Opportunities for Space Station Assembly Operations During Crew Absence

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Prior to permanently manned capability (to be achieved approximately 21 months after the first element launch), the space station will be manned for less than 10% of its total staytime on orbit. The most intensive and critical station assembly operations will occur during these early flights. Some robotic resources may be available to perform assembly operations while the station crew is absent; however, the use of robotic devices for assembly operations during unmanned phases has not yet been adopted by the space station program. This paper will study the relevant aspects of teleoperated and autonomous assembly activities and will present candidate assembly operations that could be performed during crew absence. From this analysis, the potential benefits of remote control of robotic resources can be weighed against any associated increase in cost and complexity that would accompany implementation of this capability.

Introduction

THE space station will be incrementally assembled over many Space Shuttle flights. The assembly sequence is driven by a need to provide a fully functional spacecraft (i.e., capable of actively maintaining its orbit) for each assembly increment. The current assembly sequence is success oriented, and time and resources may not be readily available to accommodate on-orbit contingencies. These contingencies can range in severity from minor operational malfunctions to emergencies requiring immediate Orbiter separation from the station for a return to Earth. In the case of premature Orbiter departure, certain crucial assembly objectives may not have been accomplished. Clearly, an approach for recovering from such a situation using remotely operated robotic resources is worthy of investigation. This may make the difference between success and a failed mission.

Space station assembly objectives may be decomposed to show the various types of operations necessary for completion. Following the activity decomposition, available assembly resources may be assigned to the appropriate tasks. The first level of assembly operation decomposition includes structural assembly, pallet installation, and pressurized module installation. Functional task designations such as transportation, positioning, and dextrous manipulation are used to better define the decomposed operations.

Robotic resources available on the station prior to permanently manned capability (PMC) include the Flight Telerobotic Servicer (FTS), the Mobile Servicing Center (MSC) that incorporates the mobile transporter (MT) and the Space Station Remote Manipulator System (SSRMS), and the Assembly Work Platform (AWP). The MT can provide transportation functions (moving hardware from storage to the worksite), the SSRMS can provide positioning functions (placing hardware in the proper position and orientation for installation), and the FTS can provide dextrous manipulation functions (making structural and utility connections). The AWP may also provide transportation and positioning for the FTS. If proper accommodations for robotic interfaces are made on the hardware components, robotic devices could be used to augment or replace human interaction for certain assembly operations.

Remote operation of on-orbit robotic resources would be performed primarily from ground-based control stations. These control stations would need to incorporate teleoperation and/or automation of robotic tasks along with significant fault-detection and safing capabilities in order to provide a high confidence level for mission success. Control station design has received considerable attention in academia and industry; human factors and the human/machine interface continue to evolve as more complex applications are introduced.

Two issues that must be addressed for remote station assembly include the effect of signal-transmission time delays and the need for extreme safety and reliability in all assembly operations. Transmission time delay is associated with the long distances and routing necessary for continuous space-ground communication links. Although direct solutions to this problem are constrained by high cost and immutable physical principles, there are several methods available for indirectly compensating for time delays. These include simulating the activity of the robot in real time with a predictive display and maintaining the bandwidth of all manipulator commands low enough to guarantee the capability for a defensive response. Implementing a higher degree of autonomy (particularly for dextrous operations) will be required in order to accommodate remote robotic operations. Space system design typically incorporates high levels of safety and reliability. These factors will be even more critical for remotely directed operations since the adaptability and diagnostic capabilities of an on-site human will not be available.

The primary value of a detailed study would be to establish a technical foundation for comparing the potential benefits for remote control capability (contingency recovery, operational flexibility) with the ramifications (cost, feasibility, complexity) associated with its implementation. Before a cost/benefit analysis can be performed, the feasibility of a remote control capability must be established. Based on this precedence requirement, the intent of this study is to directly address the feasibility issue; the results may then be applied to provide recommendations for potential benefits to the space station program if remote control of robotic resources is, in fact, a technically and operationally acceptable concept.

Space Station Assembly Overview

The space station development is based on a presidential directive to provide a permanently manned station in low-Earth

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Table 1 Assembly-phase flight manifest summary (from Ref. 1)

First Element Launch	1/1/95	MB-1	Starboard PV power module, starboard truss utilities, starboard propulsion, *erector set (AWP)*, S-band antenna, avionics pallet
	4/1/95	MB-2	Aft starboard node, starboard Thermal Control System (TCS), *FTS*, pressurized docking adapter, CMGs, TDRSS antenna, starboard propulsion
	7/1/95	MB-3	Aft port node, *MSC Phase 1*, starboard TCS, pressurized docking Adapter, FMAD pallet, airlock, starboard propulsion
Man-Tended Capability	9/1/95	MB-4	U.S. lab module
	11/1/95	MB-5	Port Photovoltaic (PV) power module, port truss utilities, port propulsion, port and starboard TCS, SSEMU verification unit lab module outfitting
	1/1/96	OF-1	Lab module outfitting
	3/1/96	MB-6	Hyperbolic airlock, *SSRMS-2*, attached payloads
	5/1/96	MB-7	Hab module
	7/1/96	MB-8	Forward nodes and cupolas (2)
Permanently Manned Capability	10/1/96	MB-9	Logistics resupply, SSEMUs (4)
	11/15/96	MB-10	Outboard PV power modules (2)
	1/1/97	L-1	Logistics resupply, *SPDM*
	2/15/97	MB-11	Japanese Experiment Module (JEM), JEM Exposed Facility 1
	4/1/97	L-2	Logistics resupply, attached payloads
	5/15/97	MB-12	European Space Agency module
	7/1/97	L-3	Logistics resupply, MMD Phase 1
	8/15/97	MB-13	JEM Exposed Facility 2, JEM logistics, attached payloads
	10/1/97	L-4	Logistics resupply
Assembly Complete	11/15/97	OF-2	Module outfitting

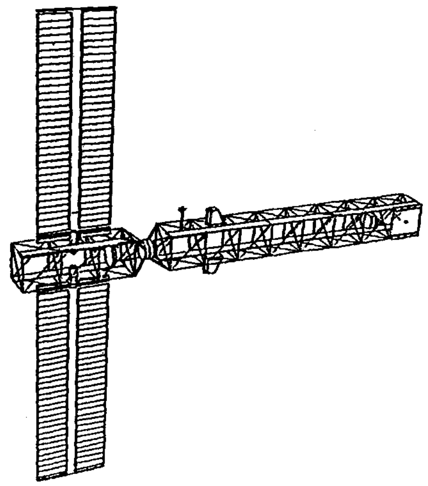

Fig. 1a First Element Launch (FEL).

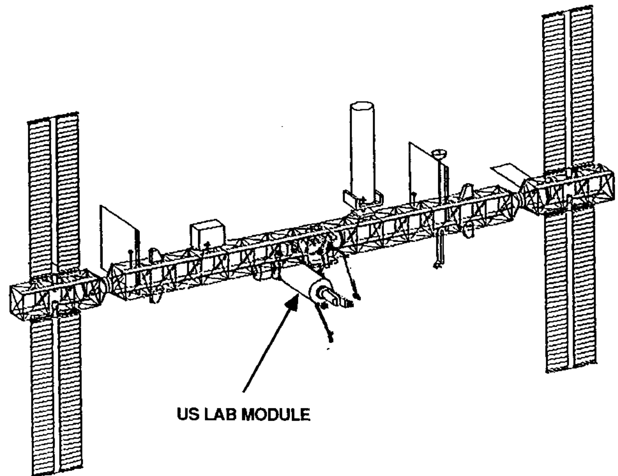

Fig. 1b Man-Tended Capability (MTC).

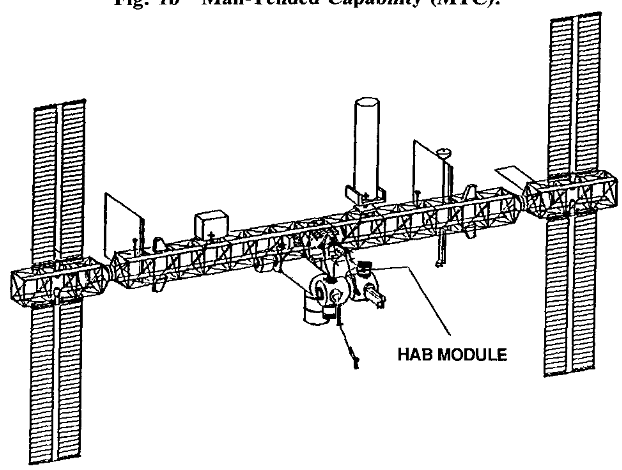

Fig. 1c Permanently Manned Capability (PMC).

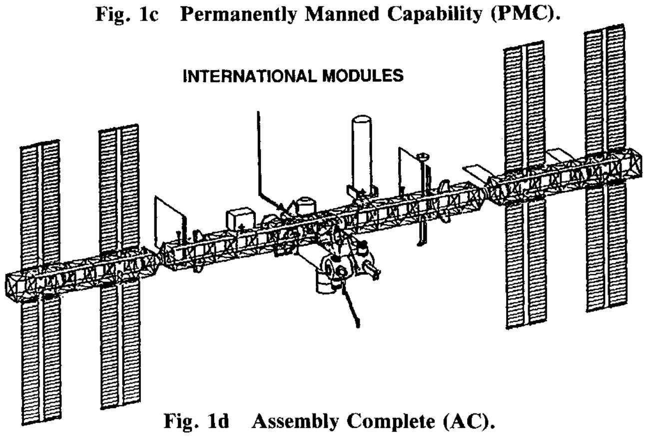

Fig. 1d Assembly Complete (AC).

orbit by the mid-1990s. The current space station configuration will be assembled over 19 Space Shuttle flights (Table 1). Several assembly-phase milestones have been identified (Figs. 1); those milestones serve as focal points for top-level requirements and provide reference points for evaluation of alternative assembly sequences.

First Element Launch to Man-Tended Capability

This part of the assembly phase (see Figs. 1a and 1b) is devoted to providing the station infrastructure (truss, power, avionics, propulsion, heat rejection, and so forth) to support the pressurized elements and attached payloads. First Element Launch (FEL) denotes the first delivery of space station hardware to orbit and will result in a functional spacecraft. This incremental approach establishes the need for a successful assembly on the first flight, with capabilities that allow the station to maintain orbit until the next Shuttle visit. Emphasis on successful completion of each flight's assembly objectives carries through all increments prior to PMC. Flights between FEL and Man-Tended Capability (MTC) increase those capa-

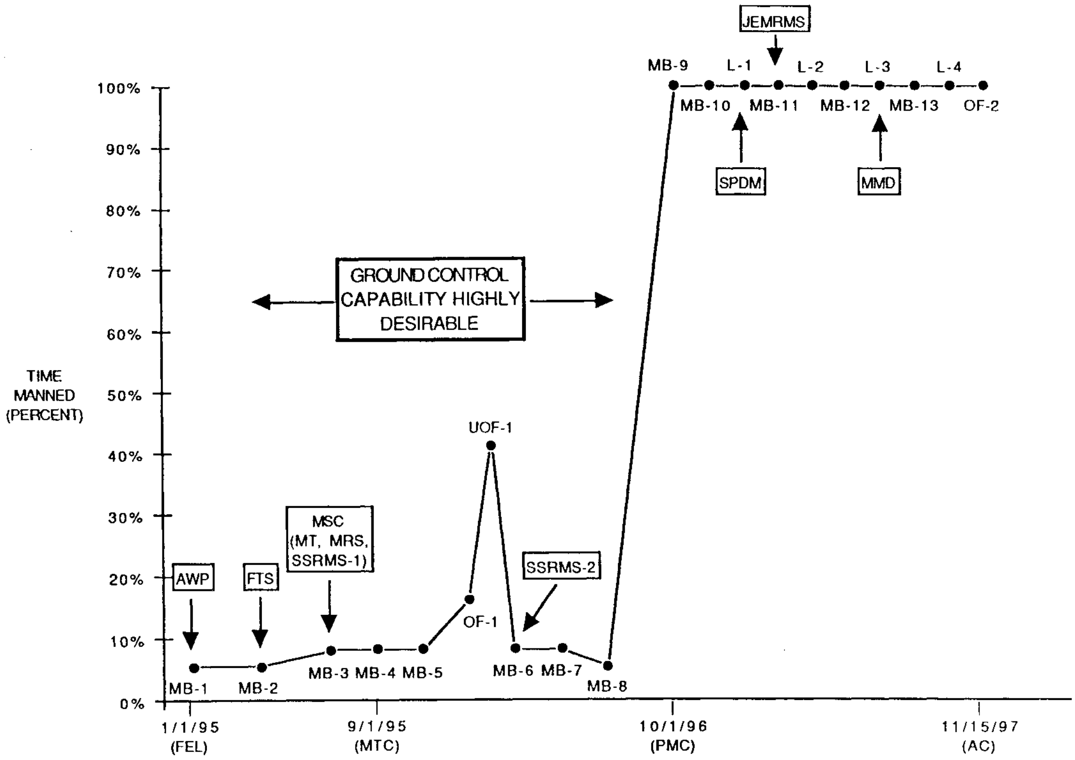

Fig. 2 Deployment of assembly resources and unmanned fraction vs time.

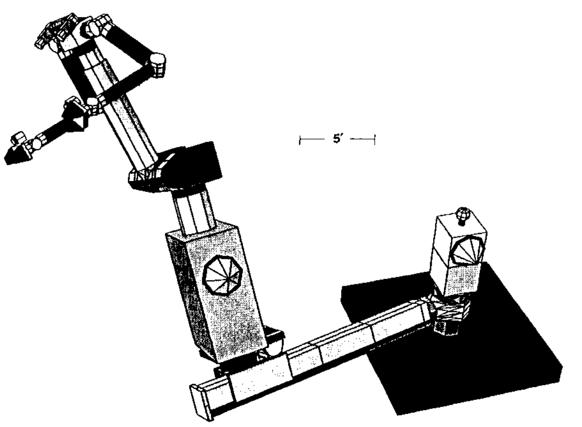

Fig. 3 Flight Telerobotic Servicer (FTS) "Tinman" concept.

bilities established at FEL and incorporate additional systems to support manned activity at MTC. The delivery, checkout, and outfitting of the U.S. laboratory module will mark achievement of MTC, a capability for use of station-pressurized elements in a shirt-sleeve environment for the duration of the Shuttle mission. At this point, periodic manned operations aboard the station may commence.

Deployment of several robotic assembly resources will occur during this period (Fig. 2). The AWP will be deployed on the first flight to support structural assembly and installation of pallets. The FTS will be deployed on one of the first two flights to provide dextrous manipulation capability. A major portion of the MSC will be deployed to provide transportation and positioning capabilities. The use of these devices would enable robotic assembly of many on-orbit components.

These pre-MTC flights are the most complex and success-oriented of the assembly phase. If an on-orbit contingency prevented the completion of the assembly objectives of these flights, the survival of the station could be in jeopardy. Remote control of robotic assembly resources could allow assembly operations to be completed if the Orbiter had to depart the station prematurely.

Man-Tended Capability to Permanently Manned Capability

This part of the assembly phase (see Fig. 1c) is primarily devoted to deploying and outfitting the remaining U.S. pressurized elements. The second half of the truss is also assembled to provide resources for pressurized and unpressurized payloads. The outfitting of the U.S. laboratory and habitation modules marks the capability for a permanent manned presence on the station. The second SSRMS is also delivered during this phase.

During this phase, robotic resources may be controlled from within the pressurized volume on the station. However, the baseline Orbiter staytime of five days limits the amount of useful work that may be performed; the desire to perform user experiments will limit the on-board crew's capability to conduct assembly operations. It is not until PMC that extensive, long-duration assembly operations can be conducted.

Permanently Manned Capability to Assembly Complete

This part of the assembly phase (see Fig. 1d) is characterized by station element buildup along with logistics resupply and module outfitting. The international pressurized laboratories are integrated into the station during this period. The deployment of outboard PV modules brings the station's power-generation capability to 75 kW. Nominally, every second flight following PMC will be a dedicated logistics flight. The outfitting of the pressurized modules marks the completion of the assembly phase. Extensive user operations will characterize the next stage in the life of the station; assembly operations will continue on a reduced scale to provide increasing station capabilities.

As just stated, station-based assembly will commence at PMC. The only major robotic addition to Station assembly capabilities between PMC and AC will be the deployment of the Canadian Special Purpose Dextrous Manipulator (SPDM).

The permanent presence of the crew following PMC reduces the need for a remote robotic control capability. However, post-PMC assembly operations are considerably less complex and critical than pre-PMC assembly operations. The implementation of ground control prior to PMC would serve to alleviate this mismatch between assembly success criticality and assembly resource control capability.

On-Orbit Robotic Resources

The robotic resources described here will be available before PMC and can provide transportation, positioning, and dextrous functions necessary for many critical assembly operations.

Flight Telerobotic Servicer

This U.S.-developed device (Fig. 3) will be used for dextrous assembly, servicing, and maintenance operations.[2] A NASA Goddard Space Flight Center in-house phase B design study yielded the "Tinman" concept to be analyzed prior to a phase C or D contract award. It has two main seven-degree-of-freedom appendages; a specialized grappling device is used to anchor the telerobot to the worksite.[3] It has a roughly anthropomorphic shape, since it will perform some tasks normally assigned to humans. The device has no mobility capability and will use the MT or a positioning device for transportation. The FTS is designed for either teleoperated or autonomous control.

Three operating modes have been identified for the FTS. These include a transporter-attached mode (where the telerobot receives power and data from the transporter), a fixed-base independent mode (where the telerobot will be detached from the transport device and will receive power from internal batteries and data via rf link with the Shuttle/station), and a fixed-base dependent mode (where the worksite provides power and data). The FTS will provide a unique dextrous robotic capability until the SPDM is deployed.

The current operational concept incorporates control from a workstation in the Orbiter or station. Ground control is seen as a future growth option. High-fidelity ground-based workstations will exist for training and simulation functions. These workstations could be interfaced to the Space Station Control Center (SSCC) and used to command the telerobot.

Assembly Work Platform

The AWP (Fig. 4) will be deployed on the first flight to support truss construction. It uses the MT to translate the truss bays as they are constructed and provides an astronaut translation device (ATD) to position the extravehicular activity (EVA) crew member during structural assembly and pallet installation operations. The FTS could also use the ATD for mobility; the ATD would only have to provide a structural interface for the telerobot that would operate using its own internal power source and an rf data link.

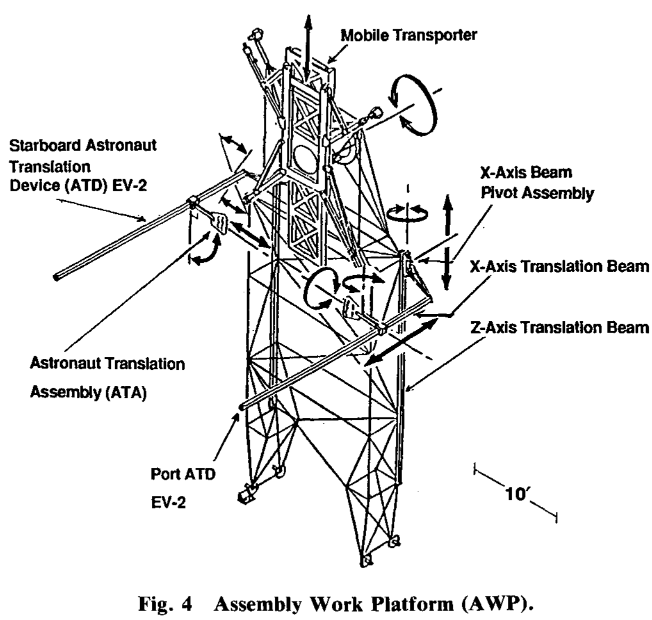

Fig. 4 Assembly Work Platform (AWP).

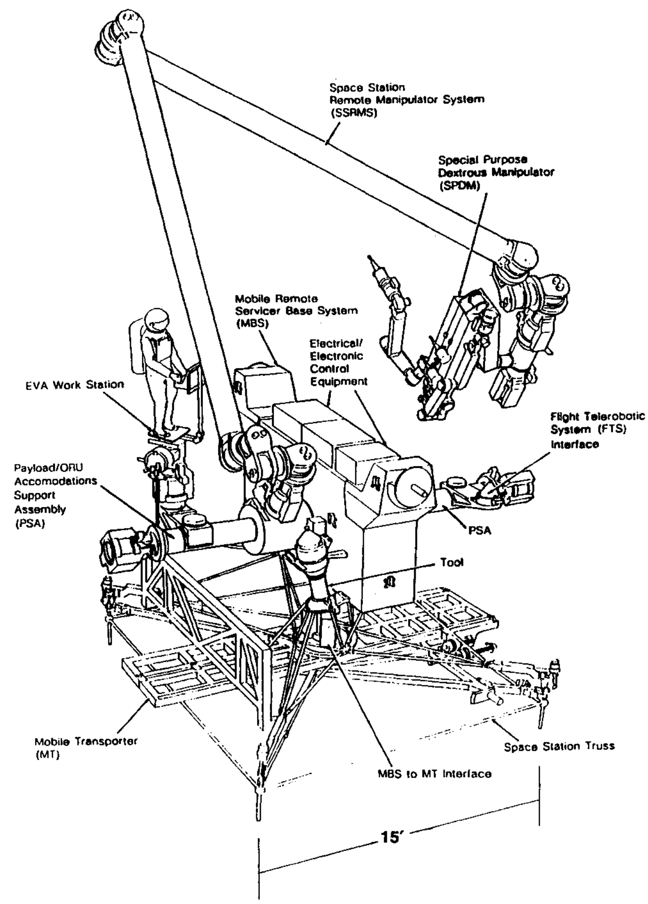

Fig. 5 Mobile Servicing System (MSS).

There is currently no ground control capability envisioned for the AWP. However, this capability would be relatively easy to implement since the ATD and MT perform relatively simple motions that could be commanded on a ground-based control panel and then uplinked to the station.

Mobile Servicing System

The Canadian mobile servicing system (MSS) consists of several components, including the MSC (consisting of the MT and mobile remote sensor) and the SPDM (Fig. 5). (An MSC maintenance depot is included in the MSS, but plays no direct role in assembly operations.) The MSS will provide a capability for translation, positioning, and dextrous manipulation.[4] The MSS components may be used together as an integral unit or distributed about the station in various combinations.

The MT provides transportation capability for the MSC and will also have the capability to carry payloads and other equipment to worksites along the structure. The MT consists of a powered drive mechanism with attachment provisions for the aforementioned devices. The MT has no inherent positioning or dextrous manipulation capabilities and is meant only as a mobility platform.

Mounted on the MT, the MRS consists of several distributed subsystems (power management and distribution, communications, data management, thermal, and so forth), the MRS base system (MBS) that provides the interface between the MT and its payloads, and one or more SSRMs. The MSC provides positioning capabilities and payload accommodation.

The SSRMS arms are 58-ft-long, seven-degree-of-freedom arms with latching shoulder/end effectors at each end. The arms are completely symmetrical and can be operated from either end (giving them a unique ability to "walk," end over end, from one Power Data Grapple Fixture to another). Like the Shuttle Remote Manipulator System, these devices have a positioning capability for large masses (they will be used to berth the Oribiter to the space station), but they have no inherent dexterous capability unless a dextrous mechanism is attached to the end effector. The FTS and SPDM are designed to be positioned by the SSRMS for dextrous operations.

All MSS components are controlled from workstations located in the station or Shuttle. Ground control capability for the MSS is currently limited to system monitoring and checkout functions. This is, however, largely an operational constraint and the system infrastructure does not preclude ground commands from being inserted into the space-ground communication link.[5] Ground-based workstations would provide the operator with a time-delayed interface to the MSS operating environment.

Candidate Assembly Operations

Structural Assembly

Assembly of the truss is critical because it provides the structure on which pallets and pressurized modules are attached. Extensive truss assembly operations will be conducted prior to PMC and involve transportation of components to the worksite, positioning at the worksite, and dextrous manipulation of structural and utility connectors.

The currently envisioned truss assembly scenario involves using the AWP to support and move the truss while it is being assembled. Truss struts and connectors are packaged in boxes and attached to the AWP to provide easy access from the ATD. The procedure then involves removing individual struts and nodes to be attached at the appropriate locations on the truss bay. As each truss bay is assembled, utility lines are deployed and connected to the truss.

Structural assembly operations may be performed robotically, using the AWP/ATD and FTS. (The MSS will greatly enhance this capability if available.) Replacing the EVA astronaut on the ATD with the FTS allows for positioning and dextrous manipulation, and the MT provides any required transportation capabilities. The assembly procedure would need to be modified to accommodate the single FTS, since typically the two EVA crew members cooperate while assembling a truss bay. Proper restraint of the partially completed truss bay by the AWP would allow the FTS to assemble one side of the bay and then relocate to the opposite side to complete the bay. Locating all required assembly components within reach of the FTS/ATD will minimize the need for relocation and improve the operational characteristics for truss assembly even under nominal conditions.

Preliminary results from the Massachusetts Institute of Technology Space Systems Laboratory indicate that robotic truss assembly operations will take 5–10 times longer than corresponding EVA operations.[6] This parameter is extremely critical when allocating tasks between humans and machines for on-orbit operations, but not as important during the periods when the station is unmanned. Ground-based operations carry only weak time constraints, and a 500–1000% increase in task completion time is more than balanced by a 1000–2000% increase in available time associated with the unmanned period. This capability to tolerate inefficient operations makes ground control of robotic resources especially attractive for unmanned assembly operations.

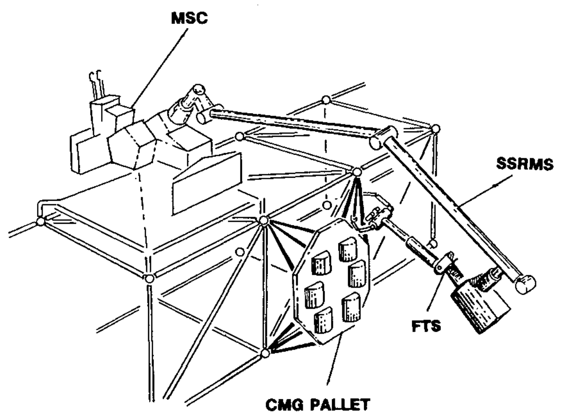

Fig. 6 Pallet installation using robotic resources.

Pallet Installation

Pallet installation is another critical assembly operation prior to PMC, as many of the core functions of the spacecraft such as power, thermal, propulsion, and avionics are installed onto external resource pallets. Like structural assembly, installation of the pallets is characterized by transportation of the pallet to the worksite, positioning near the final installation location, and dextrous manipulation of structural and utility connections. The main difference is that pallet installation usually involves only one or a few large components due to extensive ground-based integration of ORUs and support equipment on the pallet.

Pallet installation scenarios typically involve attaching the pallet to a payload accommodation location on the MSC for transportation to the worksite. The SSRMS is then employed to position the pallet near the installation location, where a dextrous manipulator performs the structural and utility connections (Fig. 6). Few or no modifications to this procedure would be required to perform this operation remotely, if we assume proper provisions for robotic accommodation are made at the worksite.

Since pallet structural and utility connectors are not yet designed, relatively little is known about the time impacts associated with performing these operations with robots. However, this allows for robotic accommodation considerations to be factored into the pallet design, potentially reducing the time differential between humans and machines. Nevertheless, the same case holds true that operational time constraints are relaxed during the unmanned period.

Pressurized Module Installation

The installation of pressurized modules is somewhat less critical than truss assembly and pallet installation, since most of the core station infrastructure will already be in place. Failure to install a module will probably not threaten the safety of the station. However, some consideration for structural and utility attachment for the module must be made in order to guarantee its survival until the next Orbiter visit.

Module installation scenarios typically involve transporting the module with the MSC or a remote manipulator to the worksite, positioning it by remote manipulator at the installation location, and then performing dextrous manipulation for structural and utility connections and pressure sealing. Relatively few modifications to the dextrous procedures are required to allow performance by robotic resources, with the exception of pressure sealing that involves some internally located mechanisms. However, the structural and utility connections should be accessible by a robotic device.

Since most of the operations involved with installing a module are performed robotically due to the large masses involved, there will be a relatively minor impact for completely robotic operations; however, safety concerns will be paramount because of the large inertial components. Human observation of any potentially hazardous robotic operations will be required.

Ground-Based Teleoperation Issues

The capability to perform ground-based teleoperation of on-orbit robotic resources effectively and safely is not yet demonstrated. The impact of time delays on the operator and the need for extreme reliability, safety, and observability must

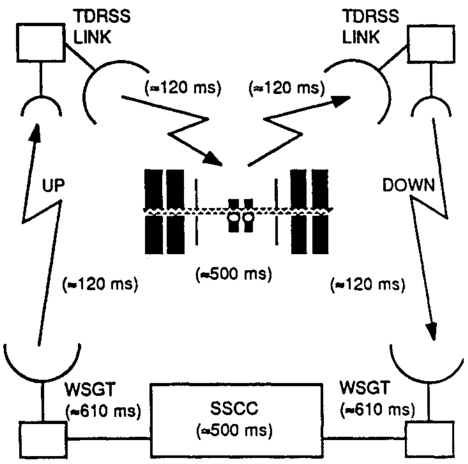

Fig. 7 Space-ground communications link at White Sands Ground Terminal (WSGT).

be addressed in order to achieve confidence in mission success. Some modifications to baseline equipment and operating procedures will also be needed; the cost of all these factors must then be weighed against the benefits associated with a useful ground control capability.

Time Delays for Space-Ground Communication

The architecture of the space-ground communication link for the space station involves extensive processing and long transmission paths (Fig. 7). The need for near-continuous communication between the station and the SSCC drives the requirement for the Tracking and Data Relay Satellite System (TDRSS) relay for data uplink and downlink. Processing and distance effects combine to give an approximately 2-3 s time delay for the roundtrip of control commands and data telemetry. Ground-based processing of the data accounts for a significant portion of the overall time delay.

Another factor to be taken into account is that the TDRSS relay can induce a variable time delay, so the timing of data acquisition at the SSCC does not always represent an accurate time history of the data transmission from the station. Clearly, the communication time delay will introduce significant limitations on closed-loop control operations between the ground and the space station.[7]

Effects of Time Delay on Teleoperation

The goal of teleoperation is telepresence, whereby the operator feels and interacts with the remote task as if actually present at the worksite. A considerable amount of research has been conducted to assess the impacts of time delays on telepresence. The extent of the impacts are influenced by many parameters such as task complexity, quality of the man/machine interface, operator skill level, etc. The usual breakpoint from telepresence is associated with an approximately 0.5 s time delay, whereby the operator begins to adopt a "move and wait" strategy instead of processing feedback concurrently with task execution.

In any case, providing force reflection data to the operator will be precluded, since the utility of such data is reduced considerably for data latency times > 50 ms. In fact, time-delayed force reflection actually can reduce task performance efficiency since the operator will have to mentally decouple the delayed force feedback from the task being performed in real time.

Another phenomenon associated with time-delayed teleoperation occurs at approximately 2-3 s. At this point, the operator's short-term memory capability is exceeded and important operational information is stored in long-term memory, with some associated decrease in cognitive "bandwidth." It is not clear that the operator will perform tasks even in the same manner as with some minimal time delay.

Methods for Time-Delay Compensation

Several techniques to improve operator performance in the presence of time delays have been developed.[8-11] The most promising technique for the problems associated with ground control of space station robotic resources involves using a predictive display (using computer-generated graphics) to give the operator a sense of real-time visual feedback. Of course, the predictive display cannot compensate for dynamic phenomena at the remote worksite, nor can it provide a defense against incorrect operations once they are executed by the operator and transmitted to the device.

It is important to remember that incorrect commands cannot be "called back" once they are transmitted from the ground control station. One method for guarding against performing unintended operations is to induce an artificial delay in transmitting commands until the operator reviews the operation on the predictive display. The length of the artificial transmission delay can be calculated by

$$T_{tr} = T_{pd} + T_{or} \tag{1}$$

where T_{tr} is the artificial transmission delay, T_{pd} the processing time associated with the predictive display, and T_{or} the operator response time. This would allow the operator to respond to any unintended operation by executing a "halt" command that would be transmitted instantly.

Modifications to Baseline Equipment

Some modifications to baseline equipment (described next) would be necessary to implement a ground control capability. These modifications will primarily affect the software and telecommunication architectures, with some impacts on control station hardware and power/data links on-board the station.

Provision for on-board processing of uplinked commands from ground-based control stations would need to be made. This capability will already exist to some extent; the modifications would involve near-real-time processing for control of the robotic devices. In addition, rapid formatting and transmission of data to the ground control station would be required.

The currently envisioned operational mode for robotic resources on early assembly flights involves control either from

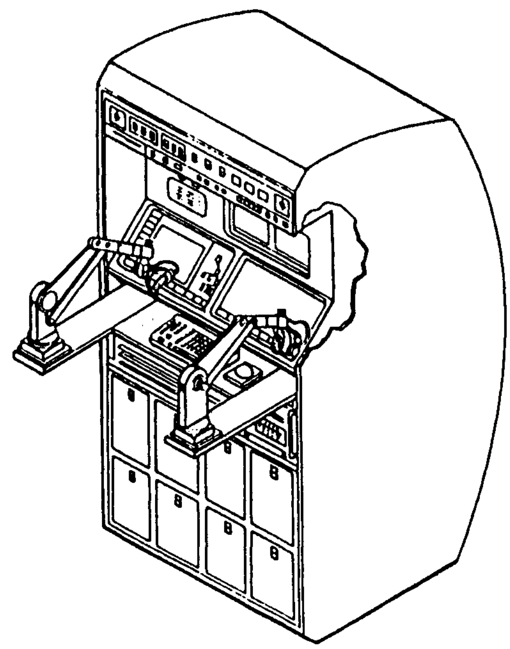

Fig. 8 FTS workstation concept.

the Orbiter aft flight deck or a pressurized station element. A station-based power/data link to the robotic elements would need to be provided as early as possible to augment the currently envisioned Orbiter-based system. Additionally, control of the AWP via software commands would need to be built into the design (currently, the AWP will be controlled via switches on the Orbiter and station).

The ground-based training/simulation control stations would need to be modified to provide the capabilities of the space-based control stations. These modifications will probably be minor since the control stations will be of fairly high fidelity (Fig. 8). The interface to the SSCC may be complex and should be factored into the system architecture design as soon as possible.

Modifications to Operational Procedures

The decision to permit ground control of on-orbit robotic resources is largely an operational one. Most of the system architecture and equipment will already be in place (with the exceptions noted previously); the manner in which remote teleoperation in the presence of time delays is conducted, however, will strongly influence the operational scenarios.

It is fairly clear that direct teleoperation of dextrous devices in the presence of 2–3 s time delays is fairly difficult and highly inefficient. Instead, low-level automation of subtasks can relieve the operator from a significant amount of cognitive processing. This would allow the operator to closely monitor the execution of the task rather than actually performing it, decreasing the likelihood that an unintended operation would be executed. This will involve additional preprogramming of tasks for supervisory control, which is currently seen more as a growth function than one for early operations.

Verification of successful execution of each assembly substep will become a strong aspect of all remote assembly operations. This could influence operational procedures that defer verification until the end of a series of assembly procedures. Other operational considerations will include an even stronger emphasis on safety and reliability. These issues are discussed next.

Safety/Reliability Issues

The use of ground control for robotic devices on the space station will have strong ramifications for safety and reliability. There will be no human presence on-orbit to back up the robot if it fails or causes an unsafe condition. Clearly, the use of the ground control capability will come as the result of some initial contingency, and it is crucial that the implementation of the remote operation not introduce additional problems.

The robotic resources involved here will already incorporate high levels of redundancy since the reliability of space-based robotics is still unknown. Additionally, several safety-oriented capabilities will be built into the robot design. One of these is force accommodation, whereby the robot can limit the amount of force it exerts if the commanded force exceeds some particular level. This capability will be extremely useful in the absence of real-time force reflection to the operator. It is likely that the force accommodation capability on both the remote manipulators and dexterous devices would be used extensively during remote operations. Furthermore, human observation of the robotic devices is an integral part of either teleoperation or supervisory control. Safety, reliability, and observability will remain as major concerns for any ground-commanded robotic operations.

Conclusions

The purpose of this study was to determine if the capabilities exist (or can be easily implemented) to use ground control of on-orbit robotic resources to recover from assembly phase contingencies prior to a permanently manned presence. The station will be unmanned for much of the early assembly phase, and successful completion of each assembly increment may be crucial to the survival of the station. In the event of a contingency that prevents completion of all critical assembly objectives prior to the Orbiter's departue, ground control of robotic resources could be the only method for safely maintaining the station on-orbit.

Feasibility and Cost Impacts

Any discussion of feasibility must factor in cost impacts. Clearly, the speed of the space-ground communication link could be improved by completely revamping the architecture of the system to provide a direct link between the station and the SSCC. Although this is technically feasible, the cost of providing such a capability would be prohibitive. Furthermore, much of the time delay is related to processing time on the ground and the station. The key is to find a method for implementing the ground control capability by using as much existing equipment and as few modifications to operational techniques as possible.

If we use the philosophy just described, implementing a remote control capability would still involve some modifications to the baseline equipment and operational techniques. These modifications are relatively minor since the ground-based training/simulation workstations will already be of fairly high fidelity, and the ground-space communication architecture is flexible enough to incorporate control commands. The influence of the time delay on the operator will be pervasive; force reflection will no longer be useful, and the wait-and-move strategy associated with time-delayed teleoperation will increase dramatically task completion time.

Given these feasibility/cost issues and constraints, most of the capability does, in fact, exist for ground control of robotic resources. The effects of time delays do not make task performance impossible, just more difficult and time-consuming. Time constraints are significantly lower during the unmanned phases, and this operational concept takes advantage of the relatively unlimited resources of personnel and computational power available on the ground. In a situation where the survival of the station is in jeopardy, the opportunity to perform assembly operations during crew absence would be extremely beneficial and comes with relatively minor impacts to existing station architecture and design concepts.

Ancillary Findings

In addition to contingency situations, nominal assembly operations could be augmented by ground-based control of robotic elements. EVA time available for nominal operations prior to PMC is constrained to 24 man-hours per increment. For certain missions (particularly those involving extensive construction and installation of truss, radiator, and power module components), this time limit may not be sufficient to accomplish all mission assembly objectives. This situation lends itself to cooperative human and machine efforts for assembly operations. Robotic devices can perform assembly operations either in conjunction with EVA, or at times during the mission when EVA will not be conducted. Having the capability for remote control of these devices will allow some assembly operations to occur during adaptation to zero gravity (space sickness) or during crew sleep time. Remote control of robotic devices would also allow the crew to take on a supervisory role, freeing them to perform other operations that require direct human presence.

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