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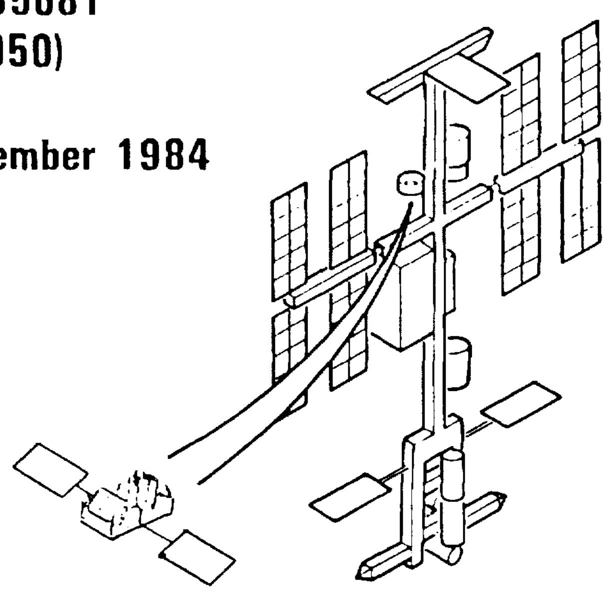
Space Station Automation Study – Satellite Servicing

Volume I
Executive Summary

Prepared Under NASA/MSFC Study Contract

NAS 8-35081
(SN 41050)

30 November 1984



ERRATA

Please note the following typographical errors in this copy of the TRW "Space Station Automation Study," Executive Summary:

p. 14, Table 4, Item 7: delete "applied to"

p. 15, text, line 5: "(Item 10)" should read "(Item 11)"

p. 19, Para. 3.7.2, line 3: replace "feasibly" by "flexibly"

p. 27, Para. 2: add "(The Z-axis is along the keel, the Y-axis along the solar array support boom, and the X-axis is normal to the Y and Z-axis.)"

p. 34, last line: enter a comma after "mode"

p. 36, Item 1, line 1: "production" should read "productive"

Item 2, line 1: last-word-but-one should read "significantly"

p. 37, Item 7, line 2: delete comma at end of line

Item A.4, line 1: last-word-but-one should read "teleoperation"

p. 38, Item 3, line 2: enter "more" before "attractive"

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 I - Executive Summary.

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

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
HO	Human Operator
HQ	NASA Headquarters
IOC	Initial Operational Capability
IR&D	Independent Research and Development
IVA	Intra-Vehicular Activity
JSC	Johnson Space Center
LEO	Low Earth Orbit
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
SS	Space Station
SMM	Solar Maximum Mission (Spacecraft)
STS	Space Transportation System (Shuttle)
T/M	Telemetry
T/O	Teleoperator
VHSIC	Very High Speed Integrated Circuits

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 for 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 by extending 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 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 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 1 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 2 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). The reference mission scenarios were:

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.

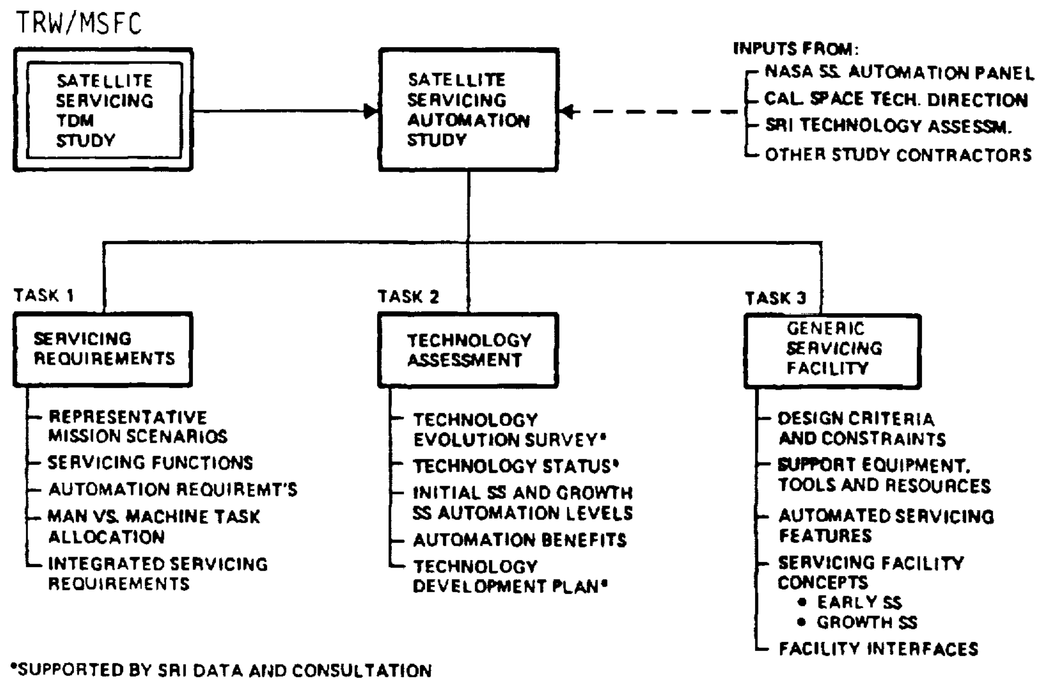

Figure 1. Automation Study Task Breakdown

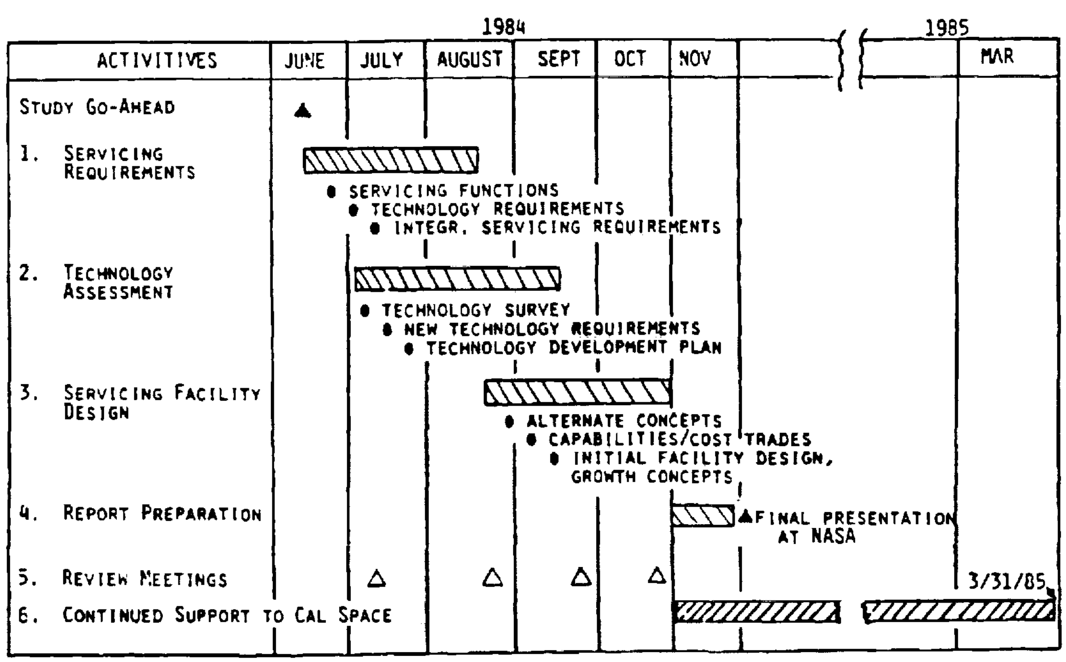

Figure 2. Task Elements and Schedule

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

4. Servicing of a geostationary satellie, 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.

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 3 through 6. 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, assuming that automated servicing support is available, and 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 using automated servicing support, often eliminating time-consuming preparation for and completion of EVA tasks.

Detailed event sequences and automation requirements are given in Table 1 for Reference Scenario 1 (GRO servicing). A corresponding event flow chart is shown in Figure 7, 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.

Similar analysis results were obtained for the other three reference scenarios. They are contained in the Technical Volume (Volume II).

3.3 Automation Requirements

A summary of the projected automation requirements for servicing support is shown in Table 2, check marks indicate the applicability to the four reference missions of each major automation feature. The final column indicates the expected utilization rate once these features

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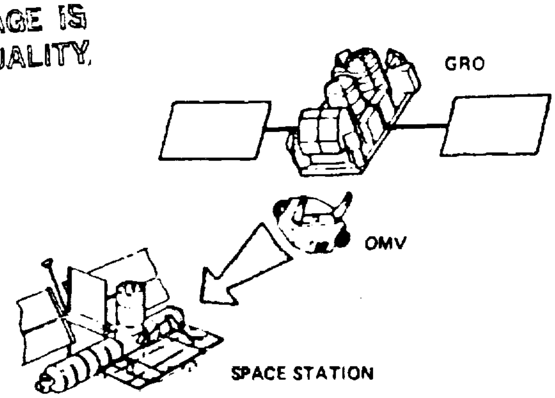
1. SCENARIO HIGHLIGHTS

- OMV RETREIVES 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 TELE-OPERATION
- PROPELLANT REFILL
- AUTOMATED TESTS, CHECKOUT, COUNTDOWN
- DATA SYSTEM SUPPORT (DATA DISPLAY, DIAGNOSTICS, TROUBLE SHOOTING)

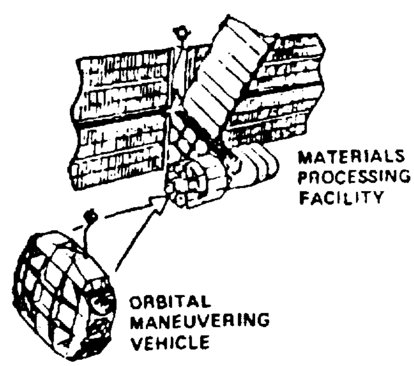
3. ACTIVITY COUNT

- ESTIMATED ELAPSED TIME 10.5 HR
- ESTIMATED TIME SAVING THROUGH AUTOMATION 10 HR

Figure 3. 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 MPS 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

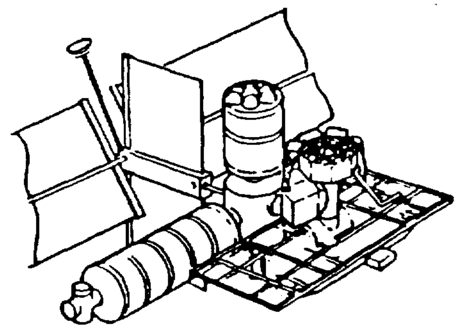
3. ACTIVITY COUNT

- ESTIMATED ELAPSED TIME 4.8 HR
- ESTIMATED TIME SAVING THROUGH AUTOMATION 7.0 HR

Figure 4. 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

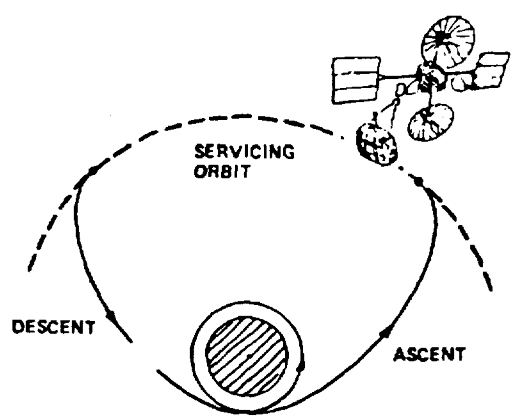
3. ACTIVITY COUNT

- ESTIMATED ELAPSED TIME 2.9 HR
- ESTIMATED TIME SAVING THROUGH AUTOMATION 3.9 HR

Figure 5. Reference Mission No. 3
Servicing of Space Station-
Attached Payload or Subsystem

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. ACTIVITY COUNT

- ESTIMATED ELAPSED TIME 11.1 TO 13.1 HR
- ESTIMATED TIME SAVING THROUGH AUTOMATION 6.1 HR

Figure 6. Reference Mission No. 4
Servicing Geostationary Satellite in Situ

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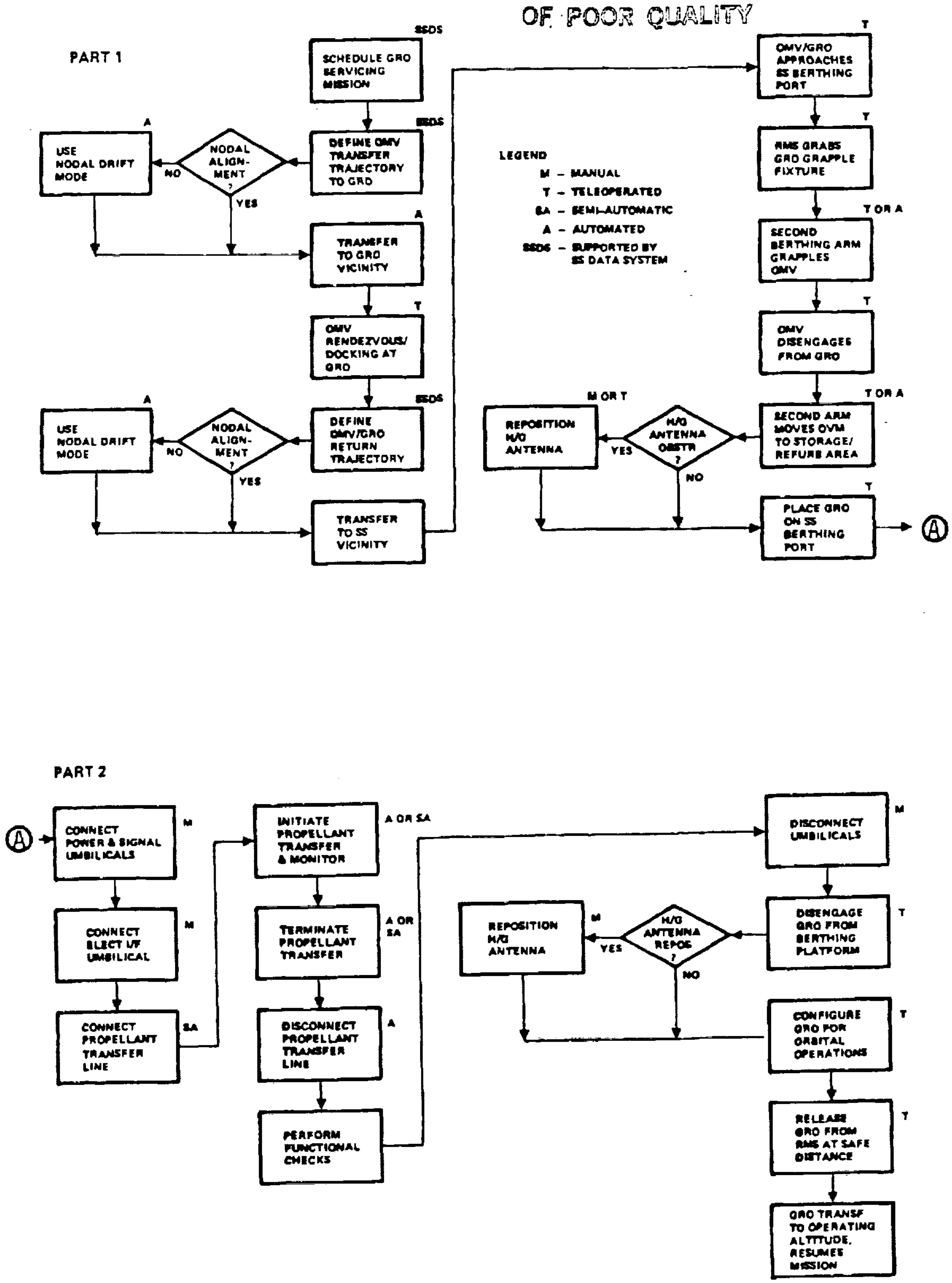

Figure 7. Event Flow - Reference Mission No. 1
GRO Refueling

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	535 (10.5 hr.)	1230 (20.5 hr.)

are made available. It is seen that with few exceptions all reference missions will make use of the various automated support features and, generally, a high utilization rate can be expected. Table 2 also indicates that among projected automation requirements teleoperation and data system support (including artificial intelligence) rank higher than robotic support. This 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 3 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 4 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.

3.4 Automation Technology Assessment

A preliminary assessment of the servicing automation technology status was performed. Table 5 summarizes the results in terms of current/near term, intermediate and longer term availability of this technology for Space Station use, and a gross ranking of priorities. A majority of the technology requirements were found to be within the state of the art, or in an advanced state of development, at least for terrestrial applications. However, additional development will be necessary to adapt terrestrial robots to the hostile space environment and to the weight and volume constraints imposed by the Shuttle as launch vehicle.

Table 2. Commonality of Automation Requirements Among Reference Missions

AUTOMATION REQUIREMENT	SERVICING REFERENCE MISSION				UTILIZATION RATE
	GRO ON SS	MAT. PROC. IN SITU	SS P/L	GEO. SAT. IN SITU	
1. TELEOPERATION					
• Equipment loading, unloading, handling	✓	✓	✓	✓	●
• Equipment storage, retrieval	✓	✓	✓	✓	●
• Berthing, securing, releasing	✓	✓		✓	●
• Load transfer by RMS on track**	✓	✓	✓	✓	●
• Unit changeout operations (local, remote)	✓	✓	✓	✓	●
• Visual inspection (by CCTV)	✓	✓	✓	✓	◐
• Unit and umbilical mating, demating	✓	✓	✓	✓	◐
• Propellant/fluid transfer	✓	✓		✓	◐
• Maneuver control of OMV, OTV**	✓	✓		✓	○
2. DATA SYSTEM SUPPORT AND AI					
• Mission and servicing task scheduling	✓	✓	✓	✓	●
• Servicing sequence and alternative modes*	✓	✓	✓	✓	●
• System data display to crew	✓	✓	✓	✓	●
• Test, checkout and countdown sequencing*	✓	✓	✓	✓	●
• Trouble shooting assistance*	✓		✓	✓	◐
• Mission profile, orbital transfer and maneuver sequence	✓	✓		✓	◐
• Logistics planning	✓	✓	✓	✓	◐
3. ROBOTIC ACTION					
• Checkout and countdown sequence	✓	✓	✓	✓	●
• Load transfer on-board SS**	✓	✓	✓	✓	◐
• Rendezvous control	✓	✓		✓	◐
• Maneuver control sequences**	✓	✓		✓	◐

UTILIZATION RATES ● - HIGH ◐ - INTERMEDIATE ○ - LOW

*Expert System Support Required
**Teleoperation or fully automated (robotic) action depending on scenario and task detail

Table 3. 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 4. 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 5. Automated Servicing Technology Assessment

KEY TECHNOLOGY	STATE OF TECHNOLOGY: NEAR TERM	INTERMEDIATE	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

With regard to the data system state of technology, Items 9 and 10 in Table 5, we differentiate between a broad range of servicing support functions, including data retrieval and computational support such as orbital transfer optimization (Item 9), 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. Thses functions require knowledge-based system development with a longer-term evolution than those under Item 9. Our findings reflect technology assessments 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.

3.5 Technology Evolution

Figure 8 illustrates the projected evolution from hands-on to 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. 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 9 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.

The presence of a significant time delay (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 10.

A preliminary projection of key servicing automation technology evolution in the next two decades is shown in Figure 11. The stages shown include technology demonstration, early and advanced automation and, in some instances,

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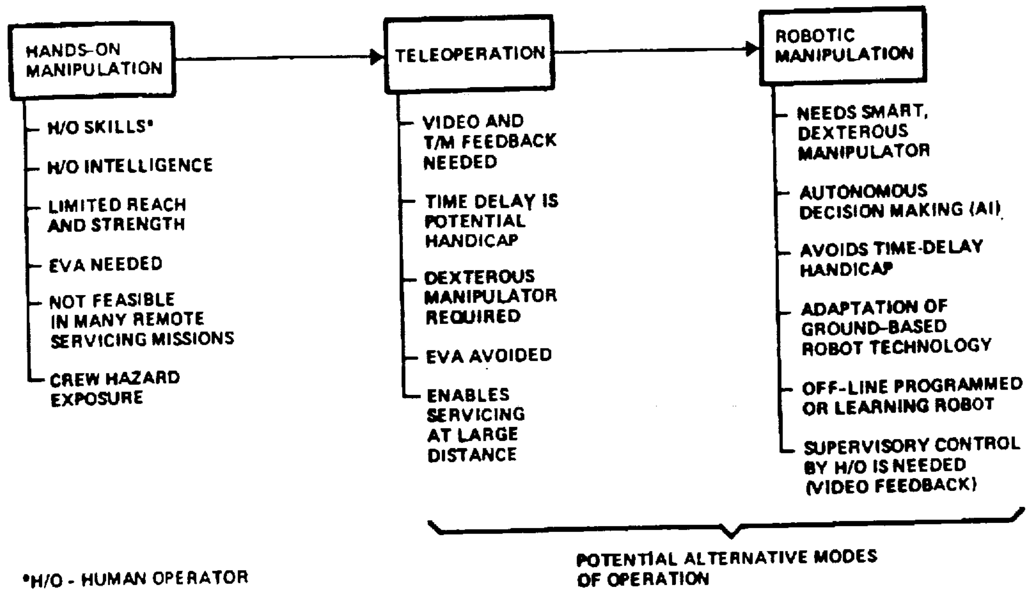


Figure 8. Evolution of Manipulation Modes in Satellite Servicing

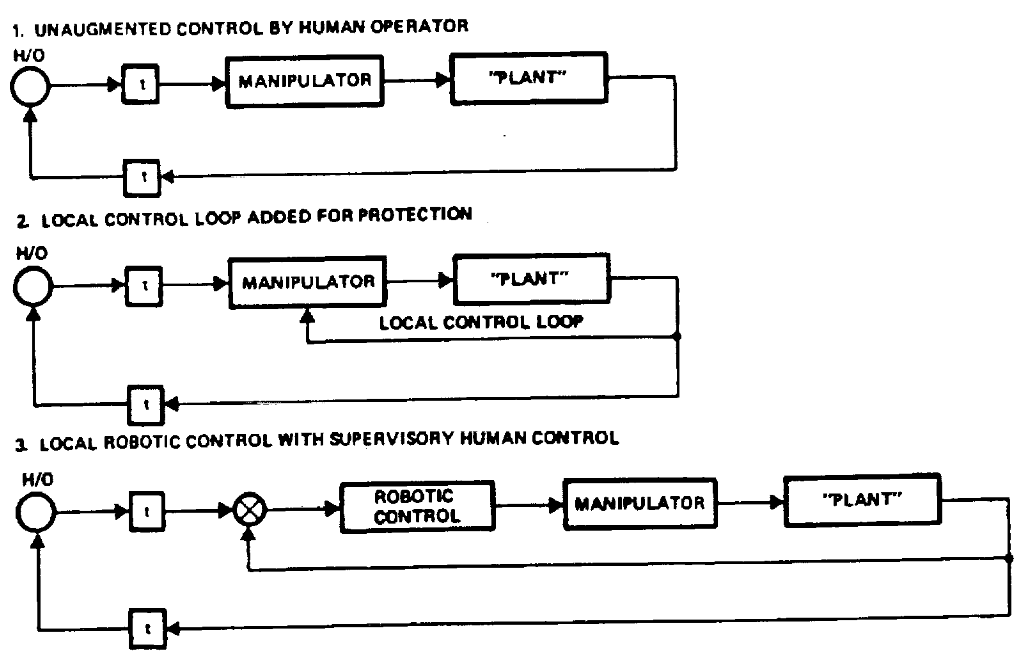
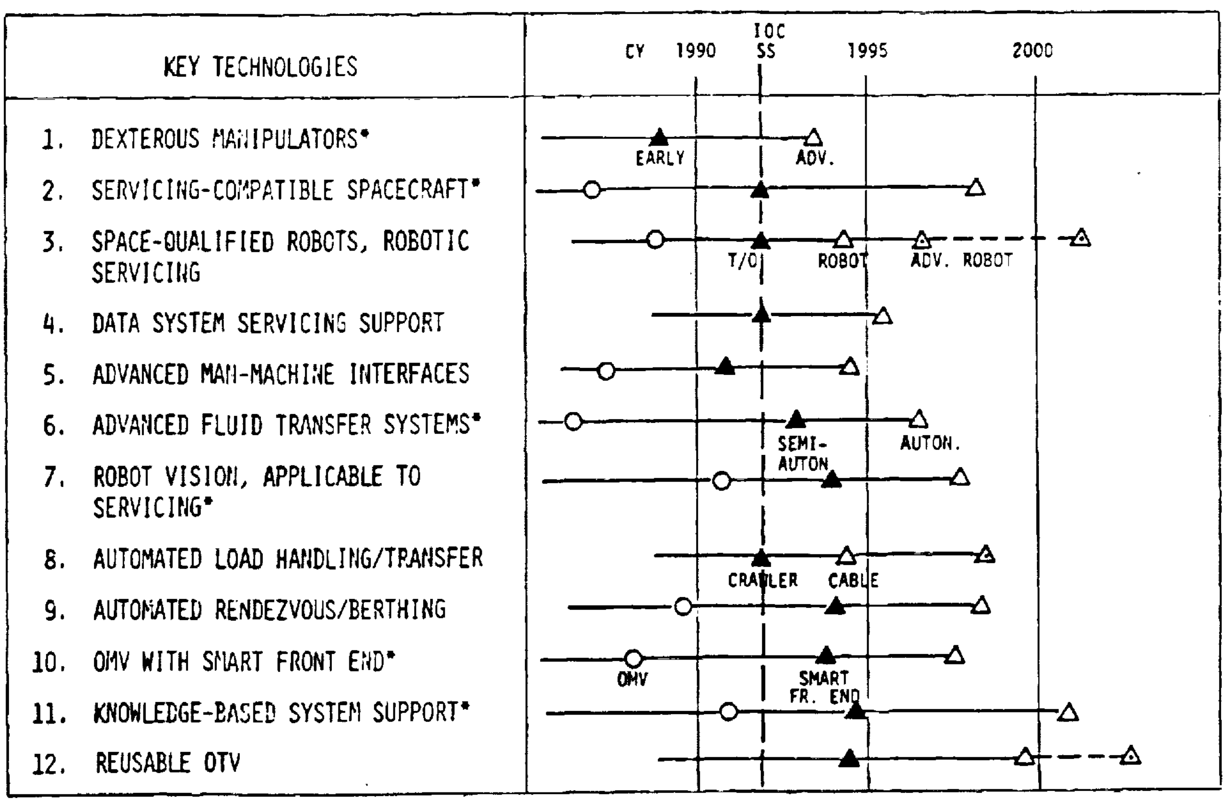


Figure 9. Alternatives of Remote Manipulation With Major Time Delay

- 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 10. Teleoperation vs. Robotics in Satellite Servicing



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

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

Figure 11. Automated Servicing Technology Development Forecast

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.

3.6 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 12 summarizes design requirements and constraints of these systems. A more detailed listing of automation attributes and resource requirements of the SS satellite servicing facility is presented in the Technical Report.

3.7 Generic Servicing Facility

3.7.1 Design Criteria and Constraints

Design criteria and constraints for a generic satellite servicing facility and the corresponding operating criteria and constraints were determined and are summarized in Figure 13.

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 SS 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 14. Specific functions directly related to the artificial intelligence requirements of the system are listed separately in Figure 15.

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 12. Automated Servicing Design Requirements

CRITERIA	CONSTRAINTS
• LARGE, UNCROWDED WORK AND STORAGE AREAS • DISPERSED ELEMENTS, KEYED TO CAPABILITY GROWTH • CONVENIENT LOCATION OF WORK AND STORAGE AREAS RELATIVE TO SATELLITE BERTHING, FUEL DEPOT • CONVENIENT LOAD HANDLING AND TRANSFER • TELEOPERATED AND ROBOTIC MANIPULATORS - READILY MOBILE • CONVENIENT AND SAFE CREW ACCESS, ALL AREAS • DISTRIBUTED TV COVERAGE, ADEQUATE LIGHTING, GLARE SHELDING • WORK AREA OBSERVABLE FROM CENTRAL CONTROL STATION • READY ACCESS TO POWER AND OTHER UTILITIES	• SERVICING AREAS AND OPERATING FUNCTIONS MUST BE COMPATIBLE WITH OPERATIONS OF ALL OTHER SYSTEMS ONBOARD SS (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 SS 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 • SS UTILITIES AND SERVICES MUST BE SHARED WITH OTHER USERS BY A MUTUALLY AGREED-ON SCHEDULE OR SEQUENCE

Figure 13. Servicing Facility Design/Operation Criteria and Constraints

• 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 ON 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 14. 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 15. Artificial Intelligence Functions

An example of the servicing facility's dependence on data system support is presented in Figure 16, which shows a typical sequence followed in planning and execution of a servicing task.

3.7.4 Servicing Facility Resource Requirements

Space Station resources required to support servicing operations are listed in Figure 17. 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.

Analysis of power, thermal control, data storage, data processing and communication link support for servicing indicated that appropriate resource allocation can avoid conflict of user requirements on the IOC Space Station.

Power and heat rejection requirements for servicing average about 4 KW. The large volume of reference data needed in satellite servicing can be handled by onboard bulk storage or by occasional uploading from data files on the ground. Maximum communication bit rates of the order of 10 Mbps are required for video feedback signals in teleoperated remote satellite servicing. By appropriate data compression techniques the required bit rates may be reduced by an order of magnitude.

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 Location of Servicing Areas

NASA's current Space Station IOC reference configuration, also known as the "Power Tower," Figure 18, (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

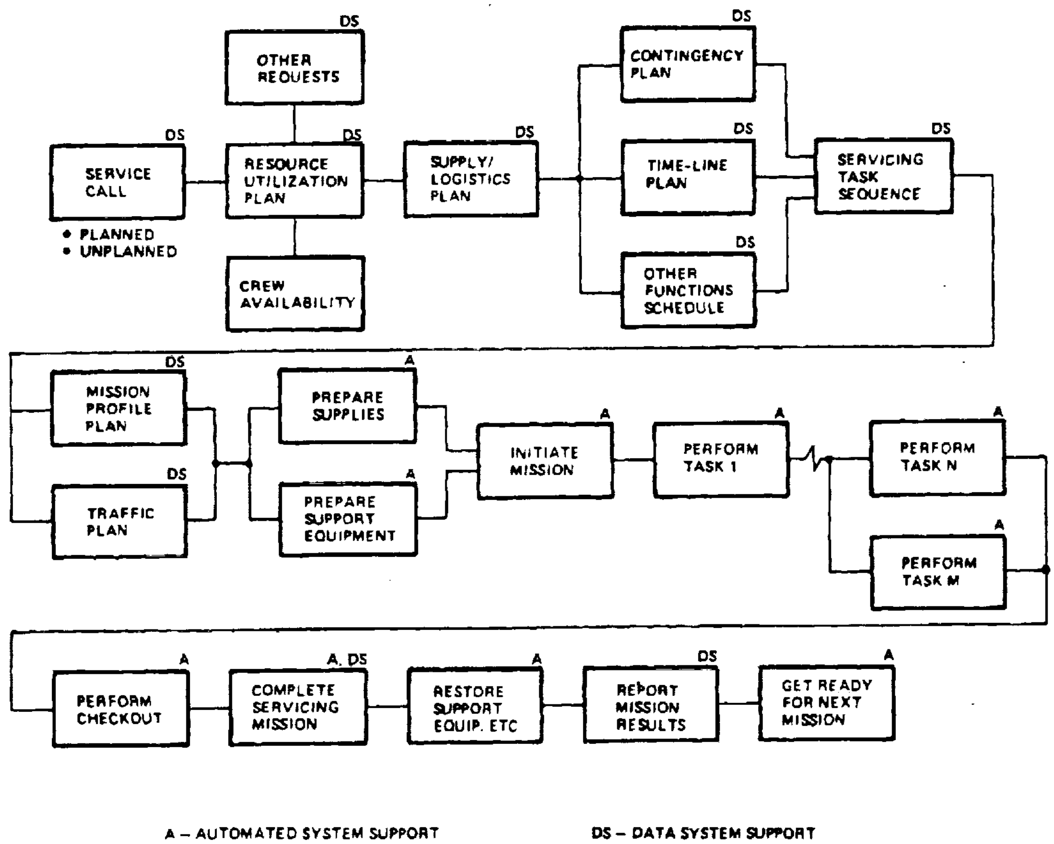


Figure 16. Servicing Mission Planning and Execution

1. CREW INTERFACES

2. POWER, POWER DISTRIBUTION

3. THERMAL CONTROL
   - HEATING
   - INSULATION
   - COOLING
   - HEAT EXCHANGE

4. LIFTING, LOAD TRANSFER AND CONTROL
   - MANIPULATOR ARM(S)
   - CONVEYOR SYSTEM
   - RAIL/DOLLY 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 17. Automated Servicing Facility Resource Requirements

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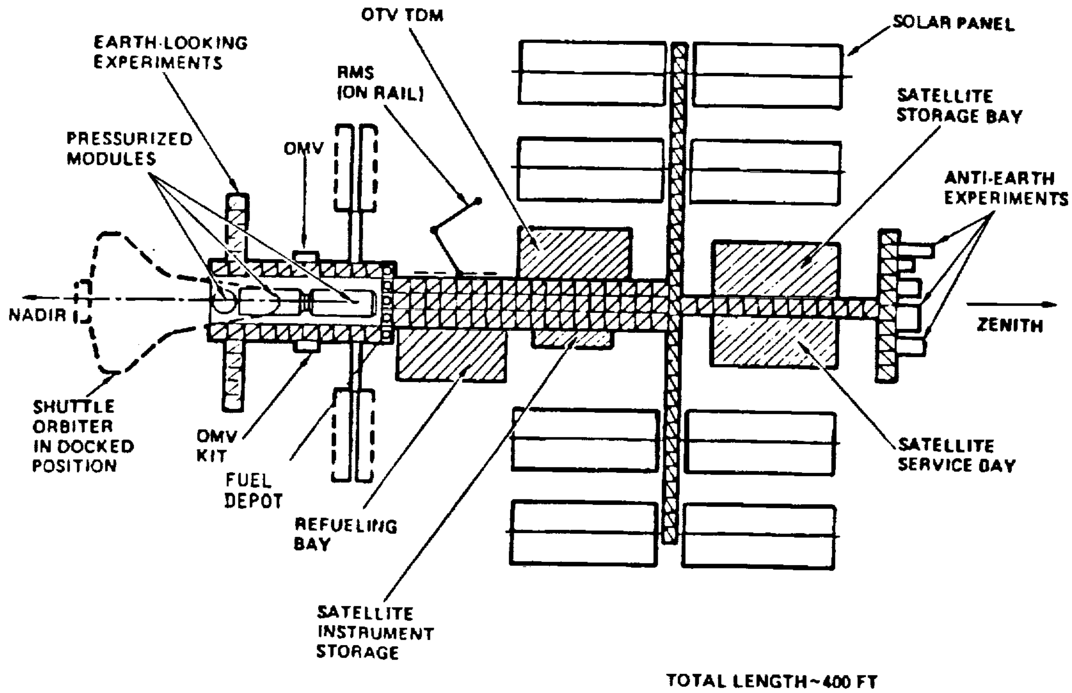


Figure 18. Space Station Design Features Related to Satellite Servicing (Reference IOC Configuration)

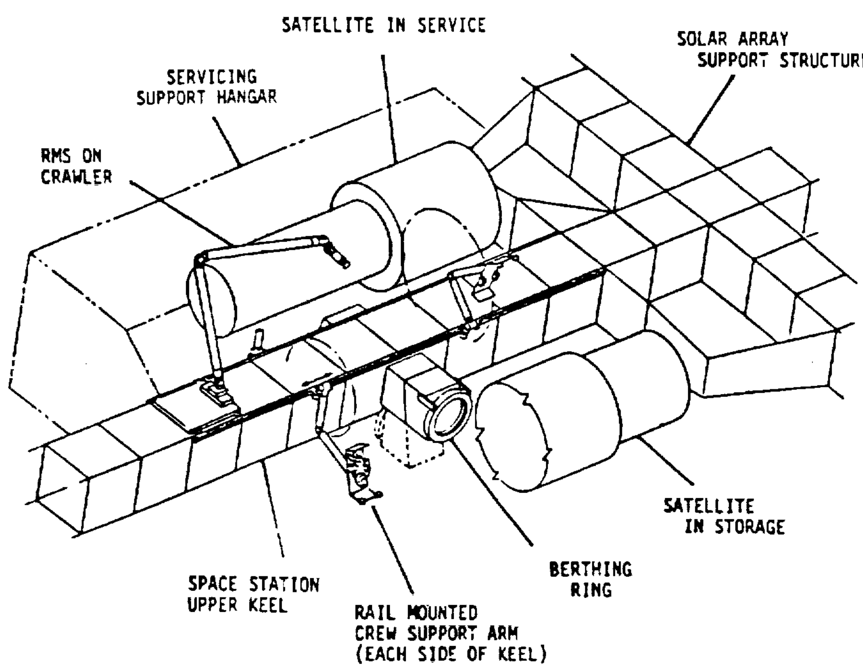


Figure 19. Access to Satellites Being Stored and Serviced

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 19 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. Alternative 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.*

3.7.5.2 Load Handling and Traffic

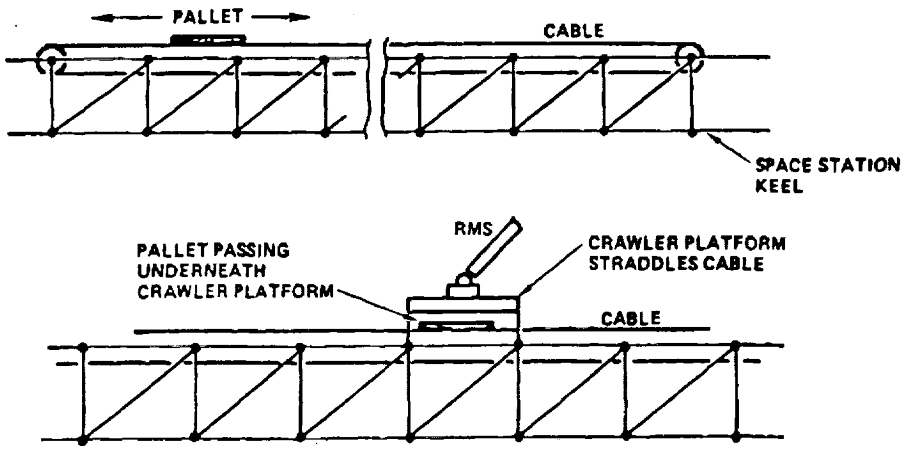
The dispersed location of service areas avoids crowding and permits unconstrained access but also necessitates more extensive and frequent transfer of crew men, support equipment, satellite hardware, tools and supplies along the Space Station keel. Traffic volume is expected to increase as demand for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

A fast and efficient system for load handling and transfer will be required to support 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 20 shows a cable-driven pallet concept which can transfer loads 20 to 50 times faster than the RMS crawler platform. The 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.

*Z-axis along keel, Y-axis along solar array boom, and X-axis normal to Y and Z-axis.

SIDE VIEW



COMPATIBILITY WITH RMS PLATFORM

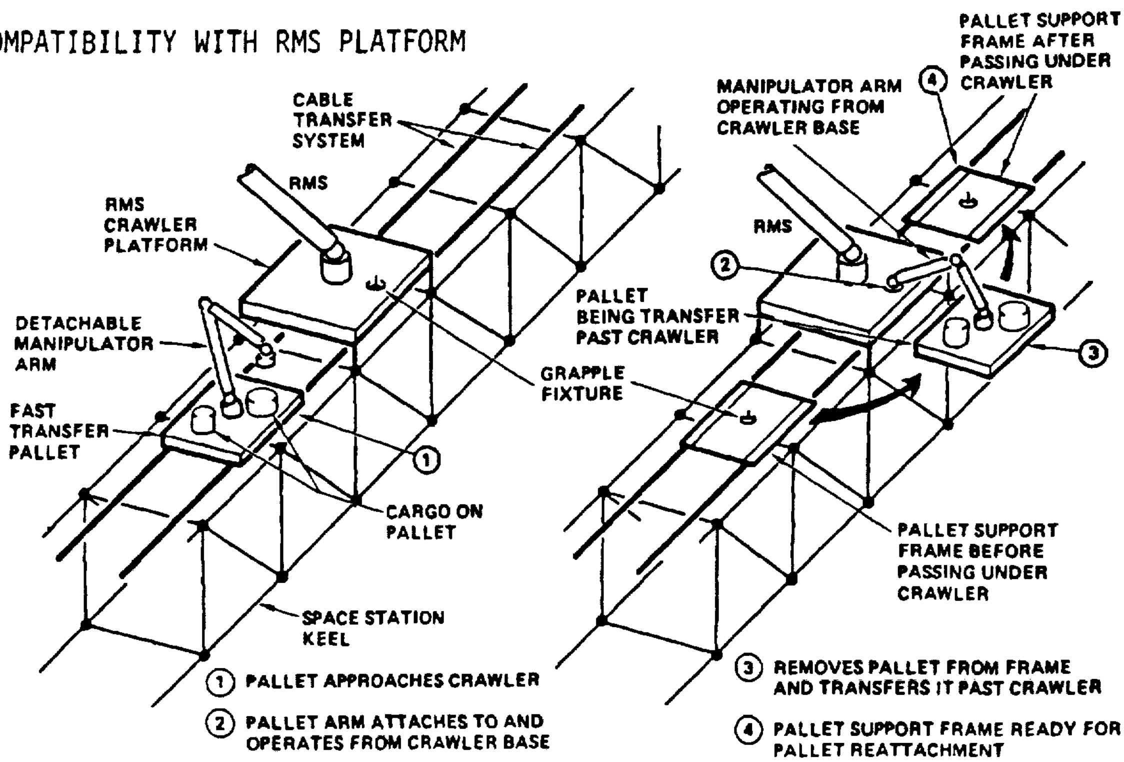


Figure 20. Cable-Driven Pallet Transfer Concept

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.

3.7.5.3 Service Bay Design

As shown in Figures 18 and 19, 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 SS keel structure, the retractable half shell configuration, illustrated in Figure 21, 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 19). 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 Marrietta (Reference Satellite Servicing Technology Development Missions, Final Report, October 1984) a rotatable satellite holding fixture is envisioned to permit reorienting the satellite

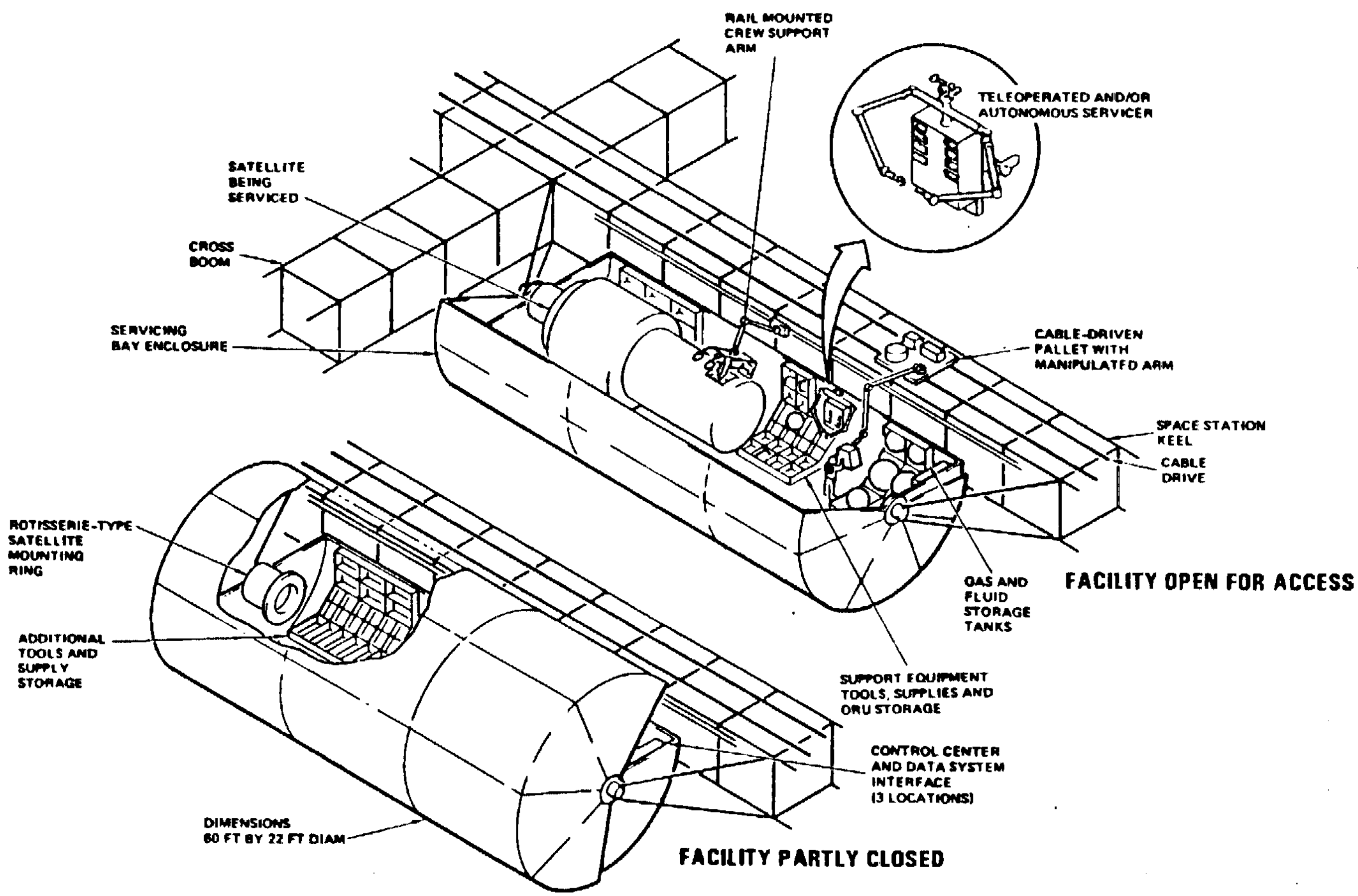


Figure 21. Enclosed Service Bay Concept

for easy access from all sides. A dexterous manipulator for 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 this design include questions of size and expandability, handling of balky satellite configurations (e.g., satellites with deployed appendages) and the possibility of future conversion of the hangar into a workshop suitable for pressurization.

3.7.6 Pressurized Mobile Work Station

A pressurized, enclosed cherry picker equipped with manipulator arms, based on concepts developed by Grumman, will be a useful adjunct to the crew support equipment used in the servicing facility. This hybrid 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. It would permit servicing a space platform in the deployed configuration in close SS vicinity without requiring station keeping maneuvers. SS 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.

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, less teleoperated 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 provisions will contribute to expanding the servicing capability by evolution rather than redesign and replacement:

1. Extra space for servicing, room to grow.

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 manipulation.

5. Provision for expanded storage facilities (tools, supplies, support equipment).

6. Control center expansion capacity, room for extra display and control panels. Potential add-on of a remote control station.

7. Provision for increased fuel storage and larger fuel transfer volumes.

8. Provision for added OMVs and accommodation of OTVs (storage, assembly space, berthing provisions).

9. Provision for RMWS (enclosed cherry picker) addition to the servicing facility (storage, support and maintenance provisions).

10. Provision for adding tethered berthing capability.

3.8.3 Advanced Technology Capabilities

The servicing facility growth will require automation technology advances in the following areas:

1. Advancement from teleoperation to robotic operation, smart robots.

2. Refinement of teleoperators and manipulators: greater dexterity, more telesensing, touch sensors, robot vision.

3. Increased use of machine intelligence: automated test sequences, expert systems for diagnostics, troubleshooting, mission planning, logistics control and other fields.

4. Increased data system support to the crew and to automated operations.

5. Automatic traffic control, rendezvous/berthing control to meet greater traffic flow, ensure safety.

6. Automated load handling and transfer, commensurate with increased traffic flow of equipment and supplies between elements of servicing facility.

7. Tethered berthing operations, automated servicing of satellites in tethered position.

3.9 Operating Issues Related to Remote Satellite Servicing

Two issues of remote satellite servicing operations needed some detailed analysis. They involve:

1. Accessibility of target satellites at low altitude and low inclination which might be too far out-of-plane for direct access by the OMV because of nodal misalignment.

2. Availability of direct line-of-sight communication links which would permit teleoperation without excessive signal transmission delay in the control loop.

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.

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. 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.

3.9.2 Direct Line-of-Sight Communication in Remote Satellite Servicing Missions

Communication by direct line-of-sight or via relay satellite link between the Space Station and an OMV performing a remote servicing task at a target satellite were investigated. Relay communication via TDRSS, assuming its current operating mode, may involve from 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. A future advanced TDRSS design would eliminate part of this complexity.

The current TDRSS operating mode may cause a total feedback signal round-trip time delay of 5 to 10 seconds including the delay due to image processing. This is unacceptable for purposes of controlling delicate tasks by teleoperation, and would impose an immediate need for autonomous fully robotic servicing.

Direct line-of-sight communication, as an alternative, reduces the signal round-trip time delay to less than 30 milliseconds to which the TV image processing delay must still be added. Thus, direct communication is more compatible with teleoperation. However, the target satellite may 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. The maximum line-of-sight distance for satellites at near co-altitude with the Space Station is about 4000 km.

Remote servicing missions to LEO satellites, e.g., Reference Mission 2, can be planned to make best use of the total direct line-of-sight contact periods, or "windows," lasting typically 4 to 10 hours, depending on differential altitude. The OMV flyout and return paths can be arranged so as to maximize the number of available operating hours within the visibility window.

Reference Mission 4 requires control of remote servicing at GEO altitude. Here the contact periods for direct communication from the Space Station are less than an hour, interrupted by about 35 to 40 minutes of non-contact, for every SS orbital revolution. A preferred operating mode would be control from a ground station, a departure from the guideline requiring SS operational autonomy. An alternative would be fully robotic servicing techniques but with supervisory control by a human operator.

4.0 CONCLUSIONS

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.

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 (expert sytem support) required in diagnostics, troubleshooting, decision making, task scheduling, and mission planning.

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 showed that about 40 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.

The principal conclusions may be summarized as follows:

1. Automation can make satellite servicing more productive, but accelerated development of automation hardware is needed.

2. Servicing poses automation requirements significantly different from those of other Space Station orbital activities.

3. Telepresence is the principal automation discipline required for servicing, with human operator involvement to handle task diversity and unforeseen situations.

4. Teleoperation or fully automated (robotic) use of the same manipulators offers flexibility and adaptability.

5. Major time delay in teleoperation on remote servicing missions can be avoided by scheduling operations for direct L.O.S. contact intervals.

6. GEO satellite servicing demands more reliance on the full robotic mode with human supervisory control. Teleoperation is performed preferably from a ground station to avoid intermittency.

7. Massive data system support is needed in planning, sequencing and execution of tasks and to provide artificial intelligence support to the crew in troubleshooting, failure analysis and emergency situations.

8. Major spin-off benefits to terrestrial applications will be in the area of flexible/adaptable automation, for economical production of small quantities, and in advanced data management and information transfer.

5.0 RECOMMENDATIONS

On the basis of the study results and conclusions discussed in the preceding sections, we summarize our recommendations as follows:

A. Near Term:

1. Load handling and transfer automation is a major development requirement to streamline traffic flow. A fast load transfer system is needed on the early Space Station in addition to the RMS crawler platform.

2. Automated rendezvous/docking is a near-term requirement.

3. Addition of a "smart front end" servicing kit to the OMV is needed for remote servicing missions.

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

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

6. Crew safety is a principal criterion in defining conventional as well as automated servicing approaches. This requires appropriate attention even in the earliest phases of automated servicing technology development.

B. Long Term:

1. Artificial intelligence (expert system) development is a long-term objective for achieving advanced robotic servicing/repair capabilities.

2. 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.

3. Aerobraking may be required to render geosynchronous servicing by reusable OTVs economically more attractive.

4. 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 can be adapted for this purpose.

5. The pressurized movable work station (RMWS) should be developed to provide flexibility and safety in remote crew operations and to offer advanced teleoperation capability.