THE SERVICING AID TOOL:
A TELEOPERATED ROBOTICS SYSTEM FOR SPACE APPLICATIONS

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ABSTRACT

The Servicing Aid Tool (SAT) is a teleoperated, force-reflecting manipulation system designed for use on NASA's Space Shuttle. The system will assist Extravehicular Activity (EVA) servicing of spacecraft such as the Hubble Space Telescope. The SAT stands out from other robotics development programs in that special attention has been given to provide a low-cost, space-qualified design which can easily and inexpensively be reconfigured and/or enhanced through the addition of existing NASA funded technology as that technology matures. SAT components are spaceflight adaptations of existing ground-based designs from Robotics Research Corporation (RRC), the leading supplier of robotics systems to the NASA and university research community in the United States. Fairchild Space is the prime contractor and provides the control electronics, safety system, system integration and qualification testing. The manipulator consists of a 6-DOF Slave Arm mounted on a 1-DOF Positioning Link in the shuttle payload bay. The Slave Arm is controlled via a highly similar, 6-DOF, force-reflecting Master Arm from Schilling Development, Inc. This work is being performed under contract to the Goddard Space Flight Center Code, Code 442, Hubble Space Telescope Flight Systems and Servicing Project.

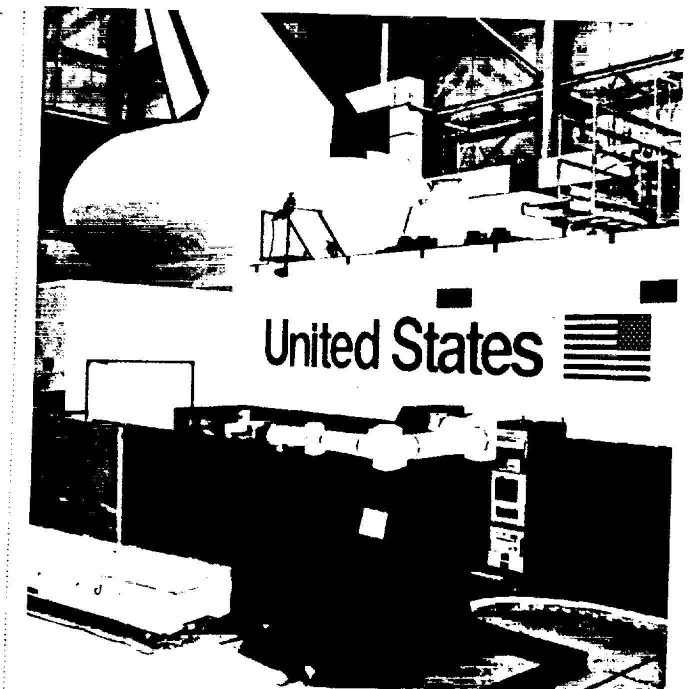
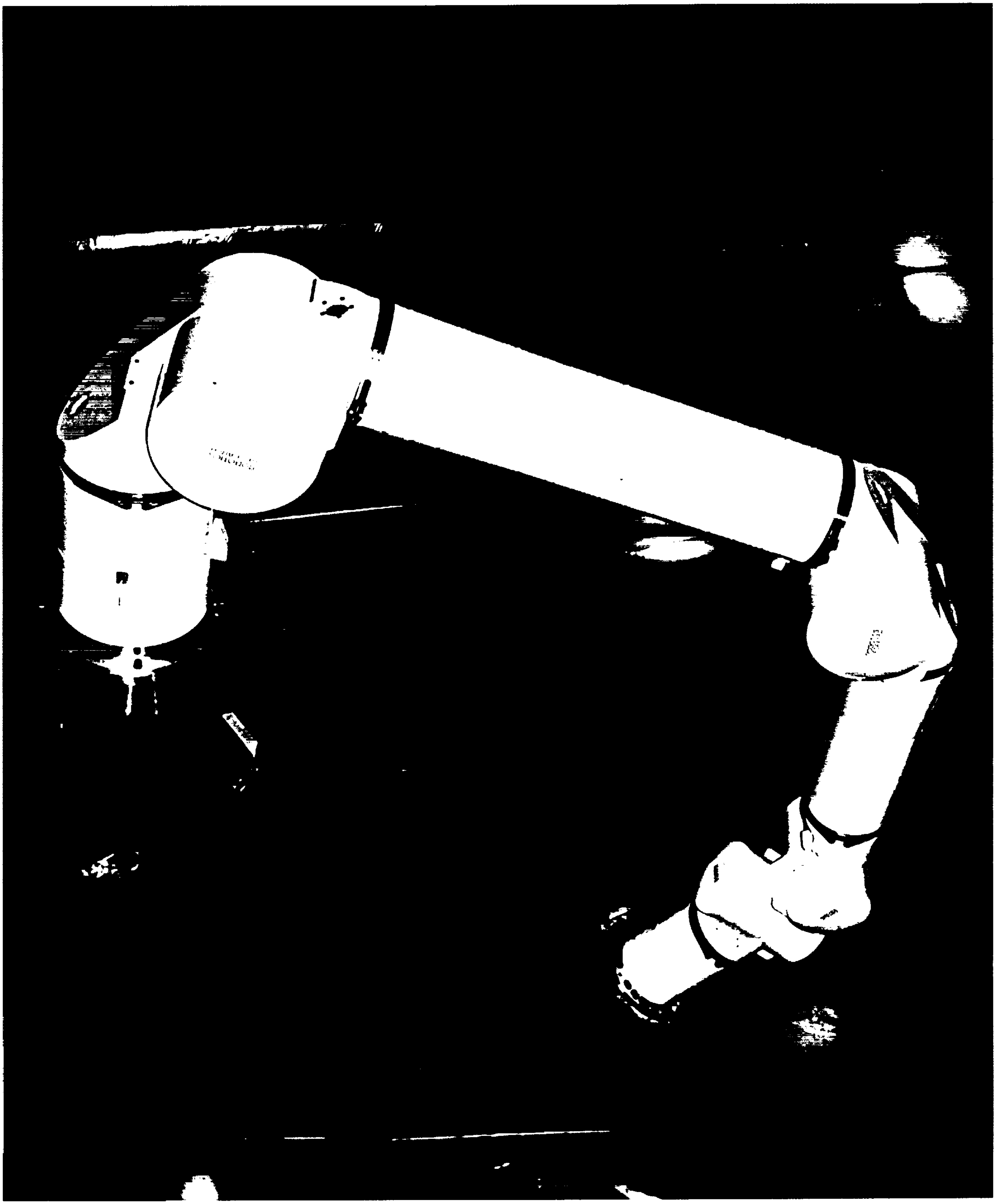


Figure 1. SAT Slave Arm at the GSFC

INTRODUCTION

In 1989, the Goddard Space Flight Center (GSFC) released a RFP for a low-cost, flight-capable, teleoperated robot system which could support 1G testing and training, and significantly improve on-orbit servicing of spacecraft. The subject robotics development program has been based on adaptations of existing robotics and military hardware, compatibility with existing and proven GSFC avionics used on the shuttle, slave arms directly descendant from the majority of robotics technology development platforms used throughout NASA and the universities, and designed ready to incorporate additional operational and controls features as may be required.



The SAT stands out from other robotics arms in the flexibility of its design to conform and adapt to changing needs with relatively little expense in doing so. Varying mission requirements and uncertain final requirements for safety compliance (anyone familiar with the safety review process knows that many failure mechanisms and corrective action requirements are not identified until the latter stages of the safety review process—not the Phase 0 or 1 levels) have received due consideration in the construction of the SAT. The SAT arm mechanism, shown in Figures 1 and 2, is composed of a series of self-contained joint drive modules joined by quick-disconnect band clamps Thus, it would be easy to re-configure the system to suit different user needs and applications. For instance, the current SAT Slave Arm has an 85 inch reach (shoulder centroid to toolplate). If determined to be advantageous for some particular flight application, the arm could be reduced to 60 inches in reach— or 48 inches or whatever dimension was appropriate— simply by shortening the hollow tubes which make up the forearm and upper arm segments. Alternatively, an additional joint could be added into one of these hollow tubes to provide increased dexterity as discussed latter in this paper.

Furthermore, the control computer has a substantial amount of growth capacity. Of 15 slots in the multibus chassis assembly, only 8 are currently used. Less than 10% of the bus bandwidth, and only 60% of the computational capacity is currently being utilized. Likewise, the companion electronics assembly to the control computer also has plenty of spare connector ports, relays, and power distribution to provide expansion.

Since the SAT is an operational 1G system it is the ideal candidate for technology transfer. Since their introduction in 1987, seven degree-of-freedom, position/force-controlled manipulators designed and manufactured by Robotics Research Corporation have served as the standard development platform across the NASA community for work in dexterous manipulation and space telerobotics. Users include the telerobotics laboratories at the Jet Propulsion Laboratory, Johnson Space Flight Center, Langley Research Center, Goddard Space Flight Center, the National Institute of Standards and Technology, Lockheed Engineering & Sciences Company, Lockheed Missiles & Space Company, Grumman Space & Electronics Group, Space Systems/ Loral, Fairchild Space & Defense Corporation, the University of Tennessee, Case Western Reserve University and NEC (Japan). As a consequence, a considerable body of advanced control technology compatible with these products, as well as in-depth application and integration experience, now exists.

At least 39 separate research and development projects have been undertaken by researchers in this community to date, 29 of which were conducted at NASA and NIST since 1987 (including 10 current NASA projects) and the remainder at academic institutions and research oriented companies.

New technology developed in these projects include alternative approaches to kinematics for 7-DOF manipulators, high bandwidth force control software using the internal joint torque sensors provided in RRC arms, calibration techniques for redundant arms, evaluations of alternate hand controllers and user interfaces, and architectures for high-level autonomous and supervisory control systems. Applications demonstrated to date include Space Station inspection, Space Station truss assembly, satellite servicing tasks, on-orbit assembly of aero brakes, simulation of spacecraft docking mechanisms and the development of robot-friendly truss fasteners.

Recently, several large U. S. industrial corporations have begun seriously evaluating the use of RRC type manipulators for factory use. In this light, the SAT offers an excellent vehicle by which to implement NASA-funded technology toward improved national competitiveness.

SYSTEM DESCRIPTION

The Servicing Aid Tool (SAT) is designed to allow an Operator to control a teleoperated six degree of freedom Slave Arm using a six degree of freedom, force-reflecting Master Arm. The master and slave arms have highly similar kinematic arrangements, both being configured in the same manner: a roll/pitch shoulder, a pitch elbow, and a pitch/yaw/roll wrist.

This allows use of a joint-to-joint control scheme: a joint on the Slave Arm is commanded by motion of only the corresponding Master Arm joint, and a torque signal is provided to each Master Arm joint as a result of the state of the corresponding Slave joint. Force commands are reflected to each master joint based on the corresponding slave joint torque sensor. The torque sensor also provides feedback for a local analog torque loop which eliminates the effect of friction in the joint.

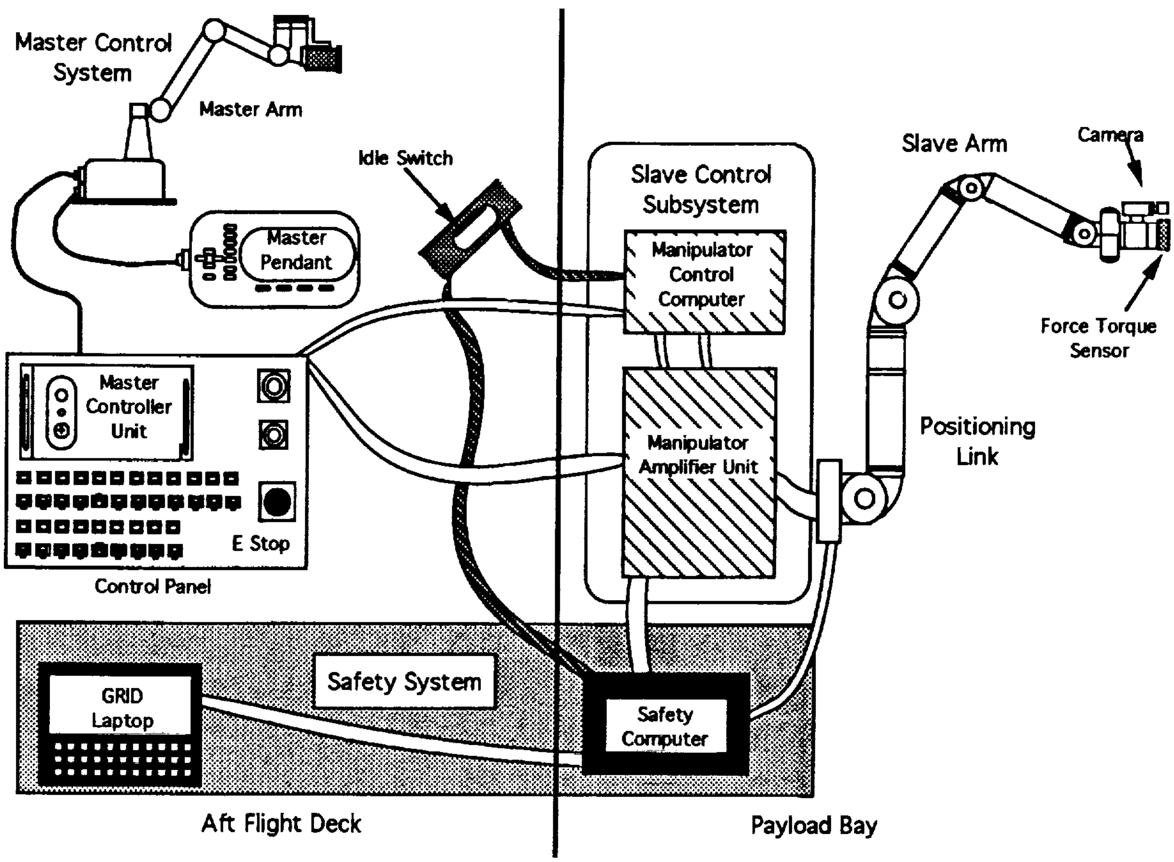


Figure 3 SAT Subsystems

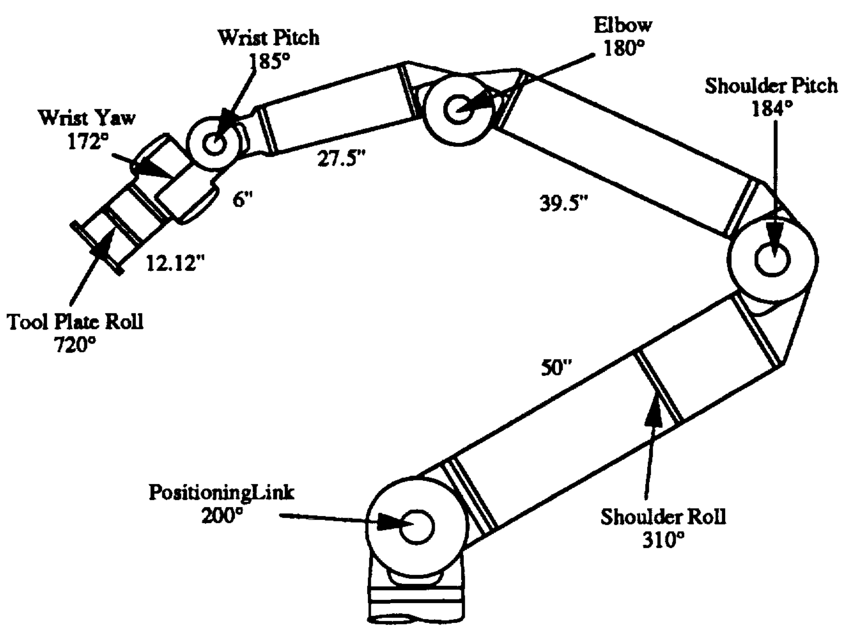


Figure 4. SA/PL Dimensions and Joint Travel

The one degree of freedom Positioning Link is controlled via operator interface keyboard commands, and operates only when the Slave Arm is disabled.

The kinematics are simple, with the three adjacent pitch joints allowing the Operator to mentally separate the position and attitude of the tool: the shoulder and elbow joints provide position; the wrist joints, attitude.

The SAT components (Figure 3) are spaceflight adaptations of existing ground-based designs. The Master Arm is a slightly modified Schilling Development OMEGA from the Titan 7F master/slave system used in undersea systems. The Slave Arm and Positioning Link (SA/PL) are configured to mimic the Schilling Titan 7F Slave Arm kinematics.

To increase the functionality of the SAT, it will be relocatable via the Shuttle Remote Manipulator System (RMS) to various worksite locations where Hot Shoe receptacles are stationed. The hot shoe will provide a releasable electrical and mechanical interface, allowing the SA/PL to be moved to another location, or to be jettisoned in an emergency. A Grapple Fixture will be provided to allow the Shuttle RMS to move the SA/PL. Remote release will be single-fault-tolerant and commanded from the Aft Flight Deck, backup release may also be performed manually via EVA. Inadvertent release will also be two-fault tolerant. The low replacement cost of the slave arm combined with the jettison capability provide a cost-effective means of compliance to the safety requirements for two fault tolerance.

SPACE QUALIFICATION

The SAT components will undergo environmental testing (vibration, thermal/vacuum, and EMI) at protoflight levels. Where necessary, modifications have been made to upgrade designs to protoflight levels. The primary effect has been on the electronics. The RRC Multibus boards in the control computer, for example, had to be replaced with military versions packaged to survive the vibration and thermal environment. A similar version of our protoflight control computer successfully flew on the shuttle for the TSS program. There have also been design changes in the RRC manipulator components to meet outgassing, venting, thermal, and fracture control requirements.

PAYLOAD BAY COMPONENTS

Slave Arm and Positioning Link

The SA/PL dimensions and joint travel are shown in Figure 4. Figure 5 illustrates the layout on the Flight Support System (FSS), a cross-bay carrier intended for supporting large spacecraft. Components in the Payload Bay are listed below.

All Slave Arm joints have brushless DC motors, operating through a 160:1 harmonic drive. The joint output side is connected through a hollow shaft to a resolver, which reads the angle between the two adjacent links, rather than motor driveshaft angle. In like manner, the strain gauges are mounted to read the output torque of the joint, being mounted at the base of the harmonic drive. Both sensors thus measure the true relationship between the input and output sides of the joint, eliminating the effects of friction and any cogging of the harmonic drives.

The travel for each joint is limited, in order, by software limits, limit switches, and hard stops. Passing a limit switch results in removal of power from the motors and brakes, thus engaging the brakes. The brakes may be remotely disengaged from the Aft Flight Deck (AFD) control panel without powering the motors to allow EVA stowing as a backup.

The SAT is designed to demonstrate its capabilities on the ground as well as to perform on orbit. It is capable of lifting a 20 lb mass in a 1-G environment at any pose within its range of joint travel. The design point for the 0-G case is for a 500 lbm payload.

To provide an interface for an exchange mechanism, tool, and camera, the Slave Arm is designed to be compatible with a variety of exchange mechanisms; it will provide power and data for operation of the exchange mechanism, tool, and camera. The exchange mechanism will be two-fault tolerant to ensure the ability to release tools and ORUs and stow the arm. Several mechanisms are currently under evaluation. Tools will be specified as part of the mission integration in a future program phase.

The maximum joint rates are specified so that no single joint runaway can cause a tool plate velocity in excess of 17 inches per second; this value was chosen as typical of RMS maximum rates.

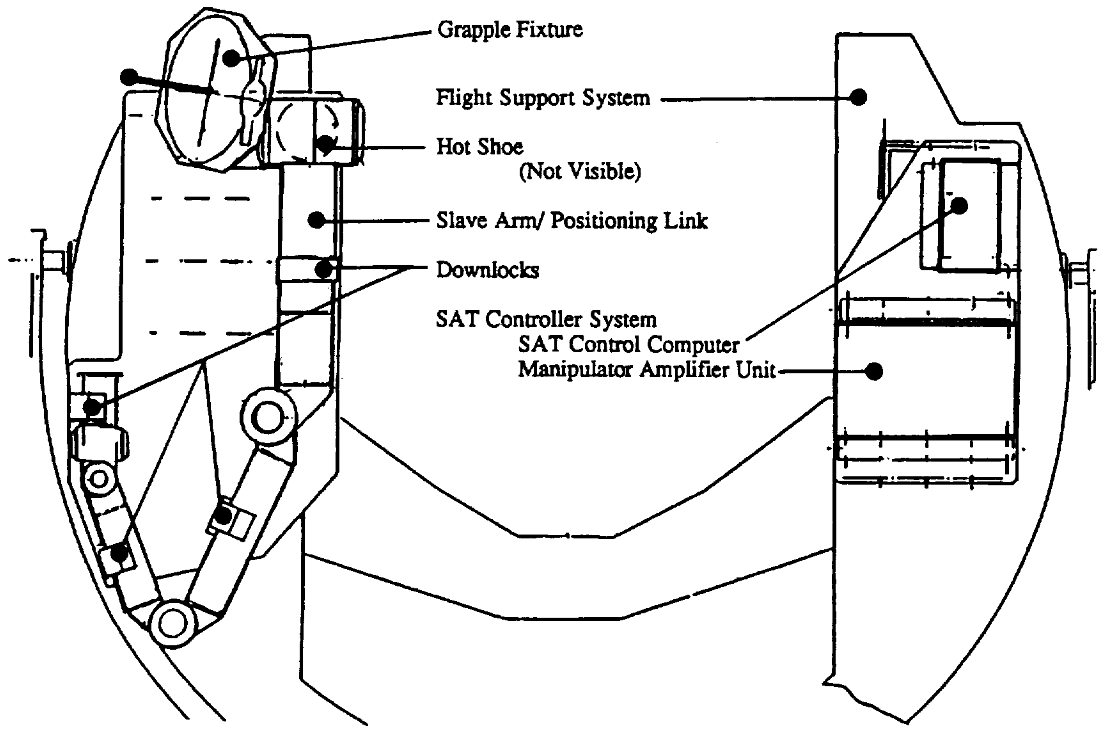
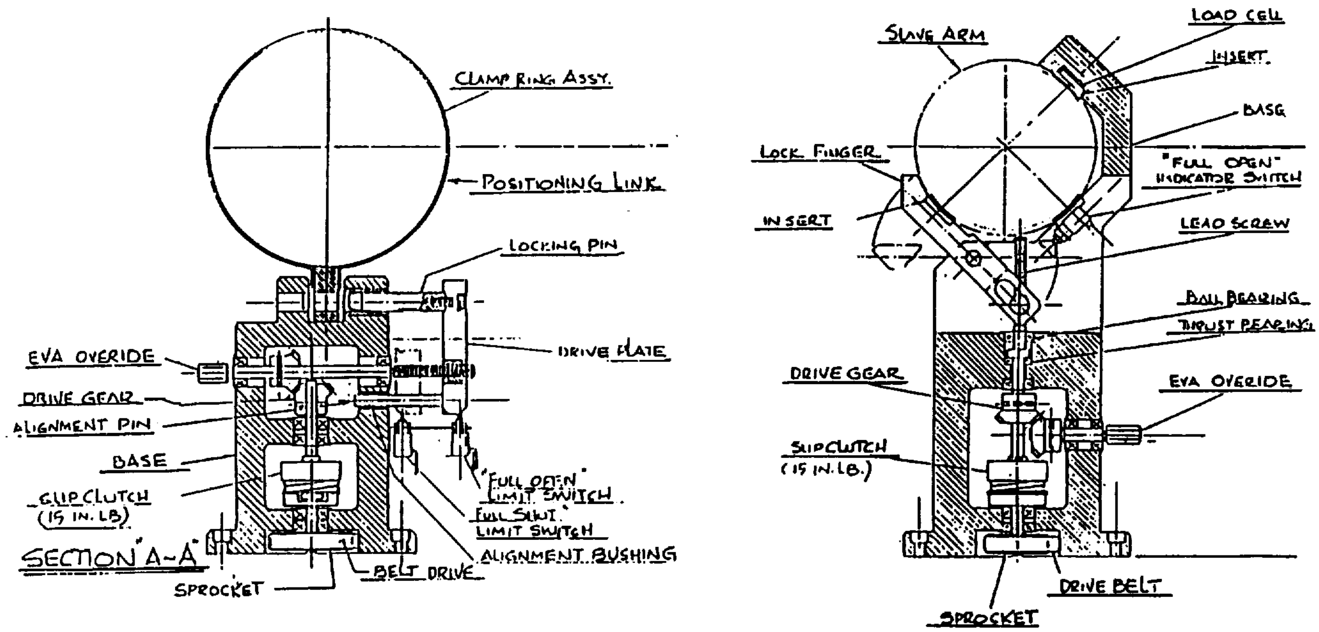


Figure 5. SAT Components Mounted on a Cross-bay Carrier



Positioning Link

Slave Arm (1 of 3)

Figure 6. Prototype Downlocks

Slave Mounting Assembly

The Slave Mounting Assembly is the means by which the SA/PL is mounted to its cross-bay carrier, and includes a Mounting Plate, Downlock Mechanisms, Hot Shoe, and Grapple-Hot Shoe Adapter Plate (GHAP).

The Downlocks secure the SA/PL for launch and landing. There is a downlock for each of the four SA/PL links - three for the SA, one for the PL. Figure 6 depicts the prototype downlock design that is to be used both for demonstration and vibration testing; these will be driven via a power wrench. The protoflight downlocks will be driven by a standard FSS Common Drive Unit, and will incorporate load sensors and limit switches to stop power to the drive unit when sufficient torque is read; slip clutches will limit forces on each SA link. Redundant sensors will be incorporated to reliably indicate that the SA/PL is positioned to allow closing the downlock, and that the SA/PL is positively locked after actuation.

Slave Controller Subsystem

The Slave Controller Subsystem (SCS) provides the interface between the master and slave systems, and the control engine and power for the SA/PL. There are two components, the Manipulator Control Computer (MCC), and the Manipulator Amplifier Unit (MAU). These are mounted on a radiator plate, which is in turn mounted on the cross-bay carrier. Both units will be subjected to the appropriate environmental testing for space qualification.

The MCC contains two 80386 based processors for SA/PL control and Master Arm force command generation and another 80386 for communications with the MCS. Slave arm data acquisition is accomplished via MCC resident A/D, D/A, and R/D (resolver to digital) hardware. The MAU contains the motor amplifiers and an analog torque loop compensator for the SA/PL actuators, and watchdog electronics which check the health of the MCC processor boards and secondary power. There are a total of 8 amplifiers, one of which is a back-up which may be switched to any individual joint for manually-controlled operation of a joint.

The system is equipped with an Emergency Stop Current Loop which, when broken, will cause the Slave Arm and Positioning Link to become disabled. The Emergency Stop Current Loop can be broken by Operator action, software command or hardware command. The current loop nodes are shown in Figure 7. Each node is actually a current pass-through which can be broken by the shown input.

AFT FLIGHT DECK COMPONENTS

Master Controller Subsystem

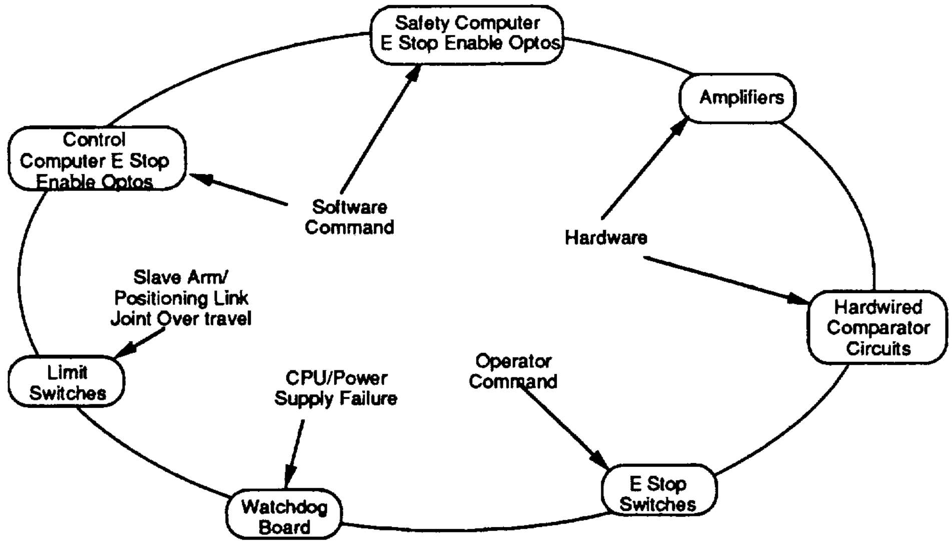
The Master Controller Subsystem consists of the modified Schilling components (Figure 8)- Master Arm with a reach of 16 inches, Master Pendant, and Master Control Unit. The Master Arm and pendant are mounted on the master Mounting Assembly; The MCU is inserted into the Control Panel. The MCS components are stowed in a mid-deck locker for launch and landing, packed in a foam material for protection from the loads.

Control Panel and Master Mounting Assembly

The MCS and Control Panel provide the Operator complete control of the system. The Control Panel, mounted in the L11 panel (Figure 8) has control switches for the SA and PL power enables; an Emergency Stop (E-Stop) button, which cuts power to the joint actuators and engages the brakes; and joint brake and limit switch overrides. The latter, in conjunction with controls for a backup single-joint means of operation, allow recovery from some fault conditions which would otherwise cause the Slave Arm to "freeze," preventing stowing.

The L11 panel also provides connections for the Idle Switch, incorporated into a mounting bar attached in the vicinity of the control panel. The Idle Switch is placed so that it provides a stabilizing grasp point for the Operator to react against the Master Arm torques (additional stabilization will be provided by foot straps on the AFD floor). The bar is positioned to allow view of the AFD monitors, as well as a view out the AFD windows, and is designed to allow mounting the master operator interface as well as other tool controls within easy reach of the operator.

In order for the Slave Arm to move, the Operator must depress the Idle Switch on the mounting bar. Releasing the Idle Switch while Slave Arm or Positioning Link motion is being commanded will cause the Slave Arm to decelerate and stop. Motors are not disabled but master and Slave Arm joints are servoed to their current



The Emergency Stop Current Loop is a continous current loop, which when interrupted causes the slave arm and positioning link to become disabled. The current loop can be interrupted by any of the nodes in the current loop.

Figure 7. Emergency Stop Current Loop Nodes

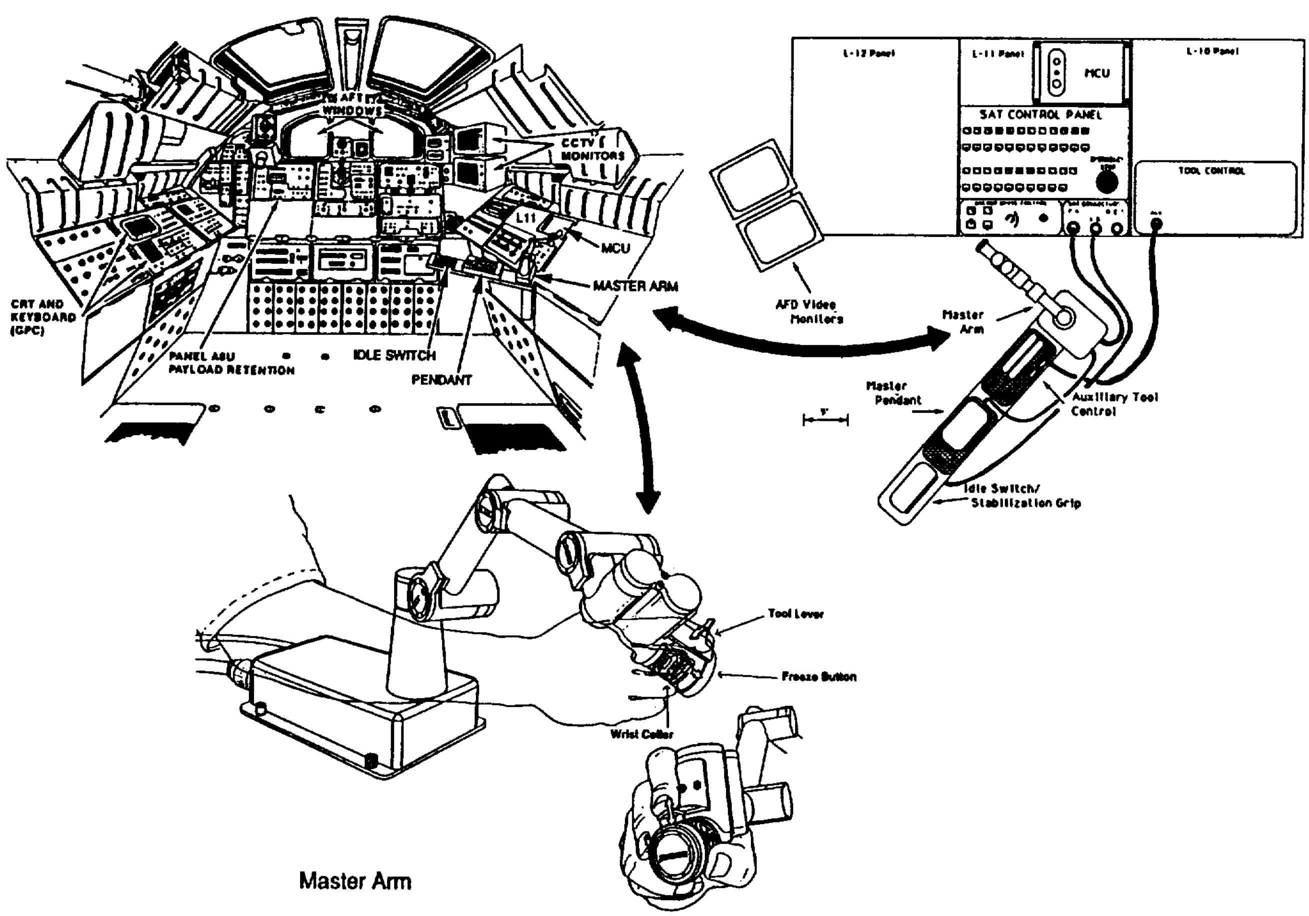


Figure 8. Aft Flight Deck Installation

position. The master and slave arms will maintain their position until the Idle Switch is pressed and the arm is commanded to move again.

SAFETY ANALYSES AND CONTROLS

In December 1991, a Technical Interchange Meeting was held with the JSC Payload Safety Review Panel (PSRP). Following some design changes a Phase 0 Safety Review was held in June 1992. The June review was intended to be a Phase 0/1 review of the SAT protoflight hardware and the level of detail for this hardware was commensurate to the Phase 1 level. However, the PSRP argued that since the tasks and ancillary tools not under contract were not well defined, the review would only count as a Phase 0. Following the review, the PSRP chairman commended the technical approach, and proclaimed that we were exceptionally forthcoming with possible fault mechanisms and creative solutions as inhibits.

A Structural Assessment and Hazard Analysis was performed for the SAT to ensure that neither normal operation nor dual failures could result in hazards to the Orbiter, crew, or other critical hardware. To perform these analyses, each subsystem was initially reviewed for its potential to create hazardous functions or effects. The review considered the subsystem design, materials, functions, and interfaces to other subsystems. This section describes the various hazard groups that were considered and the controls against them.

Aft Flight Deck Hazards

The fault tree analysis identified hazard causes within the aft flight deck since the Master Arm and the control panel are used there to operate the system. The Master Arm and control panel used on the aft flight deck can pose hazards to the crew. A mechanical hazard would be uncontrolled motion of the Master Arm; however, as the Master Arm is capable of exerting a maximum of only two pounds force, any injury would be minor.

EVA Hazards

The SAT is not presently planned to be powered during EVA operations. There are also no procedures that require astronaut intervention to return the payload bay to a safe condition except as a third control (inhibit) to removing the SAT from the bay in the event of a non-operating SAT failure where the SAT obstructs the bay doors or is failed in a position unsafe for landing.

Inability to Stow the SA/PL

If the SAT fails such that it cannot be commanded to its stow position, it could prevent closing the Payload Bay doors, or be unable to withstand the forces of re-entry and landing. In this case, the first option is to use the single-joint backup drive. The second is to disengage the joint brakes to allow an EVA crewmember to manually stow the SA/PL. This can be commanded by overrides available at the Control Panel. These cause power to be applied to the brakes but not to the actuators. An EVA crew member can then manually drive the SA/PL into the downlocks, while the override switches are held down by the Operator. The brakes and downlocks may then be engaged from the Control Panel.

If this proves to be impossible in the available time, the SA/PL may be jettisoned via command from the AFD to release the Hot Shoe. Depending on the Hot Shoe design chosen, jettison may be self-actuated, or may require the RMS to bring the SA/PL out of the Payload Bay. Remote release of the Hot Shoe will be redundant, the Hot Shoe will also provide for release via EVA should remote release fail.

Impact During Operation

Unplanned impacts during operation could cause damage to the orbiter, payloads, or SAT. Such impacts could be caused by failure of the SAT control system, sensors, or actuators; or by Operator error. The SAT system incorporates inhibits against such failures.

The maximum single-joint runaway rates produced by SAT are specified to minimize the possibility of damage to the Orbiter or payloads, and are comparable to those produced by the RMS; they are not optimized for a particular mission. Furthermore, Operator-adjustable limits are incorporated in software in the SCS, commandable via the master operator interface.

If the Operator suspects abnormal operation, he will first release the Idle Switch, which will result in a controlled stop for most faults. The Operator and/or the Monitor may also hit their respective E-Stops, which will shut down all power to the SA/PL, engaging the brakes.

Safety System

The SAT will also have a Safety Computer nearly identical to the MCC. It will monitor SAT's performance and shut down the system in the event certain parameters (Torque, joint rate, etc.) are exceeded. Some of these tests are redundant with those internal to the control computer. The Safety Computer interfaces directly to the Slave Arm analog feedback and control signals, rather than relying on data processes by the Control Computer; this reduces the chance that a computer fault might mask a fault elsewhere in the system. Additional features being considered include:

- Use of a toolplate force/torque sensor
- Incorporation of proximity sensors distributed along the SA/PL.
- World models of the Orbiter and Payload Bay to establish stay-out zones and automatic reduction in torques and rates when in proximity operations.

The SAT also incorporates independent hardwired adjustable limit-setting hardware. During operation, this hardware operates independent of all system computers, so is not susceptible to any computer faults. When any pre-set limit is exceeded, the SA/PL is disabled.

After operation has been completed the Slave Arm can be disabled by entering a disable command via the operator interface. The Slave Arm can also be disabled using the Emergency Stop Switch, however, it is primarily intended to be used when a quick shutdown is required.

SYSTEM OPERATING MODES

The SAT software operates in the following modes, which are commandable by the Operator via the master operator interface in the aft flight deck.

System Mode

The software enters the System mode when powered up, and it may be re-entered by command from the master operator interface, or by an E-Stop commanded by an Operator or by safety software. This mode allows health checks to be performed, and is the only mode that allows parameter updates. No SA/PL motion can occur, as it is unpowered, with brakes engaged.

Idle Mode

The Master and Slave Arms servo to current positions, with brakes disengaged; no commanded motion is possible. This mode is first entered when commanded from the System Mode. The other modes may then be commanded, but will not be entered until the Idle Switch is depressed. It is re-entered when the Idle Switch is released.

Teleoperation Mode

This is, of course, the mode in which most of SAT's work will be done. The Slave Arm responds to commands from the Master Arm. On transition into and out of this mode, both master and slave torques are ramped up and down to prevent step inputs to the worksite and to the operator. Scaled (slave rate less than master rate) or unscaled motion may be chosen via the operator interface. Indexed operation may be initiated by releasing the Idle Switch, moving the Master Arm to a new reference position, and then re-gripping the Idle Switch. These features have been found useful for fine control in proximity to or in contact with the worksite, and provide a flexible means of matching the Slave Arm to the Operator and to the needed task.

Automated Task Mode

A limited number of automated moves will be possible, and are commanded by keyboard input to the Operator interface. These operations still require the Idle switch to be depressed for motion to occur.

- Auto Stow/Unstow -
  SA/PL commanded into and out of the downlocks
- Master to Slave Align -
  Master assumes current pose of Slave Arm
- Slave to Master Align -
  Slave assumes current pose of Master Arm
- Slave to Commanded Position -
  Joint angle values input via operator interface
- Positioning Link is always commanded via Operator interface

Backup Single-Joint Mode

In addition to the above modes, which all require software, there is a backup Single-Joint Drive mode available, which is commanded completely via the control panel. A rotary switch is used to choose which joint is to be driven by a separate servo amplifier; another switch controls direction, and a knob the rate.

Powerup and Shutdown Operation

The MCS is powered up via the MCS Power Switch. After the MCS has initialized itself (as indicated on the MCS operator interface screen) the SCS, SA and PL can be powered up. The SCS, Slave Arm and Positioning Link are powered via the appropriate Control Panel power switches.

After the SCS has been powered it performs a self test and checks the status of the Slave Arm and Positioning Link. It communicates all status information to the operator interface. If everything passes, the Operator must verify all operational parameters. Among the status information checked are joint torque, position, temperature and limit switch status.

After all parameters have been verified, the Slave Arm can be enabled. To accomplish this, first the Emergency Stop System must be activated by pressing the Enable E Stop Switch. Next, the Slave Arm can be enabled by entering an enable command via the operator interface then pressing the enable switch on the Control Panel.

After operation has been completed the Slave Arm can be disabled by entering a disable command via the operator interface. The Slave Arm can also be disabled using the Emergency Stop Switch, however, it is primarily intended to be used when a quick shutdown is required. Note that the Idle Switch stops motion, but does not disable the arm.

POTENTIAL ENHANCEMENTS USING EXISTING TECHNOLOGY

Since the flight-qualified Servicing Aid Tool (SAT) mechanism and its control system are functionally identical to NASA's RRC laboratory units, many of the technologies that have been developed by NASA can be applied directly to the SAT to increase its capabilities for satellite servicing with minimum risk and expense. Five specific enhancements being considered are listed, as follows, in proposed order of implementation:

1. Addition of a High-Level Telerobotic Control System

One of several available versions of a high-level telerobotic control system (JSC, GSFC, JPL) could be implemented on new computer boards added to the existing SAT control system to provide programmable operation, 6-DOF kinematic cartesian control (i.e., the ability to command straight line moves) and a more powerful user interface. Space for such additional boards is already provided in the current SAT control hardware arrangement.

2. Addition and Evaluation of Alternative Hand Controllers

The Schilling replica master force-reflecting hand controller currently used in the SAT system is but one of several alternatives available. With the implementation of the above-described high-level controller and 6-DOF kinematics, two other types of hand controls which could offer advantages in certain SAT operations and may be preferred by the astronaut users can easily be interfaced and compared. Specifically, it is felt that a pair of standard 3-DOF rate controllers should be tried (as used to operate the RMS today), along with a 6-DOF hybrid rate/force controller from Cybernet Systems. Both types of hand controller have already been procured by NASA and could be made available. In general, it is anticipated that the ability to perform straight line moves with a rate controller—essentially to "fly the hand" of the SAT—will greatly simplify certain teleoperated tasks like extracting ORUs.

3. Addition of Impedance Control Software

Implementing existing impedance control software on the SAT will give the operator the ability to regulate electronically the apparent stiffness of the manipulator arm as it executes a contact operation. Essentially, this feature will permit the manipulator to control the forces and moments it exerts when mating two rigid parts (as in ORU insertion). Impedance control is particularly advantageous when using a rate controller to perform contact operations, since tool/workpiece reaction forces can be controlled (and limited) with great accuracy.

4. Addition of 6+1-DOF Kinematics

A 7-jointed manipulator arm affords an infinite number of arm postures for any given position and orientation of the tool (and the payload). Like the human arm, it can thus work around objects in the work space without collisions, providing significantly more capability to perform complicated manipulation tasks in cluttered environments. The current SAT slave arm has six degrees of freedom (one joint is also provided on the positioner link that supports the slave arm). To increase dexterity, it is recommended that a seventh joint be added to the slave arm (an "elbow roll" joint), giving the operator the ability to change the elbow orientation, as a separately controlled joint, during operations. This new seventh joint would only be used, in this case, for arm reconfiguration and would not be active during the execution of tool-handling tasks. Once the operator has selected a preferred elbow posture, the slave arm would be controlled as a 6-DOF system.

5. Addition of Redundant 7-DOF Kinematics

With no further changes to the 6+1-DOF slave arm mechanism beyond those described above, more powerful redundant control software could be added to the SAT system if a prospective servicing application demands the enhanced capabilities afforded by active redundancy. Benefits include proximity sensor-driven, reflexive collision avoidance, by which the arm automatically changes its posture to avoid collisions with objects in the workspace, and automatic selection of the optimal arm pose to avoid singularities and improve leverage.

PROGRAM STATUS & CONCLUSION

The protoflight slave arm and controller are currently undergoing verification testing at Robotics Research Corporation. This hardware is due to ship to the GSFC by mid-August. Upon delivery, the master/slave communications software, gravity model, and force feedback software will be ported over to the protoflight controller for integration of the full-up master/slave system. The protoflight system will then proceed to environmental testing expected to be completed around the end of the calendar year. In January 1994, the basic SAT will be qualified for the rigors of space flight.

Future phases of the program are anticipated to continue ground demonstrations and to include the incorporation of selected enhancements. These enhancements will primarily be chosen to best augment the SAT's capabilities to perform a range of servicing tasks directed toward the second Hubble Space Telescope (HST) servicing mission. Current mission analyses for the first servicing mission support the postulate that the SAT will enhance astronaut tasks and timelines. The Servicing Aid Tool will provide a telerobotic complement to significantly enhance extravehicular capabilities.

Reference

Pullen, J. L., et al, "The Servicing Aid Tool," Cooperative Intelligent Robotics in Space III, Boston MA, November 15-20, 1992