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THE FLIGHT TELEROBOTIC SERVICER TINMAN CONCEPT: SYSTEM DESIGN DRIVERS AND TASK ANALYSIS

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Abstract

During 1988, the National Aeronautics and Space Administration (NASA) conducted a 9-month in-house Phase B study to develop a preliminary definition of the Flight Telerobotic Servicer (FTS) that could be used to understand the operational concepts and scenarios for the FTS. Called the "Tinman," this design concept was also used to begin the process of establishing resources and interfaces for the FTS on Space Station Freedom, the National Space Transportation System shuttle orbiter, and the Orbital Maneuvering Vehicle.

Starting with an analysis of the requirements and task capabilities as stated in the Phase B study requirements document, the study identified eight major design drivers for the FTS. This paper will describe each of these design drivers and their impacts on the Tinman design concept.

Next, this paper will discuss the planning that is currently underway for providing resources for the FTS on Space Station Freedom, including up to 2000 W of peak power, up to four color video channels, and command and data rates up to 500 kbps between the telerobot and the control station.

Finally, an example will be presented to show how the Tinman design concept was used to analyze task scenarios and explore the operational capabilities of the FTS. A structured methodology using a standard terminology consistent with the NASA/National Bureau of Standards Standard Reference Model for Telerobot Control System Architecture (NASREM) was developed for this analysis.

1. Introduction

The Flight Telerobotic Servicer (FTS) will be used on the National Space Transportation System (NSTS) shuttle orbiter and Space Station Freedom to assist the astronauts in performing assembly, maintenance, servicing, and inspection tasks. Although it is primarily a teleoperated device at first, the FTS is being designed to grow and evolve to higher states of autonomy. Eventually, it will be capable of working from the Orbital Maneuvering Vehicle (OMV) to service free-flying spacecraft at great distances from the space station. A version of the FTS could also be resident on the large space platforms that are part of the space station program.

This paper discusses the technical design drivers that the in-house Phase B study identified as significant in the development of such a robotic system for space. The Phase B study started with the initial requirements of the top-level mission, system, and functional requirements for the FTS [1]. These requirements were developed during a Phase A study conducted by NASA during the fall of 1986 [2 and 3].

The output of the in-house Phase B study was integrated with the results of more in-depth Phase B studies conducted by Martin Marietta Astronautics Group in Denver, CO, and Grumman Space Systems in Bethpage, NY, to generate the requirements for Phases C and D of the FTS Program, which are expected to begin in the Summer of 1989 [4].

2. Study Approach

The Phase B study [5] started with a detailed analysis of the space station tasks described in the requirements document [1]. These tasks describe generic capabilities that are intended to be representative of the fundamental mission of the FTS as a robotic device that assists the astronauts in assembly, maintenance, servicing, and inspection tasks in the unpressurized environment of the space station.

Analyzing the tasks in the requirements document [1] led to the identification of a number of design drivers for the development of the FTS. These design drivers resulted in a series of trade studies that were used to develop candidate design solutions. The resulting design concept for the FTS was called the "Tinman." This concept resulted in a robotic system that was adequate for the assigned tasks and could perform the tasks reliably and safely.

Advanced technology items were scrutinized as to their relevance to the performance of the assigned tasks, as well as to their state of readiness. If an item was not considered necessary, it was not incorporated into the design. Some items were considered appropriate, but their state of readiness made them too high a risk for inclusion in the initial implementation of the FTS. High technology should not be used just for the sake of using it, if it should then fail in orbit. An early failure of the FTS would be a great setback for space robotics. Instead of serving as a useful tool for the astronauts, the FTS would be discarded, and the astronauts would turn to another means of accomplishing the tasks.

A program requirement is that the FTS must be capable of growth and evolution. System adaptability is necessary because of the emerging technologies that will be valuable to the program once they have matured. The FTS must be designed from the ground up with the proper "hooks" and "scars" for growth. With the appropriate systems engineering and architectures that can accommodate growth, advanced technology with software and hardware can be added later to the system with minimum impact. To accomplish this, NASA has adopted a control architecture developed by the National Institute for Standards and Technology (NIST), formerly the National Bureau of Standards (NBS), that permits this type of growth [6].

3. Design Concept

Figure 1 shows the design concept that was developed for the FTS during the Phase B study. As shown in the drawing, the telerobot is composed of three major subassemblies: the main body, the manipulator arm assembly, and the arm-positioning system.

The main body contains all the major electronic components of the telerobot, as well as the grapple fixture by which the telerobot is picked up by one of the large manipulator arms (e.g., the Space Station Remote Manipulator System (SSRMS) or the NSTS Remote Manipulator System (RMS)). The main body also contains the attachment grapple (or foot) by which the telerobot is securely fixed at the worksite.

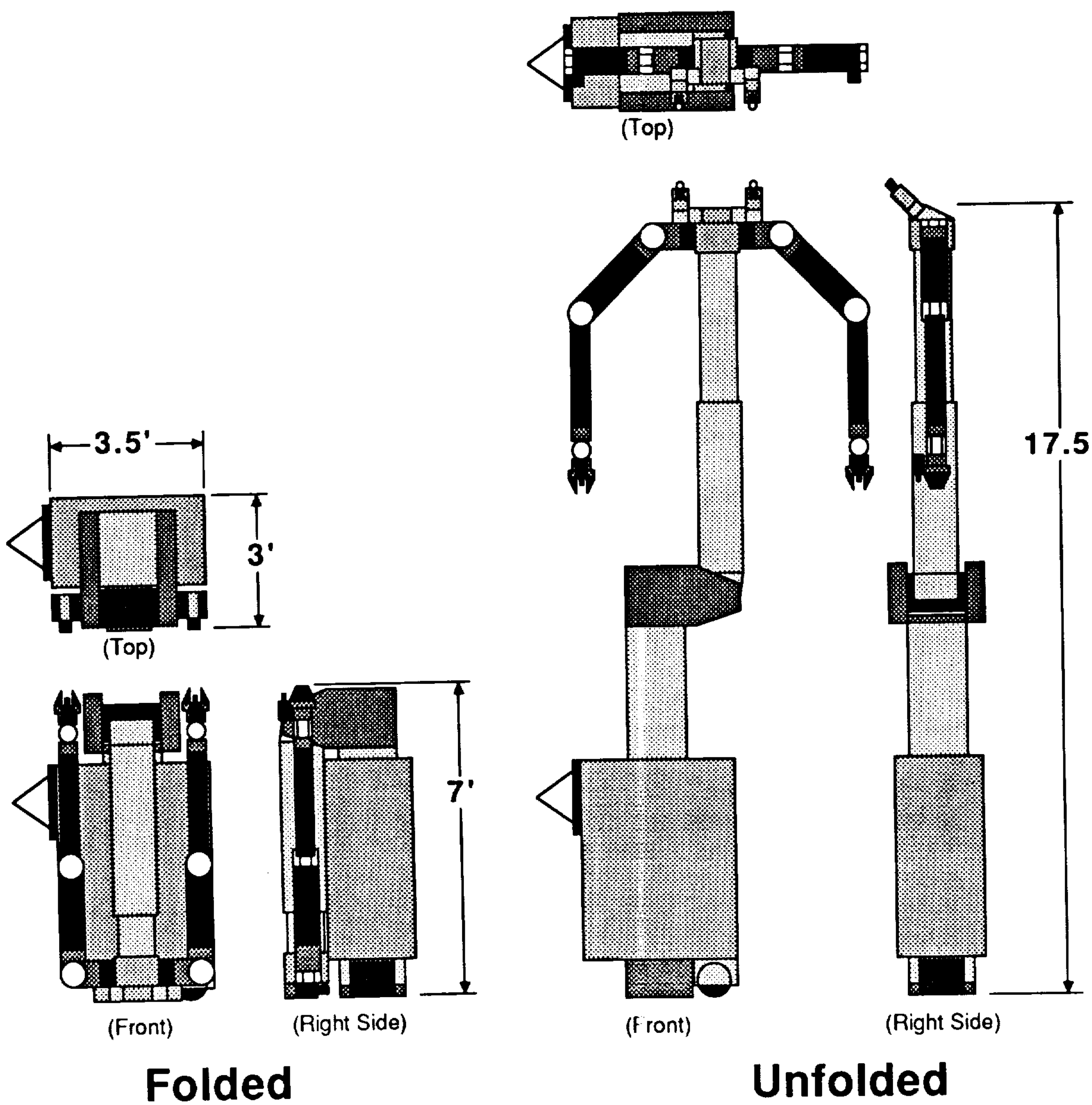

Figure 1. Flight Telerobotic Servicer (FTS) Dimensions

One of the features of the main body of the telerobot is that it is free to rotate about its central core and the attachment foot. This freedom to rotate allows the thermal radiators, which cover three sides of the main body, to be oriented for optimum heat rejection at the worksite. Main body rotation with respect to the attachment foot allows the operator of the large manipulator arm (SSRMS or RMS) another degree of freedom to help orient the FTS foot for proper mating to the worksite attachment point.

The next major component of the telerobot is the arm positioning system that consists of two, linearly driven, tubular sections connected through an offset rotational joint. The lower section is free to rotate simultaneously with respect to both the main body and the attachment foot. The manipulator arms are free to rotate $\pm 180°$ with respect to the upper section. Five degrees of freedom are obtained to position the arms relative to the telerobot main body and attachment location. There are a number of advantages to the arm positioning system: it extends the reach of the telerobot without extending the length of the manipulator arms; it allows the arms to be positioned squarely to a task so that the teleoperator approaches the task in a natural manner; and it allows the telerobot to reach out over large objects that may come between the attachment fixture and the location of the task.

The final component of the telerobot is the manipulator arm assembly that is mounted to the end of the positioning system. It consists of the shoulder assembly that rotates $\pm 180°$ about the end of the positioning system, and two seven-degree-of-freedom manipulators mounted to each end of the shoulder assembly. The manipulators are 1.524 m (60 in.) long and are configured with a roll-pitch-roll shoulder, pitch in the elbow, and roll-pitch-roll in the wrist.

In addition to the telerobot, the FTS includes two workstation designs: a stowable workstation for the NSTS, which will be mounted in the aft flight deck of the shuttle and the space station workstation, which will include FTS-unique hardware that will be incorporated into the space station Multipurpose Application Console (MPAC).

4. Design Drivers

During the analysis of the requirements and the task capabilities, the study team identified the following major design drivers for the FTS:

- o Thermal environment
- o Independent operation
- o Manipulator stability and positioning
- o Safety
- o Mobility
- o Evolution
- o 1-g operation
- o Human interface

The impact of each of these design drivers on the final design concept will be discussed in the following paragraphs. Not all of the design drivers are independent. Often, more than one of the drivers affects the design of a particular subsystem. Therefore a systems approach had to be taken to the trade studies to determine the appropriate solution leading to the best overall design concept.

4.1 Thermal Environment

The thermal environment created by the vacuum of space introduces unique problems for the FTS in an area that is only a minor concern for terrestrial robots. In space, the only way of dissipating heat is by radiation or conduction. The only paths for conduction were by hookup to the space station thermal system or by dumping heat into the FTS base mounting structure. Both options were considered too restrictive for the flexibility and usefulness of the FTS and they also created a thermal interface to the space station that the design team wanted to avoid. Therefore, radiation is the only acceptable means of heat dissipation.

Dissipating heat from a robot with peak operating power in the 1- to 2-kW range with approximately 20 motors, several high-speed computers, video equipment, and batteries with radiation as the only means of cooling is a thermal problem. The operation of the FTS should not be restricted because of the thermal environment. This meant that the FTS had to be capable of operating with arbitrary Sun angles and with partial blockages from the structure at the worksite.

To overcome these problems, the overall power of the telerobot was reduced, its total radiating capability was increased, and the main battery was removed from the telerobot.

One effect of reducing the power was the selection of motors at each joint that were sized for the tasks in zero gravity but could not operate without assistance on Earth. By using smaller motors, the manipulator thermal system could be separated from the rest of the body, and all the other heat-dissipating components could be collected into one structure that could be optimized for thermal radiation.

Figure 2 shows the concept for the telerobot body that uses heat pipes to direct the heat from the electronic boxes out to the outside surfaces, where radiators cover three sides. The main body was designed to rotate independently of the manipulators and the arm-positioning system, so that it could be controlled to track an optimal orientation to cold space as the telerobot performs its tasks.

Removing the main battery from the telerobot had a number of effects on the design. It reduced the mass of the telerobot and removed a source of power dissipation. It also freed the telerobot from the tight thermal limits that the battery imposed on the system.

The combined effect of all these design choices produced a thermal design that is independent of the space station and that will permit indefinite operation of FTS under most conditions. In some extreme cases of radiator blockage, the task may have to be halted temporarily to allow the telerobot to cool down. Consideration was made of the use of a small "backpack" composed of Phase Change Material (PCM), which could be used to absorb peak loads to enable the telerobot to continue operating for a brief time under extreme conditions. The thermal system is also an ideal candidate for the incorporation of an expert system that could continually monitor the thermal health of the telerobot and inform the operator of the amount of time that is left before a cooldown period would be required.

4.2 Independent Operation

Another requirement is that the FTS must be capable of limited operation independently of hard-wired utilities for power, data, and video from the space station.

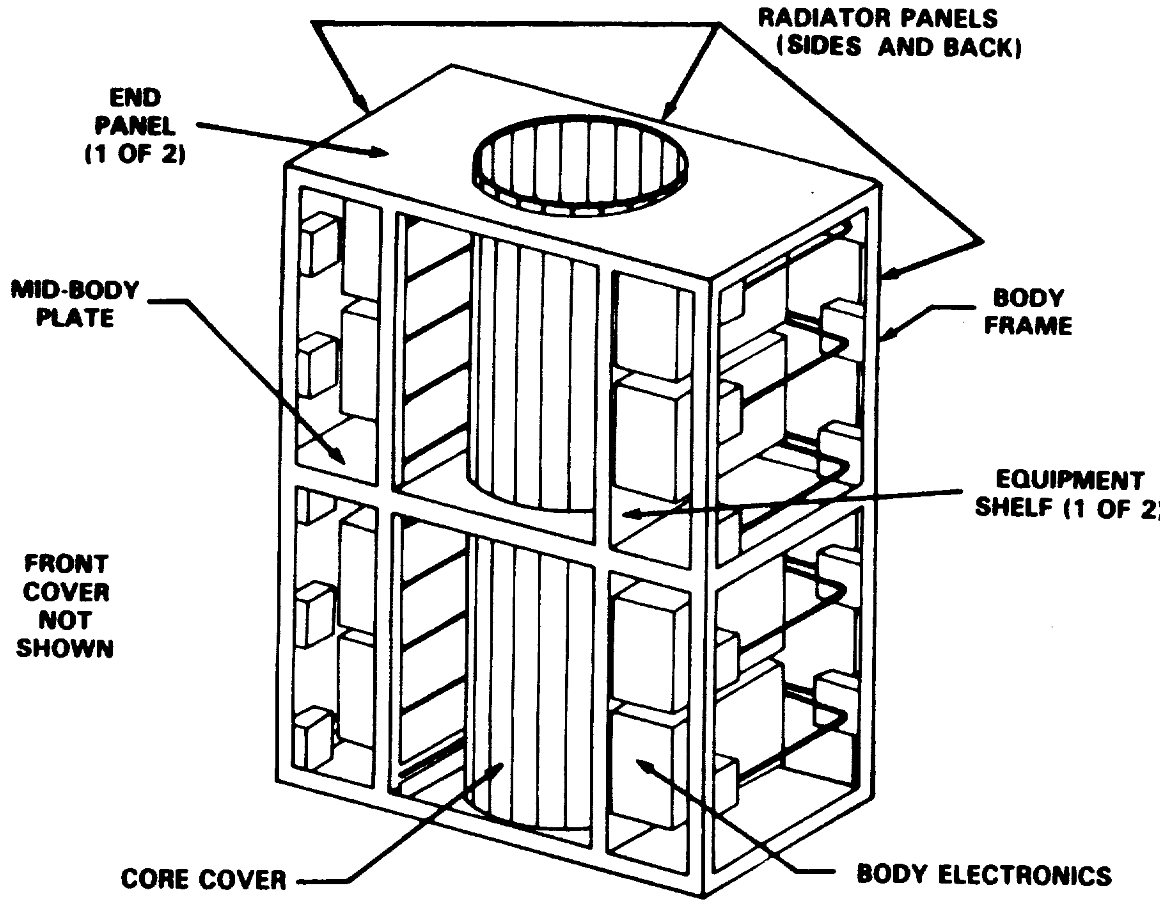

Figure 2. Structure Subsystem Tinman Design

Because of this requirement, a large battery and a radio frequency (RF) communications system were included in the design of the FTS. The FTS can never be totally independent of the space station, because it always needs a firm structural attachment when working. However, the requirement for independent operation gives the FTS a tremendous amount of flexibility, allowing it to work in areas on the space station where no utility ports are located.

A battery that would allow operation for even a few hours at the power levels of the FTS adds considerable weight and adversely impacts the thermal subsystem. Since the independent operation is not the primary mode of operation, it was decided to remove the battery and the communications system from the main body of the telerobot and locate them in a separate module called the Robot Support Module (RSM). Because there is not a requirement for an early independent operational capability, the RSM could be launched later than the FTS, thereby reducing the initial manifested weight of the FTS.

Another advantage of the separate RSM is that it would be possible to design different RSMs for the different operating environments of the FTS. Because the NSTS and the space station have different power and communications systems, a different RSM could be designed for each location. Another RSM could be built for operation from the OMV for the servicing of free-flying spacecraft away from the NSTS orbiter or the station, as shown in Figure 3. Two RSMs on the space station itself are a possibility, so that while one is being used, the other could be having its battery recharged.

4.3 Manipulator Positioning and Stability

When the work environment of the FTS is examined in both the shuttle payload bay and on the space station, the same dimension of 5 m keeps reoccurring. The shuttle payload bay is 4.57 m (15 ft) wide, and, consequently, most payloads launched by the shuttle are also approximately 5 m wide or 5 m in diameter. The space station truss bays are 5-m cubes and the Attached Payload Accommodation Equipment (APAE) sit on a 5- by 5-m base. It can be concluded from this information that the ideal reach envelope of the telerobot would be 5 m. If the telerobot is to work in these locations, it must be able to cover these types of distances. However, early analysis indicated that a 5-m reach for the manipulator arms was not feasible if the telerobot was to do any dexterous manipulation. A local mobility system and an arm-positioning system were chosen to deliver the arms to the task. This approach allows the arms to be shorter and more rigid for the fine control tasks.

Figure 4 shows the reach envelope of the telerobot. Situated in the center of the space station truss bay, the telerobot can reach all faces of the bay. The reach of the telerobot at an APAE site is shown in Figure 5, where the Orbital Replaceable Units (ORUs) in the center can be reached from either side, even if larger ORUs are in the way.

The flexibility and controllability of such a system are still areas of concern that are being investigated. Preliminary indications are that the arm-positioning system can be made rigid enough to meet the task requirements. The five degrees of freedom in the arm-positioning system are controlled open loop and, therefore, do not contribute complexity to the arm control problem. The degrees of freedom in the positioning system are commanded to set positions one at a time and are then rigidly locked before the operator begins to use the manipulator arms. It is not anticipated that the

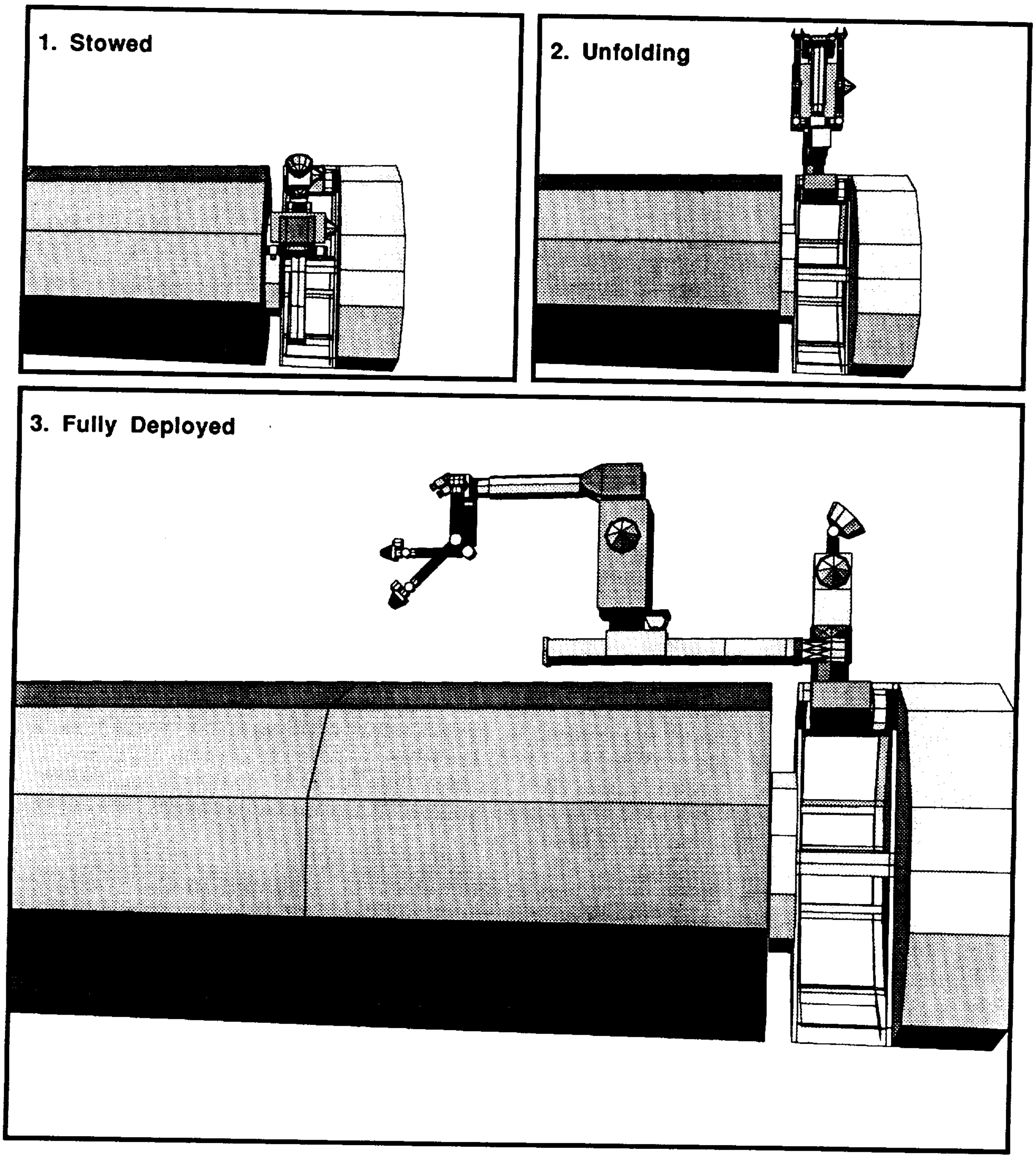

Figure 3. FTS/Orbiting Maneuvering Vehicle Servicing

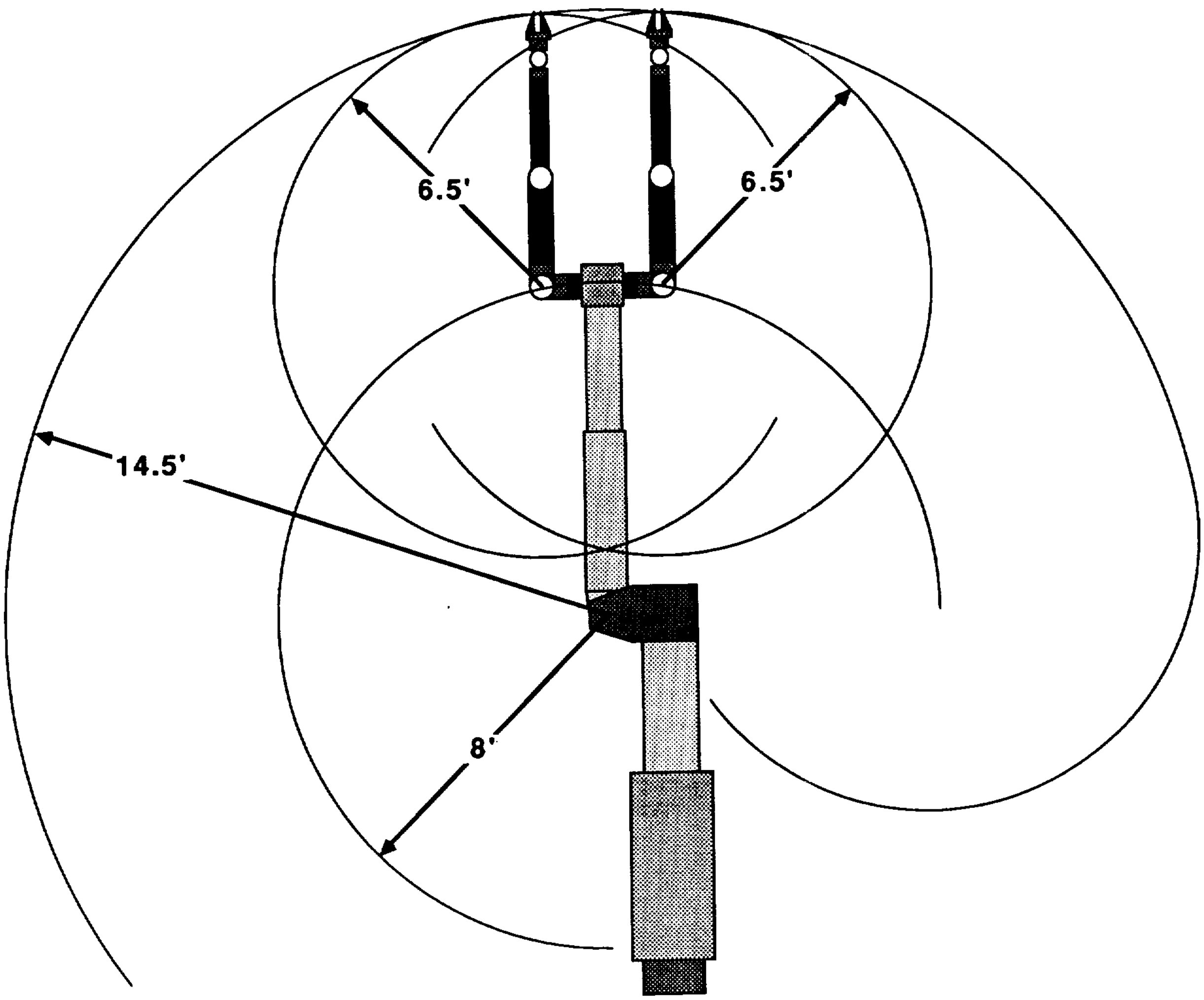

Figure 4. FTS Work Volume

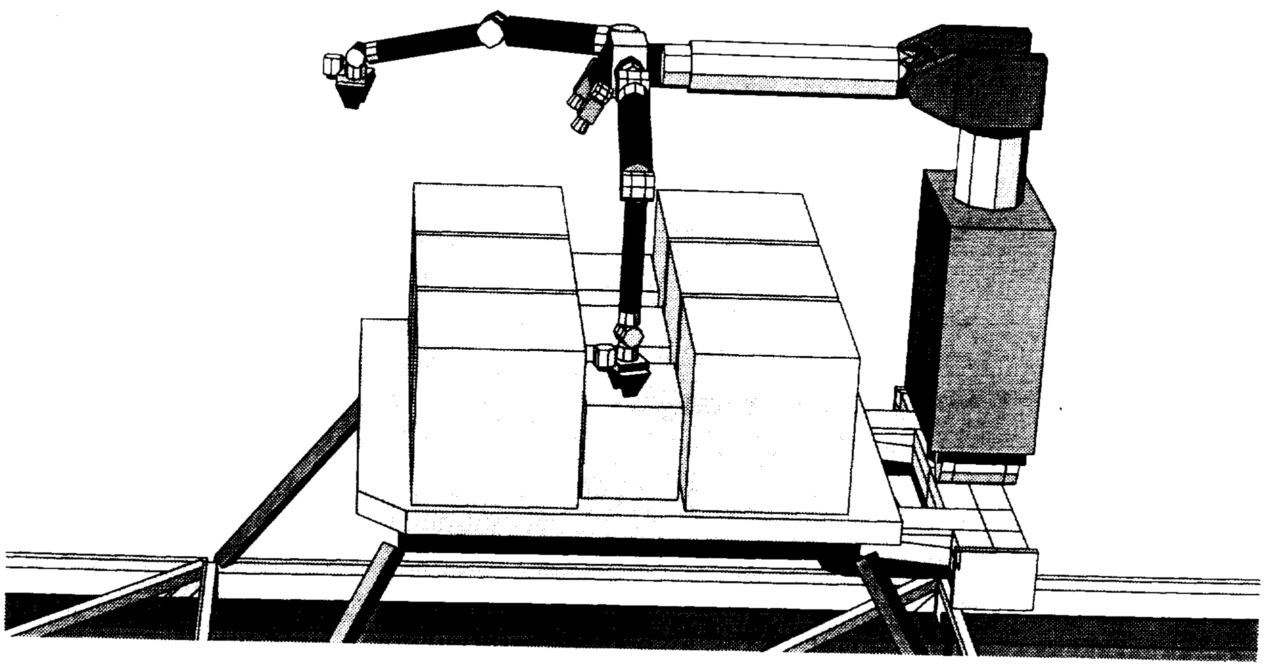

Figure 5. FTS Operating From Attached Payload Accommodation Equipment

positioning system would be teleoperated through the hand controllers. The operator could simply key in the position of the joints from a keyboard.

4.4 Safety

Safety is of primary importance in the design of the FTS. Safety influences each subsystem and must be designed into the FTS from the start. The Phase B study approach was to set up a watchdog safety subsystem that consists of redundant radiation-hardened computers and associated sensors in the telerobot to monitor all aspects of the telerobot operations and health. Also, the workstation has a safety computer that acts as a global safety monitor for workstation operations, as well as the telerobot safety subsystem. Whenever any anomalous condition is detected, the safety computers will stop all movement of the telerobot.

There is also a safety shutdown signal that originates from an astronaut on Extravehicular Activity (EVA) if he senses a problem with the telerobot. This is called the EVA safety link and allows an astronaut on EVA to have shutdown control of the telerobot whenever he works in the vicinity of the telerobot.

Each controller for the manipulator joints is capable of being programmed to limit the local parameters associated with that joint, such as velocity, acceleration. This programming allows the motions of the telerobot to be tailored to the task and the environment. A velocity limit of 0.30 m/s (1 ft/s) is imposed on the manipulators whenever the telerobot is working in the vicinity of an astronaut or critical hardware. Similar limits must be imposed on the maximum momentum the system can attain when moving an object. This may result in an even lower tip velocity, but it ensures that the telerobot can safely brake its motion to avoid collision.

Another safety feature in the telerobot is the inclusion of a small, holdup battery within the telerobot to sustain its functions and to perform an orderly shutdown in the event of a power loss. This safety feature is needed when the telerobot operates without the large battery in the RSM, and derives its power from the host vehicle.

4.5 Mobility

Mobility was identified early as an FTS design driver. There is not a requirement for the type of mobility that would allow the telerobot to walk down the space station truss. There are other means available on the shuttle and the space station to provide global mobility, such as the RMS on the shuttle and the SSRMS on space station attached to a transport device such as the Mobile Servicing Center (MSC) or the Mobile Transporter (MT). However, from a close examination of the FTS tasks, it is clear that some form of "local mobility" (or "robility") was needed at the worksite in order to make the FTS a useful tool on the space station.

The local mobility system that is part of the in-house concept is a portable rail that can ride out to the worksite with the telerobot to provide lateral movement. The portable rail, together with the arm-positioning system, allows the manipulator arms to be positioned with six degrees of freedom at the worksite. The length of the portable rail had to be traded off against the flexibility of the rail and the induced motions at the end of the rail that occur when the telerobot is in operation. The portable rail is attached to the RSM in the in-house concept, so that the telerobot/rail/RSM combination can be picked up as one unit and carried to the worksite by one of the transport devices on space station. Figure 6 shows the portable rail supporting the telerobot from the RSM.

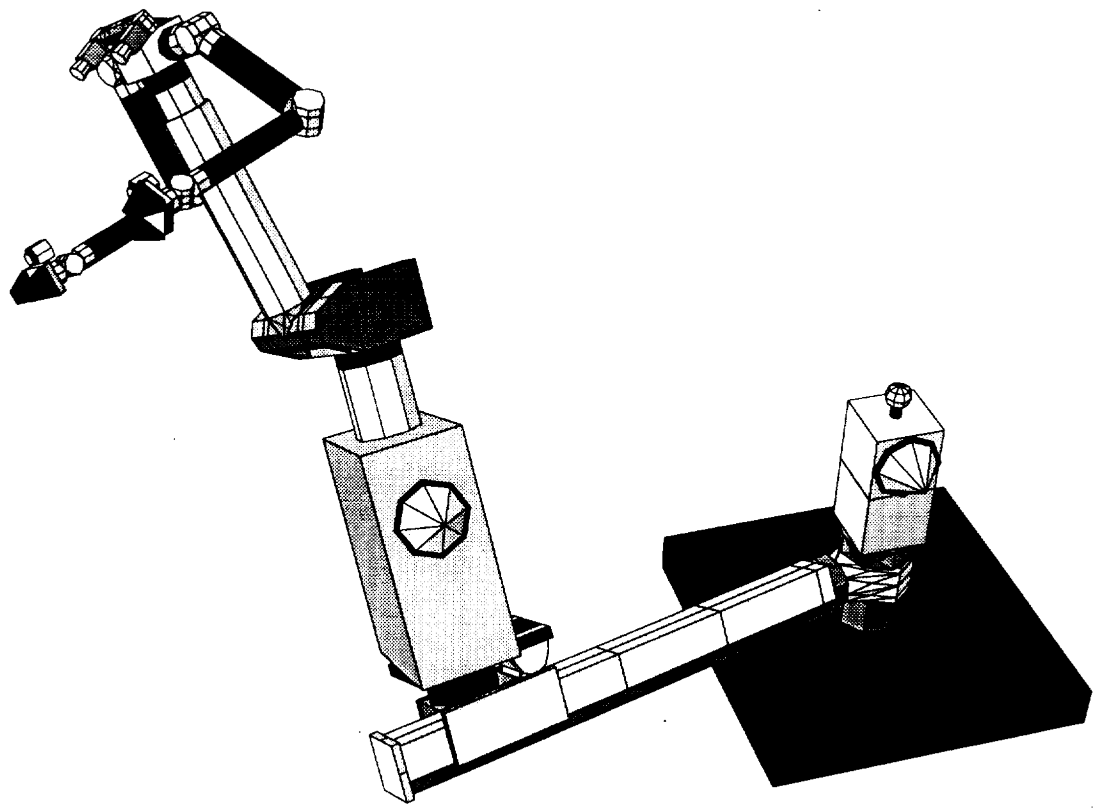

Figure 6. FTS and Robot Support Module

4.6 Evolution

The FTS must be able to evolve towards greater adaptability that includes more autonomous operation accomplished through the incorporation of advanced hardware and software items as they become available. Since the FTS is intended for permanent residence on the space station, new items must be added to the system in orbit. The FTS must be designed to easily accept these changes. This will be done by the incorporation of modularity and accessibility in the design of all subsystems of the FTS and by a careful implementation of the NASREM architecture.

Primary growth areas are expected to be in more advanced computers, upgraded software, advanced sensors with image processing, smart end effectors, and new and more efficient power systems. Also, the manipulator arms could be of a modular design, so that they can be reconfigured to provide more capability for new maintenance and servicing tasks on the space station. Power, data, and video lines would run throughout the telerobot with standard interfaces defined at the tool plate, arm joints, and other locations where hardware may be added or later changed.

A vision system, which initially is just a closed circuit video system, can easily grow to a stereovision system and eventually evolve to full machine vision. Steps that can be taken in the initial design to facilitate this growth are the choice and location of cameras and the interfaces to permit the computers to have access to image data.

4.7 1-g Operation

Requiring that the telerobot exhibit its full operational capability in the gravity environment of Earth has far-reaching impact on the system design. From a programmatic standpoint, the FTS must be capable of being tested in the performance of representative tasks on Earth before it is committed to launch. However, such a requirement has to be weighed against the impacts it causes on the structural, controls, electromechanical, power, and thermal subsystems.

For terrestrial robots, a 100:1 weight-to-lift ratio is not unusual, and a ratio of 10:1 is just now being achieved by some research manipulators, such as the Laboratory Telerobotic Manipulators (LTMs) being developed by NASA Langley Research Center and the Oak Ridge National Laboratory. This means that if the FTS were required to handle mockup hardware weighing 50 lb, the manipulators would be on the order of 300 to 500 lb each when using today's technology. This results in 600 to 1000 lb for just the manipulators. The total manifested weight for the FTS, including the telerobot and the workstation, is currently 1500 lb.

The FTS must undergo a strict weight control program that will result in motors and a structure that will be adequate to accelerate the inertias required by the tasks in the zero-gravity environment of space, but may not be capable of lifting the mockups of the same hardware on Earth. This will mean that the telerobot will need special assistance to perform its operations in 1-g, such as counterweights and other gravity off-loading devices.

Smaller, lightweight motors are a benefit to both the power and thermal subsystems of the FTS. A lighter weight structure has an impact on the control system, since the manipulators will be more flexible, but this is not viewed as an insurmountable problem for the FTS, because of the recent advances in algorithms for the control of flexible robots.

4.8 Human Interface

The design of the FTS for the human operator extends beyond the obvious human engineering of the workstation, (e.g., ensuring that the operator is presented with all the necessary displays and controls). The FTS is a teleoperated device for which the operator is directly in the control loop. The human interface has a strong influence on the design of the control system, the data system, and the sensors, including the vision system.

The FTS must be designed for operation by one operator. Inventive means must be found for the control of the cameras, illumination, and other peripheral devices when the operator uses both hands to operate the manipulators.

The study team concluded that the use of force-reflecting hand controllers should be a requirement for the FTS. This would permit the operator to sense the manipulator forces in his hand controllers. For a teleoperated device, this requirement is a tremendous asset to the operator. It enhances safety when working in an unstructured environment, and it has been proven through documented experiments in the laboratory to reduce errors and overall training time.

The problem on force reflection is the stringent data latency requirement it places on the data system for communications between the workstation and the telerobot. Because the force loop is now closed through the workstation, the stability of the control loop depends on minimizing the delay time for the round trip signal. The loop should operate at approximately 200 Hz, which results in a latency requirement of 5 ms. The FTS will use the Data Management System (DMS) on the space station to connect the workstation to the telerobot, and an assessment has to be made to see if the DMS can satisfy such a latency requirement.

5. Resource Accommodations

Just as plans to utilize humans in the space environment requires accommodations for communication and other resources, plans to use an extravehicular space robotic system requires integration of robotic interfaces and resource accommodation into that environment. Because the application of the FTS is to be in the extravehicular environment, and each task planned for execution by the FTS must be planned such that suitably equipped astronauts also can perform the task, much of the planning for the integration of the FTS can be combined with requirements for operations involving EVA. The design criteria for robot compatible hardware [7] on space stations should highlight similarities to human integration standards [8].

The requirements for robot access and interface are expected to be similar but not identical to those for the astronaut performing EVA. For example, robotic manipulation may be simplified if handling interfaces have flat surfaces of certain dimensions. An astronaut's glove may not require flat surfaces, but emphasis may be placed on rounded interfaces to prevent glove damage. Only by studying both sets of requirements can both be met and a solution to both be agreed upon. In this case, both needs can be met with handles designed with flat surfaces and rounded edges. However, even this simple case is not yet resolved, because the FTS and its tools and end effector designs have not yet been chosen, and the designers of space station hardware have only begun their interface designs.

The process of integrating the FTS into the space station is ensured because the space station program office has directed that, for extravehicular operations, all hardware be designed for telerobotic manipulation as the baseline with backup by astronauts performing EVA when practical and cost effective.

5.1 Control Station

The Space Station Freedom Program Definition and Requirements Document [9] currently identifies locations for the FTS control station within the pressurized resource nodes that connect the larger pressurized modules and house the primary station control functions. Each FTS control station will consist of the space station common workstation, augmented with unique items such as hand controllers, software, and any unique safety controls that may be required, such as for rapid shutdown of telerobotic operation.

5.2 Transportation

The space station MSC will provide transportation of the telerobot from the FTS external storage location to worksites on the truss. The MSC also will support operations from the base of its Mobile Remote Servicer (MRS) and from the end of its manipulator system, the SSRMS, as shown in Figure 7. Interfaces for structural attachment, power, data, and video must be established between the FTS and the MSC to support these operations.

5.3 Access to Utilities

At each worksite, the FTS will require structural attachment points, as well as access to power, data, and video links that are consistent with the operations planned at each worksite. Where the full capability of the FTS is required, a hardline connection between the telerobot and the control station will be provided. This connection will provide a real-time bidirectional data link between the telerobot and the control station that is capable of transmitting 0.5 Mbps, with a one-way data latency not greater than 5 ms. The connection will also accommodate simultaneous transmission of four channels of color video to the control station. This will permit bilateral force reflective feedback control and the capability to display up to four views of the worksite environment from telerobot-mounted cameras.

If operations do not require the full capability of the FTS, or if a task develops at a location where hardline utilities are not available, the telerobot may be operated in its independent mode. This will allow it to operate continuously for at least 2 hours on internal battery power. Communications are established by means of the FTS wireless RF communications equipment.

Force reflection may be impossible or degraded in this mode, because RF transmissions on the station cannot accommodate the rapid communication between telerobot and workstation that is necessary for good bilateral force reflection. However, automated control and non-force-reflecting teleoperated control will still be possible and will bring a significant remote dexterous capability to the astronauts. RF operations on the space station are currently limited to the simultaneous transmission of only three video channels, but video switching and compression techniques can still provide access to all four of the telerobotic camera views at the workstation.

5.4 Worksite Locations

Studies are underway to identify the potential worksite locations for the FTS. This effort is being coordinated with the providers of the pallets which accommodate the

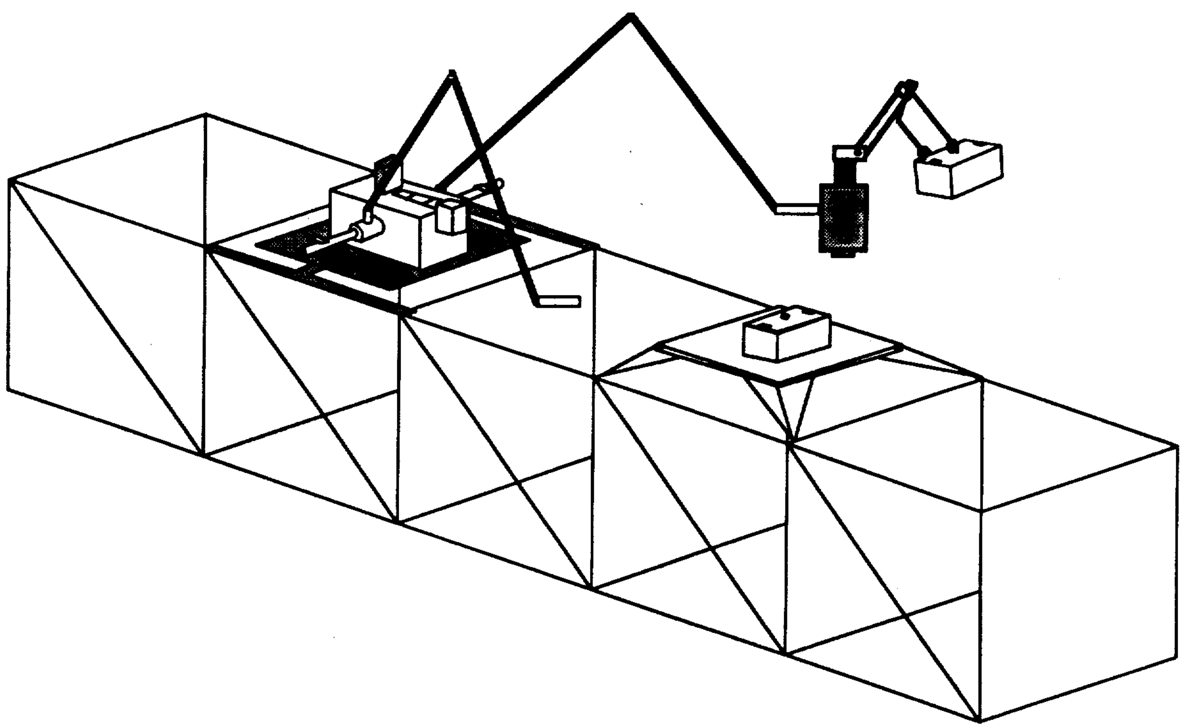

Figure 7. Transporter Attached Operation

distributed systems equipment and APAE from Johnson Space Center, Goddard Space Flight Center (GSFC), and Lewis Research Center. There are 11 locations currently identified in the space station documentation where utility ports are to be provided to support FTS operations [10]. Additional worksite accommodations will be provided to support FTS transfer of equipment to and from the Unpressurized Logistics Carrier (ULC), which is being built by Marshall Space Flight Center.

These give the FTS the capability to operate at full capability at many locations and at reduced capability virtually anywhere on the space station. Use of the FTS throughout the station is being pursued further through commonality with utility access ports for the MSC and other equipment, and by seeking distributed access to utilities where such access makes sense in the integrated planning of operations and maintenance of the space station.

6. Task Analysis

A structured task analysis methodology has been developed by the Mission Utilization Team (MUT) at the GSFC in order to analyze the FTS Tinman concept in the performance of Space Station Freedom assembly tasks. The procedures that were developed are compatible with the NASA/NBS Standard Reference Model (NASREM) [6]. The process starts at level 6 of the NASREM hierarchy with the decomposition of a mission into a sequence of tasks. On level 5, the tasks are decomposed into subtasks called steps. On level 4, these steps are then further decomposed into elementary moves (E-moves). NASREM levels 3 through 1 were not addressed in this initial effort.

Following each level of decomposition, a script was produced in which each work system, such as the RMS, the FTS, or the MSC were allocated assignments based on their capabilities. Several of the scripts were modeled with Computer-Aided Design (CAD) software to check the compatibility of the work systems, accessibility, and collision avoidance.

Finally, an assessment of the Space Station Freedom assembly tasks was made by rating system level attributes for FTS utilization as compared to EVA.

6.1 Methodology

The following account of the methodology used for this study is taken from the Flight Telerobotic Servicer Task Analysis Document [11]. The flow chart of the task analysis process is shown in Figure 8. The method consists of the main procedures described in the following paragraphs.

6.1.1 Statement of Objective

The statement of objective is the initial statement of the activity or work to be performed. It is described by the mission, task, step, or E-move. Most FTS tasks can be derived from two overall Freedom missions: assemble Space Station Freedom and maintain (or service) Space Station Freedom. For this task analysis, the objective was assembly of the Space Station Freedom elements on flights MB-2 through MB-4.

6.1.2 Decomposition

Decomposition is the process of breaking down a high-level objective, such as a mission or task, into the lower level activities and actions required to accomplish the desired objective. The activities and actions are expressed with selected verbs. An

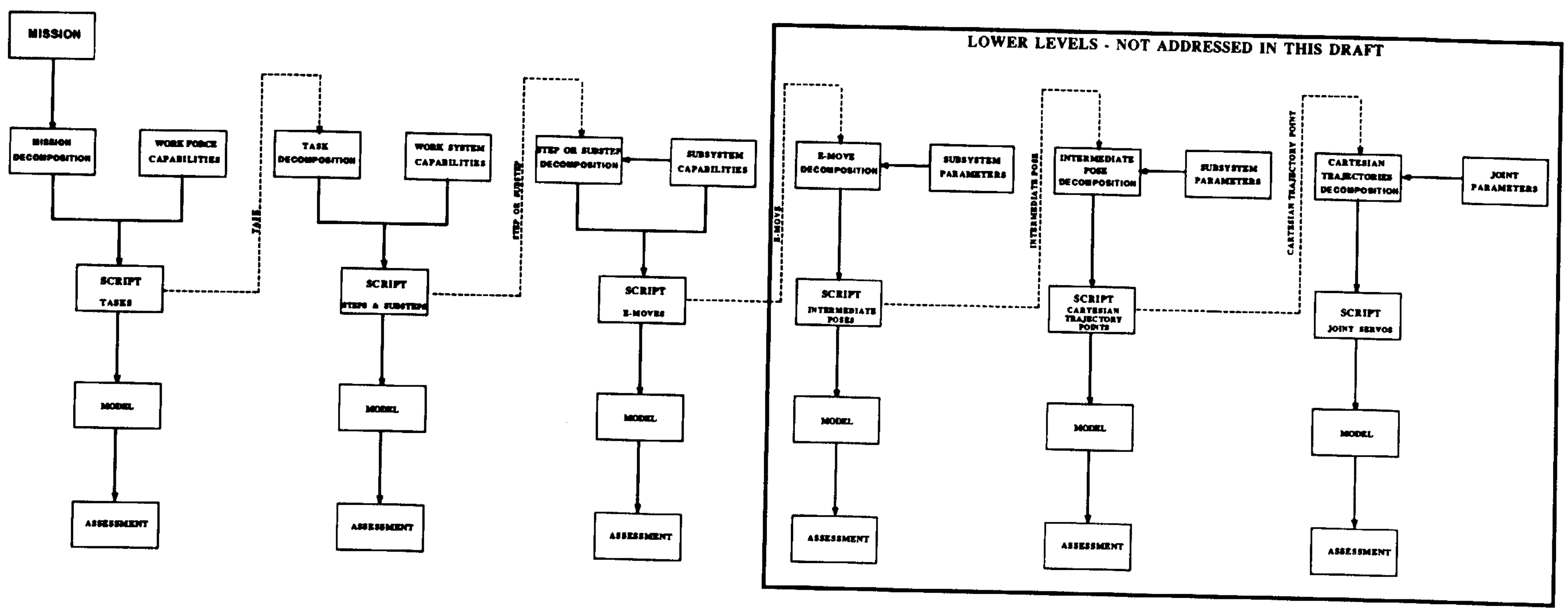

Figure 8. Task Analysis Flowchart

example of the verbs used is shown in Table 1. Decomposition at the upper NASREM levels 6 and 5 are task or object dependent and robot independent. Missions and tasks at these levels are defined and stated in terms of actions on objects. Because of the task dependence, these levels require primarily geometric information regarding the task.

Levels 3 through 1, on the other hand, process information that is task independent and robot dependent. At these levels, the upper level geometric description is converted into a low-level robot-dependent description with emphasis placed on joint motions, work system dynamics, efficient collision-free paths, and motor servoing.

Decomposition to level 3 was done only for the six baseline tasks listed in the FTS Phase C/D Requirements Document [4] and is documented in volume 2 of the FTS Task Analysis Document [11]. It was necessary to establish the scripts and interface concepts required to perform these fundamental operations to ensure that the upper level Space Station Freedom assembly tasks could be considered composed of strings of these elementary operations.

6.1.3 Tasks

The result of mission decomposition is a sequential list of task statements. For this study, the task statements came from two sources: The Space Station Assembly Operations, Functional Flows and Resource Allocations, Flights MB-2 through MB-5 [12], and the baseline task set from the FTS Phase C/D Requirements Document [4].

6.1.4 Task Steps

Steps are characterized as actions capable of being performed by a single work system (FTS, SSRMS, etc.) and are described by providing the endpoints (initial and final location or configurations) of objects. The majority of steps tend to describe actions such as positioning, attaching, and detaching objects. An example of several steps in the Power Management and Distribution (PMAD) pallet installation is:

- o Unstow PMAD pallet from payload bay
- o Position pallet to the vicinity of starboard bay No. 1 (SB-1)
- o Deploy starboard legs
- o Attach starboard legs to the starboard nodes

6.1.5 Work System Capabilities

An essential part of the task analysis process is to gather knowledge concerning the available work systems for a task. The work systems chosen for a task will depend on both the requirements of the task and the skills or performance capabilities of the work systems. The significant requirements and performance capabilities impelled on or by work systems are the following:

- o Space Station Freedom performance limitations on work systems--maximum values of the following:

  -- Velocities
  -- Accelerations
  -- Forces
  -- Moments
  -- Torques

Table 1
Examples of Selected Verbs in Decomposition

NASREM Level	Term Type	Explanation	Term
6	Missions	These verbs are inputs to level 6 and are decomposed into tasks.	Assemble Maintain (Freedom's hardware) Service (customer hardware)
5	Tasks	These verbs are inputs to level 5 and are decomposed into steps, which are then assigned to various work systems in a script.	Construct Dismantle Inspect Install Remove Repair Replace (changeout) Replenish
4	Steps	These verbs are inputs to level 4 and are decomposed into elementary moves, which are subsystem level commands.	Actuate Attach/detach Deploy Locate Measure Observe Position Stow/unstow
3	Elementary moves (E-moves)	These verbs are inputs to level 3 and are the sub-system level commands.	TBD

- Work system requirements, skills, and performance capabilities--maximum values of the following:

  -- Forces
  -- Torques
  -- Moments
  -- Stability
  -- Mobility
  -- Reach
  -- Dexterity
  -- Speed
  -- Control sophistication
  -- Resource requirements

6.1.6 Scripting

Scripting is the process of developing an operational scenario for accomplishing a task with specific work systems. A script is basically a set of lines or actions (tasks, steps, E-moves, etc.), that are to be performed by a set of actors (FTS, SSRMS, etc.). The scenario reflects the capabilities and limitations of the work systems.

Scripting can occur at the mission, task, or step level. An example from the scripting of the task of installation of the PMAD pallet, taken from a study report on the evaluation of space station assembly tasks utilizing the FTS [13], is shown in Table 2, where the steps of the primary worksystem (the FTS) are separated and proceed on different lines from those of the secondary work system (the SSRMS in this case).

Table 2
Task Scripting Example

Secondary Work Systems	Primary Work System
SSRMS unstows PMAD pallet from STS payload bay	--
SSRMS positions pallet in FTS work envelope	--
--	FTS deploys starboard PMAD legs
--	--

The scripts begin with a list of assumptions and end with a list of effects on the work systems used to deploy the FTS. Also listed are any modifications to the original task steps required to perform the task by the FTS.

6.2 Task Modeling

The results of scripting become the basis for further analysis using mathematical modeling and simulation. Parametric studies were conducted to identify requirements, computer graphics models validated such things as access and collision avoidance, and a scale model was used to rehearse the script.

Computer graphics were used to validate three of the assembly tasks that had been scripted:

- The PMAD installation
- The Thermal Control Subsystem (TCS) condenser module and radiator installation
- The inspection of the node to stringer final assembly

The IGRIP computer programming system was used on a Silicon Graphics IRIS 4D/70 GT computer. The simulations provided three-dimensional kinematic models of the FTS Tinman, the RMS, and the Assembly Work Platform Astronaut Translation Devices (ATDs). The simulations also contained geometric models of the Space Station Freedom elements and the STS. A feature of this approach that proved useful was the ability to obtain different views of the operations: for example, a view as seen by the operator using the FTS cameras; a view from the STS Aft Flight Deck; and a global, bird's eye view away from the STS.

An example of the computer graphics is given in Figure 9 where the FTS is shown deploying the PMAD leg. Note that the FTS is attached to the ATD by a Power and Data Grapple Fixture (PDGF). The FTS stabilizes itself by holding onto the PMAD pallet while the RMS holds and maneuvers the pallet for the FTS to deploy the legs.

6.3 Task Evaluation and Ranking

The FTS assembly tasks were ranked on a scale from 0 to 10 in terms of their expected impacts to the following list of attributes:

- Resources required
- EVA time saved
- Reduction in EVA hazard exposure
- Task complexity
- Task criticality
- Task recurrence
- Task similarity to baseline FTS tasks

Since these factors cannot be measured on a common scale, a ranking methodology capable of dealing with multiple factors was used. The Keeney-Raiffa Multiple Attribute Decision Analysis (MADA) was chosen.

7. Conclusion

The FTS promises to be a useful, reliable, and safe tool to assist the astronauts in performing assembly, maintenance, servicing, and inspection tasks on Space Station

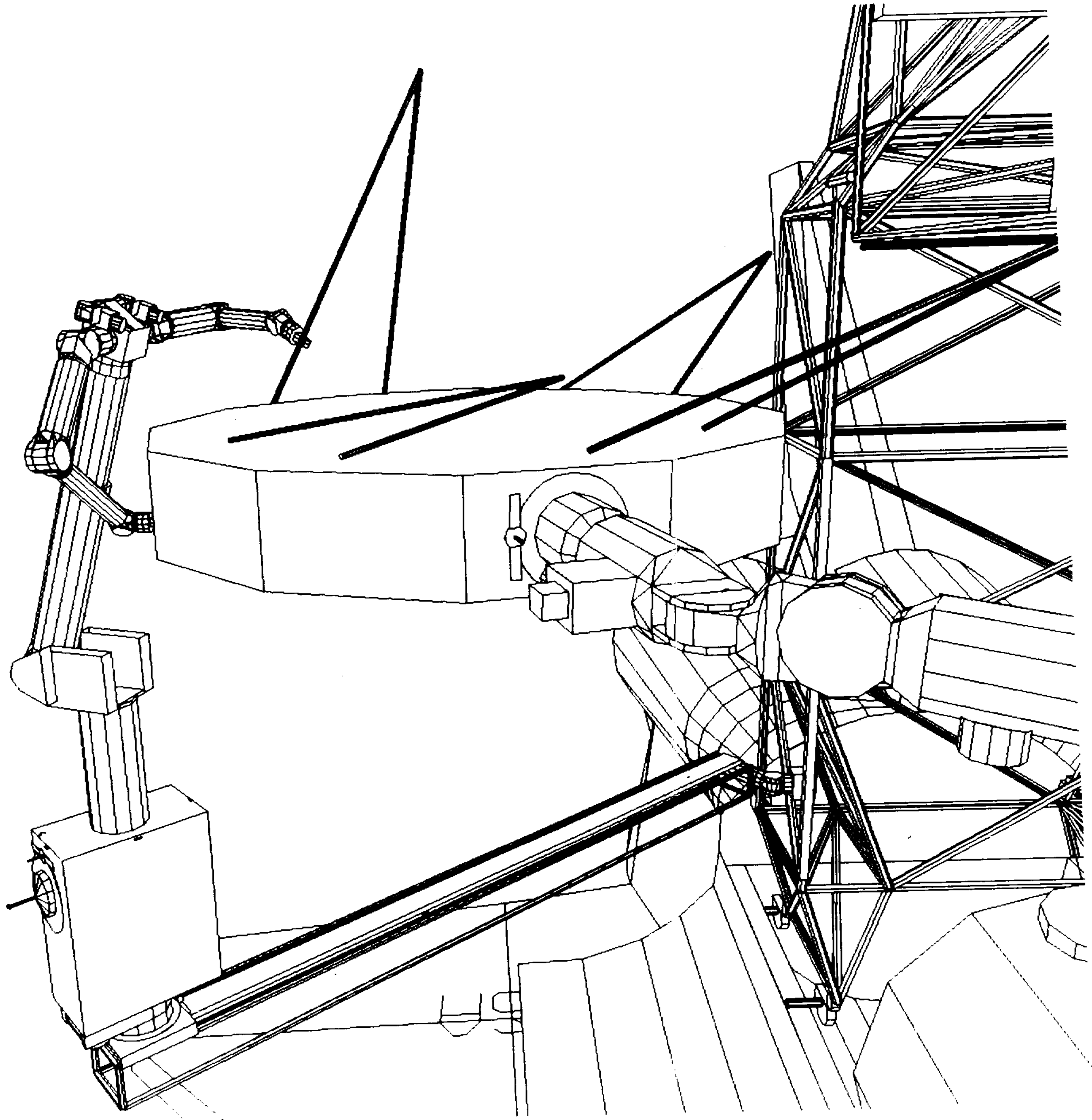

Figure 9. FTS Deploys PMAD Pallet Leg

Freedom and the NSTS. The design challenges have been identified and operational scenarios and task planning have been addressed by the NASA Phase B study team, while candidate designs were being developed by Grumman and Martin Marietta in their Phase B studies.

Progress has been made in identifying the FTS accommodations on Space Station Freedom to successfully integrate the FTS into the program as a useful tool for the space station crew. Commonality and accessibility are primary considerations in the selection of utility ports and structural attachment points for the FTS.

A structured task analysis methodology has been developed, and it is being used to construct scenarios of FTS assembly tasks. With this technique, the FTS Tinman was shown to be capable of executing a wide range of tasks, contingent upon the provision of certain resources and associated work system capabilities.

FTS is unique in that it will be required to operate in a much less structured environment than previously developed industrial robots. It will be required to perform many varied tasks with varying precision throughout its expected lifetime. Because these tasks will increase in complexity, the system must be capable of substantial growth and evolution. It is a program that focuses more on the future than the present technology.

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