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GROUND CONTROLLED ROBOTIC ASSEMBLY OPERATIONS
FOR SPACE STATION FREEDOM

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ABSTRACT

A number of dextrous robotic systems and associated positioning and transportation devices will be available on Space Station Freedom (SSF) to perform assembly tasks that would otherwise need to be performed by extravehicular activity (EVA) crewmembers. The currently planned operating mode for these robotic systems during the assembly phase is teleoperation by intravehicular activity (IVA) crewmembers. While this operating mode is less hazardous and expensive than manned EVA operations, and has insignificant control loop time delays, the amount of IVA time available to support telerobotic operations is much less than the anticipated requirements. Some alternative is needed to allow the robotic systems to perform useful tasks without exhausting the available IVA resources; ground control is one such alternative.

This paper investigates the issues associated with ground control of SSF robotic systems to alleviate onboard crew time availability constraints. Key technical issues include the effect of communication time delays, the need for safe, reliable execution of remote operations, and required modifications to the SSF ground and flight system architecture. This paper addresses time delay compensation techniques such as predictive displays and world model-based force reflection, and describes collision detection and avoidance strategies to ensure the safety of the on-orbit crew, Orbiter, and SSF. Although more time consuming and difficult than IVA controlled teleoperations or manned EVA, ground controlled telerobotic operations offer significant benefits during the SSF assembly phase, and should be considered in assembly planning activities.

NOMENCLATURE

AC	Assembly Complete
APS	Astronaut Positioning System
AWP	Assembly Work Platform
C&TS	Communication and Tracking System
DMS	Data Management System
EVA	Extravehicular Activity
FEL	First Element Launch
FTS	Flight Telerobotic Servicer
IVA	Intravehicular Activity
MMD	MSC Maintenance Depot
MRS	Mobile Remote Servicer
MSC	Mobile Servicing Centre
MSS	Mobile Servicing System
MT	Mobile Transporter
MTC	Man Tended Capability
NASREM	NASA/NBS Standard Reference Model
ORU	Orbit Replaceable Unit
PMC	Permanently Manned Capability
RMS	Remote Manipulator System
SPDM	Special Purpose Dextrous Manipulator
SSCC	Space Station Control Center
SSF	Space Station Freedom
SSRMS	Space Station Remote Manipulator System
TDRSS	Tracking and Data Relay Satellite System
WSGT	White Sands Ground Terminal

INTRODUCTION

Available time for crew intravehicular activity and extravehicular activity during Space Station Freedom assembly is severely constrained. Prior to Permanently Manned Capability (PMC), which occurs on the thirteenth flight of the currently planned 18 flight assembly sequence, the SSF will be visited for 5-7 days by the Space Shuttle at 45-90 day intervals. A crew of five astronauts will be devoted to Station assembly operations during these missions, each working approximately nine hours per day. A total of 36 man-hours of planned EVA will be available for each assembly flight [1]. On many pre-PMC assembly flights, the required crew time to support planned assembly operations exceeds the available resources described above. After PMC, a crew of four astronauts will remain on the Station to perform operations in support of user payloads and core system maintenance. However, planned EVA will only be performed while the Shuttle is present, so EVA time constraints will still influence assembly operations after PMC is achieved. IVA time constraints are significant both before and after PMC; early assembly flights have large requirements for assembly and checkout operations while later assembly missions are performed in parallel with ongoing SSF user payload operations and routine maintenance of the evolving Station.

Robotic systems such as the Flight Telerobotic Servicer (FTS), Mobile Servicing Centre (MSC), and Assembly Work Platform (AWP) will be available on-orbit to augment and reduce crew EVA by providing dextrous manipulation, positioning, and transportation of assembly elements. These devices may be operated from the Orbiter or the Sta-

tion, depending on the task and the location and availability of workstations. Operation of robotic systems from on-orbit workstations serves to reduce crew EVA time, but places a burden upon crew IVA time. Telerobotic operations take longer to perform than direct (i.e., EVA) manipulation [2]; current estimates used in the SSF program give a factor of three increase in task time for telerobotic operations over EVA. Therefore, the reduction in EVA time provided by the application of robotics must be balanced against the increase in IVA time required to support their operation. As described above, neither IVA nor EVA time will be available in great abundance during the assembly phase.

One potential alternative to IVA control of SSF robotic systems during the assembly phase is ground control. Ground control offers the advantage of relaxed time constraints and the relatively unlimited availability of ground-based human and computational resources. Robotic tasks may be performed while the crew is busy working on other tasks, during periods of crew inactivity such as sleep periods, and even when the SSF is unmanned between pre-PMC Shuttle visits. However, the application of ground control during SSF assembly presents some significant problems which must be addressed. These issues include the effects of communication time delays of up to three seconds, the need for safe and reliable

execution of remote operations, and the required modifications to the existing SSF ground and flight system architecture. This paper will trade off the advantages and disadvantages of ground control from an overall system perspective.

Ground control of SSF robotic systems is not in the current program baseline. As mission operations planning continues to identify points in the assembly phase where assembly task requirements exceed crew EVA and IVA time availability, alternative means of accomplishing assembly tasks will need to be investigated. Ground control may serve as the "invisible crewmember" to meet critical SSF assembly objectives.

SSF ASSEMBLY OVERVIEW

The Space Station Freedom is, by far, the most complex system ever deployed and assembled on orbit. The SSF will weigh over 500,000 lbs and span almost 500 ft at Assembly Complete (AC). Current planning involves 18 Space Shuttle flights to deliver assembly elements and pressurized module outfitting, with several more post-PMC logistics flights to support a permanent human presence (Table I).

Table I: SSF Assembly Flight Manifest

| Date	Flight	Assembly Elements
3/31/95	MB-1 (FEL)	Stbd Inboard PV Power Module, Stbd Truss & Utilities, **AWP, APS, MT, FTS**, Passive Dampers
6/15/95	MB-2	Stbd Truss and Utilities, Stbd Antenna, TCS, Avionics, and Propulsion Pallets
8/30/95	MB-3	Stbd and Port TCS Radiators and Condensors, Stbd Utilities, Stbd Power Mgmt, GN&C, and Payload Support Pallets, Module Support Truss
11/15/95	MB-4	Forward Port Node, Pressurized Docking Adapter, **MRS**, Cupola
1/31/96	MB-5	O_2/N_2 Repress Tanks, Port TCS Pallet, Port and Stbd Truss and Utilities
3/31/96	MB-6	Port Inboard PV Power Module, Port and Stbd Utilities, MT Batteries, Propulsion Pallet
6/15/96	MB-7 (MTC)	US Lab Module and Lab Internal Equipment
8/30/96	OF-1	Pressurized Logistics Module, US Lab Internal Equipment, **SPDM**, MMD
11/15/96	MB-8	Aft Port Node, Aft Stbd Node, Node Umbilicals
1/31/97	MB-9	Hab Module and Hab Internal Equipment
3/31/97	OF-2	Pressurized Logistics Module, Hab Internal Equipment, O_2/N_2 Repress Tanks
6/15/97	MB-10 (PMC)	Forward Stbd Node, Airlock, Extravehicular Mobility Units (EMUs), Cupola
9/15/97	MB-11	Stbd and Port Outboard PV Power Modules
2/1/98	MB-12	JEM Module and JEM External Equipment
6/15/98	MB-13	ESA Module and ESA External Equipment
9/15/98	MB-14	JEM Exposed Facility 1 and 2, JEM Experiment Logistics Module Pressurized and Exposed Sections
1/31/99	OF-3	Pressurized Logistics Module, Node and Module Internal Equipment, Fluid Mgmt Pallet, Stinger/Resistojet, Payload Support Pallet, External Equipment Upgrades
6/15/99	OF-4 (AC)	Pressurized Logistics Module, Module Internal Equipment, Pressurized Docking Adapter Internal & External Equipment Upgrades

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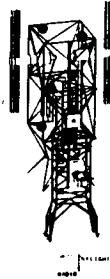
Figure 1a: First Element Launch (FEL)
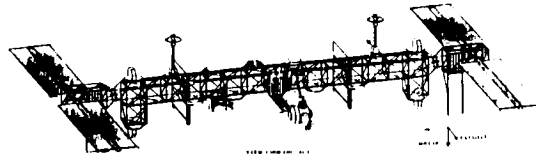
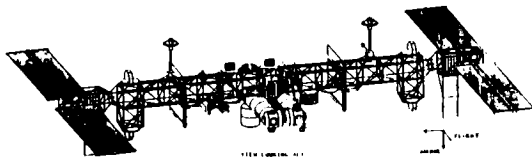**Figure 1b: Man Tended Capability (MTC)**

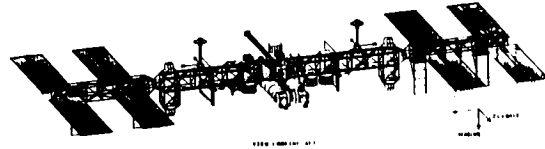**Figure 1c: Permanently Manned Capability (PMC)**

Figure 1d: Assembly Complete (AC)

The assembly phase will last over four years, beginning in early 1995 and ending in mid-1999 [3]. The assembly phase is divided into three subphases, defining logical transitions in ability to support a human crew; these milestones also correlate well with transitions in operational capabilities for SSF robotic systems. The three SSF assembly subphases and their associated crew time availabilities, robotic system capabilities, and assembly task types are described below.

First Element Launch to Man Tended Capability

This subphase (Figure 1a & 1b) spans the first six flights of the current assembly sequence, and is devoted to providing the basic SSF infrastructure (truss, power, avionics, attitude and altitude control, etc.) to support the pressurized modules and attached payloads. Extensive IVA and EVA assembly operations will be performed from the Shuttle during its five to seven day visits to the SSF. No Station-based operations will be conducted during this subphase, and the Station will be unmanned between Shuttle visits. These early assembly missions are highly suc-

cess-oriented, and an unplanned interruption of assembly operations could potentially threaten the safety of the SSF.

Several SSF robotic systems are delivered during this subphase. The FTS is manifested on the first element launch, and should be available to support dextrous assembly operations by the end of that mission. The Assembly Work Platform (AWP) along with the Mobile Transporter (MT) and its Astronaut Positioning System (APS) is also delivered on the first flight. The Mobile Remote Servicer (MRS), which with the MT comprises the Mobile Servicing Centre, is delivered on the fourth flight. By MTC, the SSF robotic systems can provide payload transportation, positioning, and dextrous manipulation to support assembly operations; the integration of these capabilities will allow many assembly tasks to be performed without the need for manned EVA.

There are two distinct applications of ground control during this subphase. First, ground controlled robotic systems can be used to inspect and checkout assembly tasks between crew EVAs, streamlining the mission timeline and making

productive use of non-mission oriented crew activity periods (pre-sleep, sleep, post-sleep, meals, etc.). Minor anomalies might be corrected via ground controlled robotic operations or deferred for later crew controlled IVA or EVA operations. The ground controlled robotic systems may also be applied to setup or breakdown of EVA worksites. The second application is during unmanned phases, where ground controlled robotic systems may be used to complete critical assembly tasks left because of an unplanned interruption of the assembly mission, or to complete non-critical assembly tasks prior to the next Shuttle visit. Obviously, reliability and safety are paramount for these types of operations, since there is no on-orbit crew present to react to a contingency induced by the robotic system.

Man Tended Capability to Permanently Manned Capability

This subphase (Figure 1c) lasts from the seventh through twelfth assembly flights, and is characterized by the delivery and outfitting of the US-provided laboratory and habitation modules. During this subphase, the SSF can support limited operations from within a pressurized shirtsleeve environment. Operational procedures relating to crew safety and pressure differentials between the Shuttle and SSF constrain the crew to the Shuttle until all planned EVA operations on that mission are completed, then SSF IVA operations can commence. Because of this constraint, assembly operations on a particular mission during this subphase tend toward either Shuttle-based external assembly or Station-based internal module outfitting and user operations, but not both. Control of SSF robotic systems will be shared between workstations located in the Shuttle and the SSF. Assembly contingencies during this phase do not directly threaten the safety of the SSF, but may impact the safety of the highly complex pressurized modules, which must be successfully installed within a limited time before subsystem damage occurs.

The only SSF robotic system delivered during this phase is the Special Purpose Dextrous Manipulator (SPDM), which provides dextrous manipulative capabilities similar to the FTS. However, the AWP is "parked" semi-permanently to the truss during this subphase, allowing the MT and MRS to function together as the Mobile Servicing Centre. Transportation and positioning of payloads along the truss is now handled by the MSC.

The two applications of ground control described in the FEL-MTC subphase section above are also valid for this subphase. Assembly operations involving installation of external equipment and pressurized modules are still largely Shuttle-based, with the associated constraints on IVA and EVA crew time. The application of ground controlled inspection and checkout during crew sleep and other periods is still highly beneficial. Again, the potential for an interruption in assembly operations must be addressed. In this subphase of the assembly sequence, the infrastructure for communication between the SSF and ground is complete and can support high bandwidth video downlink and data up/downlink for ground controlled teleoperations

while the Station is unmanned. This allows for recovery from some assembly contingencies, and can still be applied to noncritical assembly operations to "get ahead" on the assembly timeline for subsequent missions.

A third application of ground control during this subphase is in support of external assembly operations while the crew devotes its IVA time to internal module outfitting. By eliminating EVA from the timeline, the Shuttle-based crew can gain access to the SSF internal pressurized volume earlier in the mission. Performance of parallel Station-based IVA and ground controlled external assembly operations will require a well-defined choreography between the on-orbit crew and ground controllers, but offers relief from a tight operational constraint.

Permanently Manned Capability to Assembly Complete

This subphase (Figure 1d) lasts from the thirteenth through eighteenth assembly flights, and is characterized by installation of the international pressurized and unpressurized modules and the second set of photovoltaic power modules to bring the Station to its full 75 kW capability. The Shuttle acts primarily as a delivery vehicle during this phase, offloading its cargo to the Station for later Station-based installation. Therefore, robotic assembly operations will be conducted primarily from SSF workstations. However, EVA assembly operations must still be conducted from the Shuttle. SSF IVA operations scenarios during Shuttle-based EVA are still being developed for this subphase.

No new robotic systems are delivered during this subphase. The FTS, SPDM, and MSC will provide dextrous manipulation, positioning, and transportation capabilities to support assembly operations.

It might initially seem that a permanent presence of four crewmembers during this subphase would relieve the IVA time availability constraint. However, user payload operations and core systems maintenance activities will absorb most of the IVA time available, and the four-person crew will probably still operate in a single shift. This leaves large blocks of time per day when no Station assembly operations can be conducted. As described previously, ground controlled telerobotic operations during these periods of non-mission oriented crew activity can be applied to inspect and checkout recent assembly operations or to continue assembly operations along the mission timeline. In summary, opportunities for useful application of ground controlled teleoperations abound throughout the SSF assembly phase.

SSF ROBOTIC SYSTEMS

Successful execution of most SSF assembly tasks requires some combination of transportation, positioning, and dextrous manipulation of assembly elements. The robotic systems described below provide these capabilities, and will be available for use during the assembly phase.

Flight Telerobotic Servicer

The FTS (Figure 2) is a US-developed dextrous manipulator [4]. This device is designed to replace crew EVA, and so attempts to replicate human capabilities. It has two seven-degree-of-freedom manipulator arms, a body providing structure, avionics, utility distribution, and vision capabilities, and a single five-degree-of-freedom positioning and stabilization "leg". These components are arranged in a roughly anthropomorphic configuration. The FTS incorporates force reflection only when control loop time delays are very short (less than or equal to five milliseconds).

The FTS has three basic operating modes during the assembly phase. The first mode, transporter attached, is used when the FTS operates from the Shuttle RMS, SSRMS, or potentially the APS. In this mode, the FTS receives structural and utility support from the transport device, and can operate in areas offering no other means of support. The second mode, fixed base dependent, is used when the FTS operates from a fixed berthing point near the assembly task which provides structural and utility support to the telerobot. In this mode, the FTS is delivered by the transport/positioning device and then operates independently until retrieved for stowage or other operations. The third mode, fixed base umbilical, is similar to fixed base dependent except the telerobot obtains utilities via an umbilical rather than through the berthing point itself.

Prior to the delivery of the SPDM, the FTS is only robotic dextrous manipulator on the SSF. Therefore, the FTS will play a large role in any ground-based telerobotic operations requiring dextrous manipulation. It also offers the advantage of stereographic vision and easily repositionable wrist-mounted cameras, making it a very useful inspection device. It is critical that the FTS be ground-controllable for the applications described in the previous section to be viable.

Mobile Servicing System
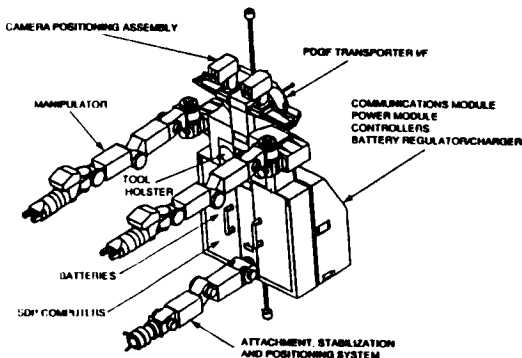
The Canadian-built MSS (Figure 3) consists of three ele-

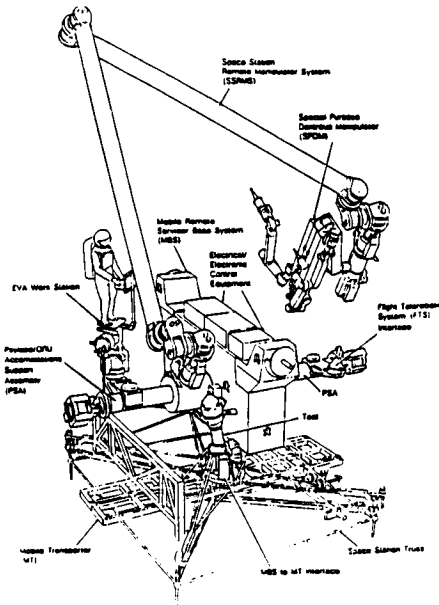**Figure 2: Flight Telerobotic Servicer (FTS)**

Figure 3: Mobile Servicing System (MSS)

ments: the MSC, the SPDM, and the MSC Maintenance Depot (which performs no manipulative functions and is not considered to be a robotic system) [5]. The MSS provides translation, positioning, and dextrous manipulative capabilities to the SSF.

The MSC, in turn, consists of the MT which provides translation capabilities for the MRS and its payloads, and the MRS which provides payload positioning capabilities using its SSRMS. The MT has an upper and lower base which slide with respect to each other as the MT translates from truss face to truss face. The MT also has the capability to rotate and change planes by independent operation of its upper and lower bases. During early assembly missions (pre-MTC), the MT will be attached to the AWP and will serve as a jig for assembling truss bays. After MTC, the AWP will be detached from the MT, and the MT/MRS combination will move along the truss as a permanently attached unit. The MRS accommodates payloads ranging in size from box-type ORUs to pallets to full-size pressurized modules. It also accommodates the SSRMS, SPDM, and FTS. The SSRMS operates from the MRS, and the dextrous manipulators are stowed on the MRS during delivery to the worksite. Thus, the MSC is both a transportation and positioning device, and must be ground controllable for many of the above-mentioned operational scenarios to be viable.

The SPDM provides dextrous manipulative capabilities to the MSS, and for the purposes of this paper is similar in configuration and characteristics to the FTS. It also operates either from the end of the SSRMS or some fixed berthing point with structure and utility support. The SPDM can play a significant role in ground controlled assembly op-

erations; however, its relatively later arrival in comparison to the FTS makes it a less critical element in a ground controlled telerobotic system. Although it would enhance and augment this capability, it is not crucial that the SPDM be ground controllable.

Assembly Work Platform

The AWP (Figure 4) is a US-built device which serves as a type of scaffolding for assembly of truss structure, routing of utilities, and installation of pallets and other assembly elements on early assembly flights (pre-MTC). The AWP also incorporates the MT for indexing of the truss bays, and the MT's two APSs which serve as analogs to terrestrial cherry-pickers for positioning of EVA astronauts and (potentially) robotic dextrous manipulators. The AWP has many degrees-of-freedom from its various components, but their motions tend to be simply controlled via binary (e.g., on/off, up/down, etc.) commands; therefore, ground control of the AWP would be relatively straightforward. However, the current AWP design has no means of obtaining utilities such as power or data when detached from the Orbiter, so a design modification would have to be made to allow the AWP to operate via ground control between Shuttle visits. The AWP is the assembly base for pre-MTC assembly operations, so it would be essential to provide for ground control of this system to conduct ground-based teleoperations during this assembly subphase.

Shuttle Remote Manipulator System

Until the MSC is available, and in lieu of operations from the APS, the FTS must be transported and positioned by the RMS (Figure 5) [6]. For assembly operations on the first few assembly flights, the RMS is a major payload delivery system. In order to conduct the inspection and checkout operations suggested earlier in this section, the RMS should be ground controllable to transport and position the FTS. Use of the RMS under ground control for in-payload bay
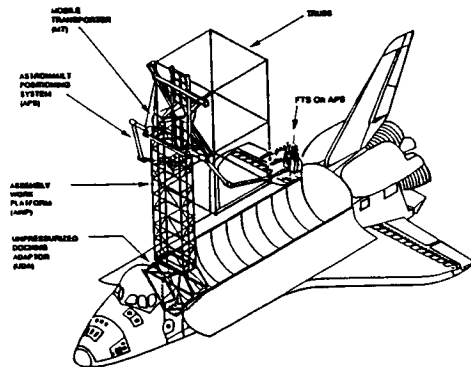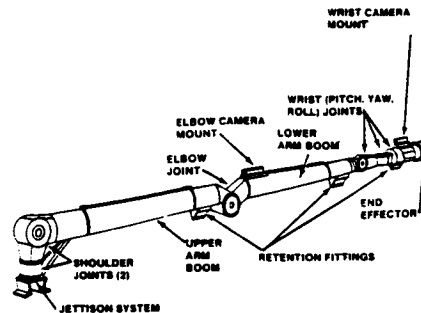

Figure 4: Assembly Work Platform (AWP)

Figure 5: Remote Manipulator System (RMS)

operations such as pallet unberthing and attachment to the truss would probably not be permitted. Nonetheless, the RMS can play a significant role in ground controlled operations on early assembly flights, and should be considered for modification as required to provide this capability.

GROUND CONTROL - ISSUES AND STRATEGIES

Ground control of SSF robotic devices during the assembly phase represents a significant departure from the currently envisioned operational concept. This section discusses potential drawbacks to the use of ground control, and presents several techniques for mitigating these problems.

Communication Time Delays

The space-ground communication link used in the SSF program can induce up to a three second time delay for round trip communications. As shown in Figure 6, communication signals pass from the Space Station Control Center (SSCC) to the SSF via the White Sands Ground Terminal (WSGT) and the Tracking and Data Relay Satellite System (TDRSS). Interestingly, most of the time delay is induced by signal processing on the ground and the SSF, not by the transits to and from geostationary and low earth orbits.

This time delay has a significant impact on teleoperations, where any more than a 0.5 second time delay will cause an operator to adopt a deliberate "move-and-wait" control strategy [7]. Performance of all but the simplest tasks under this type of control is highly inefficient, fatiguing, and error-prone. However, several techniques have been developed to reduce the time delay perceived by the operator, thereby allowing smoother, coordinated execution of task steps.

One of the best-known time delay compensation strategies involves the use of predictive displays, which overlay a
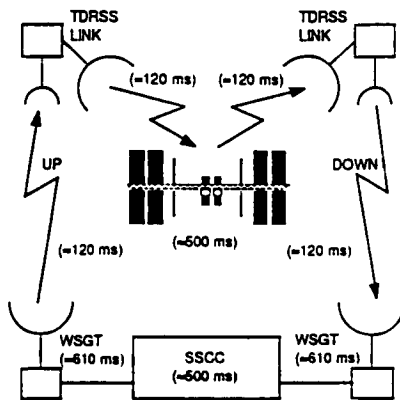
Figure 6: Space-Ground Communication Link

graphical representation of the task prior to the return of the time-delayed video image [8]. These predictive display systems incorporate some knowledge of the manipulator kinematics and dynamics, and may also implement some form of collision detection and avoidance strategy based on a world model of the worksite stored in memory and referenced to the manipulator location and orientation.

Another time delay compensation scheme involves shared or supervisory control of robotic operations, where some portions of the task are automated, relieving the operator of the burden of direct control over all manipulator degrees of freedom [9]. By using shared control, the operator can focus on task goals and monitor the critical functions of the manipulator system (Figure 7). The development of the NASREM and another types of hierarchical control architectures allows shared control to be implemented at various levels of abstraction and can compensate for correspondingly longer time delays.

A novel approach to time delay compensation involves the use of predictive force reflection [10]. This technique may be used independently or in conjunction with a predictive display to define collision free manipulator paths, based on a ground-based world model of the worksite and manipulator system. The operator is then guided away from collisions by a force reaction from the manipulator hand controller. Unlike traditional force reflection techniques, which depend on sensed contact between the manipulator and worksite, predictive force reflection can be preset to a given distance between the manipulator and worksite to warn the operator of impending collisions.

Collision Detection and Avoidance

Clearly, ground-controlled telerobotic operations on SSF pose some risk. The potential for collisions between the robotic system and the SSF and/or Orbiter is probably the largest influence against the adoption of this capability. It is

not possible to guarantee collision-free operations even for local, directly viewed teleoperations, much less remote operations under a three second time delay with limited visual feedback. Consequently, the successful application of ground control will depend on the use of some type of collision detection and avoidance strategy. These strategies tend to fall into two types-- sensor-based and world model-based-- as described below.

Sensor-based collision detection and avoidance applies local sensory capabilities (with minimal associated time delay) to compare the location of the manipulator to the worksite and warn the operator of impending contact. The sensors used can range from simple contact switches to infrared, sonic, or electromagnetic field sensors, up to complex machine vision systems. These systems offer the advantage of adaptability to dynamic worksites (which would impair the utility of a static world model-based system), and relatively low computational requirements. However, they are typically expensive and complex in terms of hardware, and less adept at distinguishing between intentional collisions (i.e., between the end effector and ORU grasp point) and unintentional collisions (i.e., between the end effector and ORU support structure).

World model-based collision detection and avoidance techniques involve the use of 3-D computer models of the worksite which are compared to the known position and kinematic configuration of the manipulator. Potential spatial intersections (i.e., collisions) between the worksite model and the manipulator are displayed to the operator. These systems are useful when the bandwidth of the sensory link between the operator and manipulator are small. For the purposes addressed in this paper, the world model would reside on the ground, and manipulator configuration data would be transmitted via the space-ground link. The world model could be as detailed as necessary to support the operation. The major disadvantage of world model-based systems is the dependance on accuracy of the model itself, and the knowledge of the relationship between the manipulator and the task (sometimes known as task registration).
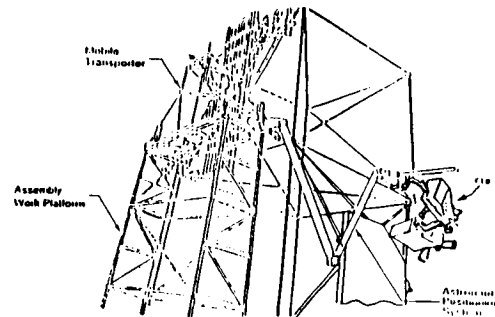

Figure 7: Pallet Installation Using Robotic Systems

Dynamic influences at the worksite such as oscillations or unmodeled equipment may not be accounted for and thus escape detection. Also, offsets between the actual and modeled manipulator due to imperfect task registration can allow collisions to occur without warning.

Operations and Systems Modifications

Implementation of ground control will require some changes to the design and operation of the SSF flight and ground systems. These modifications must be made with minimal impact to existing operations scenarios and system architectures, since ground control is meant to augment, not replace IVA teleoperation when crew time is available.

The implementation of ground control capability is mostly an operational one. The existing SSF robotic systems are commanded via the SSF distributed Data Management System (DMS) and Communication and Tracking System (C&TS). Ground-issued commands can easily be interleaved into these communication links. Therefore, it is largely transparent to the robotic system that it is being commanded remotely rather than locally [11].

The current architecture for collision detection and avoidance for SSF robotic systems relies heavily on crew observation, either directly or through video camera viewing. The difference between such local crew observation and the amount of observational capability available to the ground-based operator should be counteracted by the use of some combination of sensor-based and world model-based systems. The use of these systems would also improve the safety of IVA teleoperations by serving as a backup to crew observation.

The existing ground workstations are intended only for simulation and training purposes. Fortunately, these workstations are of high enough fidelity to serve as ground control stations with relatively minor modifications. These modifications will involve integrating the workstations into the space-ground communication link, and incorporating time delay compensation techniques such as predictive displays and world model-based force reflection.

Finally, modifications to the operating modes of robotic systems may require flight equipment modifications. For instance, the AWP is not intended to be used when the Orbiter is not present, and relies on utility provisions from the Orbiter. If ground-based operation of the AWP were to be applied between pre-PMC Orbiter visits, some means for obtaining utilities from the Station would be necessary.

CONCLUSIONS

The current SSF program baseline utilizes ground control for monitoring and limited reconfiguration of onboard systems, and potentially for checkout of robotic systems. No manipulative operations are planned to be controlled from the ground. Given the severe constraints on onboard crew time for IVA and EVA operations throughout the SSF assembly phase, ground control begins to make sense if it

can be performed efficiently and safely. The techniques defined above can be applied to increase the operators sense of telepresence and to minimize the risk of collisions between remotely controlled manipulators and the Station and/or Orbiter. More work is needed to determine the specific impacts to SSF ground and flight systems and operations to accommodate this operational mode. Based on this preliminary study, ground control may indeed solve some significant problems associated with the SSF assembly phase.

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