THE RANGER TELEROBOTIC SHUTTLE EXPERIMENT: AN ON-ORBIT SATELLITE SERVICER

Joseph C. Parrish
NASA Headquarters Office of Space Science, Advanced Technologies & Mission Studies Division
Mail Code SM, Washington, DC, 20546-0001, U.S.A.
phone: +1 301 405 0291, fax: +1 209 391 9785, e-mail: jparrish@hq.nasa.gov

Abstract

The Ranger Telerobotic Shuttle Experiment (RTSX) is a Space Shuttle-based flight experiment to demonstrate key telerobotic technologies for servicing assets in Earth orbit. The flight system will be teleoperated from onboard the Space Shuttle and from a ground control station at the NASA Johnson Space Center. The robot, along with supporting equipment and task elements, will be located in the Shuttle payload bay. A number of relevant servicing operations will be performed—including extravehicular activity (EVA) worksite setup, orbit replaceable unit (ORU) exchange, and other dexterous tasks. The program is underway toward an anticipated launch date in CY2001, and the hardware and software for the flight article and a neutral buoyancy functional equivalent are transitioning from design to manufacture.

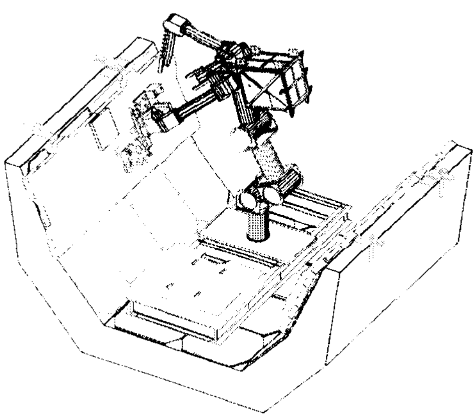

Figure 1: Ranger in Space Shuttle payload bay.

1 Introduction

As space operations enter the 21st century, the role of robotic satellite servicing systems will increase dramatically. Several such systems are currently in development for use on the International Space Station, including the Canadian Mobile Servicing System (MSS)[2] and the Japanese Experiment Module Remote Manipulator System (JEM-RMS). Another Japanese system, the Experimental Test System VII (ETS-VII)[1], has already demonstrated the ability for rendezvous and docking, followed by ORU manipulation under supervisory control. Under development by the United States, the Ranger Telerobotic Shuttle Experiment (RTSX)[3] is progressing toward its mission on the NASA Space Shuttle to demonstrate telerobotic servicing of orbital assets.

The missions envisioned for the Ranger class of servicers are for attached (e.g., to a Space Station) and free-flying (e.g., to a communication satellite in geostationary orbit) operations such as inspection, maintenance, refueling, and orbit adjustment. The approach being taken with the first flight deployment of a Ranger spacecraft is for attached operation on a cargo pallet in the payload bay of the Space Shuttle, as shown in Figure 1.

The robot will perform a series of representative tasks, ranging from simple taskboard operations to very complex EVA worksite setup using hardware that was never intended for robotic handling. In addition to obtaining performance data on these task operations, a major aspect of the Ranger mission is to compare performance via local and remote teleoperation. Several of the tasks will be repeated with varying control modalities and time delays to compare these effects. The robot will be controlled from flight and ground control stations, with commands and telemetry transferred via the normal Shuttle communications path (Figure 2).

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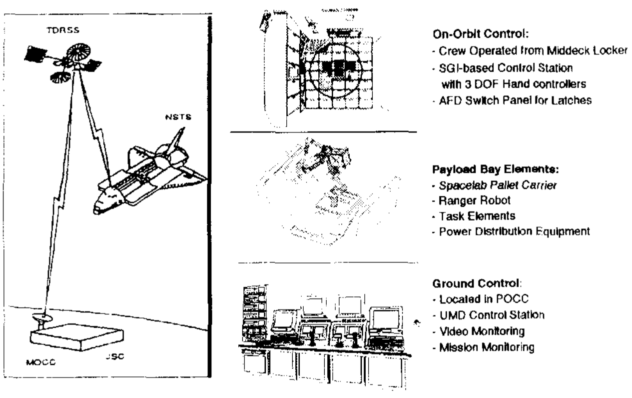

Figure 2: RTSX mission overview.

gram in NASA's Office of Space Science, and is executed by the University of Maryland under a cooperative agreement. In addition to the ground-breaking demonstrations of telerobotic servicing capabilities, the Ranger program also serves as a training program for young engineers in a truly hands-on environment. The Space Systems Laboratory at the University of Maryland College Park campus has an operational neutral buoyancy version of the Ranger robot—designed and built largely by students—and is gathering operational experience with the system at their own neutral buoyancy facility and at other NASA centers.

2 Mission Objectives

The RTSX mission objectives address three major areas[4]. The first is demonstrating a series of tasks that are representative of a wide variety of extravehicular operations, thus showing the utility and application of a dexterous robotic servicer. Second are the human factors effects of controlling space telerobots, including time delay, microgravity, and advanced control interfaces. Finally, the RTSX mission will provide flight data for comparison and correlation to hundreds of hours of data from ground-based computer and neutral buoyancy simulations.

2.1 Task Demonstrations

The first set of task operations involve tasks that have been designed with robotic compatibility in mind. These tasks provide collocated grasp points and fasteners, along with visual cues to support grasp point acquisition and fastener status indication. They are typically performable with a single manipulator arm, freeing a second manipulator (if available) for stabilization functions or as a functional spare. These tasks obviously have the lowest relative complexity and the highest chance of mission success. However, the RTSX experiment is attempting to define the limits of space telerobots, so a more challenging set of tasks will be attempted.

A second set of operations involve tasks that were originally designed only for EVA astronauts. Although EVA astronauts lack the dexterity of humans in a shirt-sleeve environment, they do have greater dexterity than most robotic systems envisioned for space operation. EVA tasks can require multiple arms for performance, and typically don't provide integrated handholds with fasteners.

A major objective of the RTSX mission is to demonstrate that space robots (equipped appropriately to interface with the hardware) can perform tasks having no special provisions beyond general EVA compatibility. This would greatly increase the set of conceivable tasks, including setup and teardown of EVA worksites—which add considerably to the overhead of EVA operations without directly contributing to the achievement of maintenance objectives.

2.2 Human Factors

Figure 3 shows the overall human factors science strategy for the RTSX mission. The two upper boxes represent operations performed on-orbit, while the lower two boxes represent operations performed from the ground. The three main effects on human factors—time delay, microgravity, and advanced operator interfaces—are decoupled to allow a clear assessment of their relative influences.

The time delay associated with ground controlled operations on the Space Shuttle may range from 5–7 seconds[5]. Any time delay greater than 0.3 seconds causes the operator to adopt a "move-and-wait" control strategy that increases the task performance time[6]. A set of robotic tasks will be performed on-orbit without time delay and then repeated with varying levels of time delay, giving a direct assessment of the effect of time delay. The effects of time delay on teleoperation has been an active topic of research at the Space Systems Laboratory.

Another significant difference between ground and on-orbit operations is the effect of microgravity. Clearly, this has a dramatic effect on the dynamics of the manipulators and manipulated elements, but there may also be effects upon the operator. It is possible to adequately restrain the operator to permit stable interaction with the control station, but the more subtle issues of lost vestibular cues and their impact on sit-

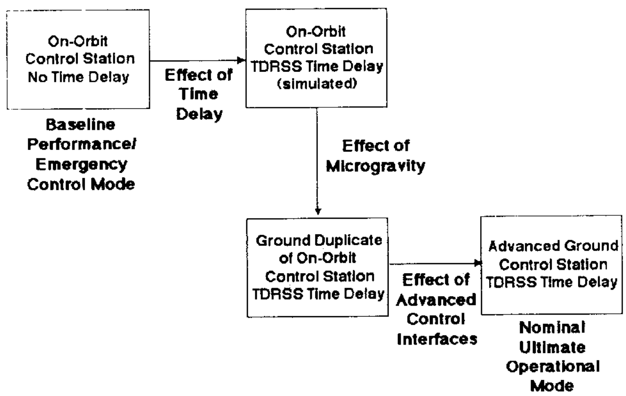

Figure 3: RTSX science strategy.

uational awareness are not well understood. Very few applicable research results are available in this area. To address this issue, functional duplicate control stations will be used on the ground and on-orbit, with equal time delay effects programmed. Therefore, the effect of time delay will be masked, and the effect of the microgravity environment may be directly measured.

Thus far, the input devices used to control space telerobots have been standard 2x3 degree-of-freedom (DOF) hand controllers; therefore, only a single manipulator can be controlled by a single operator. The only output devices have been simple monoscopic video and text displays. Initial research results[7] suggest that with intuitive 6 DOF input devices and higher fidelity output devices, it will be possible for a single operator to coordinate the operation of two 6+ DOF manipulators. A number of advanced output devices—such as head-mounted displays and stereo vision devices—promise to give operators a greater sense of telepresence than that offered by straight video and text. It may also be possible to mitigate the effects of time delay through the use of predictive displays. The ground control station will incorporate two sets of input and output devices; the first set will replicate the basic hand controllers and video displays of the on-orbit control station, while the second set will incorporate more advanced input and output devices, along with predictive displays for time delay compensation. The intent is to provide the most capable ground control station possible, and the "basic" control station will serve as the reference system.

2.3 Correlation of Flight Data to Ground Simulations

Clearly, on-orbit operational time for the RTSX mission will be limited. A number of ground simulations have been developed to support the development of the RTSX flight hardware, assist in training the flight and ground crews, and support anomaly resolution during the mission. By correlating the RTSX flight data to the database obtained from ground simulations, it will be possible in the future to use the "calibrated" ground simulators to predict on-orbit performance for tasks that have not yet been envisioned.

The simulators take the form of graphical computer displays, and also as a neutral buoyancy equivalent to the RTSX system, known as the Ranger Neutral Buoyancy Vehicle (RNBV). A free-flying RNBV is already operational and collecting data on human factors and task operations. A second-generation RNBV which closely resembles the RTSX flight article configuration and system architecture is currently under construction. Once operational, this system will be shared between crew training and task operation data collection.

3 System Configuration

3.1 Cargo Bay Equipment

The Ranger robot, task equipment, and support equipment (Figure 4) will be carried to orbit on a Spacelab Logistics Pallet (SLP), and will remain anchored in the payload bay for the duration of the mission[8]. In the event of a contingency that prevents the safe return of the payload, the entire pallet can be jettisoned remotely. There are also provisions for EVA contingency servicing if sufficient mission resources are available.

The Ranger robot consists of a body and four manipulators. The body serves as the mounting point for the manipulators and end effectors, houses the main computers and power distribution circuitry, and is the anchor point for the manipulator launch restraints and the body latches. The body is made from aluminum sheet; the manipulator attachment structure is a monocoque, while the electronics housing is a framework with body panels. This construction is stiff, robust, and allows for easy serviceability.

The Ranger robot has three types of manipulators—two dexterous manipulators, one video manipulator, and one postioning leg. The dexterous manipulators are a 8 DOF R-P-R-P-R-P-Y-R design, 48 inches in length, and capable of outputting approximately 30 pounds of force and 30 foot-pounds of torque at their endpoints. A suite of interchangeable end effectors are available for the diverse task set. The video manipulator is a 7 DOF R-P-R-P-R-P-R design, 55 inches in length, and carries a stereo video camera pair at its distal end. The positioning leg is an actively-braked 6 DOF R-P-R-P-R-P design, 75 inches in length, and

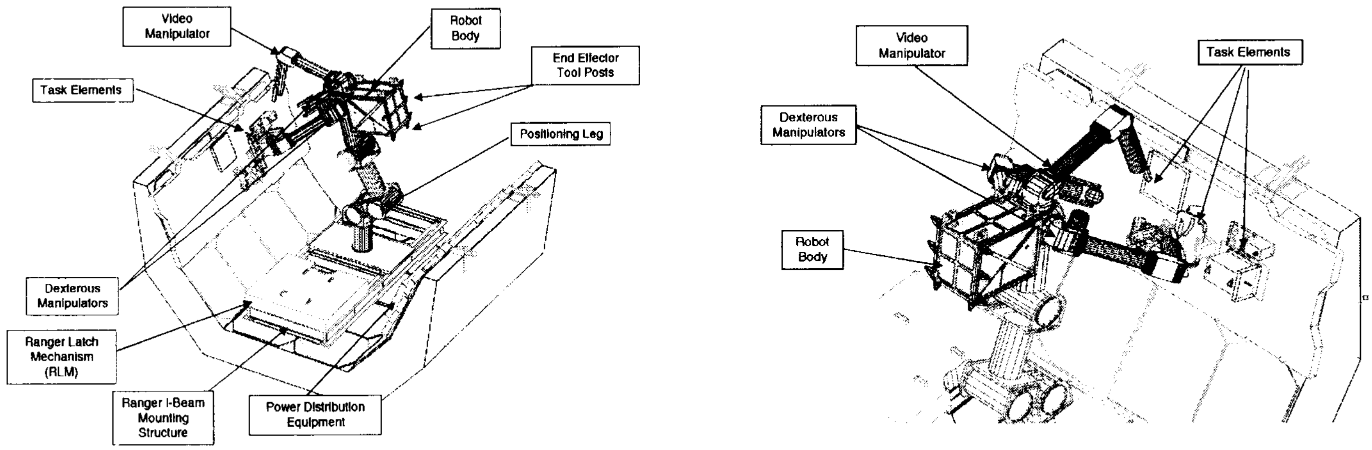

Figure 4: Ranger robot and task equipment on Spacelab Logistics Pallet.

capable of outputting 25 pounds of force and 200 foot-pounds of torque at its endpoint. In a braked condition, it can withstand a 250 pound load applied at full extension. It is permanently attached to the Spacelab Logistics Pallet for the RTSX mission.

The task element suite consists of the following components:

- International Space Station (ISS) Remote Power Controller Module (RPCM)
- Hubble Space Telescope (HST) Electronic Control Unit (ECU)
- ISS Articulated Portable Foot Restraint (APFR)
- Robotic task board

The RPCM changeout is considered to be a robot-compatible task. The RPCM ORU was designed from the outset to be serviced robotically, and incorporates misalignment tolerance, visual aids, and colocated grasp points/fasteners. The task can be performed with a single manipulator using simple motions.

The ECU is an ORU-style box that was changed out on the first HST servicing mission in 1996. It does not have collocated grasp points/fasteners, and will require coordinated dual arm operations.

The APFR is a complex, jointed device, designed to support EVA operations. It is by far the most difficult task on the RTSX mission, requiring four different end effectors, multiple arm coordination, and numerous task steps. Successful execution of this task on-orbit will help to validate the concept of telerobotic setup of EVA worksites.

The task board is comprised of a number of smaller task operations, including a set of calibrated force and torque measuring sensors, a contour-following task, a peg-in-hole task, and a visual inspection task board provided by the NASA Jet Propulsion Laboratory.

The support equipment on the SLP include electrical power conditioning and switching units, a body and manipulator latching system, and a contingency stowage box. The electrical power equipment includes DC-DC converters, filters, and relays to support the robot and the latching system. The latching system is based on a flight-proven design used for NASA's SPARTAN free-flying satellite; it secures the robot body and manipulators for launch and re-entry.

3.2 Crew Cabin Equipment

Most of the RTSX-related crew cabin equipment is located in the Middeck. Figure 5 shows the Shuttle Middeck, with RTSX flight control station (circled) deployed and attached to the middeck lockers, facing forward. The RTSX flight control station consists of a Silicon Graphics, Inc. O2™ workstation, keyboard, four flat-panel graphics and video displays, hand controllers, and networking and video processing equipment. The flight control station is stowed in Middeck lockers when not in use; the keyboard, hand controllers, and displays are deployed for RTSX operations. Additional RTSX-dedicated items in the Middeck include a Payload General Support Computer (PGSC) for monitoring Orbiter parameters, and video and still cameras to document RTSX operator interactions with the payload.

The switches that control the payload retention latches and the payload jettison function are located on switch panels in the Aft Flight Deck. If an observer is deemed necessary for experimental data collection or safety purposes, they would use direct out-the-window views and/or video displays from the Aft Flight Deck.

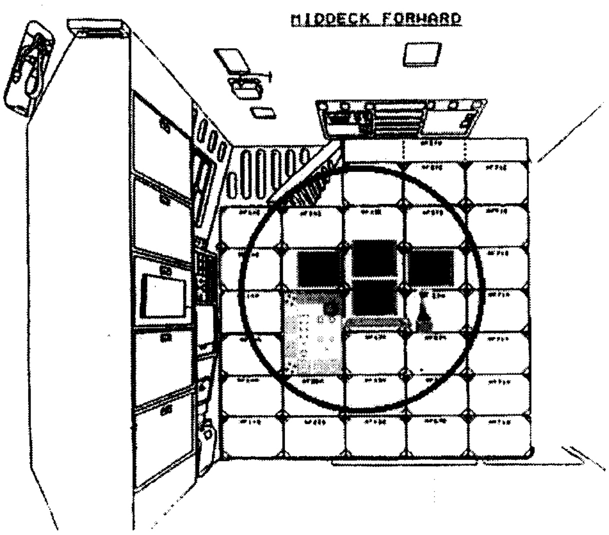

Figure 5: RTSX flight control station.

3.3 Ground Equipment

The ground control station (Figure 6) has two operator stations to support the requirements for a functional duplicate of the flight control station and an advanced control station. The ground control station will be located in the Payload Operations Control Center (POCC) at the NASA Johnson Space Center. It will tie into the payload data network and will serve both in the operational function described in Section 2.2 and as a monitor and archive for data when the flight control station is active.

Like the flight control station, the ground control station is based on Silicon Graphics, Inc. workstations. The included peripherals are graphics and video display monitors, hand controllers and other input devices, and video and data processing and archiving equipment. The architecture of the ground control station is modular; the main robot control modules are also used in the flight control station. Some other modules are unique to the ground control station; these include the interfaces to the advanced input and output devices, the simulation modules, and a module that forwards mission data back to the University of Maryland.

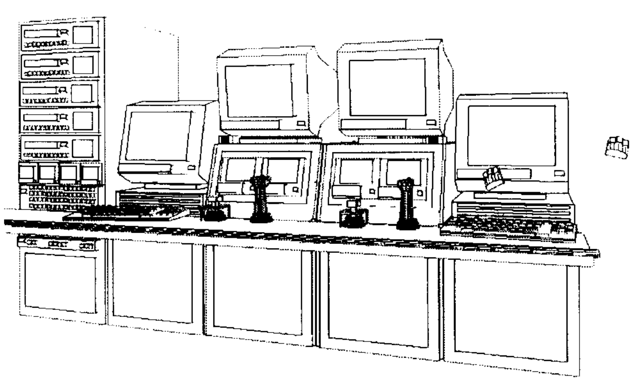

Figure 6: RTSX ground control station.

Figure 7 shows the user interface for the ground control station. It is highly graphical, and has the ability to display video from the downlinked data stream. A subset of the ground control station functionality will be implemented on the flight control station; the flight control station will lack the advanced input and output devices and predictive displays, and will be optimized for a single operator.

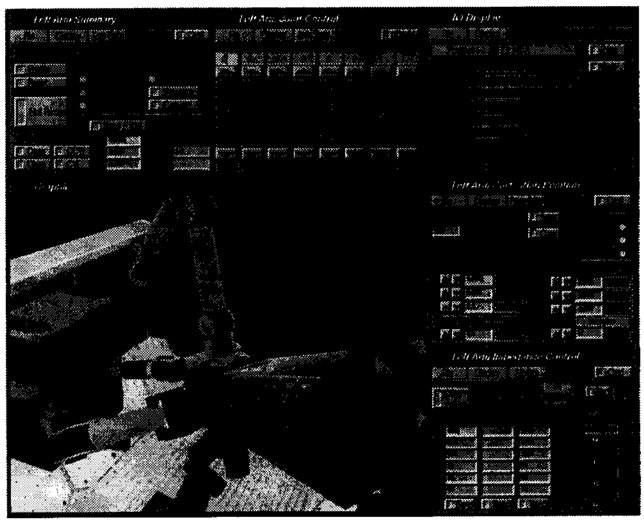

Figure 7: Ground control station user interface.

The Ranger Neutral Buoyancy Vehicle supports both operational and scientific objectives in the RTSX mission. While the first generation RNBV shown in Figure 8 is a free-flying configuration, the second generation RNBV is a functional equivalent of the RTSX robot, and is deployed on a neutral buoyancy mockup of the SLP and its associated task equipment. The RNBV structure is similar in form to the RTSX robot. The manipulator arms are almost exact duplicates of the flight arms, except for seals in the joints and surface finishes. The neutral buoyancy environment poses several significant challenges, namely the need to waterproof all exposed elements and to ensure that structure is strong enough to withstand pressure effects and the rough treatment inherent to the underwater environment. The RNBV will be surface-supplied with pressurized air, electrical power, and fiber optic data and video lines.

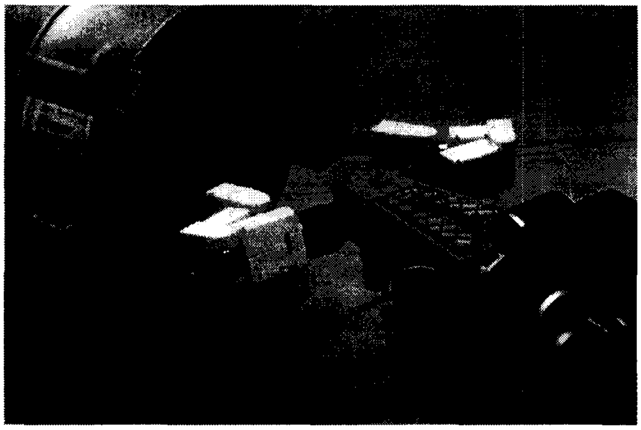

Figure 8: Ranger Neutral Buoyancy Vehicle.

Operationally, the RNBV should be an excellent replica of the flight system. Manipulator motions can be kept slow to minimize water drag effects, and the task elements can be made neutrally buoyant to simulate weightlessness. However, it will be difficult to replicate the on-orbit lighting conditions, and external flotation may be required to make the manipulators and end effectors neutrally buoyant. These issues notwithstanding, neutral buoyancy is the best simulation medium for on-orbit dexterous robotic operations, and the RNBV is a key element of the RTSX mission.

4 Operations Concept

4.1 Mission Operations

RTSX is expected to be either a primary payload or a complex secondary payload, due to crew time requirements. The RTSX mission is expected to involve approximately 48 hours of operations, divided between ground and flight control. (The flight control station will be in a monitoring mode during ground controlled operations, and vice versa.) For mission day planning and crew fatigue considerations, the 48 hours will be divided into approximately 12 four-hour sessions.

The RTSX does not have fine pointing requirements, but does expect a relatively benign thermal environment during task operations; therefore, a payload bay-to-Earth flight attitude has been requested. Orbiter thruster firings are expected to be deferred so as not to disturb task operations. Finally, no EVA operations are required for the nominal RTSX mission; however, EVA may be used to recover from an RTSX failure that prevents safe return if crew resources and mission time are available.

4.2 Session Operations

The twelve test sessions are designed to support the population of the test matrix (ground vs. on-orbit, predictive display vs. no predictive display, etc.) while achieving mission success at the earliest possible time. Only one IVA crewmember will be required to operate the flight control station, although an additional crewmember(s) may serve as a safety monitor or video/still camera operator.

A typical four-hour session will consist of robot power-up and checkout operations (approximately 30 min.), task operations (approximately 3 hrs. 15 min.), and robot stowage and power-down operations (approximately 15 min.). The task operations segment may be further sub-divided to account for ground and flight control, or to sequence through more than one on-orbit operator. If the ground control station is active, control will automatically revert to the flight control station if communications are interrupted.

4.3 Task Operations

Figure 9 gives two representative views of a task operation. This particular task is a changeout of the Hubble Space Telescope (HST) Electronics Control Unit (ECU); the left view is as might be provided by a Ranger body-mounted camera; the right view is as provided by a video manipulator camera. Although the task operations will be extensively practiced via computer and RNBV simulations, the robot will be teleoperated on-orbit. Only a few operations, such as robot deployment/stowage and end-effector changeout, will be automated. Time to complete a particular task will range from a few minutes—in the case of the task board elements and the RPCM—to possibly several sessions for the APFR task.

The RTSX hardware and software design are strongly influenced by the requirement to ensure that the robot does not pose a hazard to the Orbiter or its crew. The hazards include inadvertent contact between the robot and the Orbiter, excessive loads into task equipment, inability to safely stow the robot for landing, and potential hazards to EVA crewmembers. The NASA Jet Propulsion Laboratory is developing a methodology[9] to detect potential collisions between the Ranger and itself or with its surrounding environment. The RTSX computer architecture is highly failure tolerant, and has a hierarchical monitoring approach that permits any processor to shut down an adjacent upstream or downstream processor. The control

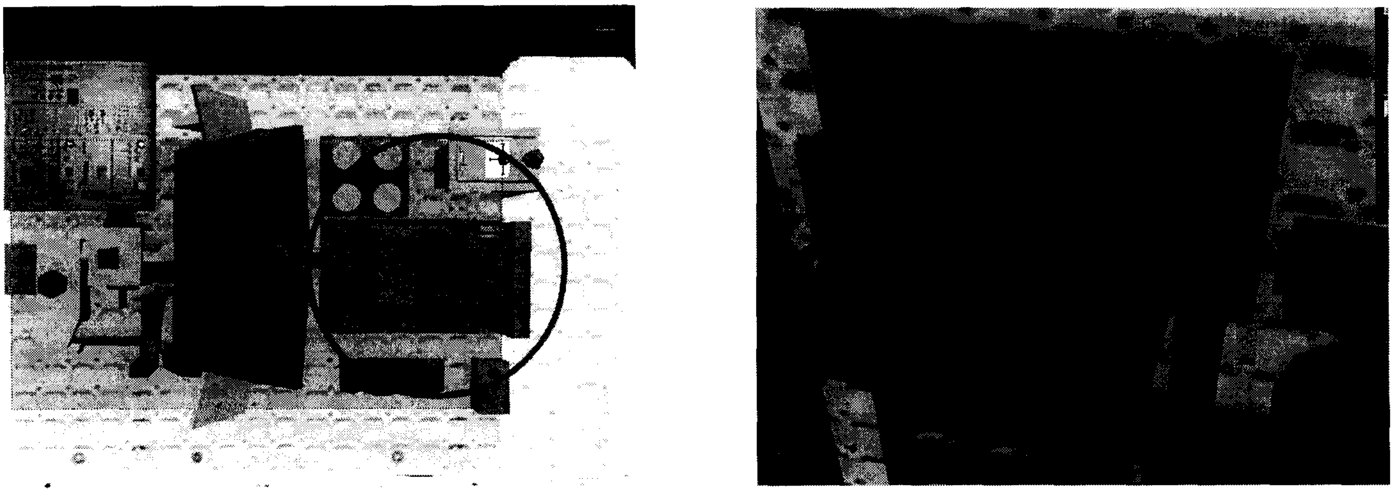

Figure 9: Ranger performing ORU changeout operation.

stations play no active role in the safety of the system, and an inadvertant operator command or loss of communication will not result in a hazardous condition.

5 Outlook

5.1 RTSX Mission Outlook

The RTSX project has completed the preliminary design phase and is undergoing detailed design. The manipulators are leading the development process, with the body and associated subsystems following shortly thereafter. The body structure for the RTSX-equivalent Neutral Buoyancy Vehicle has been manufactured and is awaiting outfitting with power, data, and pressurization subsystems. Hardware and software integration for the flight article are planned for late CY1999, with environmental testing in middle CY2000 in anticipation of a Space Shuttle launch opportunity in CY2001.

5.2 RTSX Follow-on Mission Outlook

A successful RTSX mission will set the stage for several possible follow-on scenarios. A logical follow-on to the pallet-based RTSX configuration would be a free-flying system, named the Ranger Telerobotic Flight Experiment (RTFX), which has already been conceptually designed[10]. Another possible scenario would be to deploy Ranger to a long-duration platform such as the International Space Station to extend the experimental database. Finally, there are a number of candidate assets in Earth orbit that could benefit from servicing; the lowest risk approach would be to demonstrate free-flying servicing on a failed spacecraft that would not otherwise be recoverable. These scenarios are, of course, dependent on a successful first mission with the RTSX, and this is where the Ranger development team is focusing its efforts.

Acknowledgements

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