANDS, BUNGIE CORD
- TETHERS
- POSTS, PEDESTALS, JACKS
- SOCKETS
- BALL LOCKS
- LOCKS
- RINGS

5. ELECTRONICS AND CONTROL

- COMPUTING, DATA HANDLING AND STORAGE (SEE SEPARATE CHART)
- SIGNAL PROCESSING
- SENSORS
  - -- VIDEO (SEE ABOVE)
  - -- TEMPERATURE
  - -- PRESSURE
  - -- PROXIMITY
  - -- TACTILE FORCE
  - -- TORQUE
  - -- DISPLACEMENT, ORIENTATION
  - -- VIBRATION SENSING
- TELEMETRY CIRCUITS
- CONTROL ELECTRONICS
- DIAGNOSTICS AND SELF-TEST CIRCUITS
- SEQUENCES
- SELF-ACTUATION
- SELF-PROTECTION, SHUTOFF CONTROL
- PROGRAMMABLE/LEARNING AUTOMATED CONTROLS

Figure 21. Attributes of Robotic Servicing Equipment

- Convenient IVA control of teleoperated servicing and handling equipment
- Any special servicing equipment needed by EVA crew or automated devices
- Fuel depot
- Propellant transfer lines
- IVA control station
- Support software
  - Fault detection
  - Checklists
  - Diagnostics
  - Data bases
- Automatic and semi-automatic control sequences

3.7.1.2 Work Area Distribution

The location of the servicing facilities and storage areas on the Space Station can be designed either in a centralized or a distributed manner. Advantages of each design are listed below and, depending on other configuration priorities and needs, centralized or distributed facilities or a combination of both can be incorporated into the overall design.

CENTRALIZED	DECENTRALIZED
• NEAR HABITABILITY/LAB MODULES	• REDUCES CONGESTION
• CONVENIENT FOR PRIMARY HANDS-ON SERVICING AND DIRECT OBSERVATION/CONTROL FROM CENTRAL CONTROL STATION	• FACILITATES GROWTH
• REDUCES LOAD TRANSFER DEMANDS	• EMPHASIZES AUTOMATED/TELE-OPERATION APPROACH TO SERVICING
	• EXTRA CONTROL SUBSTATION OVERLOOKING REMOTE WORK AREA DESIRABLE

Beyond these considerations work areas should be located in places which are convenient to EVA crew and load transfer equipment access so as to permit safe and efficient EVA crew movements, convenient reach by mobile RMS, and ease of spacecraft berthing.

3.7.1.3 Load Handling and Transfer

The Space Station should provide for efficient and readily available transfer of crew members, support equipment, tools, spacecraft components and other materials along its entire length. To perform these tasks teleoperated (and later, robotically) controlled RMS-like manipulators should be installed on the Space Station with ready mobility along the Space Station structure. Also there will be an eventual need for an additional transport system which can transfer men and equipment across the Space Station more conveniently and faster than the inherently slow moving mobile RMS. The design of the mobile RMS system should allow for easy growth from a purely teleoperated mode, to one which is partially or fully automated. Provision should be made for the addition of smaller, dexterous manipulators to handle more delicate and varied tasks. The evolution of the mobile RMS system also should provide for the later addition of:

- Automated spacecraft handling software and controls
- Automated equipment handling software
- Inventory system software
- Dexterous manipulator software and controls
- Changeout end effectors
- Astronaut cherry pickers and crew stations

3.7.1.4 Central Control Station

A centralized control station will be needed for the teleoperation and robotic control of servicing activities. The station will be the interface for status data and feedback control of all departing, incoming or berthed spacecraft including transfer vehicles e.g., OMV. The control center should be able to accommodate control of:

- Teleoperated mobile and stationary RMSs and manipulators (i.e., dexterous, special)
- OMV (and OTV)
- Any desired automated sequence with the use of robotic control hardware and software
- Any RF commands for incoming and berthed spacecraft
- Any teleoperated remote servicing

Control station feedback displays will include TV images, CAD pictures, status data, and other digital information on automated systems. The Space Station should have adequate TV coverage and illumination of all work sites as needed for effective monitoring at the control station. An observation window also will be needed for direct viewing of the servicing facility while service functions are being performed. The control center will be the principal point of access to the computer and data management system.

3.7.1.5 Crew Access

The servicing facilities should provide safe and convenient EVA crew access and transfer between the habitat and the work/storage areas, such as having the EVA crew members:

- Moving unaided from place to place along handrails and with tether attach points
- Riding on the mobile RMS system
- Riding on the fast transport system
- Using a cherry picker on the RMS
- Using the Manned Maneuvering Unit (MMU)

These procedures and methods must be developed to insure crew and SS safety.

3.7.1.6 Support Function Criteria

The Space Station should eventually have an automated system which can take inventory, perform storage of equipment and supplies, and schedule STS visits to restock needed items. This system will include a warehouse bay designed to be compatible with Space Station automation, and able to incorporate growing automation technology. The Space Station will also have to support OMVs and OTVs used to retrieve spacecraft or to perform remote servicing. The transfer vehicles docking bay will have to provide for deployment, retrieval, berthing, refueling, maintenance and storage of these vehicles.

3.7.1.7 Location and Size of Fuel Depot

The location of the fuel/fluids depot should permit convenient fluid transfer from the Shuttle to tanks, and from the tanks to spacecraft being refueled, and must assure crew safety and avoid contamination of sensitive surfaces such as solar panels and radiators. Two criteria relate to its location relative to the Space Station center-of-mass:

(1) It would be desirable to place the depot near the center of mass to reduce the effects of large mass transfers and fluid leaks.

(2) Placing the depot away from the C.M. would provide some artificial gravity (4×10^{-5}g's at 100 meters) for propellant settling.

A trade study is required to determine which of these locations best fits Space Station needs.

The size of the fuel depot will depend on the refueling traffic, OMV needs, Space Station propulsion needs, and STS revisit schedules.

3.7.1.8 Safety Criteria

The design of the servicing facility and related systems must take into account the safety of EVA and IVA crewmembers. Safety issues include avoidance of hazards due to RMS or other manipulator operation and due to OMV and STS firing in Space Station proximity; safe passage of crewmembers to/from all areas; prevention of contamination from fluid containers; and careful monitoring and control of the crew module environment.

3.7.1.9 Service Facility Design Constraints

Servicing facility design constraints are dictated primarily by the requirements of compatibility with the overall Space Station design and operation and that of other SS systems. Principal constraints include the following:

- Servicing areas and operating functions must be compatible with operations of all other systems onboard the Space Station (e.g., location, traffic flow, safety)
- Obstacles to load handling and transfer must neither be caused nor incurred
- Hazards to crew or to/by other systems onboard the Space Station must neither be caused nor incurred
- Contaminations (efflux, particles, waste products) that might be caused or incurred by servicing operations must be avoided or strictly controlled
- Space Station utilities and services must be shared with other users by a mutually agreed-on schedule or sequence

3.7.2 Automated System Utilization by the Servicing Facility

Key automation features and their utilization in various satellite servicing tasks were addressed in Section 3.2, 3.3 and 3.5. Automated servicing equipment will be used flexibly, depending on specific scenario requirements, task difficulty, the degree of crew involvement necessary, and the status of servicing capability growth. Utilization will differ in many respects from other, more routinely performed automated tasks like structural assembly or materials processing, as indicated in Table 3.

3.7.3 Data System Support to Servicing Activities

The Space Station central data system will have a key role in the utilization, operation and control of the satellite servicing facility and in the execution of servicing tasks by the crew or by automated systems, including systems such as the OMV and OTV operating remotely from the Space Station. The role of the data system in supporting these activities by planning, sequencing, mode selection, resource allocation and other critically important functions is summarized in Figure 22. Specific functions directly related to the artificial intelligence requirements of the system are listed separately in Figure 23.

Figure 24 illustrates the important role of Space Station data system support in the planning and execution of a typical servicing mission. The sequence of activities required to perform the mission, starting from the time a call for service is received, is indicated by the flow of major operational steps including resource utilization planning, logistics planning, mission profile planning, preparation of supplies and support equipment through task execution and final checkout.

A large share of these events depends heavily on data system support (indicated by DS). Physical activities involved in carrying out the mission, although not specifically accounted for, are assumed to involve automated equipment support (indicated by A) and often also support by the data system.

3.7.4 Servicing Facility Resource Requirements

Space Station resources required to support servicing operations are listed in Figure 25. Since they must be shared with other users, their allocation and management is an important task to be planned and executed with the support of the central computer and data system. Resource allocation must take user priorities and time criticality into account to determine optimum servicing operation sequences and task schedules.

Our analysis considered three principal resource requirements associated with satellite servicing: power, heat dissipation and required communication link capacity. Power requirements (see Table 11) increase from about 17,000 KWh/year ($\sim$ 2 KW of average power) in 1991 to 36,000 KWh/year ($\sim$ 4 KW of average power) in 2000, a reasonably small share (less than 10 percent) of total Space Station power capacity. Average heat dissipation will be commensurate with these power requirements.

• LOGISTICS PLANNING (SEE ALSO AI LIST)
- INVENTORY OF PARTS, SUPPLIES, EQUIPMENT RESOURCES ETC.
- SCHEDULE DATA
  - SERVICING SCHEDULES
  - STS TRAFFIC
  - CREW AVAILABILITY, TIME LINES ETC.
  - COMMUNICATION LINKS AVAILABLE (TIME LINES)
  - OMV TRAFFIC
  - SPACE STATION OPERATING SCHEDULE
• SUPPORT TO EVA CREW: DATA DISPLAY IN CALL
- MONITORING, CAUTION/WARNING DISPLAY
- VOICE RECOGNITION, VOICE RESPONSE
	• GENERAL DATA SYSTEM SUPPORT ("INFRASTRUCTURE")
	• TASK PLANNING DATA
	• DATA STORAGE AND RETRIEVAL OF SERVICE MANUALS, SPECS, I.F. DATA
	- DESIGN HANDBOOKS
	- OPERATING HANDBOOKS
	- PROCEDURES, CHECKLISTS
	- PARTS LISTS
	- SOURCE CONTACTS ON GROUND
	FOR ALL SYSTEMS TO BE SERVICED
	• DIRECTORY OF INFORMATION SOURCES (WHO, WHERE, WHEN, FOR WHAT?)
	• MONITORING, CAUTION/WARNING AND ALERT SERVICES
	• EQUIPMENT OPERATION, ADJUSTMENT, CONTROL, MODE CHANGE DATA

Figure 22. Data System Support Requirements (Other Than Artificial Intelligence)

- SERVICE TASK PLANNING
  - WHICH SATELLITES FIRST?
  - WHICH TASKS?
  - WHICH MODE (EVA, IVA, ROBOTIC, ETC.)?
  - WHICH TOOLS, SUPPORT EQUIPMENT?
- COST/TIME/EFFORT OPTIMIZATION
- TIME-LINING
- TRAFFIC PLANNING IN REMOTE SERVICING (IN-SITU) E.G., MAXIMUM DIRECT-LINE-OF-SIGHT COMMUNICATION LINK AVAILABILITY
- MISSION PROFILE OPTIMIZATION
- INTEGRATED LOGISTICS PLANNING
  - INVENTORY CHECK
  - SUPPLIES, PARTS, SUPPORT EQUIPMENT REQUIREMENT
  - TIME PHASING
  - DELIVERY NEEDS
- RESOURCE UTILIZATION PLANNING
  - POWER
  - CREW TIME
  - DATA SYSTEM, DATA LINKS
  - OTHER
- AID TO DIAGNOSTICS, TROUBLE SHOOTING
- EMERGENCY SUPPORT (SAFEGUARDING, TURN-OFF, ABORT, RESCUE) OF SERVICING OPERATIONS
- NORMAL AND BACKUP OPERATING SEQUENCES, EACH SERVICING TASK
- AUTOMATED CHECK-OUT AND TEST SEQUENCES, EACH SERVICING TASK

Figure 23. Artificial Intelligence Functions

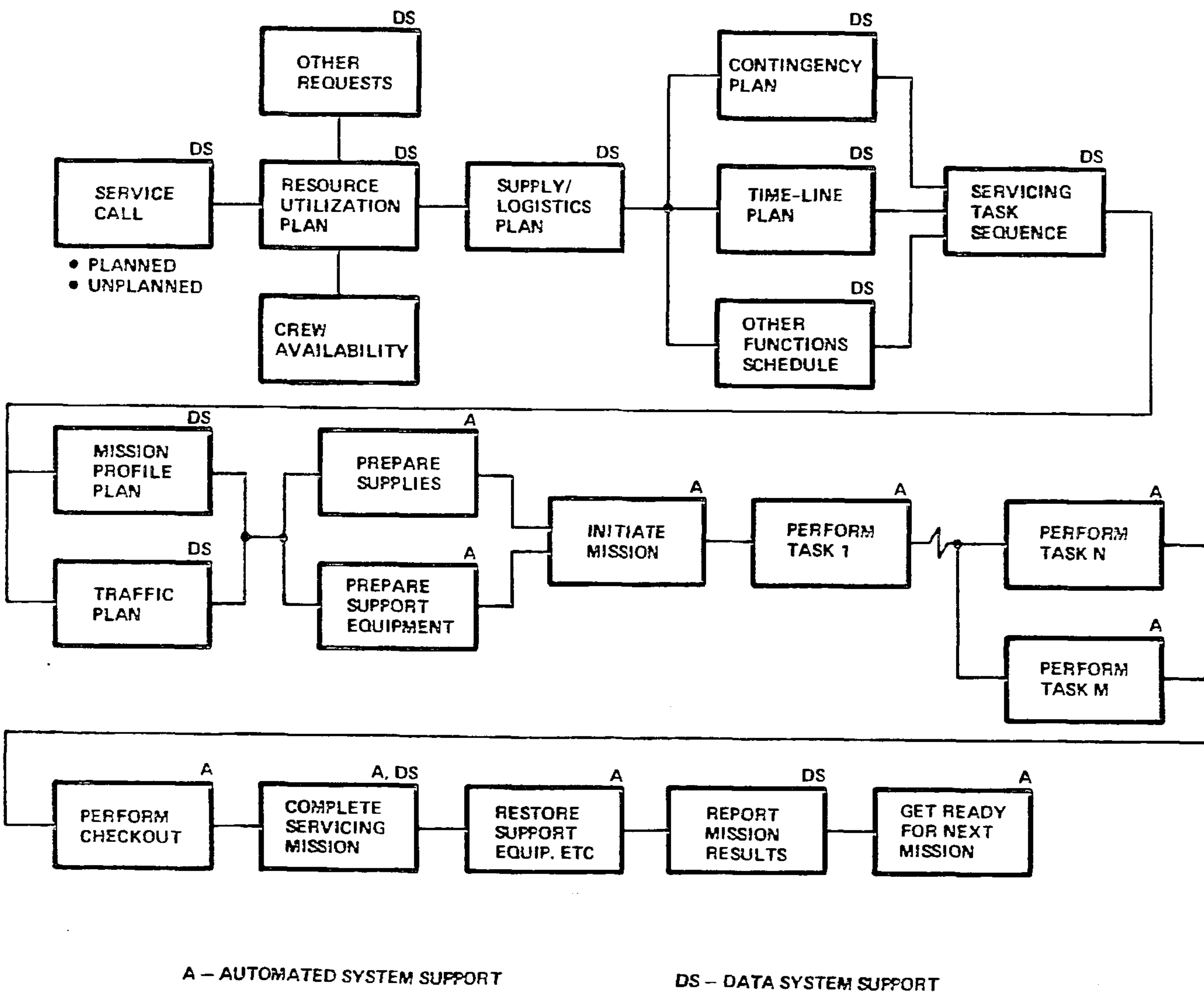


Figure 24. Servicing Mission Planning and Execution

1. CREW SYSTEMS
2. POWER, POWER DISTRIBUTION
3. THERMAL CONTROL
    - HEATING
    - COOLING
    - INSULATION
    - HEAT EXCHANGE
4. LIFTING, LOAD TRANSFER AND CONTROL
    - MANIPULATOR ARM(S)
    - CONVEYOR SYSTEM
    - RAIL/CABLE SYSTEM
5. FUEL DEPOT, FUEL TRANSFER SYSTEM
6. STORAGE, RETENTION, PROTECTION, ENCLOSURES, SHIELDING ETC.
7. COMMAND CENTER FOR CONTROL INTERFACE
8. DATA MANAGEMENT (INCLUDING ARTIFICIAL INTELLIGENCE SUPPORT) ACCESS
9. COMMUNICATION LINKS ACCESS
10. CREW SUPPORT AND PROTECTION
11. LOGISTICS SUPPORT (GROUND FACILITIES, STS SUPPORT, OTHER)
    - SATELLITE BERTHING AREAS
    - SATELLITE CHECKOUT AREAS
    - SATELLITE STORAGE AREAS
12. STRUCTURAL SUPPORT AND WORK AREAS, PLATFORMS
13. TV COVERAGE
14. ILLUMINATION, GLARE SHIELDING
15. MANEUVERING VEHICLE SUPPORT (OMV, OTV, OTHER)

Figure 25. Automated Servicing Facility Resource Requirements

Table 11. Average Power Requirements 1991 Through 2000

YEAR	KWH/YEAR	AVERAGE POWER (KW)
1991	16,894	1.9
1992	16,324	1.9
1993	20,779	2.4
1994	23,588	2.7
1995	30,468	3.5
1996	35,426	4.0
1997	36,888	4.2
1998	38,528	4.4
1999	32,796	3.7
2000	35,676	4.1

Communications between Space Station and ground via TDRSS will require maximum bit rates related to servicing primarily during assembly and checkout of satellites and at times of remote conduct of diagnostics and troubleshooting, primarily for video coverage. However, these bit rates are not likely to exceed several tens of Mbps in the worst case, a small share of the maximum KSS return link capacity of 250 to 300 Mbps.

A second mode of servicing activity requiring high data rates involves teleoperation with video feedback, either via TDRSS or by direct link to the OMV and/or satellite in question. Since only moderate frame rates and video data compression (on inter-frame and intra-frame data) will be utilized in representative closed loop teleoperation modes, the bit rates required for video feedback are typically in the range of 1 to 10 Mbps, which is no problem in the case of TDRSS relay communications. For direct link communication at modest OMV transmitter power and antenna size bit rates of about 1 Mbps will be available, even at several thousand km of Space Station-to-OMV communication range. This is sufficient to support the video feedback requirements.

Crew availability may become a limiting factor, requiring delays in initiating some servicing tasks at times when this would conflict with other crew priorities or when servicing demands are exceptionally heavy. Such conditions will arise more frequently as Space Station operations expand. Availability of time and labor saving automated servicing equipment, however, promises to alleviate or eliminate such crew-related impasses.

3.7.5 Service Facility Layout and Design Concept

3.7.5.1 Generic Servicing Facility Characteristics

The satellite servicing facility on the Space Station should be viewed as a collection of many elements scattered in different locations. Figure 26 shows these elements and their interactions as indicated by solid or dashed lines. The solid lines designate interactions that occur continuously or most often. Among the elements shown in the chart, those in the upper and right hand part dominate in defining the degree or level of traffic and activity, i.e., orbiter and satellite berthing ports, load handling and transfer equipment, the control station, data management and communications systems, and the service areas assigned to assembly, repair, and refueling.

Figure 27 presents a schematic picture of the many servicing facility elements and how they relate to each other. It includes facility elements needed on the early Space Station as well as others that would become available only with the projected Space Station growth. Among the latter category are a pressurized workshop, a shelter or hangar possibly also capable of being pressurized, accommodation for OTVs, and a fuel depot, possibly suspended on a tether line at some distance from the Space Station proper.

The tethered propellant storage concept would provide artificial gravity to aid in propellant settling, but it also would make refueling access more cumbersome. It would have the advantage of reducing safety hazards and contamination effects on the Space Station and its payloads.

3.7.5.2 Location of Servicing Areas

NASA's current Space Station IOC reference configuration, also known as the "Power Tower," Figure 28 (see RFP for Space Station Definition and Preliminary Design, dated 15 September 1984) was used as baseline in selecting a generic satellite servicing facility concept. In the drawing the shaded areas are those related to servicing activities. They include satellite storage and service bays; instrument storage; a refueling bay located next to the fuel depot; a bay for accommodating the future OTV and for handling OTV technology development; and storage for the OMV and OMV servicer kits.

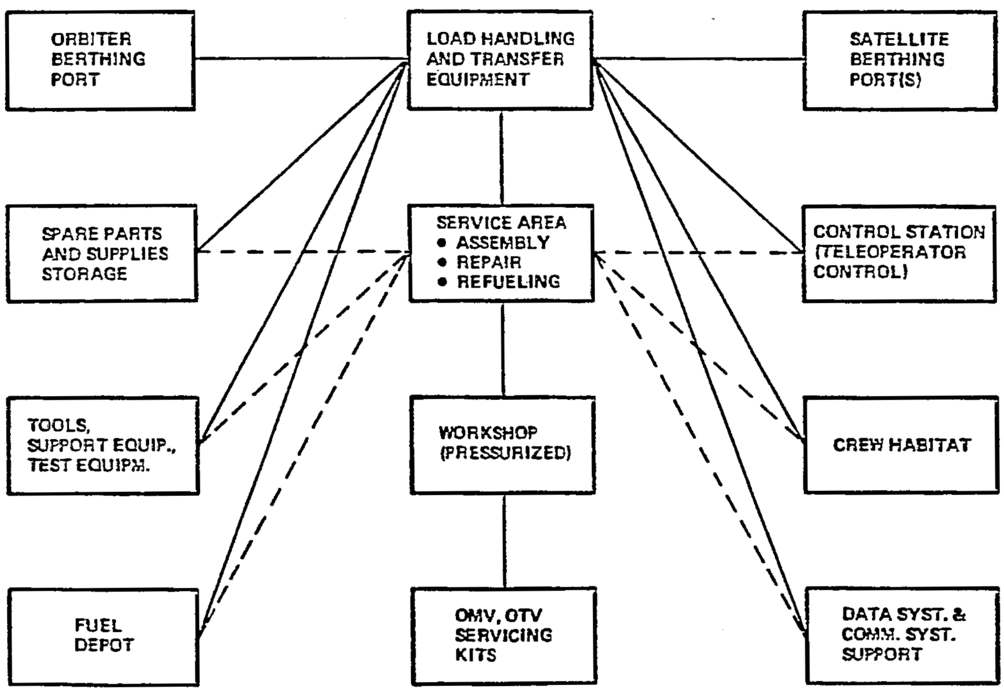


Figure 26. Elements of Satellite Servicing Facility

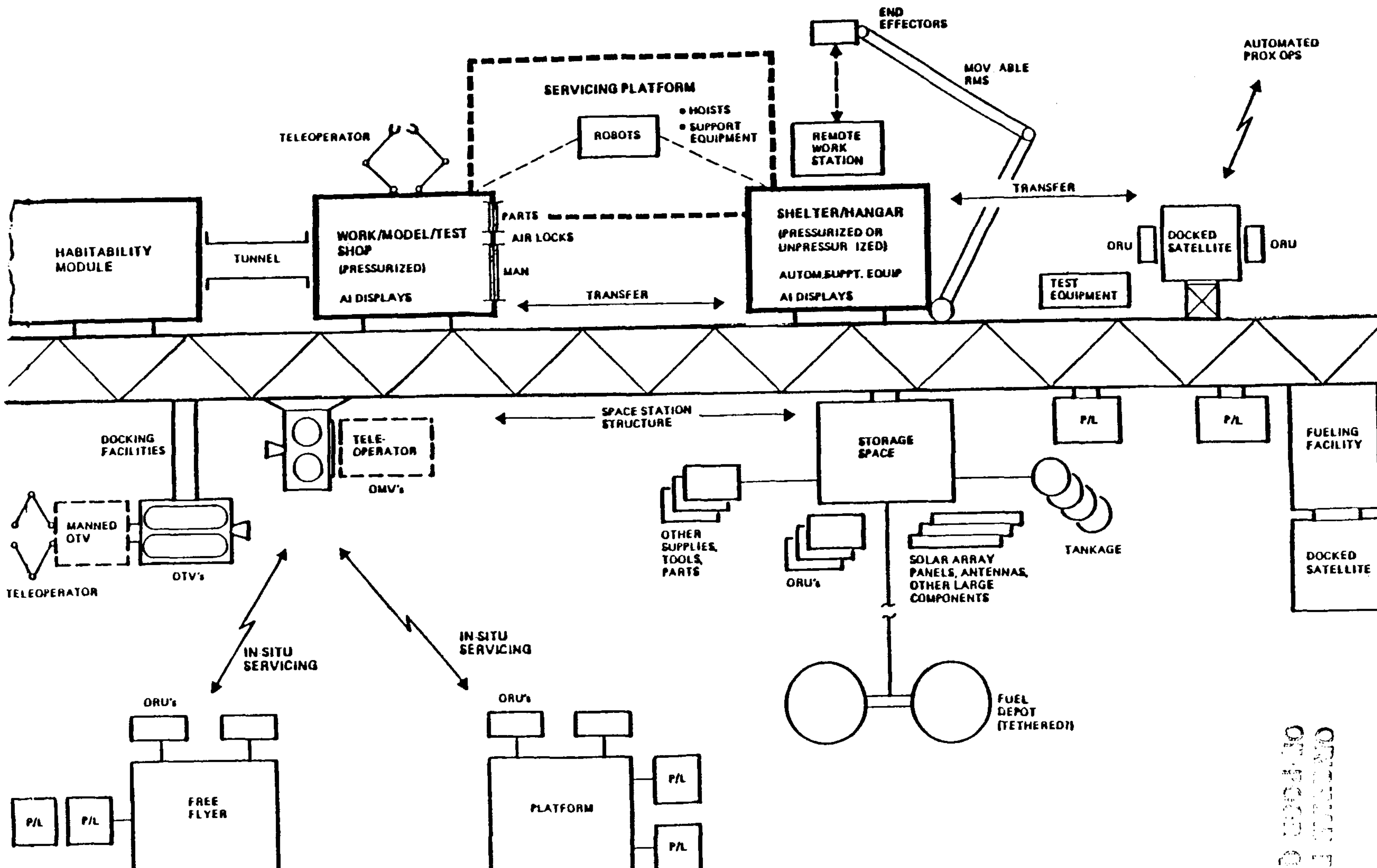


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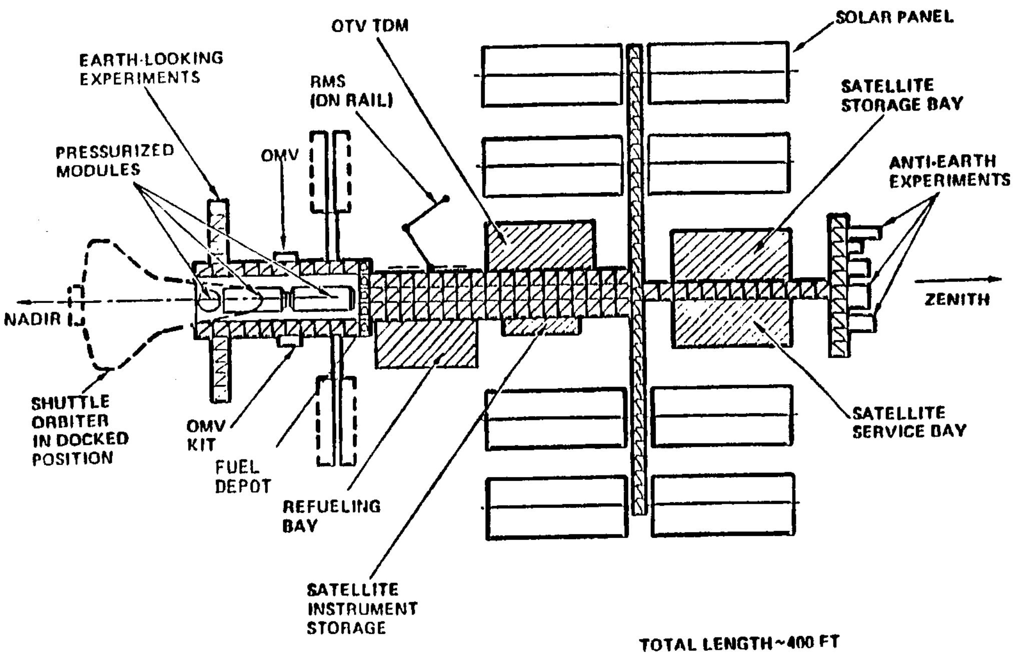
Figure 27. Generic Servicing Facility



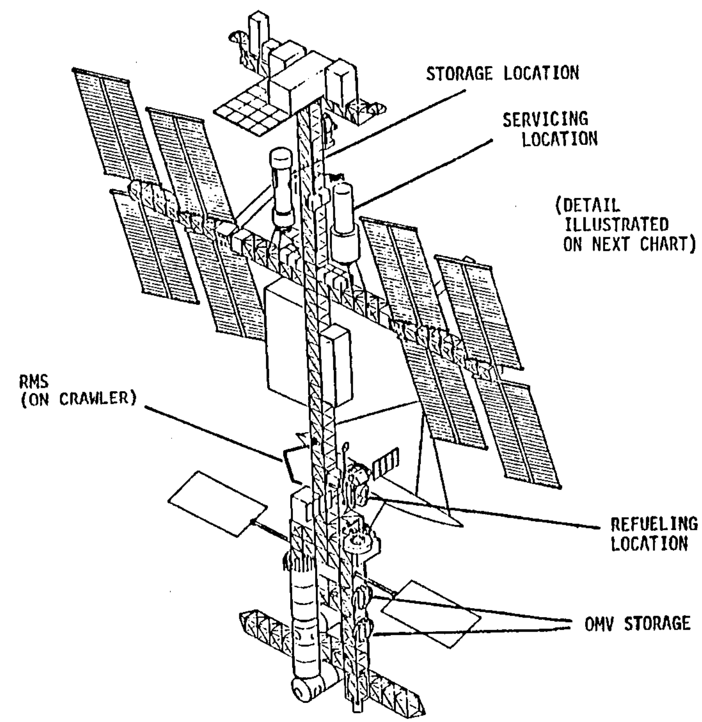


Figure 28. Space Station Design Features Related to Satellite Servicing (Reference IOC Configuration)

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Figure 29 shows one satellite in storage and one in service, both arranged parallel to the Space Station main keel axis (Z-axis). Rail mounted crew support arms facilitate crew access for servicing and equipment handling. Alternate arrangements where satellites are mounted in directions along the X- or Y-axis* may be used for better utilization of the limited service and storage space available.

Availability of servicing space may become a matter of concern and will require careful scheduling. Representative dimensions of service areas on the Power Tower configuration are listed in Table 12. An example of servicing bay occupancy by various spacecraft and other users projected for the year 1993 is shown in Table 13, and a summary of percentage occupancy of the available space is given in Table 14 for the first decade of Space Station operations. Remote servicing, starting in 1995, reduces the high occupancy rates that would prevail if all servicing were to be performed locally. In this context, the speed-up of servicing operations that would result from increased usage of on-board automation also will be a significant factor.

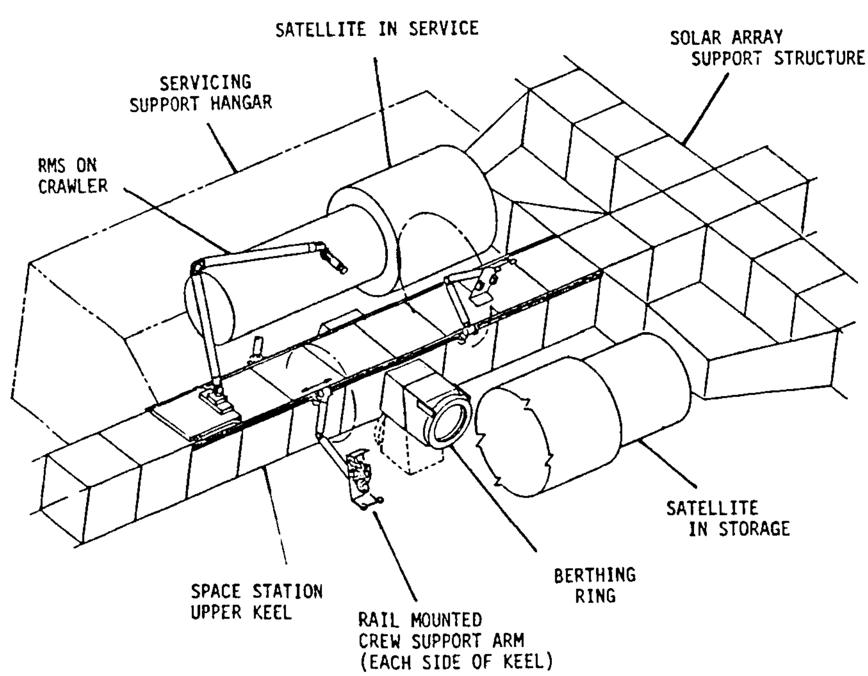


Figure 29. Access to Satellites Being Stored and Serviced

*The Y-axis is oriented along the solar array support boom, and the X-axis normal to the Y and Z-axis.

Table 12. Space Station Servicing Facilities

SPACE STATION SATELLITE SERVICING FACILITY		CHARACTERISTICS
NUMBER	NAME	
1	SERVICING BAY	CYLINDER, 30 FT DIA, 70 FT LONG
2	REFUELING BAY	CYLINDER, 30 FT DIA, 70 FT LONG
3	SATELLITE STORAGE AREA	CYLINDER, 30 FT DIA, 70 FT LONG
4	FLUID STORAGE AREA	STORE PROPELLANTS, PRESSURANTS, COOLANTS
5	OMV STORAGE AREA	CYLINDER, 15 FT DIA, 4 FT LONG
6	OMV KITS STORAGE AREA	2 CYLINDERS, 15 FT DIA, 4 FT LONG (EACH)
7	ORU STORAGE LOCKERS	10 LOCKERS, ENCLOSED RECTANGLE 3 x 5 x 5 FT (EACH)
8	TOOL STORAGE LOCKERS	4 LOCKERS, ENCLOSED RECTANGLE 3 x 5 x 5 FT (EACH)
9	PAYLOAD INSTRUMENT STORAGE	ENCLOSED RECTANGLE 10 x 20 x 30 FT
10	PRESSURIZED MODULES	CREW HAB, CONTROL/MONITORING EQUIPMENT, DISPLAYS

REFERENCE: SECTION 4.3.1.4 OF SPACE STATION REFERENCE CONFIGURATION DESCRIPTION, JSC 19989, AUGUST 1984

Table 13. Service and Storage Facility Occupancy for Year 1993

	MISSION/SPACECRAFT	NO. OF EVENTS	DAYS FOR YEAR	LENGTH (FT)	DAYS X LENGTH
1.	SPACE TELESCOPE	1	5	42	210
2.	GRO	1	5	25	125
3.	X-RAY TIMING EXPLORER	1	4	26	130
4.	FAR-UV SPECTR. EXPLORER	1	35	16	560
5.	AXAF	1	5	42	210
6.	LUNAR GEOSCIENCE ORBITER	1	35	20	700
7.	TITAN FLYBY PROBE	1	35	20	700
8.	EOS MATL. PROC. S/C I	4	180 + 16	3 + 3	588
9.	EOS MATL. PROC. S/C II	4	180 + 16	3 + 3	588
10.	OTV SERV. TECHNOLOGY MISSION	6	365	33	12045
11.	SPACE PLATFORM SERVICING	1	17	40	680
12.	COMMERCIAL S/C SERVICING	1	17	42	714
			916		17250

Table 14. Summary of Servicing Bay Occupancy Without and With Remote Servicing Between 1991 and 2000

YEAR	% OCCUPANCY WITHOUT REMOTE SERVICING	% OCCUPANCY WITH REMOTE SERVICING	% OVER
1991	83	-	3 1/2
1992	81	-	2
1993	79	-	5
1994	33	-	0
1995	48	40	0
1996	73	65	0
1997	80	69	0
1998	83	76	0
1999	93	85	0
2000	83	76	0

3.7.5.3 Load Handling and Traffic

The dispersed location of service areas avoids crowding and permits unconstrained access but also necessitates more extensive and frequent transfer of crew men, support equipment, satellite hardware, tools and supplies along the Space Station keel. Traffic volume is expected to increase as demand for servicing expands with Space Station growth.

This implies a need for convenient load transfer and support of servicing traffic. Figure 30 illustrates traffic patterns ranging from one end of the keel to the other (400 ft maximum length) and for shorter distances between areas of principal servicing activity. This includes crew movements from/to the habitat, the work and storage areas, and load transfer requirements between the Shuttle berthing port, storage facilities, work stations, the fuel depot and the satellite berthing port. Fast and convenient load transfer, locally or remotely controlled, and effective traffic flow planning supported by the Space Station data system are major design considerations that relate to servicing operations.

The Shuttle manipulator arm (RMS) with its nearly 50 ft. reach can handle load transfers locally from a fixed position, or by moving on its platform along the Space Station keel structure. The crawling platform concept developed by NASA/JSC allows the system to move step by step, from one structural node to the next, thus being able to move along the entire keel as well as the solar array panel support booms, albeit at very low speed.

An auxiliary smaller and faster-moving transportation system using rails or cables would increase load handling and transfer flexibility and speed. Figure 31 shows a cable-driven pallet concept which can transfer loads many times faster than the RMS crawler platform. This pallet can pass underneath the crawler platform or can be manipulated around it so that mutual obstruction is avoided. A detachable manipulator with 10 to 15 ft. reach can be used locally for load handling before and after transfer. With its free end the manipulator can plug into power/control terminals along the cable way being designed to be operated from either one of its end joints by a reciprocal articulation technique.

Like the RMS platform, the cable driven pallet also would be powered by rechargeable batteries to avoid use of a trailing power line or a power rail. However, most of the required operating energy would be supplied to the cable drive motor rather than to the pallet itself.

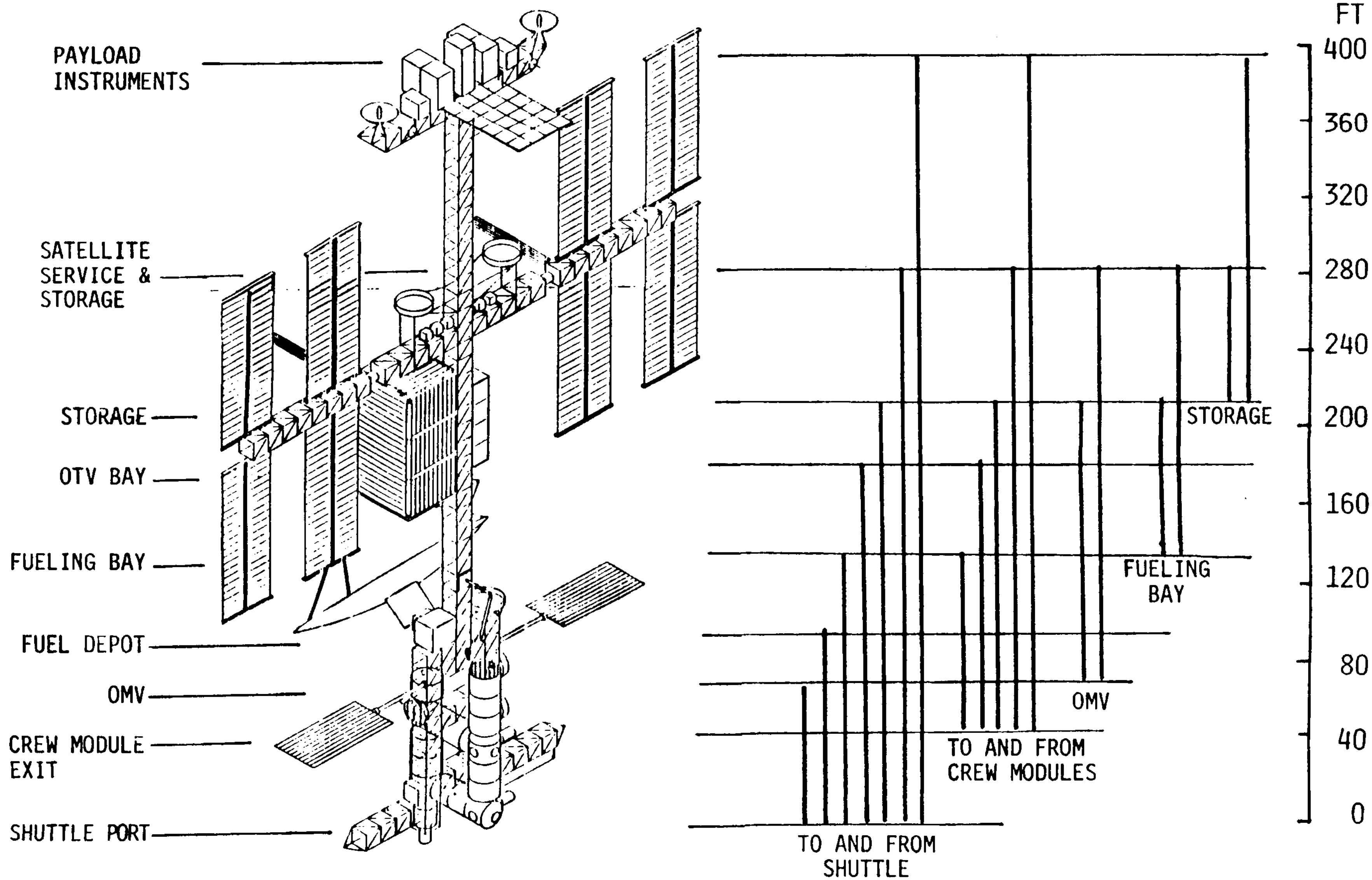


Figure 30. Servicing Traffic Along Space Station Keel

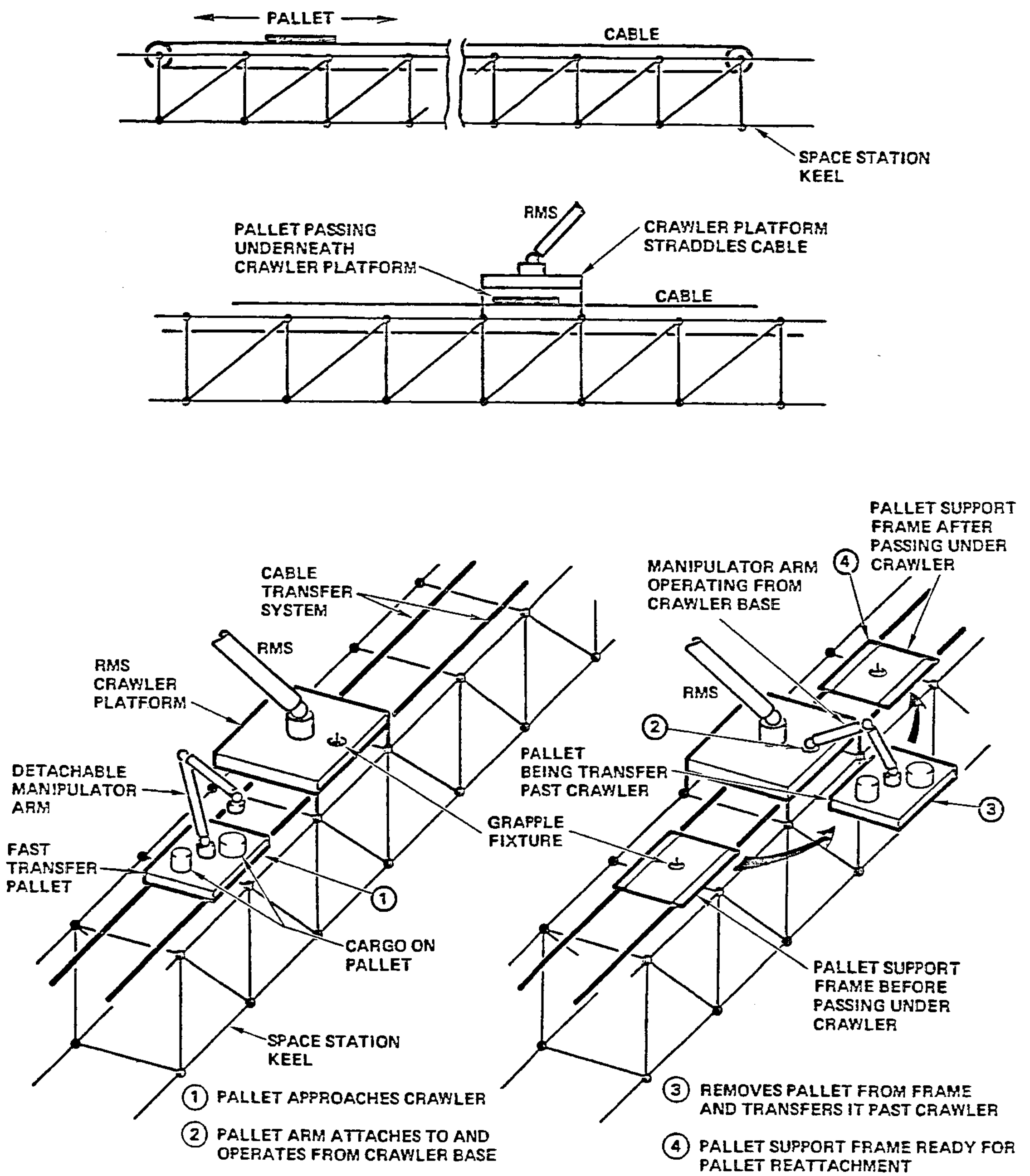


Figure 31. Cable-Driven Pallet Transfer Concept

3.7.5.4 Service Bay Design

As shown in Figures 28 and 29, the satellite berthing port and the service bay are placed in close proximity, thereby facilitating satellite transfer between the two. Incoming satellites may be retained in the berthing location if the service bay is occupied. Satellite exchange between the two locations will be expedited by use of two manipulator arms.

Evolution of servicing capabilities will call for enclosing the service bay with a hangar for crew safety and comfort and to improve working conditions. In particular, the enclosure will

- Provide thermal protection in daylight and darkness
- Provide micrometeroid protection
- Shield the work area against glare by day and facilitate uniform illumination at night
- Help prevent loss of equipment that may not be fastened securely
- Provide convenient storage space for parts, tools, equipment and supplies.

Retractability of at least part of the service bay enclosure is required for unobstructed entry/removal of satellites and full RMS access. Several alternative enclosure concepts were considered including cylindrical shapes with clam shell doors, with a retractable half shell, or with telescoping sections.

Referring to the service bay placement along the Space Station keel structure, the retractable half shell configuration, illustrated in Figure 32, is best suited for access by the RMS or cable-driven transfer system, and for compatibility with the rail-mounted crew support arm concept (Figure 29). The wall of the fixed section provides ample storage space, easily reached by the movable manipulator(s) and the crew support arm. As in the cylindrical hangar concept developed by Martin Marietta, Figure 33 (Reference: Satellite Servicing Technology Development Missions, Final Report, October 1984), a rotatable satellite holding fixture is envisioned to permit reorienting the satellite for easy access from all sides. A dexterous manipulator for

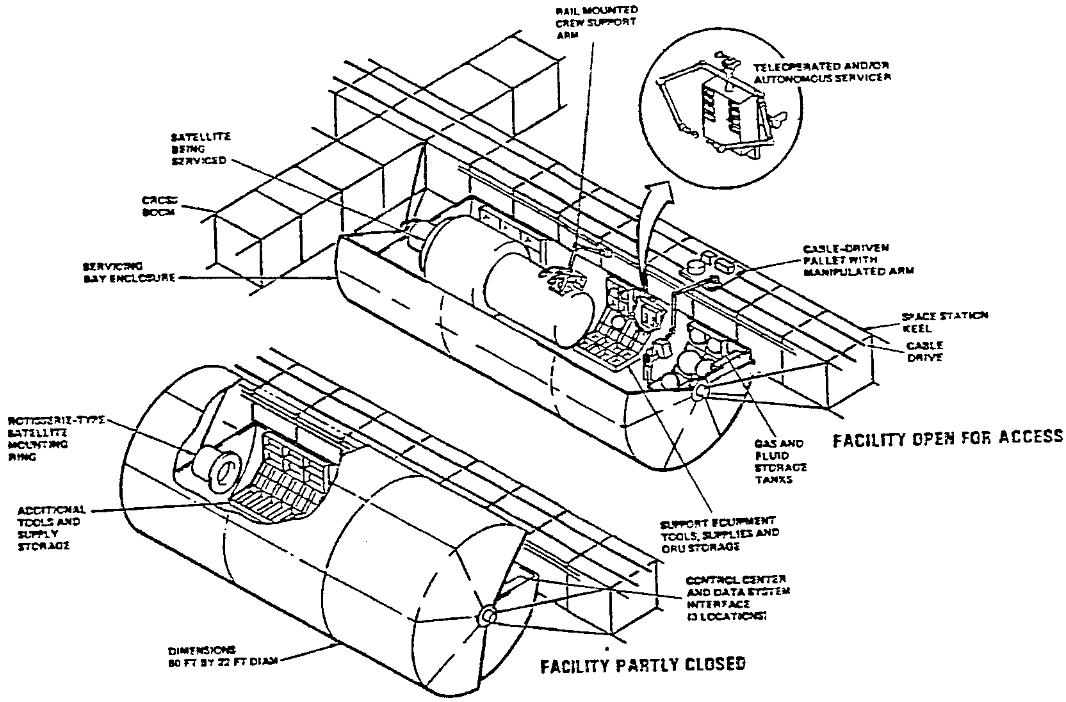
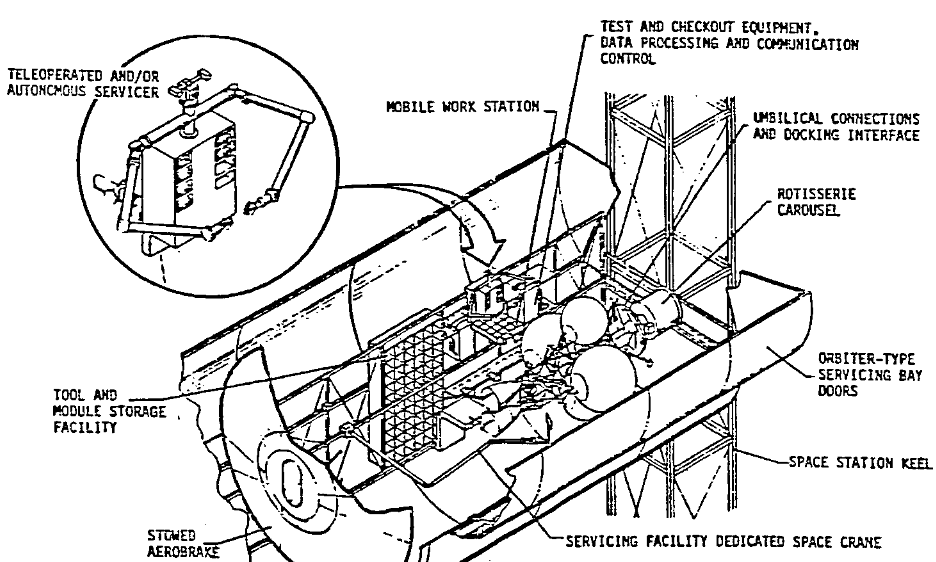


Figure 32. Enclosed Service Bay Concept



Source: Martin Marietta Aerospace "Technology Development Missions for Early Space Station Satellite Servicing" Final Review, October 9, 1984

Figure 33. OTV Servicing Facility on Space Station

teleoperated or robotic application is used within the facility, having access to any part of the satellite being serviced by being attached to the RMS or the movable crew support arm.

Unresolved issues in hangar design include questions of size and expandability, handling of balky satellite configurations (e.g., satellites with deployed appendages) and the feasibility of future conversion of the hangar into a workshop suitable for pressurization.

3.7.5.5 Portable Dexterous Manipulator Concept

Development of dexterous manipulators (DM) is a top priority for most servicing functions that initially would be performed by hands-on crew operation. The manipulator arm conceivably will have similar articulation as the standard, large Shuttle remote manipulator system (RMS), but will only be a fraction of its size for higher precision, easier control and operation in confined areas. Special end effectors will be the main element in providing greater dexterity. In principle this manipulator will be operational in the man-controlled or robotic mode.

Figure 34 shows two examples of manipulator use, satellite refueling and dexterous tool handling. Automatic changeout of end effectors or tools may be performed comparable to current industrial robot practice.

The manipulator should be designed for portability such that it can be connected to terminals in various locations on the Space Station. One design approach considered uses the "inchworm" concept which employs an arm with symmetrical ends (reciprocal design principle). Each end can be used as an end effector or plugged into a terminal which it uses as a base from which it draws power and control signals. Figure 35 shows an example of a servicing facility layout making use of a DM to assist in GRO servicing/refueling. The "inchworm" DM is stationed on a terminal base after having been transferred from the RMS crawler. Also shown in this figure is the RMS crawler, the movable EVA work platform, and an automated propellant transfer umbilical.

3.7.5.6 Storage Bays

Storage areas will have to be provided on the Space Station structure for the storage of ORUs, spacecraft, tools, space station equipment, and other support equipment. The storage area should eventually be modified to

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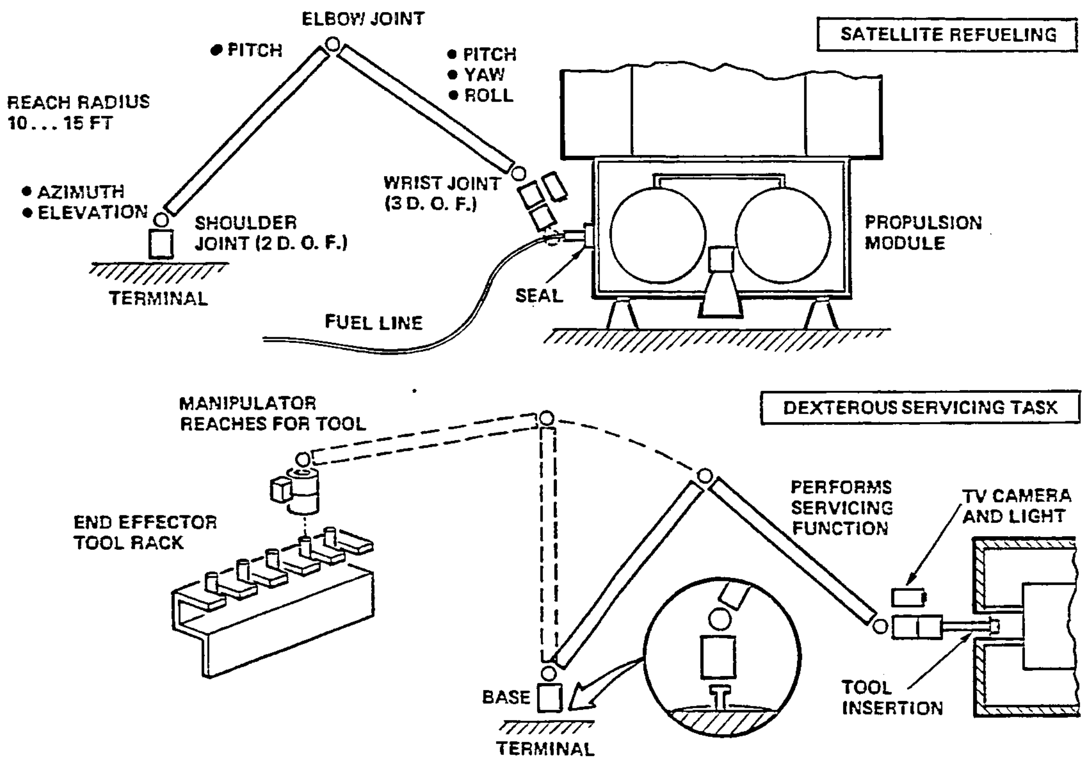

Figure 34. Portable Dexterous Manipulator Concept

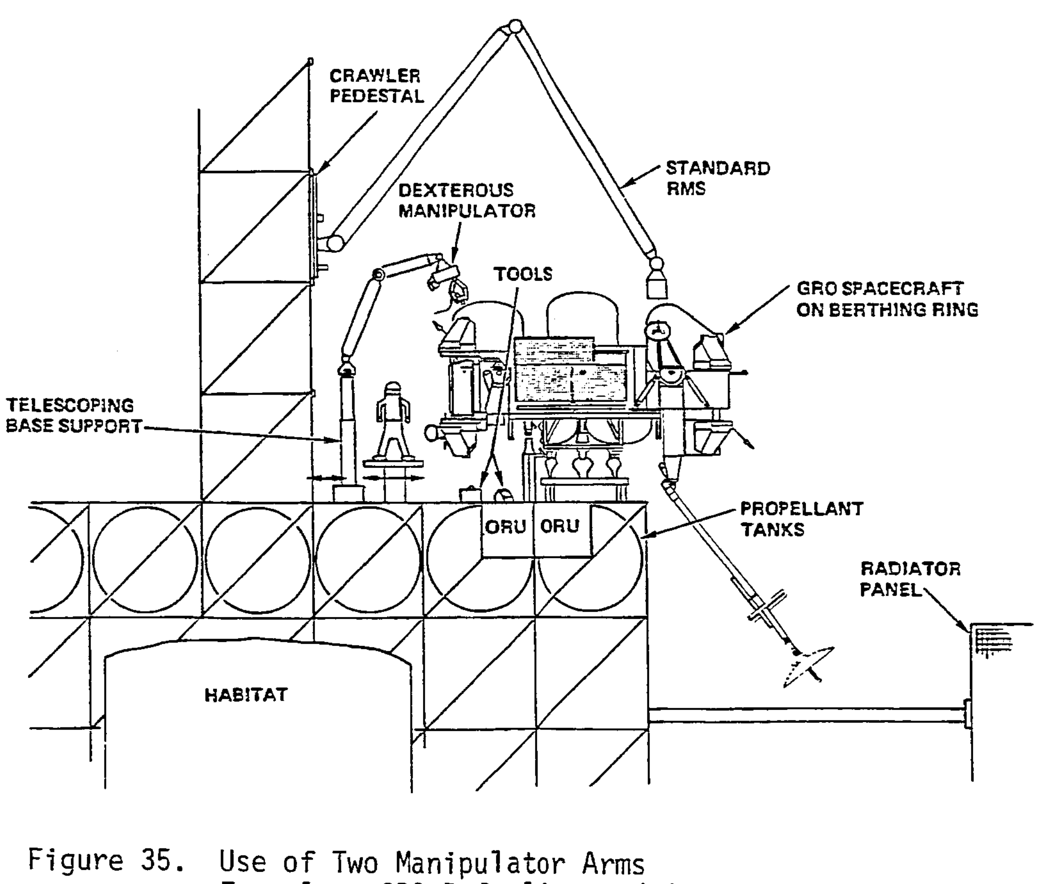

Figure 35. Use of Two Manipulator Arms
Example: GRO Refueling and Servicing

have the ability to automatically store, retrieve, take inventory, and schedule for resupply. The actual storage area would be a warehouse type configuration employing devices such as lazy susans and dedicated manipulators to retrieve and store equipment. Pressurization may be required for storage of certain types of equipment and supplies.

3.7.5.7 Central Control Station

The central control station will monitor and control all servicing functions on the Space Station. It contains all needed teleoperator controls, video and data monitors, data systems, data systems interfaces, and observation windows. Later-on, the control center should be able to readily accept newly developed robotic control, feedback, and software systems. Figure 36 shows the Grumman central control station concept. IVA crewmembers should be able to control all servicing functions from this central station, including teleoperated and robotic servicing and support operations on board the Space Station and all remote operations on free-flying remote servicers.

3.7.5.8 Software Systems

The central control station will contain the computers and other hardware to handle all the needed servicing software. Initial software requirements will include check lists, data bases, teleoperation control support, procedural information, and diagnostic aids. The system should be designed so it can handle the incorporation of new software systems and hardware. Some of the functions to be added later will include robotic control software and hardware, robot-teaching aids, automatic diagnostics and expert systems, and automated Space Station support functions (e.g., automated OMV docking, spacecraft berthing, etc.).

3.7.5.9 Tools and Support Equipment

Table 15 presents a preliminary list of required tools, equipment and software items which will have to be adapted or developed to support servicing, and especially automated servicing functions.

3.7.6 Pressurized Mobile Work Station

A pressurized, enclosed cherry picker equipped with manipulator arms, based on concepts developed by Grumman (Figure 37) will be a useful adjunct to the crew support equipment used in the servicing facility. This hybrid

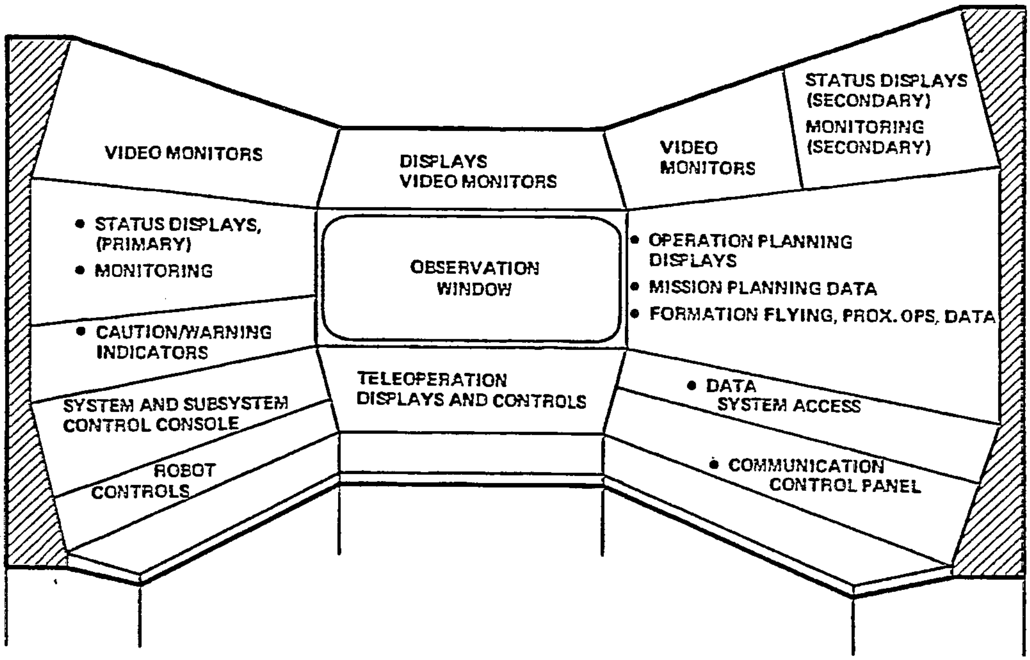

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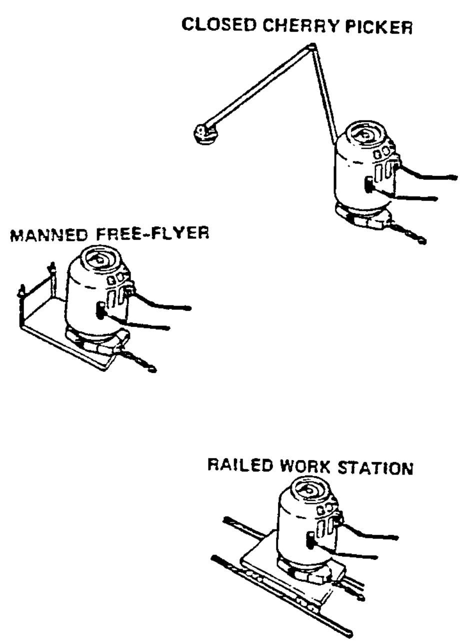
Figure 36. Central Control Station Concept
(Grumman Design)



- INITIAL DESIGN STUDIES BY GRUMMAN AND OTHERS
- HYBRID EVA/IVA CONCEPT
- EASY ACCESS TO DATA SYSTEM SUPPORT
- FLEXIBLE DEPLOYMENT
- EMPHASIS ON DIRECT CREW INVOLVEMENT AND TELEOPERATION:
  - DIRECT VISUAL INSPECTION
  - CLOSE-RANGE TELEOPERATION
  - EXTENDED CREW ENGAGEMENT POSSIBLE
  - LESS FATIGUE
  - LESS CREW EXPOSURE TO POTENTIAL EVA HAZARDS
- MODIFIED USE (WITHOUT CREW) AS TELEOPERATOR OR SMART ROBOT

Figure 37. Pressurized Mobile Work Station Concept

Table 15. Tools and Support Equipment List for Satellite Servicing

1. ELECTRONIC SUPPORT EQUIPMENT

A) DIAGNOSTIC

- DIAGNOSTIC AND SEQUENCING HARDWARE
- DIAGNOSTIC SOFTWARE/EXPERT SYSTEM
- CRT INTERFACE MONITORS
- DATA FILE WITH COMPLETE SATELLITE SYSTEM/HARDWARE INFORMATION
- REPLACEMENT CIRCUITRY, ELECTRONIC PARTS, TUBES, WIRES, ETC.

B) REPAIR

- AUTOMATIC SERVICING CONTROL SYSTEM
- SOFTWARE INPUT INTERFACE (I.E., SLOT FOR SOFTWARE CARTRIDGE)
- TELEOPERATOR CONTROLS FOR RMS AND OTHER MANIPULATORS
- TELEOPERATOR CONTROLS FOR OMV/OTV AND SERVICING KITS
- FEEDBACK DISPLAY AND TV MONITORS
- ALERT/ALARM SYSTEM

2. MECHANICAL SUPPORT EQUIPMENT

A) HANDLING SYSTEMS

- SATELLITE BERTHING STATION
- OMV/OTV/MMU DOCKING/SERVICING STATION
- RMS, ON CRAWLER
- OMV/OTV/MMU DOCKING AND HANDLING MANIPULATOR
- STORAGE
  - WAREHOUSE AREA
  - RETENTION RACKS
  - LAZY SUSANS
  - ROBOTS FOR RETRIEVAL, STORAGE, INVENTORY, AND SORTING
- OTHER MULTIPURPOSE ROBOTS
  - SPECIAL PURPOSE OR REPTITIVE TASKS
  - N-DEGREE OF FREEDOM ARMS
  - LEAD-THROUGH/TEACHABLE ROBOTS AND MANIPULATORS
- DMS (DEXTEROUS MANIPULATOR SYSTEM)
- CHANGED END-EFFECTORS FOR RMS AND DEXTEROUS MANIPULATORS
- TRANSFER SYSTEMS
  - CRAWLER FOR MANIPULATOR ARMS
  - CLOTHES LINE/CABLE TRANSFER SYSTEM
  - CONVEYORS
  - TETHERS WITH HOOKUP STATIONS/ WIRES
- END EFFECTORS
  - GRASPING
  - PROBES
  - CAMERAS
  - TOOLS (SEE TOOLS)
  - SPECIALIZED

B) MONITORING EQUIPMENT/INSPECTION/OPTICAL AIDS

- GAUGES
  - PRESSURE
  - TEMPERATURE
  - DISPLACEMENT
  - FUEL FLOW/LEVEL
  - STRAIN
  - MIXTURE RATIOS, CHEMICAL ANALYSIS
- TV CAMERAS IN APPROPRIATE PLACES
- TV CAMERAS ON ROBOTS AND MANIPULATORS
- ROBOTIC VISUAL SENSORS FOR ALIGNMENT AND CONTROL
- CCTV MONITORS IN IVA CONTROL CENTER
- PERISCOPES
- X-RAYS INSPECTION DEVICES
- LASER SCANNERS
- VARIOUS INSPECTION AIDS INCLUDING MULTISPECTRAL DISCRIMINATION, MICROSCOPES, FIBERT OPTICS, ALIGNMENT AIDS
- STROBE LIGHTS
- COLOR/SUNLIGHT FILTERS
- TV SCREEN OVERLAYS

3. SOFTWARE SUPPORT

A) PROGRAMMING SYSTEM IN CONTROL CENTER

B) TEACHING SOFTWARE FOR AUTOMATIC SYSTEMS/ROBOTS

C) SOFTWARE CARTRIDGE PLUG-IN OUTLET

D) SUPPORT SOFTWARE

- DIANOSTIC SOFTWARE
- EXPERT SYSTEM FOR PROBLEM ANALYSIS
- CHECK LISTS FOR PROCEDURES IN SERVICING
- COMPLETE INFORMATION ON SATELLITES (DATA BASE)
- AUTOMATIC CONTROL SOFTWARE
- SEMI-AUTOMATIC CONTROL SOFTWARE
- OTHER INSTRUCTION OR PROCEDURAL INFORMATION AS NEEDED

4. TOOLS/EVA SUPPORT

A) HAND TOOLS

- WRENCHES AND RATCHETS
- CUTTING TOOLS, SAWS, DRILLS
- LUBRICATING TOOLS
- SOLVENTS
- RIVETS, BOLTS, FASTENERS
- CLIPS, CLAMPS, VISES
- PFR'S
- TETHERS AND TETHER CLAMPS
- ALIGNMENT AIDS
- SCREWDRIVERS
- PLIERS, TENSION AND COMPRESSION TOOLS
- UMBILICAL CONNECTION AIDS AS NEEDED

B) CONSTRUCTION TOOLS

- RIVETS AND RIVETER
- BONDING TOOLS AND CHEMICALS
- ARC WELDERS (OPERATION IN VACUUM)
- INSPECTION AND CONSTRUCTION ROBOTS
- POSITIONING SYSTEM

EVA/IVA concept permits servicing with direct crew involvement, on location, through teleoperation or robotic capability. A crew man operating inside the pressurized enclosure would be protected against EVA hazards and is less subject to fatigue than when working in an EMU suit. Extended crew engagements for more than the typical 6-hour EVA sorties are possible. For mobility, the unit may be attached to the RMS arm, it could be rail or cable-mounted, or it may operate as a free flyer.

3.7.7 Tethered Berthing and Servicing Mode

A tether of 500 to 1000 ft. length extending from the upper end of the Space Station can be used to provide a remote berthing port at times when other berthing space on the Space Station proper would be too limited or constrained (Figure 38). It would permit servicing a space platform in the deployed configuration in close Space Station vicinity without requiring station keeping maneuvers. Space Station resources, including power, support equipment and supplies, can be utilized, and hands-on crew support is available as backup option, if necessary. Teleoperation will be unhampered by transmission time delay. Capture of incoming satellites will be aided by lateral thrusters contained in a small propulsion module at the end of the tether.

The tether tension due to the gravity gradient effect is 0.1 milli-g per 1000 ft. of tether length (measured from the combined system center-of-mass). Thus, a 50,000 lb_m platform would exert only 5 lb_f of tether tension at that distance. The tether would be a thin, braided line to keep from coiling when it is unreeled. Librations of the tether-mass system will be unavoidable but can be damped automatically by tether length manipulation.

The technology of tethered payload deployment to distances several orders of magnitude greater (e.g., 60 N.M.) for scientific measurements in the upper atmosphere is currently under development and should be directly adaptable to this application.

Deploying the tether in upward rather than downward direction is necessary to avoid obstruction of the Shuttle rendezvous approach path from below. Upward deployment, on the other hand, may at times interfere with scientific observation. Any tethered servicing operations above (or below) the Space Station therefore should be scheduled to take place on a non-interference basis, in accordance with agreed-on priorities.

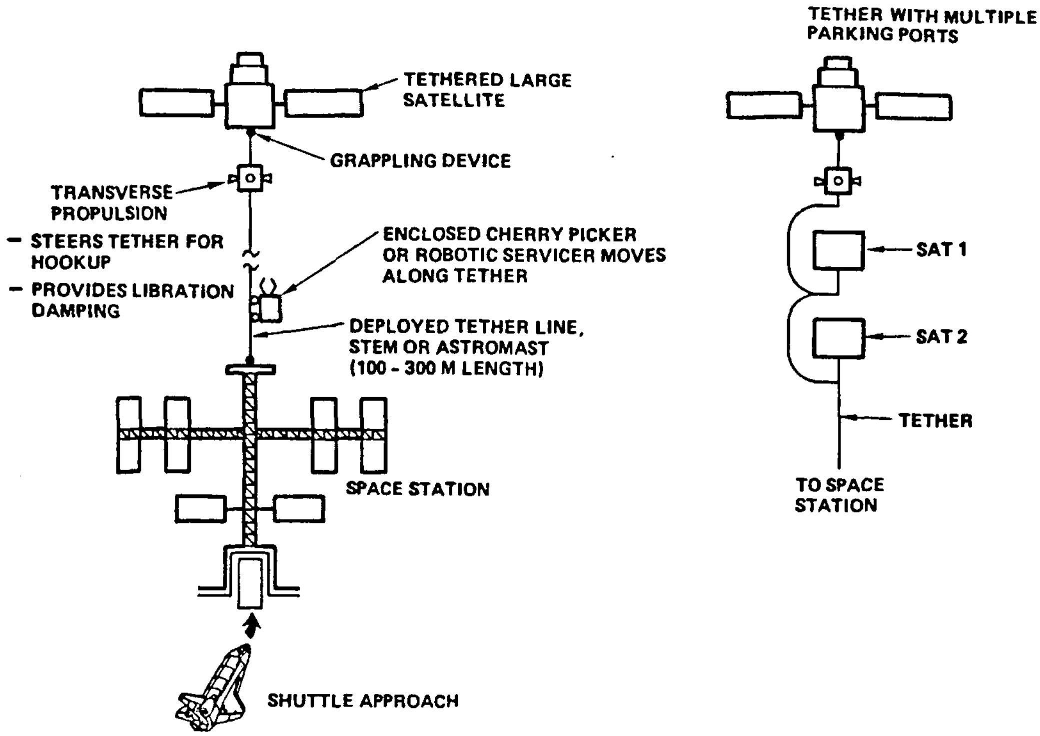


Figure 38. Tethered Spacecraft Holding Concept

3.8 Service Facility Evolution

3.8.1 Growth Requirements

Expansion of satellite servicing capabilities will be required to meet the growing demand expected for servicing, repair, refurbishment and resupply of an increasing number of satellites, both onboard and in situ. Secondly, more complex servicing tasks are to be anticipated. They will require a greater diversification as well as more advanced servicing techniques and equipment.

In terms of service facility development/evolution this implies a need for

- faster servicing operations
- increased servicing capacity (space and resources)
- advanced servicing technology: more robotic, and more sophisticated functions, less crew involvement in each task
- greater emphasis on autonomous, in-situ servicing (e.g., servicing in geostationary orbit)
- Provision of "scars" and "hooks" for future growth

3.8.2 Scarring the Space Station and Service Facility for Future Growth

The following are possible provisions for expanding the servicing capability by evolution rather than redesign and replacement:

1. Extra space for servicing, room for growth.
2. Increased utilities capacity; extra terminals for power; extra connections for fluid/gas supply and additional data system interfaces.
3. Spare data link capacity; spare data system capacity (provision of "hooks" for growth).
4. Extra plug-in locations for mobile manipulators.
5. Provision for expanded storage facilities (tools, supplies, support equipment) and automated storage systems.
6. Provisions for expansion of the control center, with addition of more control systems, robot control interfaces, and increased data base capability. Potential add-on of a remote control substation.
7. System for easy addition of software to data bases and robotic control systems.
8. Provision for increased fuel storage and larger fuel transfer volumes.
9. Provision for added OMVs and accommodation of OTVs (storage, assembly space, berthing provisions).
10. Provisions for adding a fast transport system to augment the mobile RMS
11. Expansion capability of servicing facilities for addition of dexterous manipulators, EVA work platform, cherry pickers, change-out provision for end effectors, and umbilicals for dexterous manipulators
12. Provision for growth or addition of a pressurized, shirt-sleeve servicing facility.
13. Provision for adding tethered berthing capability.

3.8.3 Growth in Number and Size of Work Areas and Support Capabilities

As servicing traffic on the Space Station grows, an increase in the size and number of work areas on the space station will be required to provide greater servicing capacity. Design concepts such as tethered servicing and pressurized work areas should be studied and trades performed to arrive at the best method for increasing servicing capacity.

Along with the growth in servicing areas there will be a requirement for increased support capabilities. Initially this capability will consist of support equipment assisting EVA crewmen in performing servicing tasks manually, and of some teleoperated equipment. The required support systems growth will involve handling and transfer equipment, manipulators, OMV docking stations, warehouse and storage facilities, the command and control center, and depots for liquids and gases. There also will be an increase in the number of mobile and dedicated manipulators and the software and automated control used for this operation. The increase in automated control will be a key growth requirement for handling the increased servicing traffic efficiently. Table 16 lists specific items of automated servicing capability growth as related to nine principal activity and task categories.

3.9 Operational Issues Related to Satellite Servicing

Operational issues such as satellite accessibility for retrieval or remote servicing, communication modes between the Space Station and a distant satellite and the effect of potentially large communication time delay on delicate manipulation tasks were addressed as part of our mission profile and technology requirements analysis under Tasks 2 and 3 of the study. Results of these and other related investigations are outlined in this section.

3.9.1 Target Satellite Accessibility

Velocity requirements for orbital transfer to and from the Space Station can become excessive, even for satellites in a low-altitude, low-inclination orbit, if the respective orbit planes are too far out of alignment due to different nodal positions. Generally, relative nodal positions shift continuously because of satellite orbital altitude differences. For example, the daily nodal regression for a satellite at a greater altitude is less than that of the Space Station. Thus, the ascending node of its orbit tends to drift in eastward direction relative to that of the Space Station. In the course of a year the differential nodal drift typically is of the order of 180 degrees, so that opportunities for an inexpensive transfer to the Space Station occur only about every other year.

Table 16. Evolution of Automated Servicing Capabilities

SERVICING TASK/AUTOMATION OBJECTIVE	AUTOMATED SUPPORT EQUIPMENT, SOFTWARE & CONTROL
SERVICING AT SPACE STATION, BASELINE 1992 IOC	• MOBILE RMS (I.E., CRAWLER), TELEOPERATED • ORU AND EQUIPMENT STORAGE AREA, RETRIEVAL AND STORAGE ACCOMPLISHED BY MOBILE RMS OR EVA CREW-MEMBERS • PROPELLANT/FLUID TANKS • PROPELLANT LINES AND REFUELING UMBILICALS • MOVABLE BERTHING RING OR CRADLE • EVA WORK PLATFORM OR DEDICATED CHERRY PICKER • INITIAL COMMAND AND CONTROL CENTER WITH: - TELEOPERATOR CONTROLS FOR RMS AND MANIPULATORS - COMPUTER HARDWARE - SOFTWARE SYSTEMS FOR DIAGNOSTIC AIDS, CHECK LISTS, DATA BASES, AND TELEOPERATOR CONTROL SUPPORT - TV MONITORS, SYSTEM DISPLAYS, AND OBSERVATION WINDOWS - OMV TELEOPERATOR AND FEEDBACK CONTROLS • OPERATIONAL OMV • OPERATIONAL MMU • DOCKING FACILITIES FOR OMV AND MMU • TV CAMERAS AND LIGHTING EQUIPMENT
AUTOMATED BERTHING OF SATELLITES TO SPACE STATION	• ROBOTIC CONTROL COMMAND INTERFACE FOR MOBILE RMS • SOFTWARE FOR ROBOTIC CONTROL OF RMS • PROCEDURE WALK-THROUGH LEARNING DEVICE FOR ROBOTIC SOFTWARE • SOFTWARE INTERFACE FOR COMPUTERS AND CONTROLS (I.E., PLUG-IN MODULES OR RF FROM GROUND) • SOFTWARE FOR BERTHING INFORMATION ON EACH SATELLITE TO BE BERTHED • PROGRAMMING CAPABILITY FOR IVA CREWMEN
AUTOMATED DOCKING OF OMV AT SPACE STATION OMV FACILITY	• DEDICATED OMV BERTHING ASSIST ARM WITH TELEOPERATED AND ROBOTIC CONTROL SYSTEMS • AUTOMATED SOFTWARE FOR OMV BERTHING TO SPACE STATION • AUTOMATED CHECKOUT AND DIAGNOSTIC SOFTWARE • AUTOMATED REFUELING SYSTEM
HARVESTING OF FREE FLYING MATERIALS PROCESSING FACILITY (MPF) (TELEOPERATED)	• SERVICING/HARVESTING KIT FOR OMV • SERVICING/HARVESTING KIT CONTROL • DATA BASE AND PROCEDURE CHECKLIST FOR MPF • ANY BERTHING ADAPTERS OR DEXTEROUS MANIPULATORS NEEDED ON HARVESTING KIT
AUTOMATED HARVEST OF MPF	• ROBOTIC CONTROL INTERFACE FOR HARVESTING KIT • AUTOMATED SOFTWARE FOR HARVESTING • SOFTWARE SYSTEM FOR SCHEDULING HARVEST TIMES AND STS VISITS FOR MATERIAL RETURN AND RAW MATERIAL DELIVERY
AUTOMATED LOAD HANDLING/STORAGE/ INVENTORY; SUPPORT FOR FAST TRANSPORT AND ASSIST IN EVA CREW POSITIONING	• AUTOMATED STORAGE AND RETRIEVAL DEVICES FOR WAREHOUSE (I.E., LAZY SUSANS, DEDICATED MANIPULATORS, ETC. . .) • FAST TRANSPORT SYSTEM ON CABLE PALLET WITH ASSOCIATED "INCHWORM" DEXTEROUS MANIPULATOR • DEXTEROUS MANIPULATOR ON RMS CRAWLER WITH CHANGEOUT END EFFECTOR AND CHERRY PICKER CAPABILITY • SUPPORT SOFTWARE FOR ALL AUTOMATED PROCEDURES
AUTOMATED ORU CHANGEOUT, UMBILICAL MATING/DEMATE, DELICATE TELEOPERATED AND AUTOMATED SERVICING TASKS	• DEDICATED DEXTEROUS MANIPULATORS OR BASIS FOR "INCHWORM" DEXTEROUS MANIPULATORS FROM RMS CRAWLER WITH CHANGEOUT END EFFECTOR AND CHERRY PICKER CAPABILITY • UMBILICAL STORAGE AREA ADAPTED FOR DEXTEROUS MANIPULATOR USE • FEEDBACK SENSORS (TACTILE, VISUAL) FOR MANIPULATORS • AUTOMATED CONTROL PROCEDURE SOFTWARE • FEEDBACK SENSOR INTERPRETATION SOFTWARE
IN-SITU SERVICING OF SATELLITES (TELEOPERATED)	• SERVICING KITS FOR OMV INCLUDING TV CAMERAS, MANIPULATORS, SENSORS, AND NEEDED TOOLS AND PARTS • TELEOPERATED CONTROLS FOR SERVICING KIT • BERTHING ADAPTER FOR SPACECRAFT TO BE SERVICED
AUTOMATED BERTHING AND SERVICING OF SATELLITES IN-SITU	• AUTOMATED BERTHING SYSTEM ON OMV (E.G., LASER SIGHTING SYSTEM) WITH ON-BOARD AUTOMATED CONTROL SYSTEM/SOFTWARE • ON-BOARD AUTOMATED CONTROL SYSTEM/SOFTWARE FOR SERVICING TASK INCLUDING DAMAGE AVOIDANCE SYSTEM

Figure 39 shows nodal regression rates at different orbital altitudes and inclinations (left hand diagram), e.g., for 100 n.mi. altitude difference at 30 deg inclination the differential regression is about 0.5 deg/day.

A trade between propellant requirements and transfer time may be useful if the servicing event can be planned several months in advance. It involves extra altitude changes in the transfer mission profile but provides the benefit of bridging moderate nodal misalignments between Space Station and target satellite orbits at an acceptable ΔV expenditure.

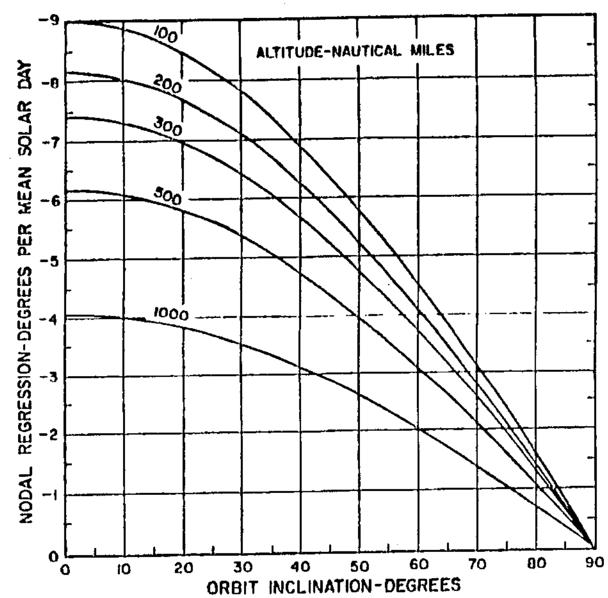
To bridge the nodal misalignment ($\Delta\Omega$) between the Space Station orbit and the target satellite orbit at an acceptable ΔV expenditure when performing an OMV orbital transfer, one may select a transfer trajectory that has a significantly higher or lower altitude than the departure or target orbit. This results in an increase in relative OMV nodal drift rate to "catch up" with the nodal difference of the target orbit while avoiding or minimizing out-of-plane maneuvers that would be more costly than the in-plane altitude change ΔH. The principle is illustrated by the ΔH-versus-$\Delta\Omega$ profiles shown on the right hand side of Figure 39.

Figure 40 shows the relation between altitude difference (and the corresponding ΔV expenditure) and elapsed time to complete the transfer between two orbits with large nodal misalignments, and indicates the possibility of a trade between time and ΔV requirements as previously mentioned.

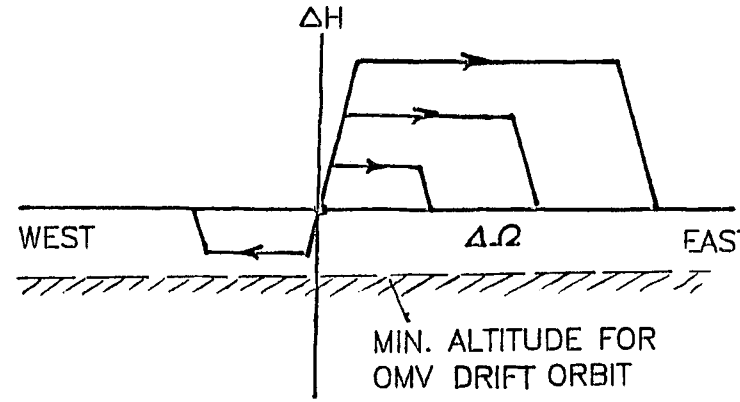
Planning and optimization of such orbital transfers, generally to be performed by the OMV flying round-trip missions, will be a major concern in servicing activities and calls for extensive data system computational support.

Figure 41 presents planning alternatives available to perform the orbital transfer of the OMV (or a satellite) to and from the Space Station for purposes of servicing. The options available under co-orbital and non-co-orbital conditions are shown by the logic flow diagrams on the left and the right side of Figure 41 , respectively.

NODAL REGRESSION RATE $\dot{\Omega}$

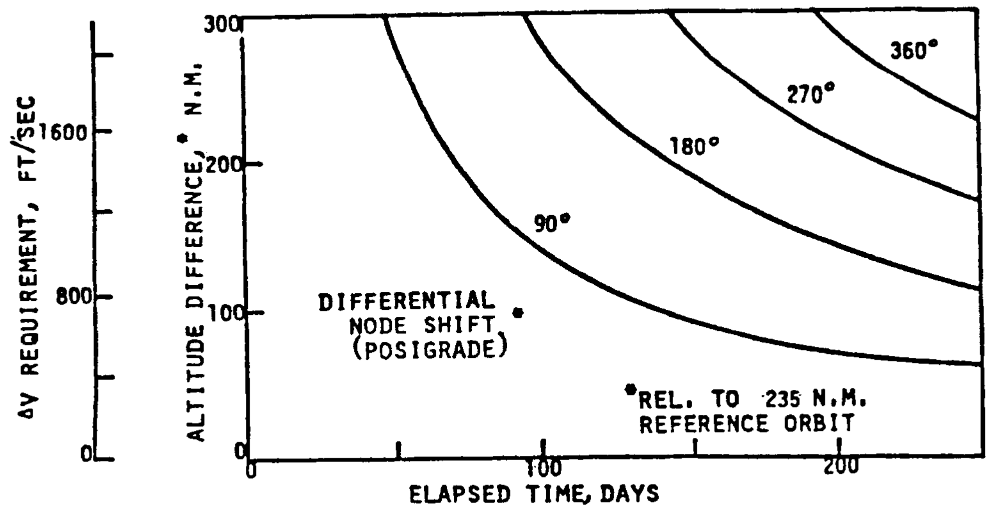


NODAL SHIFT (WEST OR EAST)
PER UNIT TIME



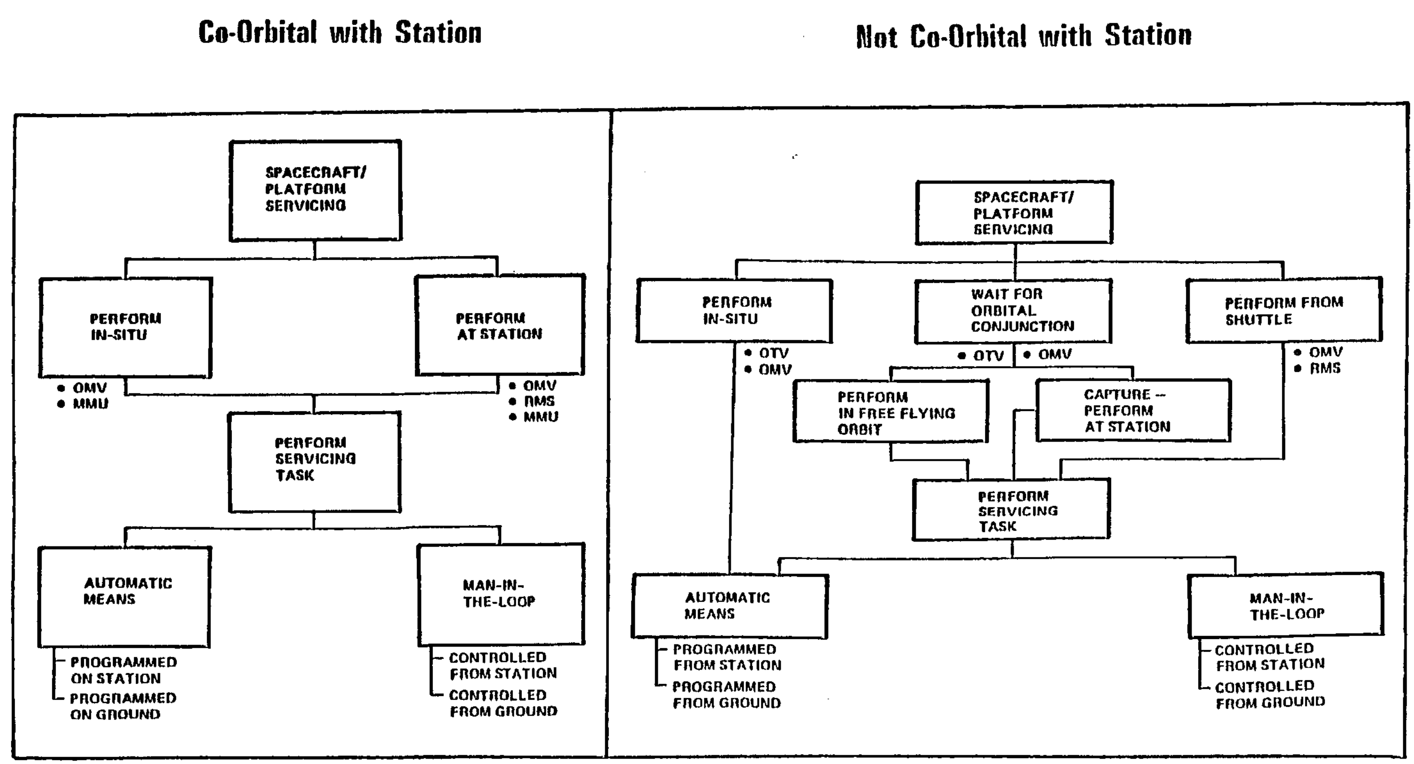
- WESTWARD DRIFT RATE LIMITED BY MINIMUM ALLOWABLE DRIFT ORBIT ALTITUDE
- FOR LARGE WESTWARD SHIFT ($\Delta\Omega$) A CORRESPONDING EASTWARD SHIFT $360^\circ - \Delta\Omega$ MAY BE SUBSTITUTED TO MAKE USE OF LARGER DRIFT RATES

Figure 39. Accommodation of Nodal Point Difference by OMV Maneuver to Differential Altitude



- DIFFERENTIAL ALTITUDE MANEUVER BY OMV CAN MAKE TARGET SATELLITE ACCESSIBLE FOR SERVICING BUT MAY REQUIRE MAJOR NODAL DRIFT TIME INTERVAL.
- FOR GIVEN NODAL OFFSET, TIME IS INVERSELY PROPORTIONAL TO ΔV REQUIREMENT
- THE MANEUVER CAN PROVIDE PHASE ERROR CORRECTION WITHOUT EXTRA PROPELLANT COST

Figure 40. Accessibility of Free-Flying Satellite Under Nodal Point Misalignment



REFERENCE: NASA TM-86652 BOOK 6, SYSTEM STATIONS, SPACE STATION PROGRAM DESCRIPTION DOCUMENT, MARCH 84

Figure 41. LEO Spacecraft and Platform Servicing Options

3.9.2 Remote Servicing Communication Issues

Two communication modes between the Space Station and an OMV performing remote (in-situ) servicing tasks at a LEO target satellite were investigated and compared, viz., communication via relay satellite link or by direct line-of-sight transmission. Another alternative, viz., that of letting the remote servicing operation be controlled by a ground station via relay satellite (e.g., the TDRS) generally should be avoided since it does not conform with the guideline of maintaining SS operational autonomy from the ground.

The relay communication mode via TDRSS is illustrated in Figure 42. The SS-to-satellite, or OMV, relay link may involve as many as 8 to 16 laps to and from synchronous altitude, counting the signal paths to the TDRS, to the TDRSS ground station at White Sands, from there to the operations control center (say at GSFC), perhaps via DOMSAT link, back to White Sands, up to TDRS and down to the target satellite/OMV. Feedback signals required to perform closed-loop control of the servicing task must travel this zig-zag route in reverse (left hand figure). This complex signal path is based on the bent-pipe signal transfer principle embodied by present TDRSS operations. A future, advanced TDRSS design would eliminate at least part of this complexity (right hand figure).

For purposes of this discussion, we have assumed the current TDRSS operation mode, which may cause a total feedback signal round-trip delay of 5 to 10 seconds including delays due to image processing. This is quite unacceptable for purposes of controlling delicate tasks by teleoperation, and would impose an immediate need for autonomous, robotic servicing.

Direct line-of-sight (LOS) communication (Figure 43) is much more compatible with teleoperation than the relay communication mode since it reduces the RF signal round-trip delay to less than 30 milliseconds. However, the target satellite will slowly drift away and disappear from view, generally after a few hours, unless it is at an altitude identical with that of the Space Station. Typically, the maximum LOS distance is about 4000 km for satellites at near co-altitude. The geometry is illustrated at the top of Figure 43 which shows the relative motion of the target satellite with respect to the Space Station.

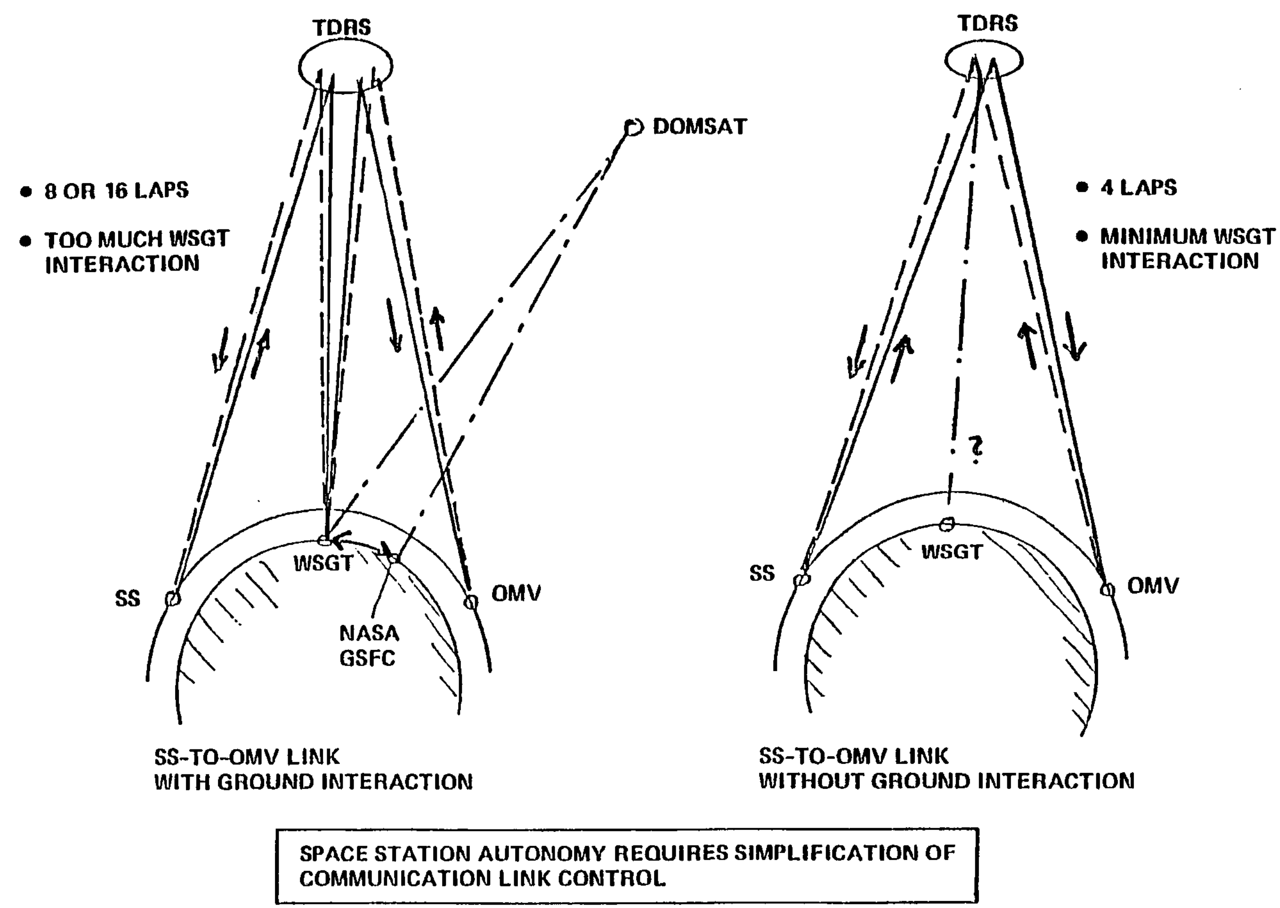


Figure 42. Remote Servicing Communication Issues

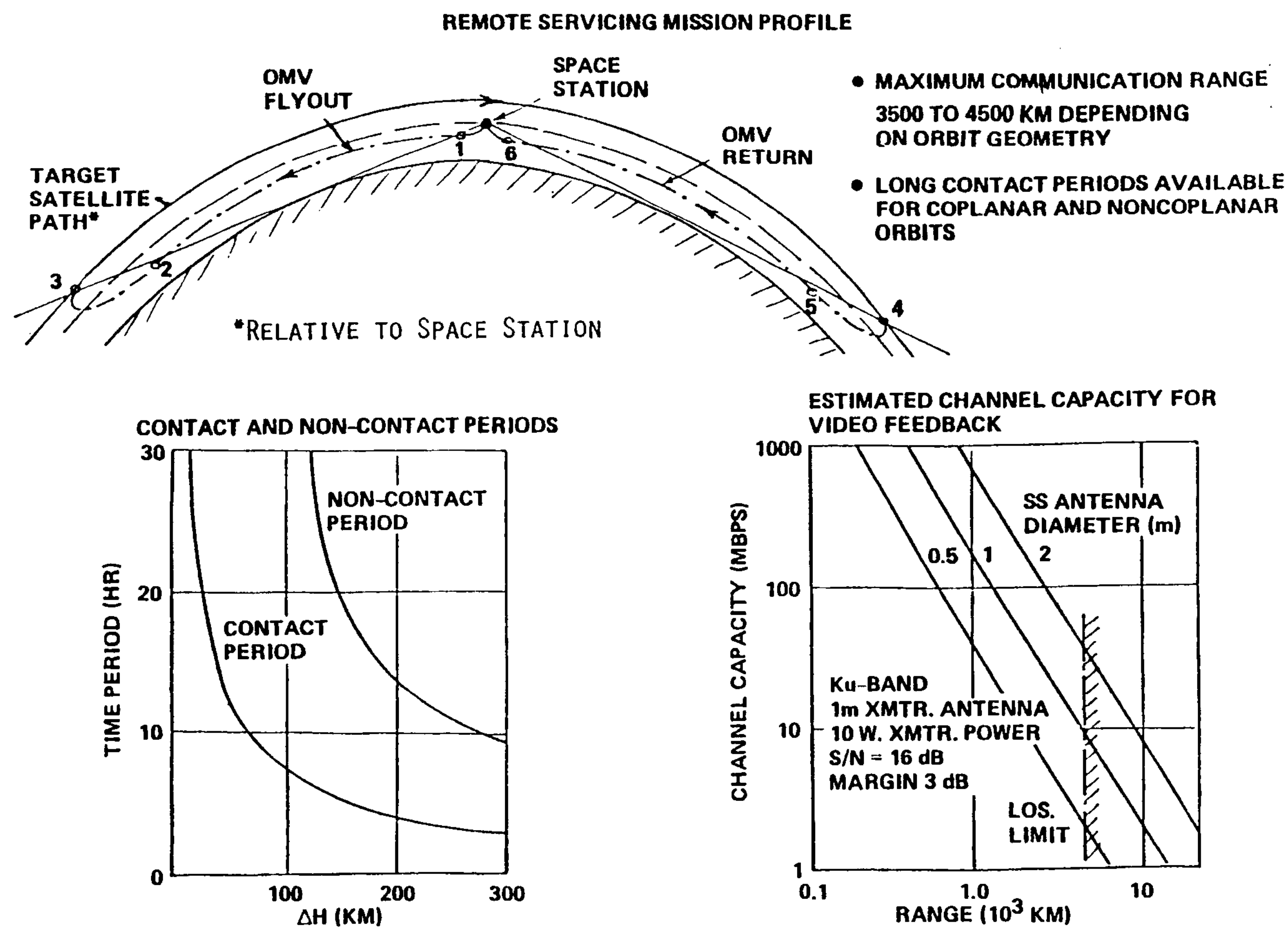


Figure 43. Direct L.O.S. Communication Characteristics

The diagram at the lower left in Figure 43 shows contact periods available for LOS communication, as well as non-contact periods, as functions of differential altitude. Remote servicing missions to LEO satellites can be planned to make best use of the total direct LOS contact periods or "windows" available, i.e., typically 4 to 10 hours. The OMV flyout and return paths can be arranged so as to maximize the number of operating hours available within the visibility window.

The figure at the lower right shows the estimated communication link channel capacity for TV image transmission as function of range for moderate antenna sizes and transmitter power. Video images of adequate quality for teleoperation purposes, at a frame rate of about 5 frames per second, are obtainable with data compression ratios of 10 : 1. For such image transmissions a channel capacity of the order of 1 Mbps would be sufficient.

Our Reference Mission 4 requires control of remote servicing at GEO altitude. Here the contact periods for direct communication from the Space Station would be less than an hour for every SS orbital revolution alternating with about 35 to 40 minutes of non-contact. A preferred alternate operating mode would be control from a ground station, a departure from SS operational autonomy. Fully robotic servicing but with supervisory control by a human operator would be another alternative. It is reasonable to assume that the required robotic in-situ servicing techniques will be well established by the time, probably in the late 1990s, when GEO satellites will first become accessible for remote servicing, awaiting the development of a reusable OTV, equipped with a dexterous servicer (see also Section 3.9.3).

Communication requirements in support of remote servicing missions must be viewed in the context of the overall communications traffic centered on the Space Station. Figure 44 gives an overview of the great diversity of communication links that may be in use simultaneously or at different times, including relay links and direct links. To plan and execute the many aspects of this communications load is a principal concern of the ongoing concurrent TRW SS Data System Architecture Study being performed for NASA/JSC and also that of the SS Automation Study subject assigned to Hughes Aircraft Company.

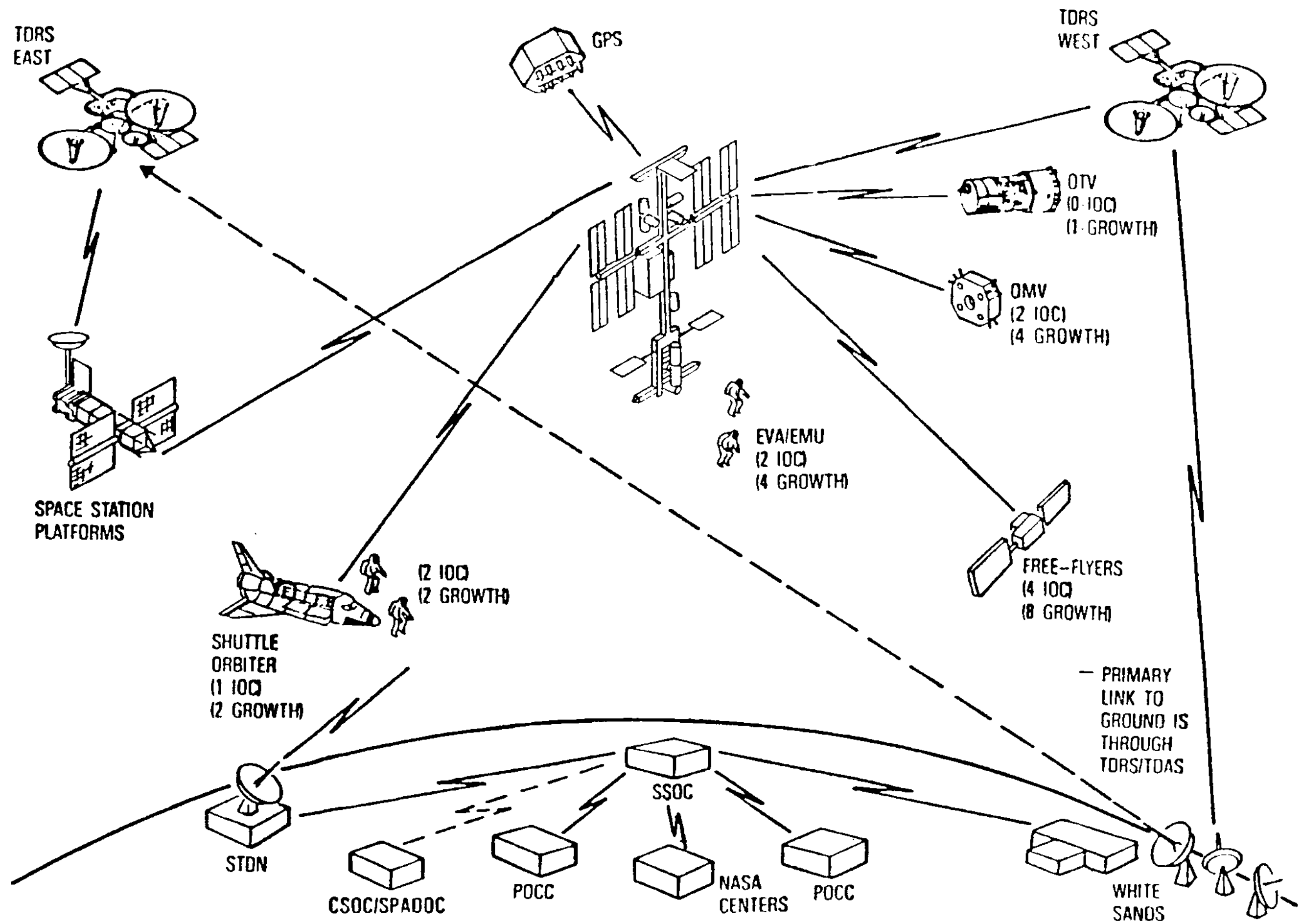


Figure 44. Space Station Communication Traffic

3.9.3 Geostationary Satellite Servicing Issues

Remote servicing of geostationary satellites primarily hinges on the availability of orbital transfer vehicles with sufficient ΔV capacity. The conventional one-way trip to GEO from the Space Station orbit, at 28.5 deg inclination, requires about 13,500 fps. The round-trip of a reusable OTV requires twice this amount.

Current OTV design concepts generally do not include staging provisions which would, of course, greatly reduce the propellant load. One approach to achieve some propellant economy includes the use of an aerobrake to eliminate the need for the last of the four major transfer impulses, i.e., the 7500 fps impulse required for capturing the returning OTV in a low-altitude circular orbit for Space Station rendezvous.

Table 17 summarizes OTV performance characteristics in a GEO satellite servicing mission, comparing payload weights with and without the use of an aerobrake for several different payload transfer scenarios and OTV configurations. The results are based on a 1983 General Dynamics study. Cryogenic propellants, LH_2 and LO_2, with an I_{sp} of $\sim$460 sec were assumed in this analysis. We note that aerobraking permits about twice as much weight to be carried on payload return missions. The performance advantage achieved on delivery missions however, is much smaller, as seen by comparing the results in columns 3 and 5 of the table.

Clearly, a 30 to 60-thousand pound propellant expenditure for a single OTV round-trip would be more affordable, economically, if not only one but several GEO satellites were to be serviced on the same mission. Toward the year 2000, with so many satellites in operation in GEO orbit, including those designed for serviceability, there may often be a need for combined missions, even if this means waiting for several servicing calls to accumulate between OTV sorties.

An alternative would be sorties of expendable OTVs, the first one to carry a self-contained OMV equipped with a smart front end, which will remain in GEO orbit for successive servicing of several satellites, receiving delivery of ORUs and other supplies (e.g., propellant) by later OTVs flying one-way missions.

Table 17. OTV PERFORMANCE IN GEOSTATIONARY SATELLITE SERVICING MISSION*
(LH_2, LO_2 PROPELLANT, I_{SP} = 460 SEC)

CONFIGURATION/MODE	TOTAL PROPELLANT (10^3 LB)	PAYLOAD WEIGHT (10^3 LB) WITH AEROBRAKING TO GEO	RETURN	ALL PROPULSIVE TO GEO	RETURN
TWO-TANK CONFIGURATION					
- P/L DELIVERY ONLY	28.6	11.0	0	9.6	0
- P/L DELIVERY & RETURN	28.6	5.9	5.9	2.8	2.8
FOUR-TANK CONFIGURATTION					
- P/L DELIVERY ONLY	57.1	28.7	0	25.8	0
- P/L DELIVERY & RETURN	57.1	15.4	15.4	7.5	7.5

*DATA FROM GENERAL DYNAMICS STUDY OF TECHNOLOGY DEVELOPMENT MISSIONS (MSFC CONTRACT NAS 8-35039), INTERIM REVIEW, 12 JANUARY 1983

Economic factors of these alternatives require further study. TRW has investigated alternative modes of supplying the Space Station with large amounts of propellant. The most attractive mode foresees the systematic utilization for propellant transport of any Shuttle cargo weight margins left unused whenever a bulky principal payload fills the available cargo bay volume but at considerably less than the total weight capacity of ~65,000 lb. Results indicate that for typical Shuttle flight schedules in the 1980s the cumulative propellant weight that could be delivered as payload-of-opportunity in eight to ten Shuttle missions can be as large as 100,000 lb, on the average, in one year. However, many related issues remain to be analyzed, including those of available fuel depot capacity and extended storage of cryogenic propellants if a cumulative delivery procedure were to be adopted.

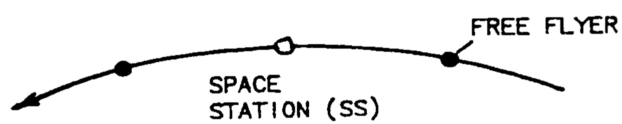
3.9.4 Proximity Operations of Satellites and OMVs

Only a brief account of the many issues involving proximity operations near the Space Station which are related to satellite servicing is included in this section.

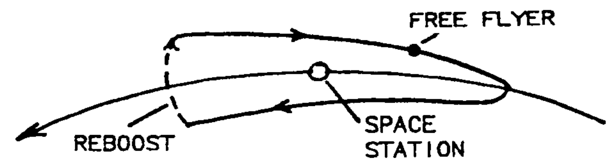
Formation flying and stationkeeping issues involving platforms and satellites co-orbiting with the Space Station are summarized in Figure 45. Some of these spacecraft may require OMV assist in periodic reboosting as well as OMV servicing for repair or resupply. The nodal alignment issue listed in the chart was already discussed in Section 3.9.1.

Issues of automated rendezvous and docking are summarized in Figure 46. The illustration at the upper left shows a laser range and angle determination sensor currently being developed at NASA/JSC and awaiting demonstration on one of the next Shuttle missions. The sensor is capable of range determination accuracies of the order of one inch at distances up to 1000 ft and angle determination accuracies of several arc minutes, well within the accuracy requirements of close-in automated rendezvous/docking control. Sets of passive retro reflectors, such as simple cats' eye reflectors, placed at appropriate locations on the surface of the approaching satellite permit accurate determination of its relative attitude and rotation rates (if any).

A. CO–ALTITUDE FORMATION, NO DRAG

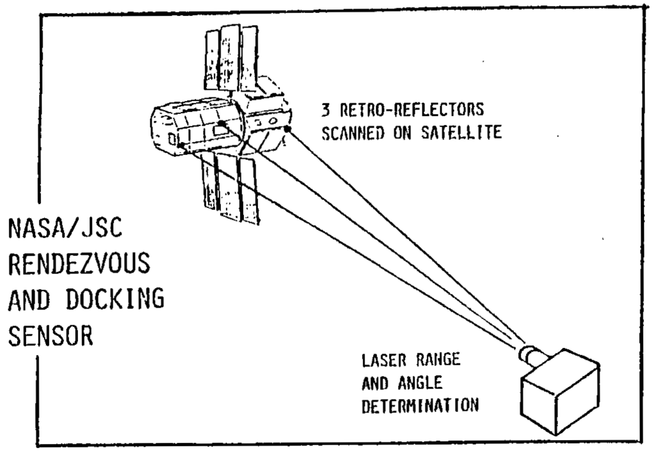


B. WITH DRAG

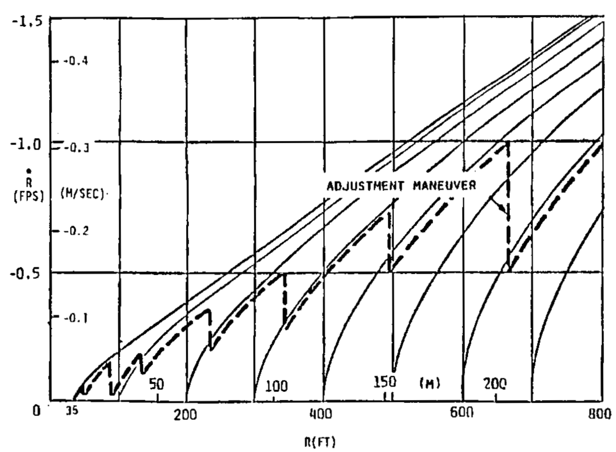


- INVARIANT RELATIVE POSITIONS AT CO–ALTITUDE ONLY IN IDEALIZED, DRAGFREE CASE (A)
- DIFFERENTIAL DRAG EFFECT CAUSES RELATIVE ORBIT DECAY OF FREE FLYER, WITH PHASE ANGLE CHANGE AND SLIGHT NODAL DRIFT RELATIVE TO SS ORBIT
- INTERMITTENT REBOOST MANEUVERS REQUIRED TO MAINTAIN FORMATION FLYING PATTERN (B)
- SATELLITES OPERATING AT DIFFERENT ALTITUDE BUT SAME ORBIT INCLI–NATION AS SS WILL BE ACCESSIBLE FOR PLANNED SERVICING PERIODI–CALLY AT TIMES OF NODAL ALIGNMENT (TYPICAL NODAL DRIFT 0.5DEG/DAY PER 100 NM ALTITUDE DIFFERENCE)
- UNPLANNED SERVICING MISSIONS MAY REQUIRE MAJOR OMV MANEUVERS TO OVERCOME DIFFERENTIAL NODAL POSITIONS

Figure 45. Formation Flying Issues



ZERO-VELOCITY RENDEZVOUS TRAJECTORY*



- SERVICING TRAFFIC REQUIRES FREQUENT RENDEZVOUS/DOCKING
  - AT SPACE STATION
  - AT TARGET SATELLITES
- AUTOMATED SEQUENCE IS ESSENTIAL FOR ELIMINATING TIME-CONSUMING ROUTINE CREW TASKS
- OPERATIONAL SAFETY IS PRINCIPAL CONCERN
- NASA/JSC LASER RENDEZVOUS SENSOR:
  - SIMPLE DESIGN AND OPERATION
  - ONLY REQUIRES PASSIVE RETRO-REFLECTORS ON TARGET SATELLITE
  - HIGH RESOLUTION IN RANGE, RANGE RATE, ANGLES AND ANGLE RATES
  - EARLY SHUTTLE DEMONSTRATION PROJECTED
- ZERO VELOCITY RENDEZVOUS APPROACH (MINIMIZING PLUME IMPINGEMENT) IS PREDICATED ON RELIABLE, HIGHLY ACCURATE SENSOR CONCEPT

Figure 46. Automated Rendezvous/Docking/Berthing

*Ref. Robert L. Anderson (McDonnell Douglas), unpublished note.

The diagram at the lower left shows relative satellite approach trajectories designed to achieve zero-velocity rendezvous with the Space Station without requiring a terminal retro-maneuver, thereby avoiding thruster plume impingement. This concept is an idealization which cannot be fully realized without iterative guidance corrections as range decreases. However, it tends to minimize the amount of thrusting by the satellite that is required in the immediate vicinity just prior to reaching the closest approach point where it can be grappled and retrieved by the Space Station's RMS.

3.9.5 Effects of Transmission Time-Delay on Teleoperation

The occurence of transmission time-delay in the feedback control loop used for in-situ satellite servicing was previously discussed in Section 3.9.2. Depending on the communication mode employed the time-delay may range from fractions of a second to 10 seconds or more, and long time-delays may destabilize the control loop if the process being controlled has a short time constant.

Table 18 lists processes and operating conditions with an inherently high sensitivity to time-delay effects and gives examples of the factors that will contribute to time-delay in video image forming and transmission.

Display techniques that are used to provide feeback information to the human operator controlling the process also are a matter of concern. A predictive or "quickened" display of a slowly responding process often can produce an improvement in its controllability.

Three principal sets of criteria listed in Table 19 indicate how sensitive to feedback time-delay a teleoperated control task will be and how much time-delay T_0 is acceptable compared with the time constant T_1 of the process.

Table 18. TELEOPERATION CONTROL SENSITIVITY TO FEEDBACK DELAY

1. EXAMPLES OF HIGH PROCESS SENSITIVITY TO FEEDBACK DELAY

- GRABBING	- CONTINUOUS CONTROL MODES
- INSERTION	- STEREOSCOPIC SENSING MODES
- OBSTACLE AVOIDANCE	- PRESSURE AND ORIENTATION-SENSITIVE PROCESSES WITH FORCE AND TORQUE THRESHOLDS AND LIMITATIONS
- ASSEMBLY	
- REMOTE DOCKING CONTROL	- LARGE EXTERNAL PERTURBATIONS

2. VIDEO FEEDBACK DELAY EXAMPLES
   - COMMUNICATION VIA RELAY SATELLITE WITH MULTIPLE SIGNAL PATHS (UP TO 16 LAPS TO/ FROM GEO ALTITUDE)
   - IMAGE FORMING/PROCESSING DELAYS AND RELAY TURN-AROUND TIME
   - IMAGE DATA COMPRESSION
   - LOW FRAME RATE

3. DISPLAY TECHNIQUE USED (EXAMPLE REMOTE RENDEZVOUS/DOCKING CONTROL)

- DISPLAY OF POSITION CHANGE DUE ΔV IMPULSE - NOTICEABLE RESPONSE TAKES 20 TO 40 SECONDS	IMPROVED BY PREDICTIVE DISPLAY TECHNIQUE

Table 19. CRITERIA OF TELEOPERATION SENSITIVITY TO TIME DELAY

1. CHANGE BETWEEN PREDICTABLE AND ACTUAL OUTCOME OF COMMANDED ACTION MUST BE SMALL ENOUGH DURING TIME DELAY SUCH THAT
   - CATASTROPHIC RESULTS ARE PRECLUDED
   - UNDESIRED RESULTS CAN BE CORRECTED FOR SUCCESSFUL TASK COMPLETION WITHIN ACCEPTABLE TIME LIMITS
   - UNSTABLE RESPONSE (OSCILLATION) IS AVOIDED

2. DETERMINE AND/OR QUANTIFY BOUNDS OF
   - UNKNOWN/UNPREDICTABLE BEHAVIOR
   - DIFFERENCE BETWEEN OPEN-LOOP RESPONSE AND UNPREDICTABLE STATE OF SYSTEM

3. TIME CONSTANT OF PROCESS (T_1) VS. TIME DELAY (T_0). (FEASIBILITY ALGORITHM)
   - PROCESS IS INSENSITIVE IF $\omega_1 T_0 \ll 0.22$ RAD $\triangleq$ 11 DEG, WHERE $\omega_1 = 2\pi/T_1$. (11 DEG PHASE ANGLE CORRESPONDS TO SETTLING TIME IN ASYMPTOTIC RESPONSE).
   - IF $\omega_1 T_0 \approx 0.22$ RAD TASK CAN BE ACCOMPLISHED STEP-BY-STEP. BUT COMPLETION TIME IS INCREASED SIGNIFICANTLY.

Consider, for example, the remote control of OMV orbit transfer and rendezvous maneuvers. External and internal influences and perturbations for which criteria 1 and 2 above are relevant are summarized below. Also indicated are some control response issues that are related to these perturbations.

- External perturbations causing relative motion and orientation changes
  - gravity gradients
  - aero torques
  - solar pressure
  - imperfect knowledge of orbit dynamics
- Internal perturbations and factors causing relative motion and orientation changes
  - sensor errors or failures (inputs to teleoperator)
  - ΔV errors due to errors from all sources
  - internal model errors when operator doesn't "understand" the physical situation
- External and internal perturbations affect
  - timely failure detection
  - length of time needed to rendezvous
  - fuel usage

Assuming the system is properly designed, functionally, intermittent control impulses by teleoperation will be permissible, and the human operator can be trained to become proficient even with moderate time-delay.

However, the amount of time-delay will determine the peak ΔV impulses that the operator should be allowed to command. It also will affect the accuracy of the maneuvers, the time elapsed to completion of the rendezvous and the total amount of propellant utilized.

Figure 47 shows a block diagram of the remote control loop with transmission time-delay (τ) in the forward and return links. In addition to human operator control inputs there may also be robotic control to augment human control action (dashed line, at left) plus local feedback control, at the site of the controlled process, to protect against potentially adverse effects of time-delay in the teleoperation loop. In rendezvous/docking control by teleoperation the human operator may be aided in his task by a simulated external view driven by relative position and orientation telemetry data (lower left).

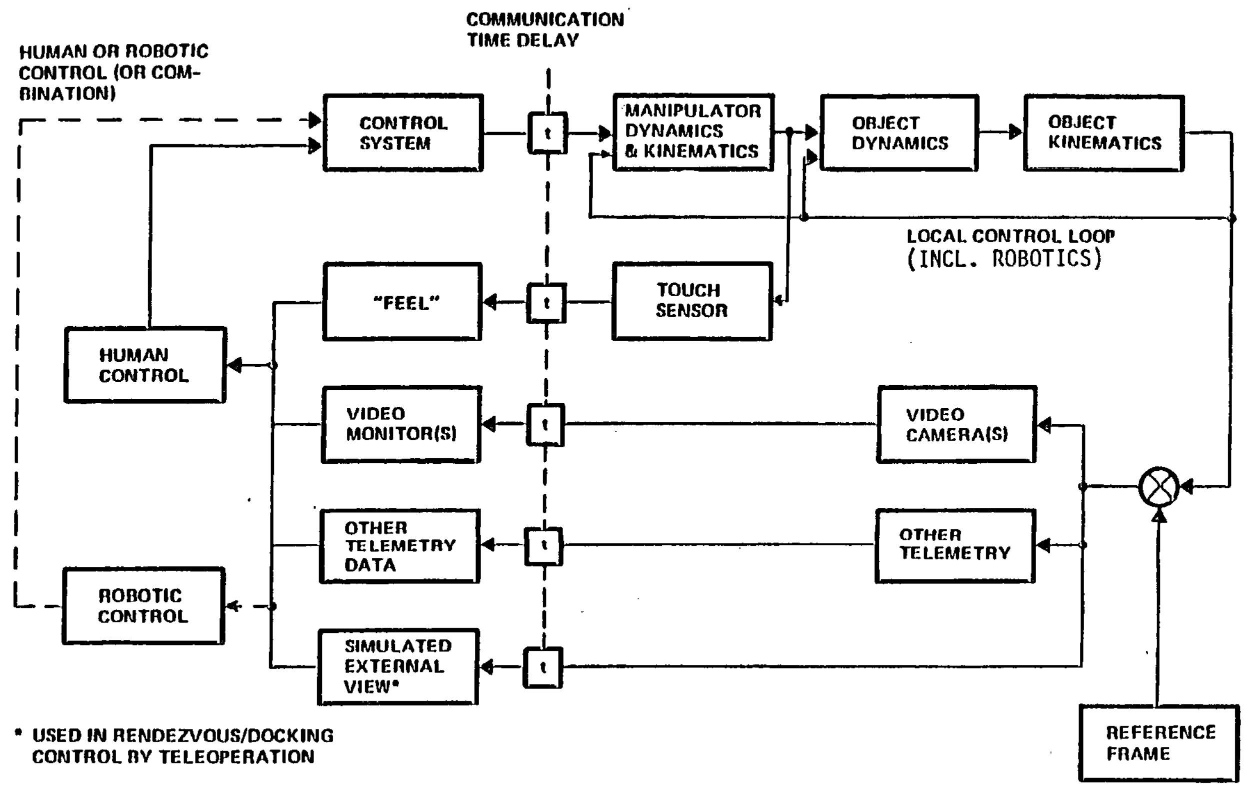


Figure 47. Major Elements in Remote Control Loop

3.9.6 Spacecraft Servicing Operation Examples

3.9.6.1 Design Features for Serviceability

Spacecraft design features and attributes required to facilitate on-orbit servicing and, in particular, automated and remote servicing are listed in Table 20. Generic design features such as those listed under (A), have been or are being incorporated in early serviceable spacecraft. The design of the NASA/GSFC developed Multi-Mission Modular Spacecraft (MMS) family which includes the Solar Maximum Mission Spacecraft (SMM) and Landsat 4 embodies these features. Other examples are the Gamma Ray Observatory (GRO) which uses several MMS replaceable modules, the Space Telescope (ST) and the Advanced X-Ray astrophysical Facility (AXAF) which will have replaceable payload instruments and support modules. The OMV also is being designed for easy serviceability on-orbit. All of these spacecraft will be serviced initially by the Shuttle Orbiter, the ST, AXAF and OMV later-on by the Space Station. The successful SMM repair mission performed in April 1984 which included changeout of the attitude control module demonstrated the value of serviceability design concepts which characterize the MMS spacecraft family.

3.9.6.2. GRO Servicing

Figure 48 shows serviceable hardware on the GRO (at left) and servicing operations in progress (at right) with the spacecraft berthed on the servicing platform mounted in the Shuttle orbiter cargo bay. Note that the solar panels and the high-gain antenna boom are left in deployed condition while servicing is performed.

GRO servicing will include subsystem module changeout if necessary, as shown by the illustration, and propellant resupply. Hands-on EVA servicing, aided by use of the RMS, is the servicing mode for which the GRO is designed. The orbit replaceable units (ORUs) are the modular power system (2) and the command and data handling module. The scientific payload instruments are not intended for orbital replacement in view of the difficulty of performing such a task at this early stage of servicing technology development.

Although not currently projected as part of the GRO mission profile, similar servicing activities might also be performed on the Space Station, on the GRO or comparable serviceable spacecraft.

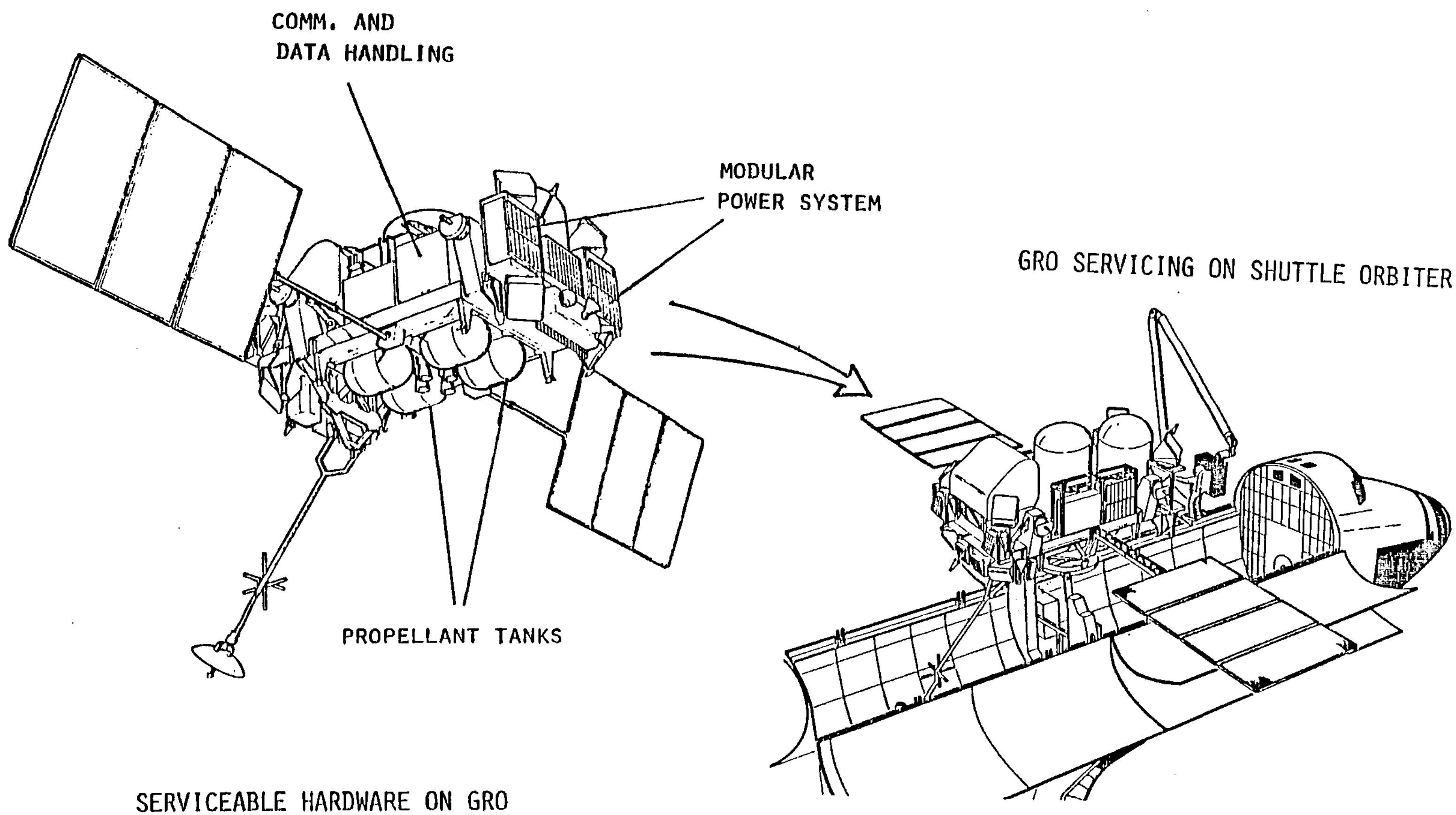


Figure 48. GRO Servicing

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Table 20. SPACECRAFT DESIGN FOR SERVICING

A. <u>GENERIC CONCEPTS</u>

- INSIDE-OUT DESIGN APPROACH, I.E., PERIPHERAL UNITS
- MODULAR SUBSYSTEMS (ORUs), E.G., MMS
- REMOVABLE/REPLACEABLE PAYLOAD UNITS, E.G., SPACE TELESCOPE
- STANDARDIZED ELECTRICAL AND MECHANICAL INTERFACES
- ACCESSIBLE TEST AND CHECKOUT TERMINALS
- EASY CREW ACCESS
- EASY MANIPULATOR ACCESS
- SAFING BY COMMAND (POWER SOURCES, PRESSURE SYSTEMS, ETC.)

B. <u>ADDITIONAL PROVISIONS FOR AUTOMATED AND REMOTE SERVICING</u>

- EASY ACCESS FOR ROBOTIC SERVICER
- SIMPLE ORU MATING/DEMATING KINEMATICS, E.G., GRO
- SIMPLE AND ACCURATE ORU ALIGNMENT PRINCIPLE
- CONVENIENT LOCKING/UNLOCKING DEVICES
- MODEST DEMANDS ON ROBOT VISION CAPABILITY
- DESIGNS FACILITATING CHECKOUT AND DIAGNOSTICS

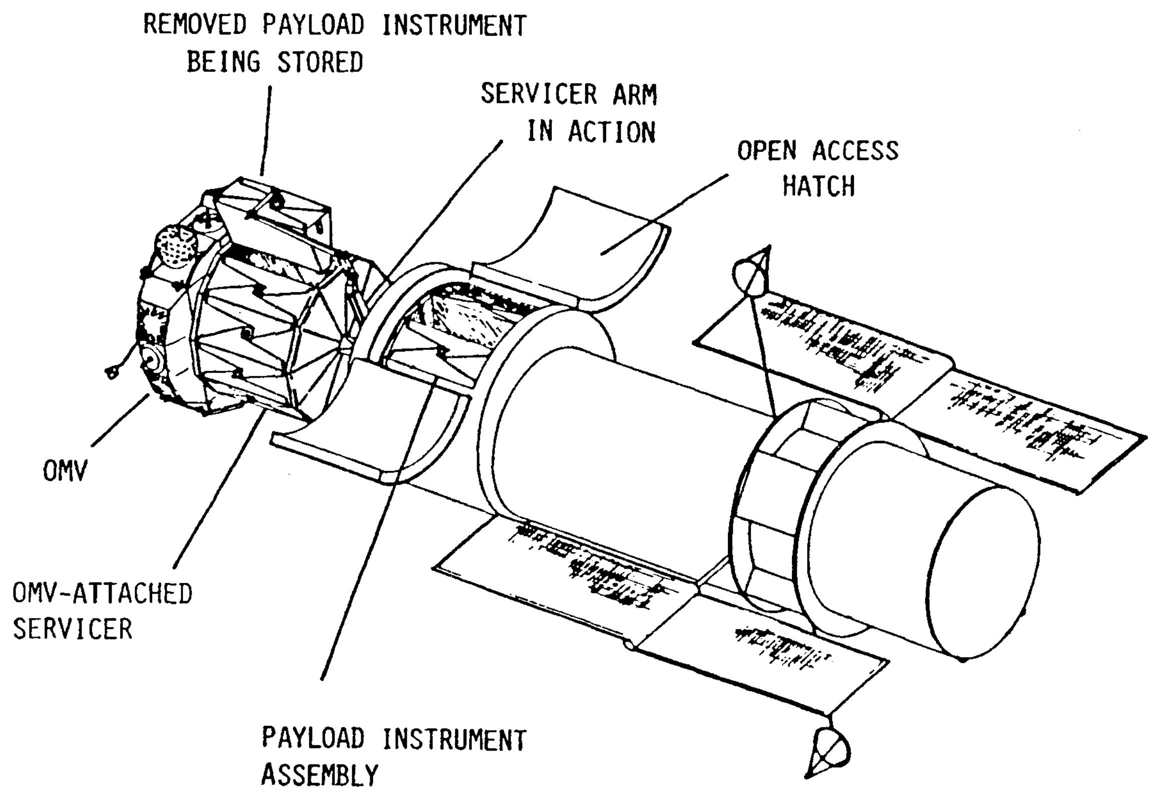
3.9.6.3 Payload Instrument Replacement on AXAF

Figure 49 shows an early concept of AXAF being serviced in the free-flying mode by an OMV equipped with a robotic servicer.

The removable payload units are focal plane instruments grouped in a cylindrical arrangement at the aft end of the observatory facility. In the design shown, payload instruments can be removed in radial (lateral) direction. To effect the changeout the servicer, berthed at the aft bulkhead, uses its manipulator arm to reach into the open access hatch, where it pulls out one instrument at a time. The instrument is shown in the process of being stored in an empty compartment of the servicer magazine. The next step for the servicer arm is to take a replacement unit from the magazine and insert it into the AXAF focal plane compartment just vacated.

AXAF servicing is similar to the instrument changeout process on the Space Telescope. However, at this time, neither AXAF nor ST are actually scheduled for in-situ servicing, remote from the Space Station

Servicing of a free-flying materials processing facility by resupply of fresh material specimens and harvesting of finished products is envisioned to use OMV attached servicer equipment similar to that shown in Figure 49. The module being shown in the process of changeout would be a magazine containing the specimens. Conceivably, the changeout would not have to be limited to specimen magazines, but might also include entire processing systems if they can be packaged in a compact, readily removable configuration.



SOURCE: J. TURNER, "TELEOPERATOR MANEUVERING SYSTEM", SATELLITE SERVICING WORKSHOP, NASA/JSC, JUNE 1982

Figure 49. Payload Instrument Replacement on AXAF

4.0 AUTOMATION TECHNOLOGY TRANSFER TO GROUND-BASED APPLICATIONS

The development of space-based automation can benefit the industrial automation field in two ways:

(1) It provides a strong stimulus to advancing the state-of-the-art so that at least part of the development cost supports the US terrestrial economy by promoting technology growth.

(2) Robotic capabilities peculiar to space-based servicing needs will be developed, tested and applied operationally on the space station. They include the adaptability and flexibility to deal economically with "one-of-a-kind" servicing functions. Such flexibility will be much in demand in the factory of the future and a direct technology spin-off potential is evident.

Listed below are typical technology advancements currently being emphasized in manufacturing and other advanced ground-based operations.

- Computer Integrated Manufacturing (CIM)
- Advanced (smart) robots
- Advanced sensing and control technology
  - Vision system
  - Tactile sensors
  - IR sensors
  - Object identification, decision making
  - Sensing position and orientation of objects
  - Voice control, voice feedback
- Software
  - Formats
  - Operating languages
  - Production control
- Working robots

  a) Carrying
  - Tools to machines
  - Material to machines
  - Finished products to storage or to other work stations

  b) Performing
  - Maintenance on machines
  - Machining operations, with tools in fixed position and the robot moving the work piece

Of particular interest in the industrial/manufacturing field are robots designed to perform in highly flexible and adaptable fashion under greatly diversified tasks and situations, just like those used in satellite servicing. Such robots are envisioned to operate in typical "factories of the future" that are being discussed today by industrial automation specialists. Under this heading the following future robotic applications are being mentioned that would directly benefit from the space-based automation, and particularly servicing automation, technology:

- Adaptable machines with flexible, as opposed to fixed, automation
- Reprogrammable machines (by keystroke)
- Responsiveness to new situations, eliminating obsolescence
- Economic production of "quantities of one" (or at least, small quantities) and mixed batches
- Low inventory/zero inventory trends
- Proliferation of models
- Software linkage between diversified computers

Other potential transfer of automation technology developed for space-based servicing may include ground-based applications in hostile or unsafe environments such as deep mining, underwater operations, nuclear power plant emergency activities, and working near explosives. Examples include robots designed for window-cleaning on skyscrapers, for fire fighting (currently under development in Japan) and defusing or neutralization of bombs placed by terrorists, a technology currently in use by security forces in Israel.

Robots designed for diversified servicing tasks on the Space Station have attributes that will be useful to the factory of the future and other ground-based applications such as those listed above, and therefore, a beneficial technology transfer can be anticipated.

In summary, robotic capabilities and attributes that are of principal interest in this context are the following:

- Space Station robots designed to handle one-of-a-kind servicing tasks
- Flexible, reprogrammable robots for diversified tasks
- Smart robots that respond to unforeseen conditions
- Moving robots that transfer equipment and supplies as instructed
- Software linkage between distributed computer systems
- Capability of operation in hostile environments such as in deep mines, under water, at Three-Mile Island, fire fighting, etc.

5.0 CONCLUSIONS AND SUMMARY

The report covers typical satellite servicing functions to be performed either on board the Space Station or remotely at the location of the object satellite. Requirements to perform these servicing functions by teleoperation or automatic means were identified, and the state of automation technology to be utilized was assessed. Scenarios of four representative servicing missions were used for illustration. Design and operating requirements for the Space Station, the object satellite and the orbital transfer vehicle to be used in these missions were identified, and benefits derived from automated servicing were determined.

All three principal automation disciplines, teleoperation, robotics and artificial intelligence are needed in the servicing missions investigated. Results show that teleoperation will be utilized more widely than fully robotic systems, at least during the early space station years, owing to the diversity and also, the unpredictability of many servicing tasks which call for the human operator's skills, resourcefulness and decision making ability. In-situ servicing in low, and particularly, in geostationary earth orbit becomes a principal driver toward fully automated, robotic manipulation techniques.

As in all other space station automation functions, there will be heavy dependence on a sophisticated, flexible, readily accessible, high-speed and high-capacity data management system, which can provide artificial intelligence support as required in diagnostics, troubleshooting, configuration control decision making, task scheduling, and mission planning. Thus, the Space Station data system will play a key role in providing comprehensive support functions in all phases of satellite servicing.

Twelve automation technologies are key to space servicing:

1. Dexterous manipulators*
2. Servicing-compatible spacecraft*
3. Space-qualified robots, robotic servicing
4. Data system servicing support
5. Advanced man-machine interfaces
6. Advanced fluid transfer systems*
7. Robot vision*
8. Automated load handling/transfer
9. Automated rendezvous/berthing
10. OMV with smart front end*
11. Knowledge-based system support*
12. Reusable OTV

Those marked by asterisks are enhancing capabilities on the IOC Station.

Space-based servicing will draw on current developments in automation technology such as advanced robotics, expert systems, robotic vision, speech recognition, natural language, data processing and display, fault detection/recovery, computing and software. However, practical application of this technology to Space Station automation objectives requires a continuing major development effort. Spin-off benefits to terrestrial applications could be in the area of flexible/adaptable automation, for example in the economical production of small quantities, and in advanced data management and information transfer.

Automated satellite servicing capabilities will be required on the Space Station to maximize crew productivity, to reduce the frequency and duration of extra-vehicular activity, and hence, crew exposure to hazardous conditions. Study results show that 40 to 60 percent of the crew time can be saved by using automated support if it is developed and implemented.

Automation also will speed up servicing schedules and thus help reduce any backlog that may develop due to growing demands for maintenance, repair and refurbishment of satellites in low and high earth orbit as well as servicing of the Space Station itself, its subsystems and attached payloads.

A significant degree of commonality was found between the automation requirements of various servicing functions, and a generally high utilization rate of automated design features, once they are implemented.

Principal conclusions from this study may be summarized as follows:

- Many satellite servicing functions benefit from, or rely on, automation support
- Automation will expedite on-orbit satellite servicing and will increase productivity of crew operations
- Orbital servicing of satellites and of the Space Station, itself, is a principal driver of automation technology development. Technology evolution, in turn, will greatly expand servicing capabilities.
- Satellite servicing requires more teleoperation and less robotics than other automated Space Station activities
- Teleoperation or fully automated (robotic) use of the same manipulators offers flexibility and adaptability
- Robotic servicing development is driven by in-situ, particularly geostationary, satellite servicing objectives

- In-situ servicing by teleoperation will be feasible only if transmission delays are reasonably small depending on characteristics of the task

- The transmission delay (feedback control delay)in remote servicing missions can be greatly reduced by communication during direct L.O.S. contact intervals rather than via relay satellite

- Major data system support is essential for planning, scheduling, execution, monitoring and other servicing functions

- Servicing support by artificial intelligence will expand with Space Station evolution

- Twelve key automation technologies were identified, some of which are needed for servicing on the IOC Space Station

- Ground-based automation technology will be applicable to satellite servicing

- Servicing automation, in turn, will benefit ground applications, i.e., industrial production in small quantities, as a space technology spin-off

6.0 RECOMMENDATIONS

In implementing the Space Station Program, NASA intends to advance the state-of-the-art in automation and robotics:

(a) For use in Space Station operations, and

(b) To benefit the U.S. economy by exploiting space-based automation progress through technology spin-off to earth-based applications.

In line with these objectives, and based on our study results, we offer five major recommendations with regard to servicing and automation technology as input to the current planning for the Space Station definition phase.

- Crew safety should be the principal concern of defining conventional as well as automated servicing approaches. This requires major attention even in the earliest phases of automated servicing, planning and technology development

- On-orbit servicing requires that the early and growth Space Stations be designed for rendering effective and economical servicing functions. It also requires that space systems to be serviced incorporate into their configurations, the ability to accept servicing with a minimum of crew effort, support equipment, down time, and cost. This two-way thrust should start as soon as possible under an integrated government (NASA and DoD) policy for designing, planning, and executing of space servicing

- The IOC Space Station should include automated features such as: load transfer capability, integral verification and test systems, advanced data handling and information processing techniques, a master program for logistics management, appropriate fuel and fluid handling and transfer equipment, and automated Space Station proximity operations, rendezvous and docking

- The IOC Space Station must accommodate growth in servicing and automated systems. Provisions for early mods to the IOC station, through hooks and scars, as well as aggressive planning for expanded resources to support servicing must be reflected in the impending Phase B study efforts and programmatic decisions

- Key automation technology developments should start as soon as possible. An integrated plan for design, development, test, and evaluation of automation/robotic/AI devices should be formulated and implemented with adequate funding.

In addition the following specific recommendations are made with regard to automated satellite servicing:

- Load handling and transfer automation is a major requirement to streamline traffic flow. A fast load transfer system is needed and should be developed in addition to the RMS crawler platform

- Automated rendezvous/docking should be developed in the near-term

- A "smart front end" servicing kit for the OMV should be developed for remote servicing missions

- Robotic vision is a key to advancement from teleoperation to robotics. Only modest vision system capabilities are required initially. Existing robot vision technology should be adapted to satellite servicing needs

- Early attention is required on new spacecraft to the development of standardized servicing interfaces, and in particular, design features compatible with automated servicing

- Artificial intelligence (expert system) technology should be developed for achieving advanced robotic servicing/repair capabilities and for effective crew support in difficult failure analysis and troubleshooting tasks

- OTV development combined with a smart front end servicer kit (adapted from the advanced OMV) is essential to enable remote servicing missions of geosynchronous and other satellites inaccessible to OMV

- Aerobraking may have to be developed to render geosynchronous servicing by reusable OTVs economically more attractive

- Tethered satellite berthing and servicing offers a promising growth option and alternative to remote servicing. Tether system technology currently under development for use on the Shuttle orbiter should be considered for adaptation to Space Station use.

APPENDIX A

CRITERIA FOR EMPLOYING AUTOMATION, ROBOTICS, AND ARTIFICIAL INTELLIGENCE IN THE SPACE STATION AUTOMATION STUDY*

Certain questions repeatedly arise in program planning and advocacy. The following critical questions represent current concerns and issues related to man/machine operations in conjunction with a Space Station. These are categorized by major functional relationships between human and machine in a question-and-answer format.

No hard qualitative or quantitative criteria exist for making the allocation decision between man and machine performance of function, so that information in this Appendix is based on intuitive thinking of what is practical and reasonable and cost effective for the IOC (1992) Space Station.

SPACE STATION AUTONOMY

Question 1. What is autonomy in the context of the Space Station? How should autonomy be viewed in this context?

The generic meaning of autonomy is independence or freedom from outside control. Examples of Space Station autonomy might include station independence from ground control, machine independence from human control, crew freedom from unnecessary tasks, free-flyers functioning independently, or the end-effectors of a teleoperator system removing bolts during satellite repair without a human presence.

Autonomy includes three facets. The first facet is locus of control - where does the system control intelligence reside? A machine which is self-controlled has a high degree of control autonomy, whereas a machine controlled by a human has low autonomy. Note that the object of autonomy is the machine itself and not the human/machine system. The second facet involves physical task performance. If the task is done almost entirely by a machine, then the machine has high autonomy. The third facet is locale

*Excerpt from an interoffice memorandum by D. M. Waltz dated 25 June 1984.

of control. Humans, machines, or human/machine space systems that are relatively free of control from the ground have high autonomy. An object or system controlled more directly from Earth is less autonomous.

<u>Question 2</u>. In the 1990s, how autonomously (from the ground organization and system) can the Space Station operate?

Some long-term unmanned missions have not required the extensive and expensive mission control personnel of the manned flights. The Space Station, viewed as a system for a continuing manned mission, should display more of the attributes of these long-term unmanned activities. The station will become more autonomous from ground-based human supervision. Control and decision making will shift increasingly to the Space Station. Much of the monitoring currently done by people can be highly automated. Earth-based human experts will be available for backup if unexpected servicing problems arise.

The early Space Station may not be significantly more autonomous from the ground than present manned systems, but over time there will be a gradual shift in locale of control. By the mid- to late- 1990s, there could be substantial Space Station autonomy as confidence in automated systems grows with increasing use. NASA should try to automate the system as much as possible. Some suggested decision rules for re-allocating task locale from ground to space include: (1) Can the service task be performed in space only with the required reliability? (2) Is the immediate judgment of the space crew necessary for the task? (3) Is it less expensive to do the servicing task in space with the required reliability?

TASK ALLOCATION AND DECISION RULES

<u>Question 3</u>. What is the nature of an on-board task that determines whether it is appropriate for automation? What type of tasks should be allocated to humans? What combinations of humans and machines will be most effective?

At the present time there is no good systematic approach available for the allocation of all servicing functions between human operators and machines, let alone between astronauts and automated systems. Tables of satellite servicing tasks best performed by humans or machines have been compiled, but these are incomplete. Some monitoring and control systems can be automated with current technology. Tasks requiring complex levels of decision making in repair missions probably will not be automated until the end of the century; functions requiring judgment and interpretation of unexpected events will be automated only in the long term. Tasks demanding human-like dexterity will be difficult to automate with current technology unless they are repetitive and very limited in their requirements for fine manipulation.

In general, machines tend to be quite reliable but lack flexibility while humans tend to be less reliable than machines but far more flexible.

If the service subtasks remaining after automation (such as watching monitors) are more boring than the original task, then it is better not to automate and to let astronauts perform the task in its entirety. Humans have the ability to supervise and control and should not have to perform menial subtasks which subordinate people to machines. An effective human/machine combination is teleoperation or telepresence. In these systems the human remains in a safe environment and performs tasks which may otherwise: (1) be unsafe, (2) require strength beyond human capability, or (3) require prohibitively expensive EVA or vehicle life support systems or development of an autonomous machine beyond the reach of current technology.

Question 4. What are the decision rules for allocating servicing functions between humans and automated systems, whether in space or on the ground?

One approach to devising decision rules is to create an expert system. An expert system is an artificial intelligence approach to decision making, which builds up evidence for choices by asking users questions based on an established set of rules.

Strong reasons for the decision to automate servicing may exist (1) if the task requires perceptual abilities outside the range of human limits; (2) if the task involves safety or health risks outside tolerable limits for humans; (3) if the task requires computing ability; (4) if the task entails detection of infrequent or rare events; and (5) if the task requires continouus monitoring of systems.

Weaker reasons for favoring automation arise (1) if it is technically feasible to automate the task; (2) if it is economically feasible to automate the task; (3) if the task involves storing and recalling large amounts of precise data for short periods of time; (4) if the task involves routine repetitive precise tasks; (5) if the task requires regularly an attention span of more than 20 minutes; and (6) if humans don't like to do the task.

Strong reasons favoring humans for a task may exist (1) if the task requires deductive reasoning ability; (2) if humans like to do the task; (3) if the task requires the ability to arrive at new and completely different solutions to problems; (4) if the task requires the ability to detect signals in high noise environments; (5) if the task requires ability to use judgment; and (6) if the task entails many unexpected unpredictable events.

Weaker reasons for using people may arise (1) if the task requires EVA; (2) if the task requires the ability to profit from experience; and (3) if the task cannot easily be decomposed into a series of preset procedures.

HUMAN/MACHINE INTERACTION

Question 5. What is the astronauts' role with respect to onboard autonomous subsystems? In what operational modes does man serve best?

The astronaut will function as supervisor or manager and must understand basic system behavior, diagnose faults, and repair or replace faulty components. However, many subsystems will be self-contained and will operate independently. With automated Space Station monitoring, subsystem abnormalities will cause a higher-level system (machine or human) to be alerted. Using fault-tolerant computing and redundant systems, many faults can be handled without human intervention. If the troubleshooting procedure for the detected fault is well specified, then the computer should complete as many of the steps as possible before alerting the crew. This avoids the inefficient current practice of human monitoring and execution of an entire troubleshooting procedure which is largely routine. Of course, if a critical system must be shut down or a redundant system started up, humans should be consulted or informed so that there is an opportunity to intervene.

There are many faults which are unanticipated or for which no simple step-by-step procedure can be written. In these cases, assistance and operational information should be provided by the station data management and information retrieval systems, but the human must make the decisions, perform the troubleshooting and make the repair. Ideally, the crew should still be capable of repairing faults in critical systems, such as communications, autonomously.

Question 6. What are the management principles for operation of autonomous servicing equipment, particularly as a function of machine intelligence?

They are largely unknown. Intelligent systems are currently most adept at dealing with symbols rather than material objects, and can work with sets of rules (as in expert systems). If the operation of the equipment, which may include fault detection and resolution, can be reduced to a specific set of conditions and remedial actions, then the system can be managed by machine intelligence. If the system requires changes in operation based on unexpected or unpredictable results, then state-of-the-art artificial intelligence techniques are inadequate.

Current expert systems produce impressive results, but these packages generally are used by people whose expertise is comparable to that embodied in the software. Expert operators are required, both to ensure the "common sense" of results and to modify the system's rules as new expert knowledge accumulates. Learning and automated theory formation are reasonable goals for the future. For the initial station design, prudence suggests limiting the use of expert systems to domains in which they are known to work, such as monitoring and fault diagnosis of power systems or interactive, real-time crew scheduling. As other workable systems are demonstrated and evaluated they should be added to the evolving Space Station. Caution is advised, but it should be possible to identify potential domains where an expert system might be suitable for future station implementation.

Question 7. How does one determine when human intervention is required? What are the principles which determine how to provide status information to the human? How can unsafe human interventions be prevented?

Humans should be involved in the control of an action or decision which is irrevocable or which significantly affects system safety or mission success. The level of action to be taken and the seriousness of the event requiring action determines how status information will be presented. A major failure should attract attention immediately, probably through both audible and visual alarms. Additional information describing the cause and nature of the failure should be displayed on a CRT. But printed warning messages are less effective than using both audible (e.g., voice or sound) and visual signals (e.g., a flashing light). Minor events should activate a small visual indicator or log a message for later review.

The two main concerns with unsafe human intervention are that (1) an unauthorized person might interact with the system, and (2) an authorized person could make a mistake adversely affecting the system.

Fail-safe interlocks and passwords can prevent unauthorized action. Good training and a basic understanding of the systems will provide significant assurance against mistakes. Other steps can also be taken. For example, if an action could cause major damage, then the assent of more than one person might be required - perhaps that of a crew member as well as another person on the ground. Computers could perform a contingency analysis for the crew, or request that crucial commands be repeated, prior to taking action, and display a list of consequences resulting from such action.

Question 8. What new skills do people need in dealing with autonomous subsystems? What skills (organizational, personal, and physical) need further development?

The needed skills are similar to those presently required for the astronaut program. People who deal with autonomous subsystems must be comfortable working with automation technology and must thoroughly understand the displays and information presented by station systems. This requires intensive training and an ability to maintain high levels of familiarity with the technology. Strong decision making skills are essential, such as when serious component failures or other stressful situations necessitate rapid assessment of the accuracy of autonomous subsystem responses - especially if this information conflicts with intuition or common sense.

Organizational and personal skills needing development are the ability to live (and thrive) in a cramped, fragile, artificial habitat located in a hostile environment from which immediate escape is impossible; and the ability to design and operate decentralized systems (i.e., greater autonomy for organizational subunits), multimode computer-augmented communications networks, and evolutionary human/machine systems.

EVA, TELEPRESENCE, AND ROBOTICS

Question 9. What are the decision rules which apply to extravehicular operations? What advancements in technology are required to shift the task allocation?

There are strong reasons favoring manned EVA (1) if the task can be done with safety or (2) if the task requires working with non-standard equipment and tools; and weaker reasons (1) if the task cannot be reduced to a series of preset procedures or (2) if the task requires sensitivity to a wide variety of stimuli. There are strong reasons favoring the use of telepresence (1) if the task is dangerous or (2) if the task is repetitive and only requires limited dexterity; and weaker reasons (1) if the task must be done immediately or (2) if the task requires continuous work of six hours or more.

Technologically, the primary components of an early telepresence system are available but integration of these components is necessary in order to provide an operational system in the near future. Ground-based telepresence has limited application because of communication delay. A larger variety of end-effectors with greater effectiveness and dexterity must be developed, and tactile sensors must be improved. However, standardization of connectors, fasteners, attachment methods, module configuration and tools could accelerate the use of telepresence as an operational system even without the aforementioned advances.

Question 10. How can the man/machine mix be optimized for off-station activity? What evaluation criteria apply?

Manned EVA is useful in many situations because intelligence and flexibility are important human characteristics. However, the space environment places severe restrictions on human activities (e.g., reduced dexterity, restricted operational time, bulky life support systems). With the limited abilities of available intelligent machines, the use of teleoperated systems may provide an effective and, with foreseeable technology, near-optimal human/machine mix. With the astronaut as operator, telepresence employs human judgment and manipulative skills, takes advantage of machine durability and mechanical performance, and can incorporate autonomous robotic technology as it becomes available.

SYSTEM EVOLUTION

Question 11. What kind of evolution of human/machine systems in space is feasible over the next 20-30 years? How will the human/machine interaction change over time? What is the role of people in human/machine systems as these systems evolve with technological advances?

When the Space Station is first launched in the early 1990s, people will still play the dominant role in almost all human/machine servicing related systems. Manned EVA will be used extensively in construction and satellite servicing. Remote manipulators with limited dexterity and sensory feedback also will be employed. These will be teleoperators or telepresence devices with human controllers and decision makers. Monitoring will be done by computers of limited intelligence (e.g., fault-tolerant systems), but under human supervision. Much of the decision making control will shift from ground to the Space Station and the crew will receive intelligent assistance from on-board computers. Some major computers for monitoring and mission operations will remain on the ground together with a limited number of operators and experts.

This mode of operation will change drastically over the next 20 years. Information will become much more available and cheaper, just as most other resources will become more expensive. The human/machine interface will become more flexible and effective, allowing easier transfer of information. This process is already underway in terminal design, head-up displays, voice interaction, system architecture, database organization, attempts at natural language front ends, and expert systems evolution.

It is unknown how intelligent machines can become. The conservative assumption is that problems in developing basic artificial intelligence theory will prove as intractable as those of turbulent flow, but, to extend the analogy, that some very useful systems will be flown nevertheless. In all likelihood, advances in artificial intelligence will lead to truly intelligent machines. Highly-developed sensory capabilities will extend the uses of autonomous robots. Intelligent assistance and monitoring systems will be created and installed on the Space Station.

The use of autonomous, intelligent machines will not reduce the amount of work that humans do but rather will permit the effective performance of an ever-increasing number of more complex and productive servicing tasks.

APPENDIX B

AUTOMATION REQUIREMENTS AND CONCEPTS APPLIED TO REFERENCE SERVICING MISSIONS

Automation requirements for the reference servicing missions discussed in Section 3.2 and 3.3 were identified in Tables 1 through 4 (page 12 to 16) but only in rather general terms. Tables B1 through B4 in this appendix provide additional information on automation requirements and automation concepts envisioned for the respective mission scenarios. The requirements are subdivided into those of (1) data system and artificial intelligence support, (2) teleoperation support and (3) robotic support.

It is apparent that each of the missions require data system support for a broad range of servicing activities. This involves data management, storage,retrieval, display and computational analysis as well as applications of artificial intelligence in functions such as task planning and sequencing, monitoring and control, diagnostics and decision making. As previously explained in Section 3.3 (see Table 6, page 24) teleoperation tends to be used in a broader range of servicing activities than robotic operation, at least in the early years of Space Station operations, owing to the diversity and also the unpredictable characteristics of many servicing tasks.

TABLE B1

AUTOMATION REQUIREMENTS AND CONCEPTS

REFERENCE MISSION 1 - SERVICING GRO ON SPACE STATION

AUTOMATION REQUIREMENT	AUTOMATION CONCEPT
1. DATA SYSTEM SUPPORT AND AI	
• Mission and task scheduling	Expert system program*
• Mission profile determination	Mission analysis and design program
• Orbital transfer optimization	Mission analysis and design program
• Equipment and supplies requirements listing	Data retrieval and analysis
• Supply logistics planning (STS delivery)	Inventory and mission data management
• Servicing sequence control	Sequencing routines
• Satellite deployment and maneuver sequencing	Mission analysis and design
• Automatic checkout and countdown	Expert system program*
• Diagnostic and trouble shooting	Expert system program*
• Display of system design and operation data to crew	Data retrieval
• Determination of alternate servicing procedures and sequences	Expert system program*

*Artificial intelligence utilization

TABLE B1 (CONTINUED)

AUTOMATION REQUIREMENTS AND CONCEPTS

REFERENCE MISSION 1 - SERVICING GRO ON SPACE STATION

AUTOMATION REQUIREMENT	AUTOMATION CONCEPT
2. <u>TELEOPERATION</u>	
• Docking and berthing • Loading and unloading • Equipment retrieval and stowage • Equipment transfer • Propellant transfer • Umbilical connecting/disconnecting • Visual inspection (CCTV)	(also: Remote docking control at GRO using video and proximity sensor feedback signals) Manual RMS control* (direct vision or video feedback to operator)
3. <u>ROBOTIC ACTION</u>	
• Automated load transfer • End effector changeout	Automatic RMS operation*
• Rendezvous and docking control	Propulsion commands to OMV based on guidance and control sensor signals (crew supersivion)

* Assumes RMS mounted on track covering entire SS length

TABLE B2

AUTOMATION REQUIREMENTS AND CONCEPTS

REFERENCE MISSION 2 - SERVICING MATERIALS PROCESSING FACILITY

AUTOMATION REQUIREMENTS	AUTOMATION CONCEPTS
1. DATA SYSTEM SUPPORT AND AI	
• Scheduling and servicing sequence control, checkout and countdown, display of system data to crew as in Reference Mission 1 • Free flying platform orbit-raising maneuver sequence	• Data retrieval, analysis and display as in Reference Mission 1 • Expert system programs for checkout, countdown, trouble shooting and alternate procedures and sequences • Mission analysis and design program
2. TELEOPERATION	
• Docking, berthing, loading, unloading, retrieval, stowage and equipment transfer as in Reference Mission 1 • Control of sample magazine changeout or materials processing payload system changeout at free flying platform	• Comparable to Reference Mission 1 using RMS on tracks • Teleoperation commands by SS crew to MPF servicer (video and status signal feedback)
3. ROBOTIC ACTION	
• Load transfer, rendezvous and docking control as in Reference Mission 1 • Sample magazine transfer to changeout port on MPF	• Automated RMS operation and OMV propulsion control as in Reference Mission 1 • Automated transport provisions on MPF (e.g., Lazy-Susan concept)

TABLE B3

AUTOMATION REQUIREMENTS AND CONCEPTS

REFERENCE MISSION 3 - SERVICING SS-ATTACHED PAYLOAD OR SUBSYSTEM

AUTOMATION REQUIREMENT	AUTOMATION CONCEPT
1. DATA SYSTEM SUPPORT AND AI	
• Scheduling and servicing sequence control, checkout, verification, diagnostics and trouble shooting, display of system data to crew as in Reference Mission 1	• Data retrieval, analysis and display as in Reference Mission 1 • Expert system programs for checkout, trouble shooting, alternate procedures and sequences
2. TELEOPERATION	
• Handling, loading, unloading, retrieval, stowage and equipment transfer as in Reference Mission 1	• Comparable to Reference Mission 1 using RMS on tracks
• Inspection by CCTV	• Moved by RMS
3. ROBOTIC ACTION	
• Automated load transfer to and from system operating station, servicing platform	• Automated RMS operation as in Reference Mission 1

TABLE B4

AUTOMATION REQUIREMENTS AND CONCEPTS

REFERENCE MISSION 4 - SERVICING A GEOSTATIONARY SATELLITE

AUTOMATION REQUIREMENT	AUTOMATION CONCEPT
1. DATA SYSTEM SUPPORT AND AI	
• Scheduling and servicing sequence control, checkout and countdown, trouble shooting support, display of system data to crew as in Reference Mission 1	• Data retrieval, analysis, display comparable to Reference Mission 1 • Expert system programs for checkout, countdown, trouble shooting and alternate procedures and sequences
• Control of time allocation during intermittent, direct line-of-sight contacts between SS and target satellite	• Automatic task sequencing to be synchronized with visibility intervals
2. TELEOPERATION	
• Docking, berthing, loading, unloading, equipment retrieval/stowage and transfer on-board SS as in Reference Mission 1	• Comparable to Reference Mission 1
• Control of in-situ servicing operations at geosynch. orbit	• Teleoperation commands by SS crew to servicing module, incl. refueling sequences (video and status signal feedback)
3. ROBOTIC ACTION	
• Load transfer, rendezvous and docking control as in Reference Mission 1	• Automated RMS operation (as in Reference Mission 1)
• Selected simple servicing sequences at geosynch. orbit	• Automated rendezvous/docking control monitored by crew • Automated changeout sequences at destination, monitored by crew

APPENDIX C

COST-BENEFIT CONSIDERATIONS

A preliminary analysis of relative costs and benefits associated with automated satellite servicing was performed to derive an index of comparison of major automation elements for assessing relative cost benefits.

Table C1 lists principal cost drivers and benefit categories related to the level of automation provided. We note that higher levels of automation needed to enhance or enable servicing capabilities tend to drive up initial costs but also tend to lower operational cost per unit time or unit servicing event. This is illustrated in Figure C1 which compares cumulative costs associated with operating at a lower and higher level of automation. After reaching a breakeven point, the more highly automated operations tend to be less costly. Results shown in Figure C1 were obtained in the previously referred-to THURIS study of McDonnell Douglas* which established quantitative cost-breakeven conditions of this type for about 40 specific crew functions in space at automation levels ranging from purely manual, augmented manual, teleoperated, to semi-automatic and fully automatic modes. The automation level that yields the highest cost effectiveness, as determined by the THURIS study, depends on the number of operational steps involved in a specific task, i.e., the task complexity, and on the number of repetitions required during the life of the system. Low task complexity and low numbers of repetitions favor low automation levels and vice versa. See Figure C2.*

A quantitative analysis of automation costs and benefits was beyond the scope of this study. Instead, only a qualitative assessment of cost and benefit categories was performed. From these, a relative cost benefit index was derived based on the benefit-to-cost ratio where benefits and costs are measured on a scale of 1 to 3. Table C2 presents results of cost-benefit assessment for eight principal automation elements. The second, third and fourth columns indicate the functions performed, the benefits obtained and the benefit category assigned. The cost category (column 6) is determined on the basis of technology readiness levels, ranging from 1 to 7. (The highest technology readiness implies the lowest

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*Reference 21.

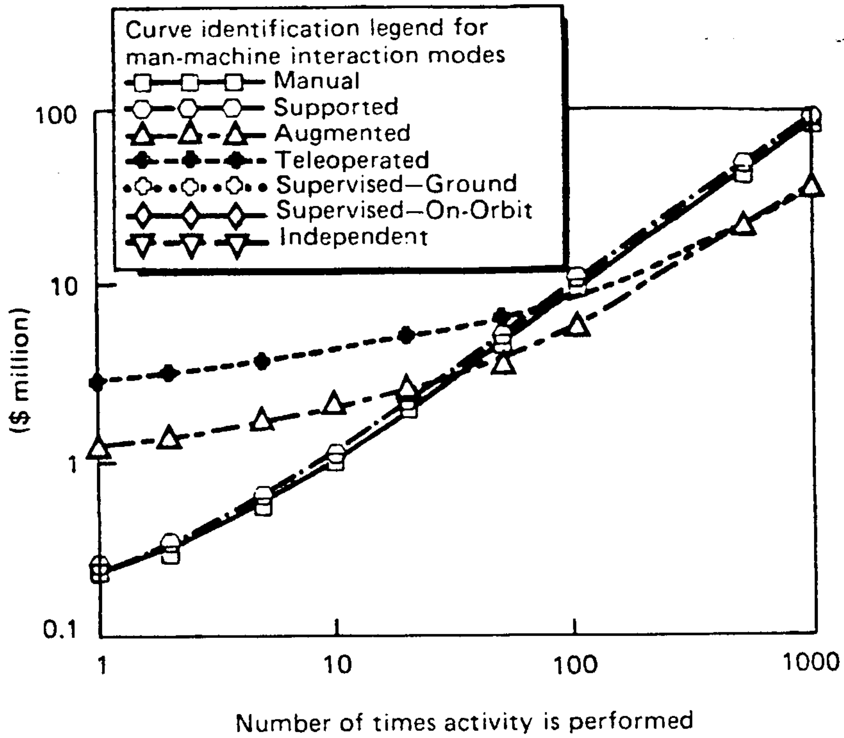

Figure C1. Cumulative Cost Versus Number of Times Activity is Performed in Surface Reconditioning Task*

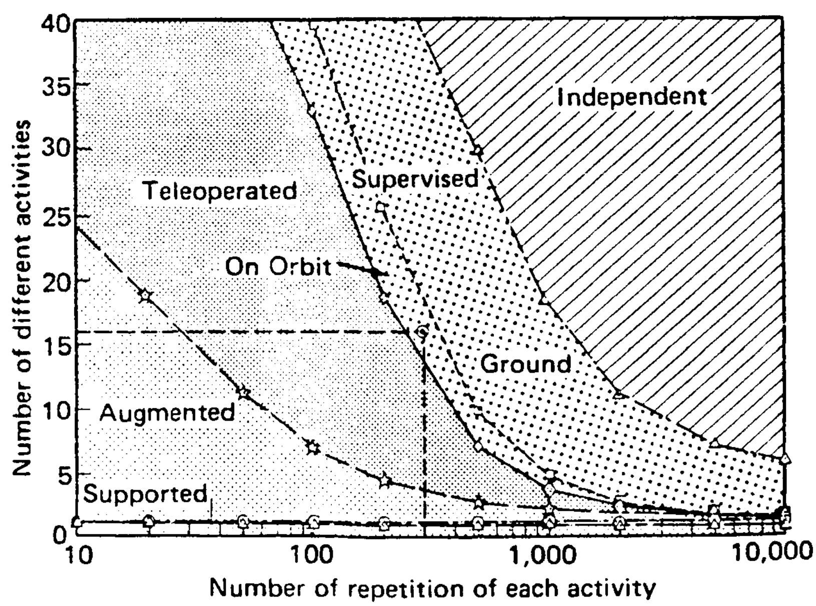

Figure C2. Ranges of Most Cost-Effective Servicing Automation in Releasing/Securing Task of Replacement Module*

*From THURIS Study, McDonnell Douglas Aerospace Co., (Reference 21).

Table C1. Servicing/Automated Systems Cost - Benefit Overview

SERVICING AUTOMATION LEVEL	COSTS	BENEFITS
HANDS-ON (EVA)	- SUITS - EXPENDABLES - PREPARATION - CREW SUPPORT EQUIPMENT	- USES MAN'S OBSERVATIONAL, MANIPULATIVE, AND DECISION MAKING ABILITIES - RESPONSE TO UNFORESEEN SITUATIONS.
TELEPRESENCE	- DISPLAY/CONTROL - COMMUNICATIONS - ACTIVATORS - SENSORS - INTEGRATION - STORAGE/UPKEEP	- SAFETY IMPROVEMENT - TIME SAVING - DESIGNED TO JOB - NO MAN-CONSTRAINTS
ROBOTICS	- DISPLAY/CONTROL - ACTIVATORS - SENSORS - INTEGRATION - STORAGE/UPKEEP - PROGRAMMING/TEACHING ROUTINES	- UNATTENDED OPERATIONS - PRECISION MOVEMENT - SAFETY IMPROVEMENT - PARALLEL JOB ACCOMPLISHMENT - MAX.TIME SAVING
DATA SYSTEM SUPPORT AND MACHINE INTELLIGENCE	- DISPLAY/CONTROL - COMPUTERS - LOGIC - DATA MANAGEMENT	- STREAMLINED OPERATIONS - AUTONOMY - RAPID Diagnosis - OPTIMIZED SERVICING FUNCTIONS AND MISSIONS

Table C2. Automation Element Cost - Benefit Assessment

PRINCIPAL AUTOMATION ELEMENT	FUNCTION PERFORMED	BENEFIT	BENEFIT CATEGORY	TECHNOL. READINESS LEVEL	COST CATE-GORY	COST BENEFIT INDEX
1. DEXTEROUS MANIPULATOR	AUTOMATED EQUIP. HANDLING. T/O OR ROBOTIC	• REDUCES EVA • ENABLES ALL IN-SITU SERVICING	3	4	1	7
2. LOAD TRANSFER SYSTEM	TRANSFERS LOADS OR CREW ALONG SS	• ESSENTIAL SUPPORT TO MOST SERVICING TASKS	3	1	2	5
3. LIQUID TRANSFER EQUIPMENT	AUTOM. TRANSFER OF PROPELLANTS, COOLANTS, MPS FLUIDS, ETC.	• ENABLES REFUELING	3	4	2	5
4. AUTOMATED RENDEZVOUS/ DOCKING	SUPPORTS REND/DOCK AT SS AND AT TARGET SATELLITES	• FASTER AND SAFER RENDEZVOUS/DOCKING • SAVES PROPELLANT	2	3	2	4
5. ROBOT VISION	ALIGNS/CONTROLS MANIP./ END EFFECTORS	• ENABLES MOST REMOTE SERVICING FUNCTIONS	3	4	1	7
6. AUTOMATED TEST EQUIP.	TEST SEQUENCING, FAILURE DETECTION, VERIFICATION TASKS	• ESSENTIAL TO SERVICING FUNCTIONS	3	4	1	6
7. DIAGNOSTICS, FAULT ANALYSIS	DIVERSIFIED DIAGNOSTICS & TROUBLE SHOOTING BY EXPERT SYSTEM	• ESSENTIAL TO AUTONOMOUS TROUBLE SHOOTING	3	4	2	5
8. OTHER EXPERT SYSTEMS	PLANNING, SEQUENCING, MISSION OPTIMIZATION, LOGISTICS FUNCTIONS	• ENABLES OR STREAMLINES SERVICING ACTIVITY	3	1	2	5

NOTES:

BENEFIT CATEGORIES	1 TO 3	BENEFIT ÷ COST	0.33	0.5	0.67	1.0	1.5	2.0	3.0
COST CATEGORIES	1 TO 3	COST-BENEFIT INDEX	1	2	3	4	5	6	7
TECHNOLOGY READINESS	1 TO 7								

cost category of developing a specific automation technology). As index of technology readiness we adopted the definitions used by SRI as follows:

Technology Readiness Levels

Level	Definition
1	Basic principles observed and reported
2	Conceptual design formulated
3	Conceptual design tested analytically or experimentally
4	Critical function/characteristic demonstration
5	Component/breadboard tested in relevant environment
6	Prototype/engineering model tested in relevant environment
7	Engineering model tested in space

All automation elements listed are found to yield a high cost benefit index. The highest values were obtained for the dexterous manipulator, robotic vision and automated test equipment; the lowest for automated rendezvous and docking.

Table C3 assesses the cost benefits of six top level automated service functions. Key automation technologies involved in each of these functions are indicated in columns 4 through 9. The resulting cost benefit values are uniformly high (levels 4, 5 and 6) for most of the functions listed except item 4 (mating of OMV or OTV to the payload). The relatively low index level (2) obtained for this function reflects the low benefit category assessment in column 3.

It is apparent that the qualitative comparisons made here have a somewhat subjective character, and further, more quantitative analyses would be desirable.

Table C3. Top-Level Automated Service Function Cost Benefits

SERVICING FUNCTION	BENEFIT	BENEFIT CATEGORY	KEY AUTOMATION TECHNOLOGY DM	RV	ES	AT	AR	LT	COST CATE-GORY	COST - BENEFIT INDEX
1. ORV REPLACEMENT										
- AT SS	ESSENTIAL S/C SERVICE FUNCTION	2	●			●			1	4
- IN SITU		3	●	●		●	●		2	4
2. P/L CHANGEOUT										
- AT SS	ENHANCES S/C UTILITY	2	●			●			2	4
- IN SITU		3	●	●	●	●	●		3	4
3. REFUELING										
- AT SS	ESSENTIAL SERV. FUNCTION FOR MOST S/C	2	●			●		●	1	6
- IN SITU		3	●	●		●	●	●	3	4
4. MATE OMV, OTV TO PAYLOAD	REDUCES EVA REQUIREMENTS	1	●	●		●			2	2
5. GEO SERVICE (ALL FUNCTIONS)	ESSENTIAL LONG TERM GOAL	3	●	●	●	●	●	●	3	4
6. MPS RESUPPLY & HARVESTING IN SITU	ESSENTIAL TO COMMERCIAL MPS PROGRAM	3	●			●	●	●	2	5

LEGEND: DM - DEXTEROUS MANIPULATOR; ES - EXPERT SYSTEM; AR - AUTOMATED RENDEZVOUS
RV - ROBOT VISION; AT - AUTOMATED TEST EQUIPMENT; LT - LIQUID TRANSFER

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