Science Planning for the Ranger Telerobotic Shuttle Experiment

David L. Akin

Space Systems Laboratory
University of Maryland
College Park, MD 20742
dakin@ssl.umd.edu

Keywords: telerobotics, servicing, dexterous robotics, human factors, operations, space shuttle, International Space Station, flight experiments, neutral buoyancy, simulation

Abstract

The Ranger Telerobotic Shuttle Experiment is a low-cost demonstration of highly dexterous robotics for on-orbit operations. The Ranger robot consists of two dexterous manipulators with interchangeable end-effectors, a positioning manipulator for a stereo camera pair, and a positioning leg attached to a Spacelab pallet. The tasks Ranger will perform on-orbit in 2003 include fiduciary tasks such as force plates and contour following, a Remote Power Controller Module from the International Space Station, an Electronics Control Unit from Hubble Space Telescope, and an Articulated Portable Foot Restraint. This paper describes the Ranger system, then goes into detail on the underlying science design of the mission. The scientific objectives are grouped into four major categories: telerobotic design and performance verification, telerobotic human factors, system performance, and correlation of flight data to earth-based simulations. Ranger represents a significant increase in capability over current and planned robotic systems, at a small fraction of their development cost.

1 Introduction

With the routine orbital operations made possible by the space shuttle, there has never been any doubt that robotics could markedly augment current operational capabilities. The Canadian Remote Manipulator System (RMS) has enabled a number of satellite deployments and retrievals, and indeed has been the critical system for the assembly of the International Space Station (ISS) to date. The recent deployment of the Space Station Remote Manipulator System (SSRMS) will allow the continued assembly of the ISS beyond the reach of the shuttle RMS. Similar European and Japanese manipulators will allow multiple external ISS activities to take place simultaneously.

However, dexterous robotics have not been keeping pace with the use of the larger crane-type manipulators such as RMS and SSRMS. This has partially been due to programmatic limitations. The American Flight Telerobotic Servicer (FTS) program was downgraded to plans for a single development test flight, then canceled. Other potential dexterous systems, such as the Servicing Aid Tool (SAT), have not proceeded to flight status.

The “conventional wisdom” is that dexterous robotics is not achievable within current funding limitations. FTS, prior to cancellation, was nearing a total cost range of a billion dollars. The Canadian Special Purpose Dexterous Manipulator (SPDM), while still under way, has been downscaled and delayed from original planning.

Indeed, we seem to have reached a “Catch-22” in the development and application of dexterous robotics for space operations. No significant government funding is forthcoming for robotic systems development until it is identified as a requirement in critical programs. Yet, no other program will acknowledge robotics as a critical requirement when there is no such system in existence, or even in the planning cycle. Without a breakthrough in this conundrum, there is little prospect for near-term applications of advanced dexterous robotics technologies in space.

The Ranger Telerobotic Shuttle Experiment (TSX) is designed to break the thought cycle restricting the development and application of advanced robotics. At a total program cost of approximately $20 million, it will demonstrate that capable robots do not necessarily require nine- or ten-digit budgets. With significantly greater capabilities than SPDM, it will also demonstrate
that robotic systems are able to perform a much greater variety of servicing, assembly, and maintenance tasks than they are currently called upon to do.

This paper will briefly describe the objectives of the Ranger Telerobotic Shuttle Experiment, and summarize the current configuration and status of the program. It will then go into some detail on the science and engineering objectives of the mission, and elaborate on how the system design was created to facilitate achieving the technical objectives.

2 Ranger TSX Objectives

Ranger TSX has three basic program objectives. Each of these will be explained briefly in this section; more details will be forthcoming in the section on mission science and experiment design. The three objectives are:

To quantify on-orbit the capabilities and limitations of state-of-the-art dexterous telerobotics technologies, including the effects of human-in-the-loop ground control - A number of robotic technologies have been proven in the laboratory environment for years, but are not currently under consideration for use in flight operations. SPDM is arguably a reduction of scale in RMS and SSRMS, with little increase in dexterity or adaptability to alternate interfaces. Similarly, there are currently no formal plans to use ground control for SSRMS or SPDM, requiring limited on-orbit crew resources to operate these systems. Ranger TSX will demonstrate a number of advanced robotics technologies, including interchangeable end effectors, and will baseline ground control, using advanced human interfaces to ameliorate the effects of communications time delay.

To measure the correlation between flight robotics operations and neutral buoyancy simulation - The University of Maryland Space Systems Laboratory has a long history of performing complex simulations of space operations in the neutral buoyancy (underwater) environment. This effort led to the Experimental Assembly of Structures in EV A (EASE), a shuttle-based experiment to measure the capabilities and limitations of extravehicular astronauts flown in 1985. Since the early 1980’s, the SSL has been developing underwater telerobotic systems to simulate space operations, both independently and in cooperation with EVA subjects. Just as the EASE experiment quantified the correlation of underwater EVA simulations with flight data, the Ranger TSX program is designed to do the same correlation between neutral buoyancy and flight robotic systems.

To demonstrate, via an alternative development strategy, the potential for low-cost flight system development - Ranger TSX is being developed by the University of Maryland Space Systems Laboratory, with limited assistance from Veridian and Payload Systems, Incorporated. The total development team for this program is approximately 20 people, half of whom are undergraduate and graduate students. This approach is an amplification of that used successfully with the EASE program, and with the ParaShield flight experiment from 1989. By restricting the scope of the project, both in objectives and in personnel, the entire program is budgeted at approximately $20M.

With these three objectives explained, it is important to emphasize what Ranger TSX is not. It is not an operational robotics system. It is “single string”, and operations will be terminated following a component failure. It is designed for the range of temperatures expected in shuttle operations, which are not as broad as the thermal range seen in ISS operations. However, a successful Ranger TSX flight will demonstrate the utility of truly dexterous telerobotics, at a cost far below that which “conventional wisdom” would require for such a capable and complex system.

3 Ranger TSX Configuration Overview

The Ranger program originated as a design experiment in the Space Systems Laboratory. Drawing on more than a decade of organizational experience in both EVA operations and telerobotics, the overarching goal of the design process was to develop a telerobotic servicing system that was capable of performing any task that is currently performed by astronauts in pressure suits. A significant component of this goal, as a outgrowth of systems studies performed by the SSL in the early 1980’s, was the requirement to not design to a specific robotic interface, but to design the robot to accommodate all standard EVA interfaces. This would allow the maximum interoperability between EVA and robotic systems, and would dramatically simplify the development and logistics requirements for the end-user of the system. The requirements also dictated the design of a flight system based on Pegasus launch, and then the development of a neutral buoyancy version of that vehicle.

Based on extensive structural assembly and satellite servicing tests with prior robotic systems, the final form of the initial Ranger concept is shown in Figure 1. Two dexterous servicing manipulators are provided to allow bilateral operations, in either telerobotic or telepresence control mode. Since it was not felt to be practical to
attempt to replicate the dexterity of the human hand, interchangeable end effectors were selected to allow the use of multiple arbitrary interfaces. Video was selected as the primary feedback path to the remote operator; since there was limited bandwidth, a pair of stereo cameras mounted on a dedicated positioning arm provided the maximum flexibility in the choice of camera views. A grappling arm allowed the free-flying vehicle to attach to and control the target spacecraft during servicing operations. All four of these manipulators were mounted well forward around a small manipulator module, to allow EVA-compatible access into restricted volumes. Operations of the neutral buoyancy version of this concept are shown in Figure 2. Beyond the limits of the flight planning detailed in this paper, this vehicle has also been used to investigate potential approaches to direct EVA/robotic cooperation in the worksite, as illustrated in Figure 3.

When the Ranger development team was directed in 1996 to redesign the system for launch on the space shuttle, a number of design modifications had to take place. The free-flight capability was dropped to better adhere to shuttle safety limitations. The grapple arm turned into the positioning leg, which was greatly expanded in size to provide a high-bandwidth rigid attachment to the Spacelab pallet chosen as the shuttle carrier structure. With the removal of stowage limitations from the expendable launch vehicle, the body of the vehicle was redesigned from the original pyramidal shape to a rectangular form more convenient for fabrication. The current Ranger TSX design configuration is shown in Figure 4. This vehicle is a neutral buoyancy mockup of the Ranger TSX robot, developed for EVA training relevant to contingency stowage following a systems failure.

The neutral buoyancy version of the Ranger TSX flight hardware is currently in assembly at the University of Maryland. By the end of 2001, this vehicle will be in routine operational use at the UmD Neutral Buoyancy Research Facility, developing procedures and validating software for the Ranger TSX flight, as well as being used for advanced research into robotic space operations. Flight hardware is currently in fabrication in anticipation of a mid-2003 launch date. However, Ranger TSX is not currently manifested for a specific shuttle launch. With the severe constraints placed on shuttle operations and NASA funding resources by the International Space Station, it must be admitted that Ranger TSX currently faces tough competition for a very limited number of non-ISS payload opportunities.
In the development of the Ranger Telerobotic Shuttle Experiment mission design, the overriding consideration was to collect and document the entire development and flight process for future applications. Within this goal, the mission system was divided into programmatic, engineering, and scientific assessments.

Many of the approaches to Ranger TSX mission design are common to most flight programs. For example, under the programmatic assessment process, all of the steps of the development, qualification, testing, and flight process are captured and documented. This includes both the quantitative metrics (e.g., manpower and cost trends, performance against schedules) as well as subjective assessments, such as an ongoing "lessons learned" document. Similarly, the engineering assessment documents the design, development, and testing process, and creates sufficient assurance of on-orbit performance to satisfy shuttle safety and flight readiness requirements.

Of particular interest to this paper are the portions of Ranger TSX mission design that are unique to this program. This primarily deals with the science and technical objectives, in which the Ranger TSX Investigator Team is trying to maximize the useful data return from the mission.

Science assessments are grouped into four major categories: those specific to the design and implementation of a dexterous robot, those dealing with the human in the control loop, those that provide metrics on the performance of the overall system, and those relating to correlation of flight performance against ground-based simulation. These are referred to as robotics, human factors, operations, and simulation correlation, respectively. While these will be further detailed in order, it is important to keep in mind that design decisions described in one section will frequently have significant impacts to other assessment categories as well. The details presented here are highlights of the Ranger TSX data matrix, in which 52 detailed mission objectives are correlated in matrix form against 68 specific design details. The data matrix allowed the development of a consistent set of design goals, and provided a rationale for downselecting to a limited set of experimental objectives that provide maximum data return from a constrained set of design options.

Since this will be the first flight of this category of dexterous robotic system, a number of robotics design elements must be quantified and evaluated. One of the significant questions is the satisfactory performance of the compliance algorithm, which will maintain stable manipulator control even when constrained by contact with an external object. To this end, each dexterous manipulator is designed to incorporate wrist force and torque sensing, which is used for compliance control. The force-torque sensors are calibrated, and the compliance controller performance evaluated, through the use of force and torque plates, wherein the manipulator will deflect a contact surface with a known spring constant. Similarly, compliant algorithms will be verified through the use of a contour task, where the robotic end effector will slide along a complex three-dimensional contour while attempting to hold a constant contact force. Further manipulator assessment tasks, such as verifying control gains, assessing the boundary management algorithms, and verifying alternative control modes, will be facilitated by the use of a set of fiduciary robotics tasks, including unconstrained arm motions and peg-in-hole tasks. Extensive operational data, including servo-level control parameters for each actuator of each manipulator, are stored on-board for postflight assessment.

Telerobotic human factors are critical to the performance of Ranger TSX, and to future operational robotic servicers. Of primary importance to a ground-controlled telerobot is the effect of communications time delay. Ranger TSX is commanded through the shuttle Ku-band link, and will have a probable time delay in excess of one second. In order to get a direct comparison, Ranger will also be controlled by on-board astronauts. However, little is known about microgravity work station design for complex telerobots.

To understand the effects of human control in the fine scale, the Ranger TSX Investigator Team has developed
a sequence of control cases, each correlated to the adjacent case. For the first case of each correlative task, Ranger will be controlled from a simple shuttle middeck control station. This will have only the latency inherent in the Ranger control system, which is designed to be less than 100 msec. The same crew will repeat the task, artificially inducing time delays representative of TDRSS communications. Since the only change in test conditions is the addition of time delay, this data provides a direct correlation of human performance with and without time delay. The same task is then repeated from the ground, using a control station which replicates the views and interface limitations of the flight control station. This will provide a simple correlation of the effects of microgravity on the control process, although this step is complicated by the necessary use of different operating personnel. Finally, the same ground controllers will repeat the task for a fourth set of data, using an advanced ground control station. This advanced technology control station incorporates predictive displays, advanced 6DOF hand controllers, and virtual reality presentation of stereo imagery from Ranger. This last step will demonstrate the capability of current technology to ameliorate the effects of time delay, and will provide an ultimate correlation between on-orbit control and the current best approach to mediated ground control in the presence of time delays. Correlative data in this approach will consist of both operational performance (time to complete a task), as well as data quantifying the process of learning and adaptation to repeated performance of a task. For this reason, the primary task to be performed under this objective will be the removal and replacement of a Remote Power Control Module from ISS. This task is designed for robotic actuation, and is quite straightforward for Ranger. Since each repetition will require less than ten minutes, this task will be performed repeatedly in each of the four modes described above.

Perhaps of primary importance to the external community will be the issue of telerobotic performance assessment. The critical requirement in this category is to quantify the capabilities - and the limitations - of dexterous space telerobots against realistic tasks. The simplest of these will be the RPCM task described under the human factors section. This represents the easiest test case, and data from the human factors testing will directly satisfy the requirements of the operational performance assessment.

To challenge the test subjects more often, the Investigator Team has also selected the Electronics Controller Unit (ECU) changeout from Hubble Space Telescope (HST). This task, which has been performed EVA on past HST servicing missions, was not designed for robotic servicing and is beyond the capabilities of SPDM. The orbital replacement unit (ORU) has no handle for manipulation, and controlling the position of the ECU for reinsertion will require a specialized Ranger end effector to rigidly grasp the EVA tether ring, which is the only mechanical interface to the unit. This task requires coordinated dual-arm operations, as one arm will secure and control the ECU while the other releases the launch clamps (four J-hooks) and then does an end effector changeout to a right-angle drive tool to release the unit from the cradle. This process is then reversed to reinsert the unit. This task, while not of primary interest for quantitative correlation, will be repeated in each of the four control modes described above. The HST ECU task is of intermediate difficulty in the Ranger TSX task set.

The most difficult task selected is also the most useful operationally. One of the ways in which dexterous telerobotics may immediately augment EVA capabilities is in worksite preparation. Using the prototype Ranger neutral buoyancy vehicle, the SSL has demonstrated its capability to prepare an HST mockup for EVA servicing, including emplacement of foot restraints, opening access panels, and inspection of the servicing site. For the “difficult” task, the Ranger TSX team has selected the articulated portable foot restraint (APFR) system designed for ISS. For this activity, Ranger TSX will remove an actual APFR from its launch restraints, place it in a WIF socket, and adjust it to a predetermined attitude, then reverse the process to restow the unit. This task will verify the ability of a telerobot to perform a task which currently takes a significant amount of limited EVA time to accomplish, and will demonstrate the potential of dexterous telerobots to make a significant near-term contribution to on-orbit operational capabilities. This will be the most complex of the operational tasks chosen for Ranger TSX, and will require all of a planned four-hour test session to accomplish fully. For this reason, this task will not be used for formal correlation data, and will only be performed under on-board control without time delay and under ground control with all of the time delay mitigation technologies active.

Current plans are for Ranger TSX to be active in four-hour blocks, at 12 different times over the course of the shuttle mission. All test objectives will nominally be satisfied after ten test sessions, leaving the last two to make up missed test points or to allow the principal investigator to select additional test points where the data appears particularly useful.

The final science category is that of simulation.
correlation. While the Ranger TSX team has developed a computer graphics simulation for procedures training, the critical operator training and baseline science data collection will be performed using the Ranger Neutral Buoyancy Vehicle II. This unit, a high-fidelity underwater duplicate of the Ranger TSX flight robot, will be used in the University of Maryland Neutral Buoyancy Research Facility to verify flight software, train both the astronauts and the ground control personnel from the University of Maryland, and to develop procedures and ground truth data prior to flight. Flight data will be compared to the neutral buoyancy data to provide a direct quantitative correlation between the two environments. This will allow the use of almost two decades of SSL data in underwater simulations of space telerobotic operations to develop a correlated data base on telerobotic capabilities, which would be of great use to mission planners and systems analysts in better understanding the utility of dexterous telerobotics in future operational tasks.

5 Conclusions

The National Research Council of the United States has given a clear and unambiguous endorsement of advanced telerobotics, and specifically Ranger, as being of great value to NASA. In its 2000 report Engineering Challenges to the Long-Term Operation of the International Space Station, the NRC stated “NASA’s plan for using robotic devices for the maintenance and servicing of the ISS after Assembly Complete is not as well developed. In fact, a compelling case can be made for incorporating new robotic technology in this phase of the program.” They expand upon the specific capabilities of Ranger by stating, “A robotic system with Ranger’s capabilities could access objects in the tight confines of the assembled ISS structure that would not be accessible with the robotic systems now planned for the ISS (i.e., the SSRMS and SPDM). A Ranger vehicle would also be able to service the ISS without disturbing the microgravity environment.” The discussion concludes with “The potential for incorporation of any of these capabilities into the ISS program is remote, however, until they have been demonstrated in flight.” All of this was summarized in a formal recommendation of the report: “Recommendation: The National Aeronautics and Space Administration should continue to explore advanced robotic technologies that have the potential to increase the efficiency of human-robotic teams on board the International Space Station. This should include space flight testing of the Ranger vehicle as a proof of concept.”

With a successful Ranger test flight, the data collected and disseminated as described in this paper will form the existence proof, with quantified performance data, for highly dexterous space telerobotics using standard EVA interfaces. Threatened by the lack of discretionary flight opportunities in the current shuttle manifest, Ranger TSX is the best near-term opportunity to show what telerobotics can do to improve our capability for routine operations in space.