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THE FLIGHT TELEROBOTIC SERVICER (FTS) NASA'S FIRST OPERATIONAL ROBOTIC SYSTEM

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ABSTRACT

NASA has completed the preliminary definition phase of the Flight Telerobotic Servicer (FTS) and is now preparing to begin the detailed design and fabrication phase. The FTS will be designed and built by Martin Marietta Astronautics Group in Denver, CO, for the Goddard Space Flight Center, in support of the Space Station Freedom Program. The design concepts for the FTS are discussed, as well as operational scenarios for the assembly, maintenance, servicing and inspection tasks which are being considered for the FTS. The upcoming Development Test Flight (DTF-1) is the first of two shuttle test flights to test FTS operations in the environment of space and to demonstrate the FTS capabilities in performing tasks for Space Station Freedom. Operational planning for DTF-1 is discussed as well as development plans for the operational support of the FTS on the space station.

INTRODUCTION

Project Status

The Flight Telerobotic Servicer (FTS) project was formed in 1986 to develop a telerobotic device to perform assembly, maintenance, servicing and inspection tasks on the space station, the shuttle orbiter or the Orbital Maneuvering Vehicle (OMV). A phase A study was conducted in the fall of 1986 with agencywide participation [1]. The output of this feasibility study was a preliminary requirements document and a request for proposals (RFP) for competitive phase B studies to establish a preliminary design of the FTS. The phase B study contracts were awarded to Grumman Space Systems Division in Bethpage, NY, and Martin Marietta Astronautics Group in Denver, CO. These studies ran for 9 months and were concluded in September 1988.

An in-house phase B study was conducted by NASA in order to refine the requirements for the FTS and to begin working the interfaces with Space Station Freedom [2 and 3]. The in-house study was started several months earlier than the contractor studies, because NASA needed some early estimates of the FTS resources and operational capabilities to work interface issues with the Space Station Freedom Program, which had already completed its own phase B study and was preparing to start detailed design and implementation.

One of the outputs of the phase B studies was a new requirements document for the phase C/D. This became part of the phase C/D RFP which was released November 1, 1988. Proposals were received on January 3, 1989, and Martin Marietta was selected for negotiations on April 20, 1989. This paper describes the proposed Martin Marietta design for the FTS, which is shown in Figure 1.

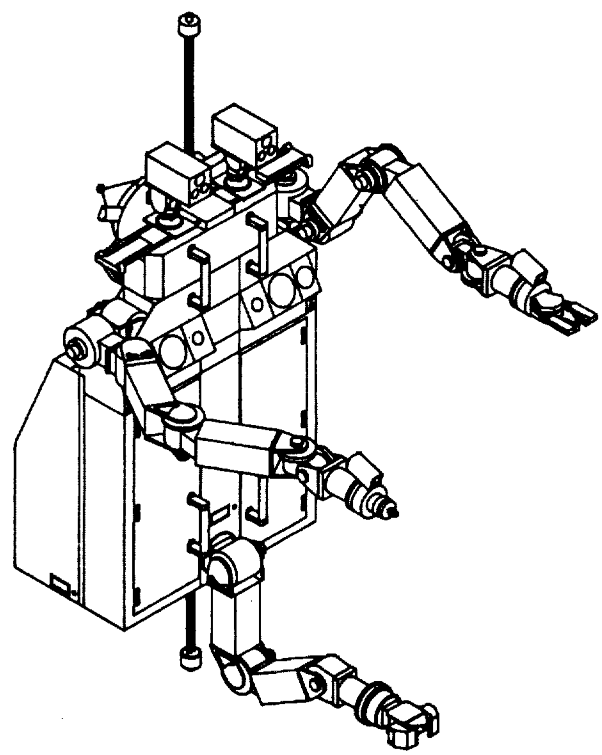

Figure 1. Flight Telerobotic Servicer (FTS)

Test Flights

Before describing the space station FTS (SSFTS), which will be launched on one of the early Freedom Station assembly flights, there are two early shuttle test flights which should be mentioned. They are the Development Test Flight (DTF-1), scheduled for launch in August, 1991, and the Demonstration Test Flight (DTF-2), scheduled for launch in 1993.

The DTF-1 will be flown as an attached payload to test the control and performance of the manipulators in zero gravity, as well as the human-machine interface through the workstation. Test tasks will be performed, and data will be collected so that the performance on orbit can be compared to the performance in the laboratory. The present concept of the configuration of the payload bay elements for DTF-1 are shown in Figure 2. The manipulators and the upper torso of the telerobot body are mounted to a Multipurpose Experiment Support Structure (MPESS) bridge. There will be one or more task boards attached to the MPESS. They contain the task elements which will be manipulated during the flight. An astronaut will teleoperate the DTF-1 from the workstation located on the aft flight deck of the orbiter with two minimaster hand controllers and television screens that display images from the four cameras that are located on the telerobot. There is also a fifth global-view camera that will be set apart from the telerobot for viewing the entire work area.

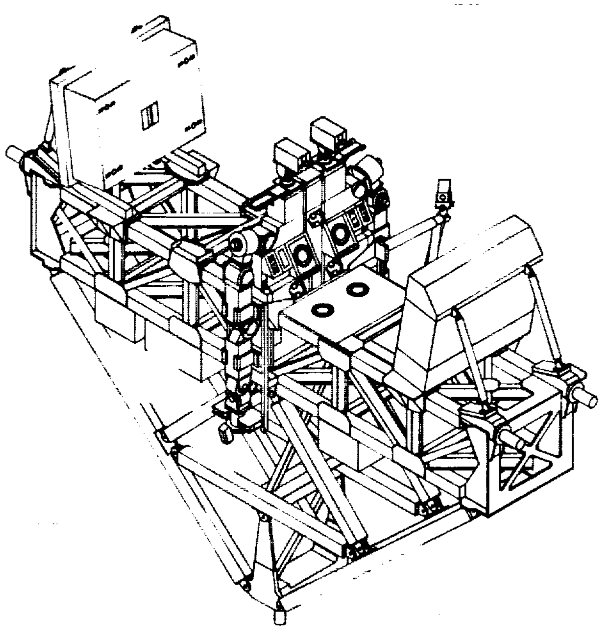

Figure 2. Configuration of Payload Bay Elements for Development Test Flight

In 1993, the DTF-2 will be flown with a mature version of the SSFTS to verify and demonstrate the system's capabilities to perform representative tasks for which the FTS will be responsible as part of its assembly, maintenance, servicing, and inspection tasks on Freedom Station. The workstation will be located on the aft flight deck of the orbiter, as in DTF-1, but this workstation will be the final SSFTS shuttle workstation which will be flown during the assembly flights of S.S. Freedom. DTF-2 will use the shuttle Remote Manipulator System (RMS) for mobility in the payload bay. The RMS will attach its end effector to a power and data grapple fixture located on the back of the telerobot and transport the telerobot to a worksite. These manuevers will involve close coordination between the operators of the two manipulator devices and will demonstrate the cooperative capabilities of the total system. The RMS provides the large motion and large torque capabilities, while the FTS provides the fine motion and dexterous manipulation. The FTS workstation will be located to the left of the RMS operator's workstation so that close communications can be maintained. Each operator will have an aft flight deck window located above his workstation for occasional viewing of the payload bay activity.

Evolution

The FTS system is designed for growth and evolution over the years. Initially it will be a teleoperated device with some autonomous functions for accomplishing routine operations in a well-structured environment. Over the 30-year lifetime of Freedom Station, the FTS will be upgraded through software and hardware changes to higher levels of autonomous activity. The vision system, which starts out as a closed-circuit television system, will expand to stereo vision, including some autonomous image recognition and location capabilities.

This capability for growth is only possible through careful planning and systems engineering at the outset of the program. A functional architecture was selected early in the program to guide the development of the software and hardware. This is the NASA/NBS Standard Reference Model for Telerobot Control System Architecture (NASREM) [4]. The software and computer architectures support this functional architecture so that orderly growth can be accomplished without major hardware changes. The SSFTS subsystems are designed with capacity margins for growth.

TECHNICAL OVERVIEW

System Description

The FTS system consists of a telerobot capable of working on a space station, shuttle, or OMV, a workstation for the shuttle orbiter, a workstation for the space station, spare parts and the storage accommodation equipment for storing the telerobot and its spares on the space station. Included as part of the telerobot are two manipulator "arms," an attachment, stabilizing, and positioning subsystem (ASPS) or "leg," cameras and lights, and all end-of-arm tooling.

The workstations are the principal point of human interaction for the control of the telerobot. Each workstation will be equipped with two six-degree-of-freedom (DOF) minimaster force-reflecting hand controllers. Video displays in the workstation will be capable of displaying up to three video images simultaneously, or two video images with health and status information displayed on the third screen. The telerobot cameras will be voice controlled, allowing the operator to maintain both hands engaged in manipulator teleoperation.

The telerobot will have a set of tools and end effectors that can be autonomously selected through the use of the end effector changeout mechanism (EECM) located on the end of each manipulator. Tool holsters located on the front of the telerobot body store extra end-of-arm tooling when not in use.

There are three ways that the FTS can be operated: fixed-base dependent operation, fixed-base independent operation, and transporter-attached operation.

In the fixed-base dependent operation, the telerobot is attached and stabilized to a worksite and derives its power, data, and video from an integral connection at the worksite attachment or an umbilical to a nearby utility port.

In the fixed-base independent operation, the telerobot is attached and stabilized to a worksite but derives its power from its own internal batteries. Communication between the telerobot and the workstation is by a wireless link through the space station communications system.

In the transporter-attached operation, the telerobot is attached to an external transporter device, such as the shuttle RMS, the space station Mobile Servicing System (MSS) with the SSRMS, or the OMV. The telerobot derives its power, data, and video by way of a hardwire connection from the host transporter.

The total weight of the telerobot and the shuttle workstation will not be more than 1500 lb. In the stowed configuration, the telerobot will fit in a volume that is 7 ft x 3.5 ft × 3 ft. The power required by the SSFTS will not exceed 2000 W peak power, 1000 W average power, and 350 W standby power.

The SSFTS will have a system accuracy of less than 1.0 in. in position and ±3.0° in orientation. System accuracy is defined as the ability to position and orient the tool plate center within a sphere of a given radius and a given tolerance in roll, pitch, and yaw relative to a Cartesian coordinate frame with the origin at the worksite attachment interface.

Space Station Freedom Interfaces

The SSFTS is designed to help in the assembly and maintenance of the Space Station Freedom and as such needs to operate off both the Space Transportation System (STS) shuttle orbiter and S.S. Freedom. Operations off of the STS will occur during the early Freedom Station assembly flights, and the SSFTS will make use of the standard STS interfaces, with perhaps the addition of a special umbilical for RMS operations. The SSFTS will require a workstation in the STS aft flight deck and interfaces to the STS power, data, and video systems in the payload bay. The RMS will be employed to move and position the SSFTS for operations on the STS. This requires the SSFTS to be equipped with an RMS-compatible grapple fixture for structural attachment to the RMS. As mentioned previously, an umbilical may be needed to meet the SSFTS power, data, and video requirements when operating from the RMS.

Once the SSF early assembly flights are completed, the SSFTS will begin operating off Freedom Station. This requires SSFTS workstation interfaces with the SSF Multipurpose Applications Console (MPAC) and interfaces to the SSF Data Management System (DMS), Operations Management System (OMS), Communications and Tracking (C&T) and Electrical Power System (EPS).

The MPAC will serve as the SSFTS Workstation with the addition of SSFTS-unique components. Currently, the FTS project intends to provide two six-DOF force-reflecting hand controllers, two standard data processors, and an adjustable restraint system to augment the MPAC. The MPAC is also the SSFTS interface to the OMS.

Other SSFTS interfaces fall into the areas of transportation, resources and storage. The SSFTS is designed to be transported by and operated from the Space Station Remote Manipulator System (SSRMS) and will meet the SSRMS mechanical, power, data, and video interfaces. The same grapple fixture on the SSFTS used for attachment to the RMS will be employed for attachment to the SSRMS. The SSFTS is compatible with the Freedom Station 120-Vdc EPS, Ku-band C&T, and DMS systems. Operations away for the SSRMS are possible in two basic modes. The first is the fixed-base dependent mode and requires a worksite attachment fixture that provides mechanical, power and data interfaces to the SSFTS. The second mode is the fixed-base independent mode and only requires a mechanical interface for attachment and stabilization. In this mode, the SSFTS receives power from its own battery and data through the S.S. Freedom C&T system.

Additionally, the SSFTS requires storage accommodation on the SSF. This includes power for battery charging and checkout, data for health and status monitoring, mechanical attachment, and storage for associated equipment and spares.

The SSFTS is also designed for Intravehicular Activity (IVA) maintenance. This limits the maximum size of the SSFTS so that it can be passed through a space station hatch.

SUBSYSTEM DESCRIPTIONS

Manipulators and End-of-Arm Tooling

The FTS telerobot contains a pair of 7-DOF manipulators, approximately 5 ft long from the shoulder to the tool plate. The kinematics of the manipulators are symmetric with roll-yaw-pitch at the shoulder, pitch at the elbow, and pitch-yaw-roll at the wrist. The manipulators are capable of producing a tip force of 20 lb anywhere within the work envelope.

The manipulator joint actuators each include a brushless dc torque motor, harmonic drive transmission, output torque sensor, output position sensor, fail-safe brake, cable wrap, and the housing and bearings required to carry structural loads. The brakes are designed to release when power is applied and engage when power is removed. The three shoulder actuators are all of common design and each produces 99 ft-lb of torque. The elbow actuator produces 58 ft-lb of torque. Each of the three wrist actuators, which are of similar design, produces 24 ft-lb of torque.

The manipulators have a repeatability of less than 0.005 in. in position and ±0.05° in orientation. The incremental motion of the manipulators is less than 0.001 in. and less than 0.01° at the center of the tool plate.

The manipulators are backdriveable to allow stowing by an astronaut on Extravehicular Activity (EVA) or by another manipulator. The manipulators have camera assemblies mounted on the wrist roll assembly to allow the operator a close view of the end effectors and tools and the objects that they are manipulating. A force/torque sensor is mounted on the end of the manipulator to measure the forces and torques produced at the tool plate. The tool plate accommodates passthrough of power, data, and video to the end effectors and tools. The tool plate also accommodates the manipulator affixed element of the end effector changeout mechanism (EECM) by which tools and end effectors are automatically exchanged by the telerobot.

Attachment, Stabilizing, and Positioning Subsystem

A third appendage or leg on the telerobot is the ASPS. Its primary purpose is to attach the telerobot to the worksite and to position the body so that the manipulators can properly approach the task. The ASPS must be stiffer than the manipulators and be capable of locking rigidly in place so that the forces and torques generated by the end effectors and tools can be properly transferred to the attachment mechanism.

The ASPS is a five-DOF manipulator, a little over 4 ft long from its base to the tool plate. The kinematics are roll-pitch-pitch-pitch-roll. The actuators are each capable of 24 ft-lb of torque. The torque capabilities when the brakes are locked is 180 ft-lb in the two shoulder actuators, 210 ft-lb in the elbow, and 240 ft-lb in the two wrist actuators. The minimum braked stiffness is 200,000 ft-lb/radian.

On the end of the ASPS is the Worksite Attachment Mechanism (WAM) by which the telerobot attaches to a fixture located at each worksite [see Figure 3]. For fixed-base dependent operations, the WAM makes electrical connection to the space station power, data, and video systems at the same time that it makes the mechanical connection. Self-aligning scoop-proof connectors in the WAM are mated when the WAM pulls itself into the attachment fixture.

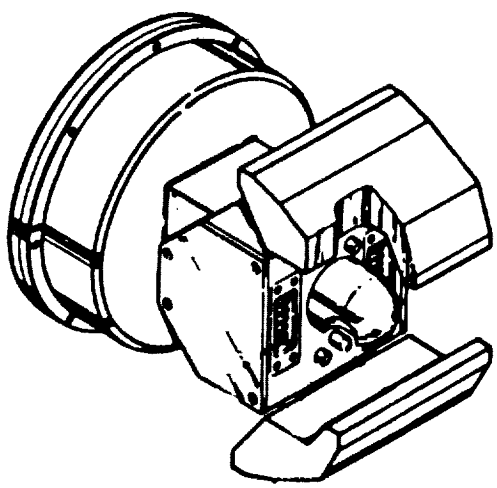

Figure 3. Worksite Attachment Mechanism

Data Management and Processing Subsystem

The Data Management and Processing Subsystem (DMPS) hardware and the software that executes in it are critical subsystems of the FTS. The SSFTS DMPS is a highly distributed processing system comprising multiple computers and networks which meet the stringent S.S. Freedom safety and reliability requirements. The DMPS implements a fault tolerant, redundant architecture which provides extensive growth capability because of its modularity.

The SSFTS DMPS is physically distributed: throughout the robot itself, in the FTS storage accommodation equipment, and packaged with the hand controllers. In addition to the computers provided by the FTS, the DMPS interfaces with the computers contained in the space station MPAC which is used as the work station by the astronaut FTS operator.

The FTS approach toward data management and processing is based on commonality with the space station. All FTS processors are in the 80386-80387 family of computers, which is the S.S. Freedom standard. The computers are connected through standard space station networks. All FTS processors access 1553b networks.

The computers internal to the robot use redundant 1553bs for communication. The SSFTS computers housed in the storage accommodation equipment are also connected to the space station Fiber Distributed Data Interface (FDDI) network.

The FTS computers include both space station Standard Data Processors (SDPs) and special purpose FTS joint controllers. The SDPs are used for high-level control and monitoring functions. The joint controllers perform servo level control of the manipulators, end-effectors, cameras, hand controllers, etc. Redundant processors provide backup capability in the event of failures of primary processors.

The SSFTS DMPS provides approximately 40 Million Instructions Per Second (MIPS) of processing power distributed among 16 joint controllers and 4 SDPs. The robot contains 14 controllers and 2 SDPs. The storage accommodation equipment houses 2 SDPs. The portable hand controllers contain two joint controllers. Later, additional capacity will be added as the FTS evolves toward autonomy. As an example, additional computers could be added for vision processing.

The flight software that executes in the DMPS must perform complex real-time processing. It is both CPU and input/output intensive. The basic control cycle runs at 50 Hz, and so the teleoperation of the manipulators appears instantaneous to the operator.

Every 20 ms the software must complete all processing and communications associated with the control cycle. This includes sampling the sensors in the hand controllers, interpreting the sensor data as either position or resolved rate commands, integrating the commands into Cartesian coordinates, converting the Cartesian commands through closed-loop form inverse kinematics into joint angle commands for the manipulators, and sending the commands to each actuator in each manipulator and end effector. To close the loop, the entire sequence is reversed by sampling the sensors in the robot, translating coordinates, scaling and indexing, and commanding the actuators in the hand controllers to provide force feedback. In addition to the basic control cycle, the FTS flight software must monitor and control all FTS subsystems, perform collision avoidance processing, support all the text, data and graphics interaction with the operator, and interface with the space station OMS.

NASREM provides the architecture for the FTS flight software. NASREM defines a set of standard hierarchical and horizontal modules and interfaces that correspond to different levels of autonomy. By adhering to NASREM, the FTS software can be developed incrementally. Initially, FTS will be primarily a teleoperated machine. With time, increased capability will be added allowing for the evolution to robotics. By enforcing the NASREM architecture on the FTS software, the addition of new modules and the exchange of existing modules with better algorithms is facilitated. NASREM will be used for all FTS flight software, including the two shuttle test flights. By SSFTS, the flight software will implement the first four levels of NASREM.

The FTS flight software will be implemented in Ada. It will be developed with the NASA Information System Life Cycle methodology. It will be rigorously validated prior to each mission in a high-fidelity software test bed.

Workstation and Hand Controller Subsystems

The workstation is the man-machine interface to the FTS, providing the displays and controls that permit the FTS to be operated by a single individual. The degree of human interaction with the workstation and its location is a function of the evolutionary state of the FTS. Initially, FTS requires teleoperation through master hand controllers that are located on orbit with the slave manipulators. Teleoperation from the ground is impractical because of the time delays associated with RF communications. In the future, when the FTS evolves into an autonomous robot, hand controllers will no longer be the primary means of control. At that time, the FTS workstation may be on Earth.

During the two DTF flights and early S.S. Freedom assembly missions, the FTS will be operated by an astronaut from the shuttle Aft Flight Deck (AFD). Later, when the Freedom Station is more complete, the SSFTS will be operated from workstations located inside the pressurized modules. When the autonomous FTS is mounted on an OMV, it will be operated from a workstation that could be located anywhere, perhaps even on the ground.

The FTS STS workstation is provided by the FTS contractor. It consists of a display assembly panel, hand controllers, restraint system, and electronics. The hand controllers and the display assembly panel are stowed in the middeck lockers for STS launch and landing. The electronics are mounted before launch in the L10 payload station. The FTS display assembly panel will be unfolded by the astronaut and mounted to the A6 panel prior to FTS activation. It contains three color flat panel displays that will be used by the operator for viewing of any three FTS video cameras. Optionally, one of the displays can be used by the operator to monitor computer generated text and graphics. The FTS shuttle workstation also contains audio caution and warning indicators and lights, voice recognition hardware, keyboard, various hard-wired control switches, video recorders, data recorders, and assorted programmable function keys. The STS FTS restraint system, which is required because of the torques caused by the hand controller force reflection, consists of the Mission Specialist's chair reversed to face aft. The FTS hand controllers are mounted on the chair by the astronaut on orbit.

The SSFTS workstation, depicted in Figure 4, will use the standard MPAC, which provides the electronic interfaces between Space Station Freedom application programs and onboard operators. This will be augmented by portable FTS hand controllers, so that FTS can be operated from one of several workstations. The restraint system for the SSFTS workstation will be designed on the basis of the evaluations of operator performance during the shuttle test flights.

The FTS hand controllers are Martin Marietta/Kraft six-DOF, force-reflecting hand controllers, as illustrated in Figure 5. The FTS design is predicated on a mature design that has been in use in nuclear and undersea applications since 1980 and is the leading force-reflecting hand controller in use today. Among the improvements for FTS are shifting the wrist joints to a coincident point of rotation and adding force feedback to the wrist

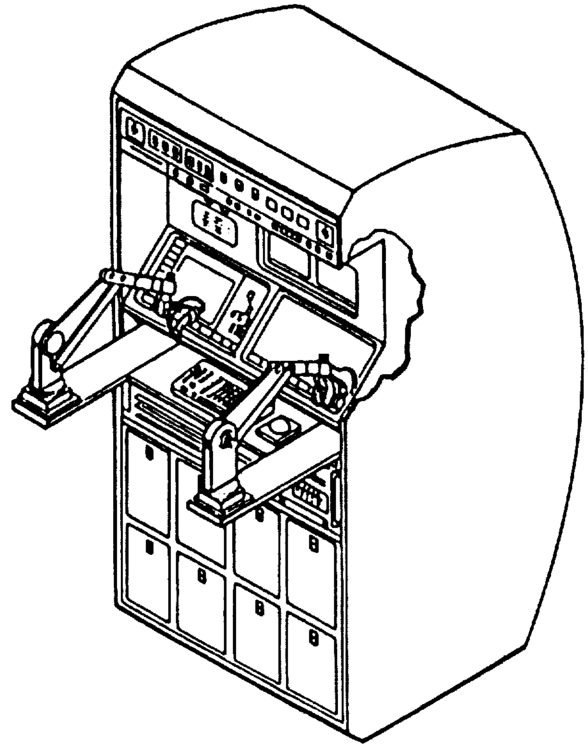

Figure 4. Space Station Freedom FTS Workstation

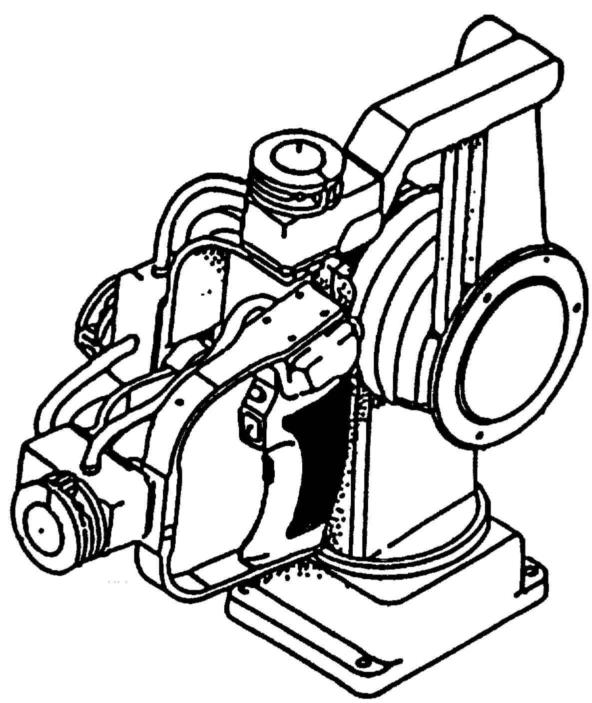

Figure 5. Six-Degree-of-Freedom Hand Controller

roll. The hand controller developed and tested on DTF-1 will be the basic approach for all FTS missions.

The FTS hand controllers are easy to use, because they support an intuitive relationship between the operator's shoulder, elbow, and wrist movements and those translated to the manipulator. They can be used for both position and rate control. Because of the force reflection requirements, the FTS hand controllers themselves are robots having actuators and sensors, and they are tightly coupled to the FTS control system. The FTS operator will use voice commands to control the cameras, so that he does not have to let go of the hand controllers while he is working. Switches on the hand controllers are used to enable any potentially hazardous activity, such as changing end effectors.

Vision Subsystem

The SSFTS Vision Subsystem consists of color cameras, lighting, and video switches. There is one camera on each manipulator wrist, with positioning provided by the manipulator. Two head cameras are mounted on Camera Positioning Assemblies (CPA) for global viewing. Also, the ASPS is scarred for the later addition of a camera for use in autonomous docking. Focus, aperture, head camera positioning, and light are all controlled by the vision subsystem. All cameras are color, using charged coupled devices (CCD). Each light will have the capability of providing up to 100 foot-candles of illumination. The four video channels are routed through a 6 by 4 video switch to either analog-to-digital (A/D) converters for the radio frequency (RF) link or an umbilical for transmission to the SSF C&T video processors. The C&T video processors select and process the signals to be displayed on the workstation monitors. For the early flights, when the SSFTS is operating from STS, the four channels will be transmitted via umbilical to a 5 by 3 video switch in the payload bay. Three of the four channels can be selected for display at the STS workstation.

Communications Subsystem

The Communications Subsystem (COMS) provides the two-way RF communication link between the telerobot and the workstation, and the one-way RF EVA safing link between the EVA astronaut and the telerobot. The communication links provide command data from the workstation to the telerobot, and telemetry data, and video from the telerobot to the workstation.

The COMS consists of a Ku-band Video/Telemetry/Command data transceiver and the EVA safety shutdown functions of a Ku-band EVA safety shutdown transmitter and EVA safety receiver.

The COMS is a Ku-band transceiver and is compatible with the SSF C&T system. The COMS modulates and transmits telerobot video data (up to four video channels) and telerobot health and status data on two Ku-band carriers. These carriers are received and processed by the SSF C&T. Likewise, the COMS receives and demodulates telerobot command and control data that is transmitted from the space station C&T.

The COMS also receives power-up command and control, and transmits status and health when queried, from within the telerobot storage accommodations on space station.

The COMS module houses the baseband modulator microwave transmitter and command demodulator and provides all necessary interfacing to the computers and power system. The COMS amplifies and transmits the digitized video and telemetry data on two carriers at 14.63 and 14.67 GHz, respectively. The EVA safety receiver also operates at Ku-band, but its operating frequency has not been determined.

The antenna assembly consists of one Ku-band circularly polarized omnidirectional antenna. Two antenna assemblies are mounted on the telerobot, one located on the top and the other on the bottom of the telerobot. The Ku-band antenna is approximately 0.7 in. in diameter and 0.5 in. high and sits on an extendable boom that can be retracted for telerobot stowage.

The EVA safety shutdown transmitter is on the EVA suit. Each EVA safety shutdown transmitter will be activated by a simple switch. To satisfy the fail-safe requirement, the transmitter will transmit a "heartbeat" version of the safety shutdown code when safety shutdown is not activated to indicate a healthy transmitter.

Power and Electrical Subsystems

The Power/Electrical subsystem receives power from the SSF or NSTS and provides conversion, regulation, and distribution of power for telerobot use. An independent power capability is provided by an internal battery for detached telerobot operation, to provide uninterruptible power to safety critical loads and to maintain keep-alive power for critical telerobot memory. Load control and circuit protection for FTS loads and interfaces are also provided by the Power/Electrical Subsystem.

The Power/Electrical Subsystem interfaces with NSTS power at 28 Vdc and SSF power at 120 Vdc. The 120-Vdc power from the SSF is conditioned (with a 120- to 28-Vdc converter) to provide a common 28-Vdc "Main Bus" voltage for distribution at 22 to 32 Vdc within the telerobot. The Battery Module Unit consists of three NASA standard 20 Ah batteries and a dedicated charger. The batteries are sized to support 2 hr of telerobot detached operations.

Thermal Control Subsystem

The SSFTS is required to operate under all environments for indefinite task durations while working on the NSTS and SSF. The SSFTS thermal design meets this requirement with an approach that is fundamentally passive, relying on selected coatings, special shielding, and carefully chosen equipment placements and mountings. It is augmented with controlled electrical heaters on selected components to compensate for varying power dissipation levels.

The exterior surfaces of the SSFTS are used to balance external heat loads against heat loss to space and thus maintain required temperature levels and to reduce sensitivity to orbital and orientation environmental variations. Internally mounted equipment boxes and interior surfaces are generally coated with a flat absorber (black) type coating for interior group component temperature control.

Workstation equipment are located in the pressurized compartments with the crew. This equipment is maintained within their allowable temperature limits by air cooling in the STS aft flight deck or Freedom Station node.

Control Algorithms

The FTS control algorithms support all the telerobot operations in both teleoperated and autonomous modes. They also support bilateral force reflection, which enables the operator to experience the forces and torques sensed by the force/torque sensor at the tool plate of the manipulators. Bilateral force reflection has a number of advantages for teleoperation. It improves safety by giving the operator immediate confirmation that the manipulator has come in contact with another object. It reduces training time and eliminates errors by giving the operator a more natural feel for the operations and the environment.

But force reflection comes with a price, which is the low data latency requirement which must be satisfied by the data system on the space station. For force reflection to be useful, it requires a minimum around-the-loop control rate of 50 Hz. This means that all the control computations and the data transfer from the hand controllers to the manipulators and from the manipulators back to the hand controllers must be accomplished in 20 ms. Half of this 20 ms is allocated to data transmission, which means that the control calculations must be completed in 10 ms under all operating conditions.

Initial tests using coded algorithms in machines of equivalent speed to the flight computers indicates that the 10 ms is achievable with some margin. The biggest uncertainty is whether the space station Data Management System (DMS) will be capable of meeting the FTS data latency requirement, considering the amount of traffic on the DMS bus. Consideration is being given to a dedicated bus for the FTS in the event that the common bus cannot meet the requirement. Such action has been taken with the space station Guidance, Navigation, and Control System, which also has stringent time delay requirements.

The control algorithms provide a number of features that make the FTS a safe and useful tool for the astronauts. The operator will have the capability of selecting and defining coordinate reference frames, and he will be able to perform dual-arm coordinated control of a grasped object with a single hand controller. The control algorithms are also capable of shared control in which the operator controls motion in one or more coordinate axes, and the telerobot autonomously controls the motion in the other axes. The algorithms provide a smooth, safe transfer between autonomous and teleoperation control. They also ensure that manipulator singularities can be driven through and that joint stops can be reached and recovered from. There are backup methods of control being investigated, so that the operator will be able to reconfigure the FTS for safe transport in the event of a failure of the primary system.

OPERATIONS SUPPORT

Although the hands-on operation of the FTS will be by the astronauts on orbit, there are a number of activities that will be conducted on the ground in support of the on-orbit operations. A number of these operations look to the future by developing new task scenarios as new jobs are identified for the FTS and by developing new hardware and software for the future growth and evolution of the FTS. Still other operations are involved in the logistics and maintenance functions necessary to sustain a system for the duration of the Freedom Station design life of 30 years. Finally, there are the normal engineering ground operations that involve the collection and monitoring of data and the generation of the appropriate commands and software loads. A number of facilities, equipment and approaches are being developed to accomplish these activities.

Task Analysis

The GSFC Mission Utilization Team (MUT) has evaluated potential FTS assembly, maintenance, and servicing tasks through the use of the Task Analysis Methodology Document developed by the team [5]. The output for each task is an operational script that isolates individual task activities of the FTS, the RMS, the Astronaut Positioning System (APS) and the Mobile Servicing Centre (MSC). In addition, the stability/resource attachment points for the FTS ASPS and handhold locations are defined. Reach capabilities are assessed either through use of Computer Aided Design (CAD) video models or small-scale physical models with the proper kinematics.

This process has identified tasks that contribute to the assembly of Space Station Freedom and reduce the amount of crew EVA time. One of the potential tasks currently under investigation is the installation of resource pallets by using the FTS. These are the large, tablelike structures that attach to the nodes of a truss bay and support elements of the various space station systems, such as the Guidance, Navigation, and Control System.

The operational approach is to perform FTS tasks before EVA during a 3-hr period when the astronauts are preparing for the EVA. The task analysis must be sensitive to the operational flow; e.g., a truss must be built prior to the installation of a pallet by the FTS. Initial studies have the FTS working independently from the astronauts.

Figure 6 shows the FTS attached to the APS during installation of a typical pallet. The RMS has located the pallet so that the four legs are in the vicinity of their respective attachment points at the truss nodes. The FTS softdocks the pallet to the truss while stabilizing with one manipulator system to a truss node. After performing the leg attachment, the APS moves the FTS to each leg in turn. For those pallets where the fourth attachment is outside the APS/FTS reach, the RMS releases the pallet (which is still held at three attach points), attaches to the FTS grapple, and transports the FTS to the final attachment location. The FTS operates while on the RMS for this operation and for the connection of the pallet utility harness to the space station utility tray. Local stabilization is achieved by attachment of one manipulator to the truss, pallet, or utility tray as required.

Facilities and Equipment

There will be a number of facilities at the GSFC and the Johnson Space Center (JSC) to support the on-orbit operations, maintenance, and growth of the FTS. Prior to any of the FTS missions extensive crew training will be conducted by the JSC at their facilities. A high-fidelity crew trainer will be installed at JSC for this activity. Also, a telerobot simulator will support crew training. This is a real-time, kinematic simulation of the telerobot. It will exercise all the workstation interfaces, taking hand controller inputs and driving all the functions in the workstation except force reflection. System kinematic information will be available for display, including graphic representations of all telerobot camera views.

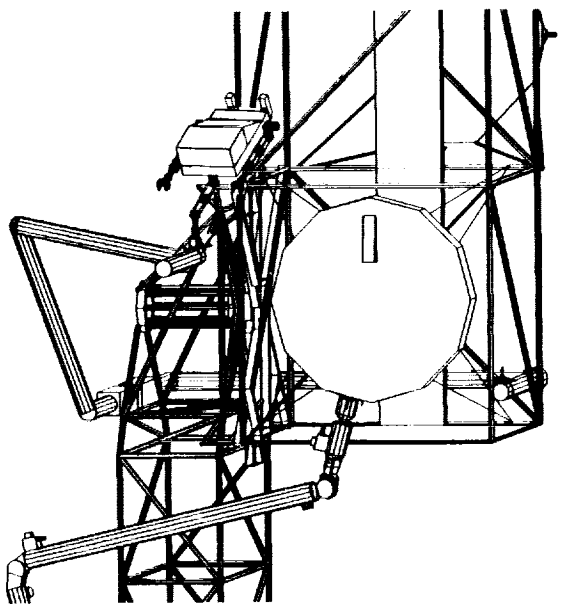

Figure 6. FTS Attached to Astronaut Positioning System

Full-scale kinematic mockups of the telerobot will be available for testing in the JSC Weightless Environment Test Facility (WETF). These will be passive mockups that will be used to verify EVA interfaces and handling, such as manual release of the attachment mechanism, restowing and transporting back through the space station hatch for repair. There will also be light-weight mockups for use on the JSC Manipulator Development Facility (MDF) to exercise the interfaces and operation with the RMS.

When DTF-2 is returned from its mission it will be refurbished to become a ground-based version of the FTS, called the Engineering Test System (ETS). The ETS is a functional duplicate of the SSFTS, the space station workstation, and the storage accommodations. The ETS will be housed at GSFC in the new Spacecraft Systems Development and Integration Facility (SSDIF). The ETS will serve as a high-fidelity testbed for the development and testing of flight hardware and software. It will also be used to support on-orbit anomaly investigation.

The primary facility for monitoring the FTS operations and for the analysis, archiving, and trending of data will be the Engineering Support Center (ESC) at GSFC. The FTS will share part of the Work Package 3 ESC and will provide its own workstations and support computers as needed. Commands and software loads will be generated in the ESC and transmitted to the space station control center (SSCC) at JSC for relay to FTS. Similarly the downlink data comes to the ESC through the SSCC.

There will be a software development facility (SDF) at GSFC for the maintenance of the flight software and for the generation of new code as new capabilities and new hardware come on line and as new task scenarios are developed.

The present GSFC robotics laboratory or Development, Integration, and Test Facility (DITFAC), as it is officially known, will support the FTS operations as an advanced development testbed. Candidate hardware for future addition to the FTS will be tested and evaluated in the DITFAC before being selected for implementation. Such activities as tool development and evaluation and task element design and test will be conducted here. Currently the laboratory is involved in a number of activities in support of the FTS development, including the evaluation of hand controllers, Orbital Replaceable Units (ORUs), task scenarios, camera locations, and workstation designs.

It is necessary that all of these ground support facilities be interconnected with voice, video, and data links so that the operations support can be properly coordinated and managed. Work is currently underway to determine the requirements for these communications links.

CONCLUSION

The FTS project is ready to start the detailed design and implementation phase, confident of the results of the phase B preliminary design work and the considerable effort by Martin Marietta in preparation for the DTF-1 preliminary design review. The FTS promises to be a safe, reliable, and useful tool for the astronauts on both the space shuttle and S.S. Freedom. The program's success is promoted by the cooperation we are receiving from the JSC for system interfaces, human-machine interfaces, and crew training, and the program office in Reston, Virginia, for the overall guidance, the allocation of resources and the establishment of stationwide interfaces.

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