Ranger Telerobotic Shuttle Experiment (RTSX): Status Report

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ABSTRACT

This paper updates the status of the Ranger Telerobotic Shuttle Experiment (RTSX). The first Ranger mission 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 CY2000, and the hardware and software for the flight article and a neutral buoyancy functional equivalent are transitioning from design to manufacture. This paper addresses the technical and programmatic status of the flight experiment, and lays out plans for the future.

Keywords: telerobotics, spacecraft servicing, neutral buoyancy, manipulator, space station, space shuttle

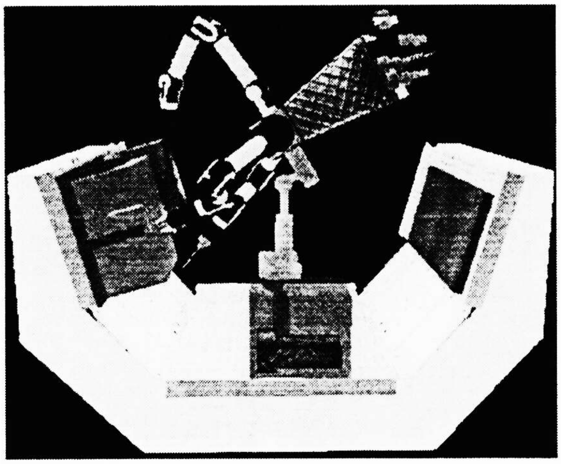

Figure 1. RTSX deployed in Space Shuttle payload bay.

1. INTRODUCTION

Originally presented at the SPIE Telemanipulator and Telepresence Technologies (T&TT) III Conference in 1996,[1] and updated at the T&TT IV Conference in 1997,[2] the Ranger Telerobotic Shuttle Experiment (RTSX) is progressing toward its mission on the 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. As shown in Figure 2, 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. The robot will be controlled from flight and ground control stations, with commands and telemetry transferred via the normal Shuttle communications path.

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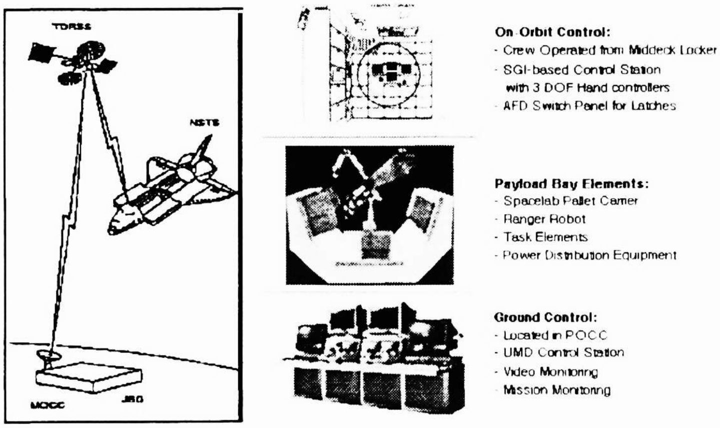

Figure 2. RTSX mission overview.

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 experiment is sponsored by Telerobotics Program 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.

This paper is divided into six sections. Section 2 discusses the RTSX mission objectives. Section 3 describes the configuration of the flight and ground systems. Section 4 gives the mission operations concept. Section 5 addresses a series of experiments in teleoperation. Section 6 provides an outlook for the RTSX mission and potential follow-on missions.

2. MISSION OBJECTIVES

The RTSX mission objectives address three major areas. 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.

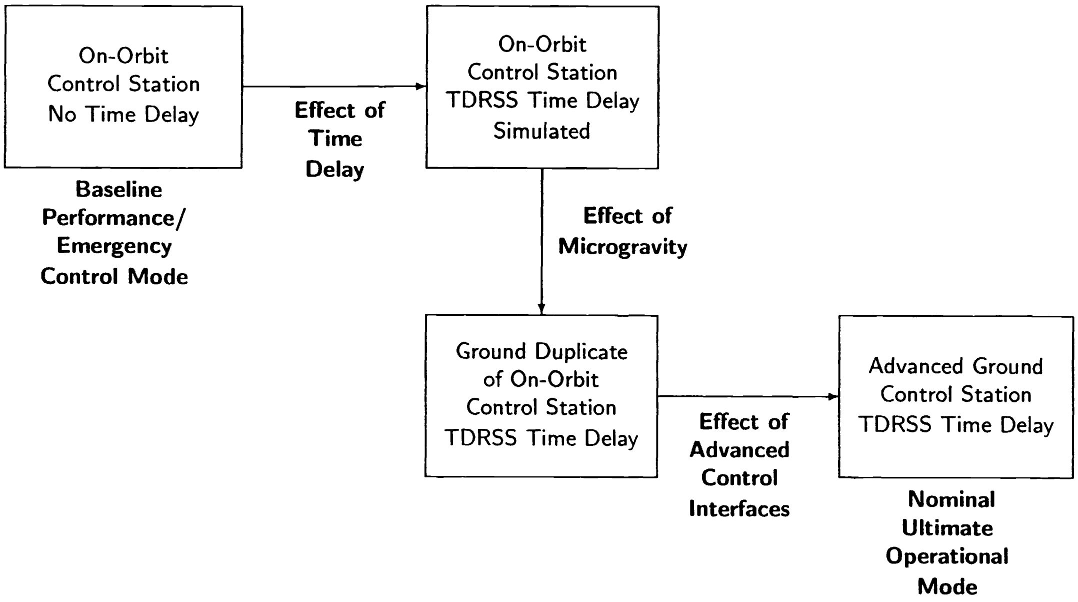

Figure 3. RTSX science strategy.

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.[3] 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.[4] 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, as discussed in Section 5.

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 situational 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[5] 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

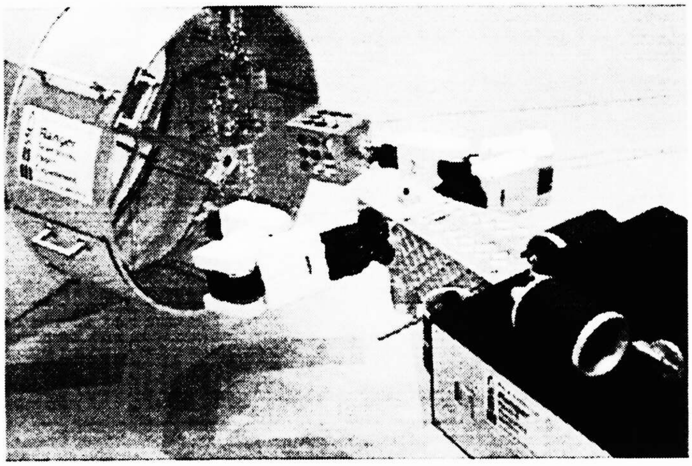

Figure 4. Ranger Neutral Buoyancy Vehicle.

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). As described in Section 1, a free-flying RNBV (Figure 4) 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 5) 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. 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.

3.1.1. Ranger robot

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 grapple manipulator. 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

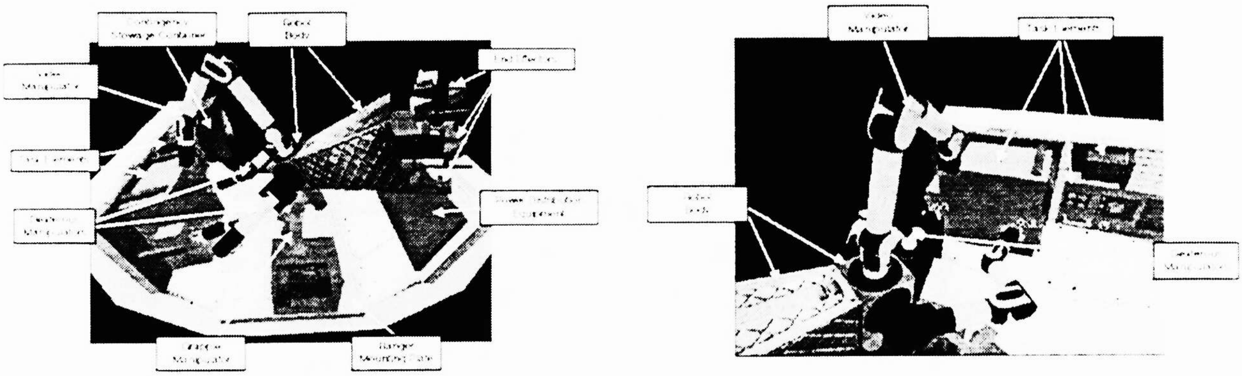

Figure 5. RTSX robot and pallet equipment.

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 grapple manipulator is an actively-braked 7 DOF Y-P-R-P-P-Y-R design, 106 inches in length, and capable of outputting 25 pounds of force and 225 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 term "grapple" refers to an earlier mission concept that had an active end effector at the distal end.

3.1.2. Task equipment

The task element suite (Figure 6) consists of the following components:

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

The battery ORU and the RPCM are considered to be robot-compatible tasks. The battery ORU has already flown as an experimental unit on a Shuttle mission in 1997, so a considerable amount of data on human operation is available for comparison with the RTSX robotic operation.

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 an EVA handrail grasp point, an ISS H-Handle grasp point, a hinged door with J-Hooks and a Microconical grasp fixture, an EVA pip pin, and a visual inspection task board provided by the NASA Jet Propulsion Laboratory.

3.1.3. Support equipment

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. The contingency stowage box is an adaptation of an EVA tool stowage box, and is used by the crew during contingency EVA operations to stow tools, end effectors, and small task items.

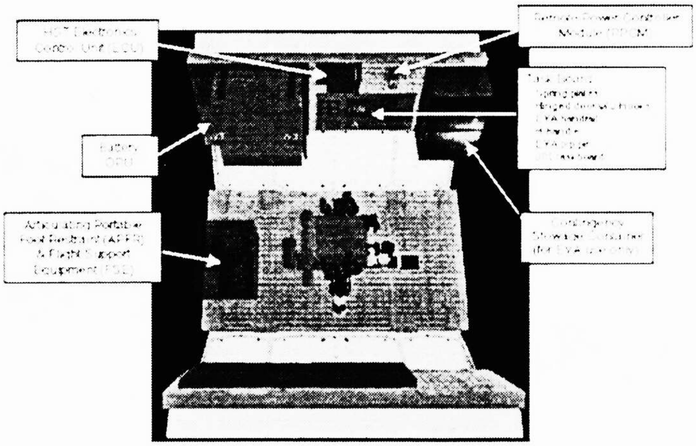

Figure 6. Task equipment on Spacelab Logistics Pallet.

3.2. Crew Cabin Equipment

Most of the RTSX-related crew cabin equipment is located in the Middeck. Figure 7 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$^{\text{TM}}$ 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.

3.3. Ground Equipment

3.3.1. Ground control station

The ground control station (Figure 8) 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

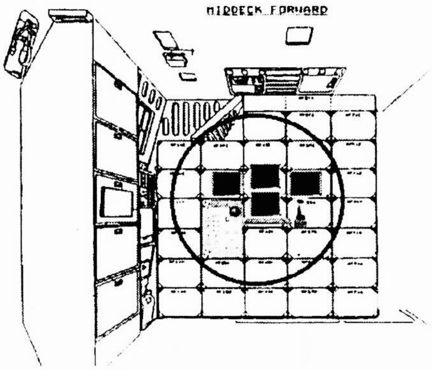

Figure 7. RTSX flight control station.

Figure 8. RTSX ground control station.

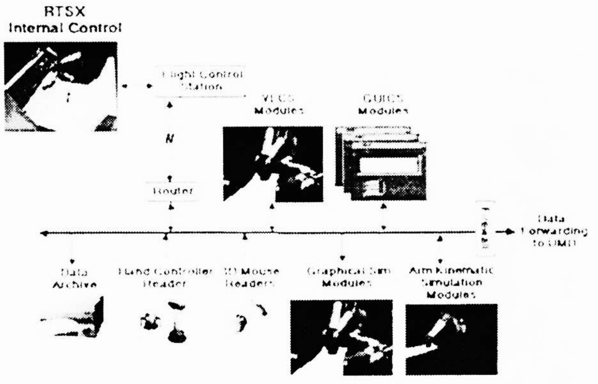

Figure 9. Ground control station architecture.

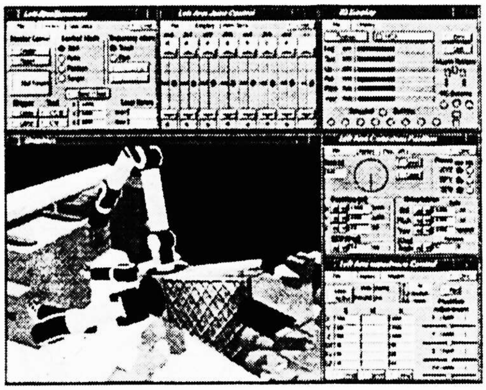

Figure 10. Ground control station user interface.

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 (Figure 9) 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 10 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.

3.3.2. Neutral Buoyancy Vehicle

As described in Section 2.3, the Ranger Neutral Buoyancy Vehicle supports both operational and scientific objectives in the RTSX mission. While the first generation RNBV shown in Figure 4 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.

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; session operations are described in Section 4.2.

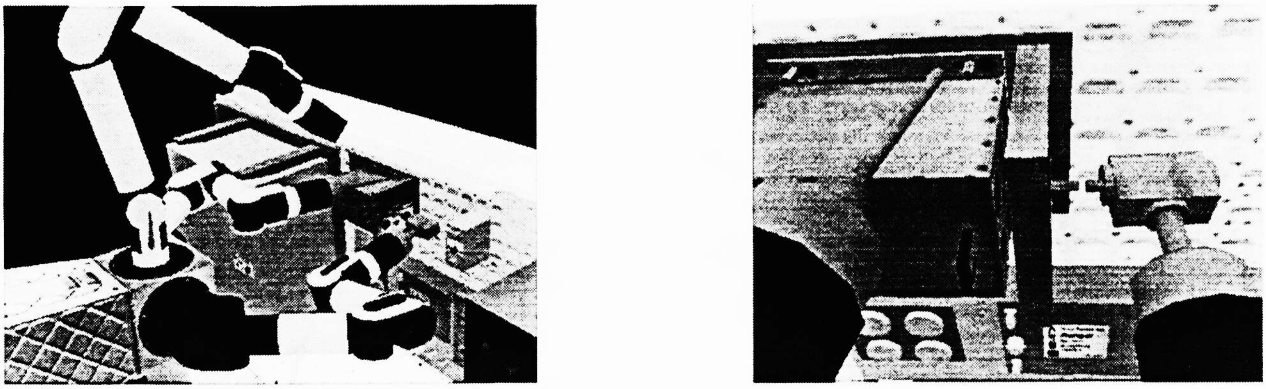

Figure 11. Ranger performing ORU changeout operation.

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 11 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 an Orbiter payload bay bulkhead 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 to detect potential collisions between the Ranger and itself or with its surrounding environment.[6] 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 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.

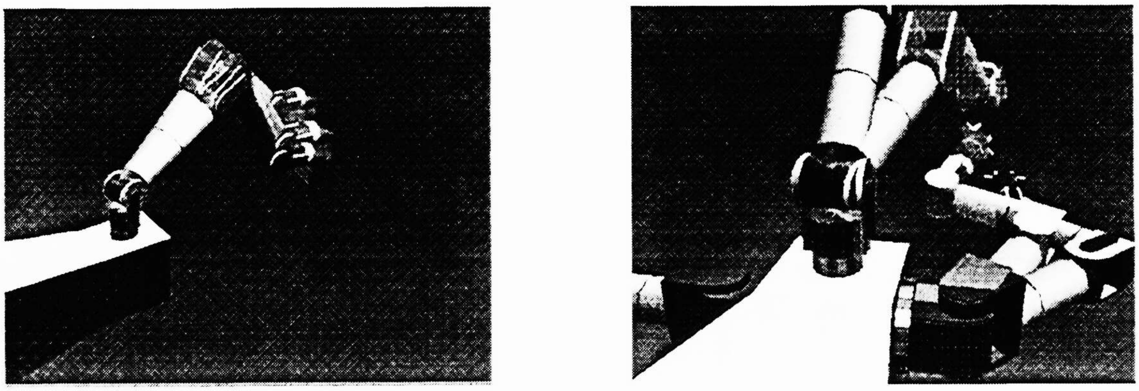

Figure 12. Predictive displays.

5. TELEOPERATIONS APPROACH & RESEARCH

As the experiment's title implies, teleoperation is the primary operational mode. Local operations from the Orbiter Middeck will not be subject to communication time delay, but additional challenges remain to mitigate the loss of situational awareness resulting from lack of direct viewing of the robot. Furthermore, the flight control station will not be outfitted with advanced input or display devices. The ground control station will be augmented with advanced display devices, but will be subject to time delay effects and relatively low update rates due to the bandwidth of the Orbiter-to-ground data stream. A number of teleoperations-related studies have been conducted or are being planned to address these issues.[7]

5.1. Telerobotic Arm Control Human Factors Study

In order to quantify the effects of time delay, command update rate, and manipulator tip speed limitations on task performance, a series of test subjects were asked to perform a modified Fitts' Law task using a graphical simulation of the Ranger dexterous manipulator. The subjects used 2x3 DOF hand controllers to move the manipulator tip into contact with a sphere that appeared somewhere in the manipulator workspace. In addition to the task performance time, the experiment tracked inadvertant collisions with a virtual wall behind the sphere.

The results of the study indicate that time delay has the greatest effect on task completion time, followed by manipulator tip speed limitations, and then by command update rate. For a 6.0 second time delay (not unusual for Space Shuttle ground control), the increase in task completion time was almost 500%. Clearly, some mitigation will be required to enable efficient task execution under this amount of time delay. Manipulator tip speed limitations influenced task performance time by about 30% when the tip speed limit was reduced from 6.0 inches/second to 1.3 inches/second. Command update rate had a dramatic effect when the update rate was reduced below 5 Hz. It is expected that an update rate of 5 Hz or more will be available for the RTSX mission, so this effect should be mitigated.

5.2. Predictive Displays

The experiment described in Section 5.1 above was repeated, this time using a predictive display (Figure 12) of the manipulator and tooltip position. The predictive display attempts to mitigate the effect of time delay by providing nearly instantaneous feedback of control inputs, allowing operators to execute a relatively continuous set of inputs rather than a move-and-wait strategy.

Results from this experiment indicate that predictive displays can enable a dramatic reduction in task completion time. The predictive display reduced the average task completion time by 50% in the case of a 1.5 second time delay, by more than 60% in the case of a 3.0 second time delay, and by more than 70% in the case of a 6.0 second time delay.

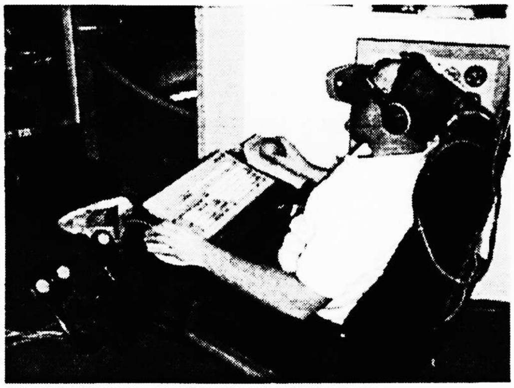

Figure 13. VEVI control station.

Figure 14. Control station with CrystalEyes^{TM}.

5.3. 3D Graphics Output Study

A number of advanced output devices are available to augment the typical monoscopic video display. Many of these devices attempt to provide a stereoscopic view to improve operator situational awareness and provide a sense of depth. Of course, a stereo input is required to drive the display; RTSX will have stereo video camera pairs on the body and the video manipulator.

Two styles of stereoscopic imaging systems were evaluated in this study; the first device was an immersive head-mounted display (HMD) as part of the NASA Ames Virtual Environment Virtual Interface (VEVI) Control Chair (Figure 13), and the second device was a set of synchronized-LCD CrystalEyes^{TM} glasses (Figure 14). The test subjects were presented with a synthetic scene showing three spheres, with the center sphere offset either forward or aft of the outer reference spheres; the subjects were then asked to indicate the direction of offset. The test matrix varied the reference sphere distance from the operator and resulted in associated "threshold" offset distances at which the subject could no longer distinguish the direction of offset.

The comparative results indicate that subjects had lower threshold values when using the CrystalEyes^{TM} glasses. In addition, test subjects using the HMD reported significantly larger incidences of simulator sickness, characterized by eye strain, fatigue, difficulty focusing, and general discomfort. Based on these results, the RTSX ground control station will be outfitted with the CrystalEyes^{TM} system.

5.4. Future Studies

Another series of human factors studies are planned to address issues relating to input devices and multiple arm control. The input device study will compare several styles of 6 DOF devices against the reference baseline of 2x3 DOF hand controllers. The set of candidate devices is expected to include a mini-master, wireless hand tracking devices, and more traditional 1x6 DOF resolved rate controllers.

Since the Ranger system has a total of four manipulators, the ability of the input devices and the control station to support multi-arm operations is critical. These multi-arm operations may take the form of independent operations (e.g., one dexterous arm removes a fastener while a second dexterous arm restrains the ORU), coordinated operations (e.g., two arms move in concert to handle a large, massive ORU), or servoed operations (e.g., the video manipulator tracks the endpoint of a dexterous manipulator during a task operation). Some of the more complex multi-arm operations may involve simultaneous motion of more than 20 manipulator joints, so the challenge is great.

6. OUTLOOK

6.1. RTSX Mission Outlook

The RTSX project has completed the preliminary design phase and has commenced 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 1999, with environmental testing in early to middle 2000 in anticipation of a Space Shuttle launch opportunity in late 2000.

6.2. Ranger 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.[8] 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.

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