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The Ranger Robotic Satellite Servicer and Its Autonomous Software-Based Safety System

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Bold exploration missions proposed for the Moon and Mars will require a significant robotic presence on and above these extraterrestrial bodies. Building on the recent success of the Mars rover pair, planetary surface missions will likely grow significantly in preparing the Moon and Mars for human presence. Orbiting spacecraft will also play a key role in planetary exploration, with tasks ranging from science data collection—such as weather monitoring on Mars—to the formation of communication and navigation networks that support surface operations.

Given high launch and support costs, safety and reliability are critically important throughout every mission. Capable onboard software is emerging to efficiently and robustly manage both routine operations and anomalous system behaviors, including failures. These missions, however, have achieved autonomy on a system-specific basis, particularly when sensors or knowledge of the remote environment is limited.

NASA and the US Department of Defense have considered robotic spacecraft servicing as a means to refuel, repair, and upgrade spacecraft systems. As an example, the Hubble Space Telescope has acquired a wealth of astronomical data over a mission extended through hardware upgrades provided by Space Shuttle astronauts on extravehicular activity (EVA). As the aging HST nears the end of its life, significant public support exists for launching a servicing mission to extend its lifetime and prepare for de-orbit. Given risks associated with servicing by a shuttle crew, NASA has pursued robotic servicing alternatives, providing an opportunity to both extend HST's mission and demonstrate the ability to perform satellite servicing without astronaut EVA.

The University of Maryland's Ranger robot is a teleoperated dexterous manipulator platform designed to perform the kind of on-orbit satellite servicing that Hubble requires. Its manipulators offer tool tip velocities exceeding eight meters/second, operating close to delicate space hardware that can't be damaged. Safety, which is of paramount importance, is handled autonomously—and exclusively—by the robot's computer control system.

Here we describe the Ranger robotic system and its autonomous hazard control system, which is designed to meet the stringent criteria imposed on space shuttle payloads. Mature Ranger systems have enabled evaluation of telerobotic servicing tasks in a variety of 1-g and neutral buoyancy environments. These evaluations have included rigorous testing with operators that ranged from experienced system designers to small children who frequently activate the safety system as they operate manipulators without skill or caution. Originally developed to demonstrate space-based robotic servicing as a shuttle payload, Ranger has subsequently evolved into an Earth-based test bed for robotic servicing tasks.

This article summarizes tests performed to date, particularly regarding the safety system, and describes ongoing

Editor's Perspective

NASA has announced a bold new direction for the agency, specifying renewed objectives for space exploration—a return to the Moon, with humans on Mars as the ultimate objective. As never before, there will be great emphasis placed on how humans and robotic systems will work together to accomplish mission and program objectives within a robust and extensible system of systems architectural approach. Already, NASA's lead field centers for human exploration (Johnson Space Center) and robotic exploration (Jet Propulsion Laboratory) have begun to school each other on their mission operations concepts and lessons learned in preparation for the challenges and excitement ahead.

Research at the University of Maryland on the Ranger robotic satellite servicing system already has been tackling some of the central technical issues that will be relevant: How to assign tasks and responsibilities appropriately across the human-machine interface boundary, particularly when communications delays are present? How to validate that the robotic system, when commanded remotely and at a high level, will "do the right thing"? Notable results from the Ranger research program as described here have this work well positioned to make important contributions to NASA's future human-robotic systems.
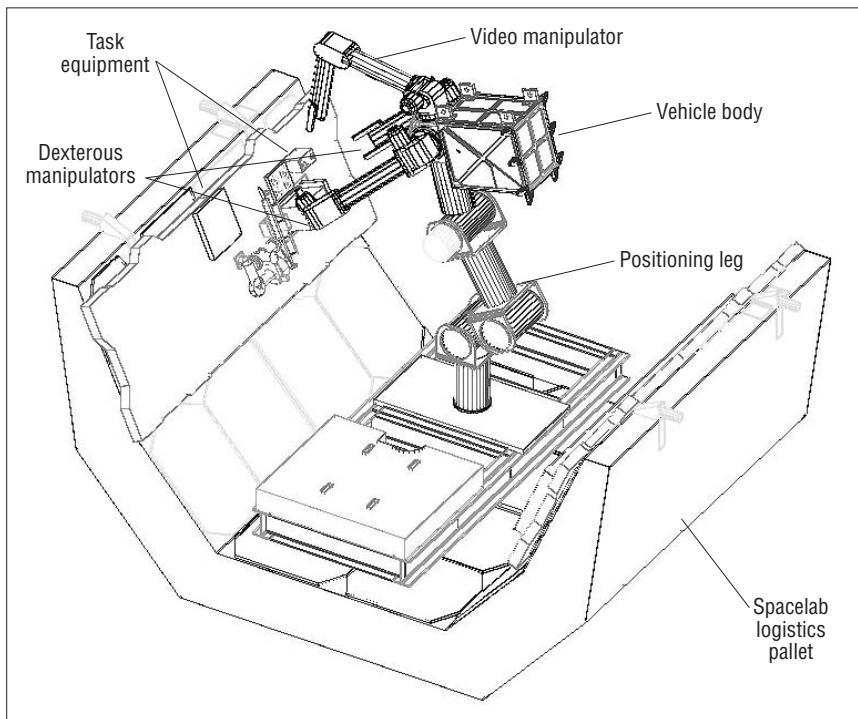
—*Richard Doyle*

Figure 1. Ranger satellite servicing system in its Space Shuttle configuration.

work to apply Ranger technologies with higher autonomy levels to new robotic systems, including an ambitious project to autonomously collect geologic and biologic samples around hydrothermal vents under the Arctic icecap.

System configuration

The Ranger satellite servicing system is designed for on-orbit robotic servicing of spacecraft and satellites, a task requiring multiple manipulators to grapple a satellite or component, provide video feedback to operators, and execute tool-based operations on components being serviced. The robot consists of a central body housing the main computers and serving as a base platform for all the manipulators, any subset of which can be used during a test. Ranger has two eight-degree-of-freedom dexterous manipulators for object manipulation and a seven-DOF video manipulator for positioning a stereo camera.

Its positioning leg anchors it to a fixed base, which could be modified to enable grappling or docking to a spacecraft. Each manipulator is approximately two meters long, giving a total vehicle reach from the base of the positioning leg to the tip of an outstretched manipulator of about 4.5

meters. The custom-designed joints are capable of 45 deg/s velocities and 900 deg/s^2 acceleration, with tool-tip velocities in excess of eight meters per second. It's also capable of exerting 130 Newtons and 40 N/m in any direction at each dexterous tool tip.

As a sample workspace configuration, Figure 1 shows the Ranger Telerobotic Shuttle Experiment (RTSX) in which Ranger was to have flown aboard NASA's Space Shuttle. This flight demonstration experiment was to show on-orbit robotic servicing, principally by replacing standard orbital replacement units (ORU) from both the International Space Station and the HST. These activities require numerous dexterous tasks of varying difficulty and fidelity, including

- Loosening and tightening bolts
- Task equipment removal and reinsertion
- Grasp and turn activities
- Coordinated dual manipulator motions

Manipulator end effectors to accomplish these tasks include straight-line bolt drivers, right-angle bolt drivers, multiple forms of parallel-jaw grippers (with different sets of "fingers" attached, to enable

grasping of differently shaped task parts), as well as customized end effectors for specific tasks.

To build a system model for the safety software, objects in the workspace fall into two types: contactable and noncontactable. Contactable objects are those designed to survive a worst-case robotic impact and include the robot itself, manipulator end effectors, all task equipment, and the robot's latching mechanism. Noncontactable objects are all other objects, and in the case of RTSX, consist of those that can't absorb more energy than standard NASA EVA kick-loads.[1] These include the shuttle itself, other payloads, and portions of the spacelab logistics pallet (SLP) that are not covered by contactable objects.

The typical control station configuration shown in Figure 2 provides each of two operators with a computer display, multiple video feeds, and hand controllers for manipulator control. The operator control stations communicate with the vehicle using standard Internet protocols, so they can be located at any remote location. Ranger's basic system configuration is representative of any remotely teleoperated robot. Issues of a remote operator being less contextually aware of the environment, and of simple human mistakes, are prevalent with many teleoperated robots.

The unique factors for space-based robots, including Ranger, are increased radiation, operation within a drag-free 0-g environment, and communication time delays, on the order of 2 to 7 seconds for Ranger due to speed-of-light limitations and multiple satellite signal relaying between the shuttle and the Houston payload operations center. The first two conditions were important factors when building the software-based hazard control system: On Earth, letting go of an object doesn't potentially allow it to float away and cause damage elsewhere in the environment, nor do Earth-based systems suffer the same radiation upsets as orbiting spacecraft.

A manipulator operator is continually interested in where to place the manipulator tool tip, how much force the manipulator is applying, how fast it's going, and where the current object of interest is in relation to the tool tip. This involves a continuous process of selecting appropriate video views (including graphically simulated views), mentally synthesizing multiple views into a 3D model of the environment, selecting a

strategy to grasp or activate a part, and actually directing the manipulator tool tip to the location of interest. Although the tool tip is the manipulator's primary point of interest, the operator must also be cognizant of the manipulator's pose in respect to its environment, particularly the elbow, which might jut out and interfere with other objects. Underlying the operator interface is robust navigation and control software that translates commanded end effector trajectories into smooth, collision-free joint motions.

Hazards

As with all robotic systems, Ranger must deal with the possibility of component or system-wide failures, without damaging equipment or injuring or killing human beings. Its unique operating environment presents additional possible failure modes. The space shuttle configuration will encounter three basic hazards:

- Manipulator motion physically damages the shuttle or prevents a safe return to Earth, such as by preventing the payload bay doors from closing.
- Releasing an untethered object—for example, an orbital replacement unit—damages the shuttle or becomes orbital debris.
- Excessive force or torque breaks an object such as an orbital replacement unit restraint bolt, with the subsequent pieces damaging the shuttle or becoming orbital debris.

Traditional fault-tolerant approaches such as "human in the loop" or mechanical clutches will not work to control these hazards, which lead to the design of a computer-based, autonomous safety system for Ranger.[2] The component failures that could cause any of these hazards, and hence must be dealt with by the autonomous safety system, are

- *Hardware failure.* Includes failures of sensors, actuators, and I/O operations.
- *Computer failure.* Includes code defects and upsets from radiation.
- *Communication failure.* When two or more processors fail to communicate correctly or prevent other computers from being informed of a failure or impending hazard.
- *Operator error.* The operator attempts to execute a command that would result in a hazard.

Figure 2. Typical Ranger operating configuration.

Actuator motion causes all these hazards: physically damaging nearby equipment requires the manipulators to move, releasing an object requires the grippers to open, and applying force or torque requires actuator motion.

Table 1 describes how individual failures can cause a particular hazard, showing how we can reduce the number of computer controlled hazards to two: motion caused by an illegal command and uncommanded motion.[3] The "Autonomous Safety System" sidebar describes the software architecture deployed on Ranger to cope with these hazards.

Application to satellite servicing and beyond

The first Ranger dexterous manipulator began operating in April 2002, followed by a positioning leg in October 2002 and a second dexterous manipulator in April 2003. These three manipulators, along with two separate vehicle systems (comprising the necessary power, air, and computing facilities to support operations), have served extensively in multiple lab settings, as well as in a neutral buoyancy environment. To date, the positioning leg and one dexterous manipulator have over 40 hours of continuous operations underwater. Between them, the two dexterous arms have more than 250 hours of operational time in the lab environment.

Current operating modalities

Ranger currently operates in a lab setting and under water in the Neutral Buoyancy Research Facility at the University of Maryland Space Systems Laboratory (SSL). Fig-

Table 1. Methods by which a component failure can cause a hazard.

| | Hazard | | |
FAILURE	PHYSICALLY DAMAGE SHUTTLE	RELEASE UNTETHERED OBJECT	OVER-TORQUE AN OBJECT
Hardware	UM	UM	UM
Computer	UM, IC	UM, IC	UM, IC
Communications	IC	IC	IC
Operator	IC	IC	IC

IC   Illegal command
UM   Uncommanded motion

Autonomous safety system

Ranger's autonomous safety system is designed as a fail-safe system. The vehicle has two fundamental system states: safe, in which it can't cause a hazard, and operating. The system safe state occurs when the control system detects a failure; in this state, all motors are incapable of motion due to three independent inhibits, which satisfies two-fault tolerant requirements.

Figure A shows the computer architecture that implements the hazard control system. The onboard local processing units handle joint level control and interact directly with the robot's sensors and joint actuators. The power management units control power relays that feed power to the LPU computers and to the joint actuators. The two data management units communicate with the control stations, all LPUs, and the PMUs. The main DMU executes the arm control algorithms, while the monitor DMUs acts primarily as a safety monitor.

We performed software verification according to a NASA-certified, formal software development process that included extensive unit, integration, and system testing, as well as inspection of all safety-critical code. All safety-critical functionality resides solely onboard the robot; the control stations don't participate in decisions regarding safety. This approach simplifies the software verification process by removing the control station and communications subsystem from safety considerations. We also made this decision because hardware failure of control station input devices is indistinguishable from a malicious operator attempting to drive the robot to cause a hazard. Hence relying on operator input through a control station for safety critical functions introduces the possibility of inadvertently executing hazard functions.

The onboard safety system uses only the vehicle's actual telemetry in determining whether a hazard is imminent; the computers do not attempt to process, filter, and reject commands that would cause a hazard. Given the workspace's complexity and the dexterous manipulators' complexity and speed, preprocessing all commands before acting on them would impose a substantial processing burden on the computers. This processing would interfere with Ranger's stringent real-time deadlines imposed by the arm and joint control algorithms, thereby increasing the possibility of instability. The preprocessing would also introduce substantial additional complexity, increasing the burden of software verification and the likelihood of system failure.

This software safety system was the first such system to be certified by NASA under the Computer Control of a Hazardous Payload specification.[1] This approach differs from the traditional NASA fault-tolerant approach, in which human or mechanical elements are required to control hazards and also because it doesn't require extensive sequence validation of software commands.

Passive concurrence

Although each LPU and PMU receives commands from both DMUs, no form of active concurrence occurs between the two DMUs. Each LPU and PMU simply takes the "most-safe" of the commands each DMU supplies. This form of passive concurrence reduces the communications system's complexity and also lets each DMU be independent from the other DMU.

An example is a command to change an LPU's operating state (see Figure B). Possible states are

- *Safe,* in which the LPU is incapable of causing a hazard
- *Halt,* in which the LPU isn't asserting its electronic motor inhibits but is commanding the motor to be stationary
- *Running,* in which the LPU is actively servoing its actuators

If one DMU illegally commands running while the other DMU correctly commands safe, the LPU selects the most-safe command, the safe state, and notifies the system of the discrepancy.

Energy impact analysis

Energy impact analysis served in determining the minimum allowable separation distance between any part of Ranger and any noncontactable object.[2] The safety-related goal was to guarantee failures causing uncommanded motion couldn't impart excessive energy before the system detected the failure and transitioned to a safe state. This minimum distance is a function of the robot's reaction time, the maximum operating velocity, the inertia seen by the manipulator, and the distance the manipulators will take to drift to a stop when power is removed from the actuators.
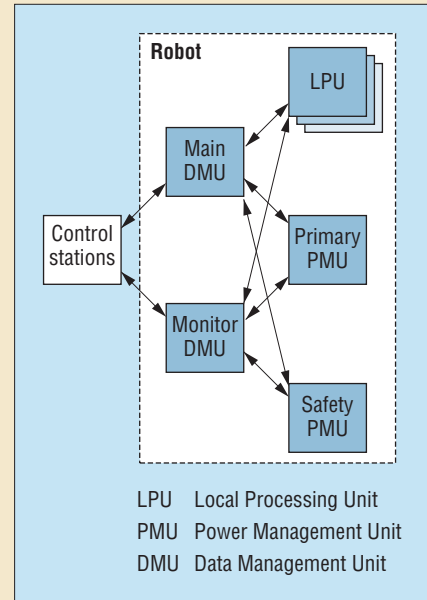
Figure A. Ranger computer architecture.

LPU   Local Processing Unit
PMU   Power Management Unit
DMU   Data Management Unit

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ure 3 shows a recent test during which a manipulator grasped and maneuvered a mock-up of an HST scientific instrument.

The dexterous arms have also spent many hours operating in a 1-g lab environment, evaluating grappling tasks and ORU replacements. Figure 4 shows a pair of dexterous arms cooperatively removing a mockup of an HST electronics control unit (ECU).

In the early summer of 2004, we took a pair of dexterous arms to the Proximity Operations Testbed at the Naval Research Laboratory in Washington DC, to demonstrate proximity grappling and servicing operations. Figure 5 shows an HST ECU mockup being removed while Ranger is suspended over 7.5 meters in the air on the end of an NRL robot. These tests involved over 25 separate ECU removals and insertions, all carried out over video feed by a distant operator.

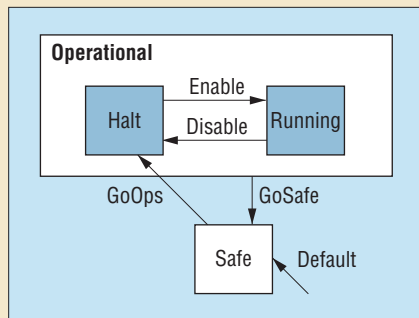## Observed system performance

The software safety system is fundamen-

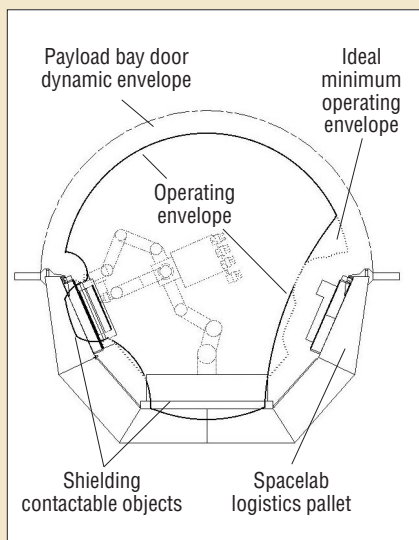**Figure B. Local processing unit state chart.**

Figure C. Operating envelope for dexterous manipulators in space shuttle configuration.

Given a system-wide worst-case reaction time of 0.030 seconds, the analysis determined a maximum operating velocity of 20 cm/s and a minimum approach distance of 30 cm for the dexterous manipulators, and 12 cm/s and 2.5 cm, respectively, for the positioning leg (the large difference between these numbers occurs as the positioning leg is the only manipulator with brakes).[3]

Figure C shows a 2D cross section of the spacelab logistics pallet and Ranger, along with the operational envelope for the dexterous manipulators. The envelope is a conservative simplification of the concatenation of the minimum approach distances from all noncontactable objects. In some cases, the operational envelope appears to go below noncontactable objects, which is acceptable as a sufficiently strong contactable object is shielding the noncontactable object. Recall that all contactable objects are built to survive a worst-case robot impact and so are designed to take substantially more than the NASA standard EVA kick-load for which noncontactable objects are designed.

Vehicle-wide safety checks

The two DMUs are the only computers with vehicle-wide knowledge and, in particular, complete kinematic knowledge of the manipulators. Both DMUs execute a suite of safety algorithms that monitor robot telemetry and prevent the creation of hazards. The primary components are

- *Position.* Enforces the minimum approach distances determined by the impact energy analysis to prevent position violations.
- *Velocity.* Enforces the system wide maximum velocity determined by the impact energy analysis.
- *Inadvertent release of task equipment.* Prevents release of untethered task equipment in the payload bay from damaging the shuttle or causing orbital debris.
- *Excessive force or torque of an interface.* Prevents breaking off, or damaging, of fasteners or task equipment that subsequently damage the shuttle or cause orbital debris.

Of these four safety components, only one—position—is independently developed;[4] the other three components are identical on both DMUs. The independence of the two computers arises because the two DMUs each use different position data (each joint in the robot has three independent position encoders of differing technology). The claim of higher reliability of independently developed programs—and that independently developed programs fail independently—has been controversial in recent years.[5–7] In this instance, we have deemed the data to be sufficiently independent that coincident failures are not considered credible.

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tally responsible for preventing undesirable manipulator motion—or runaway, the uncommanded motion by one or more motors. To assess the performance of Ranger's software safety system, we have characterized how many runaways the system has suffered and for what reasons.

In the course of the over 250 hours of Ranger system operations, only three system failures, or runaways, have occurred.

In the first, the system failed to detect a damaged joint encoder that subsequently caused a runaway. This runaway occurred during development, when an operator disabled a safety check, and isn't possible in the software's flight build.

In the second, a defect in the system specification caused the control station to incorrectly bound an input parameter. Subsequent hand controller inputs caused a large amount of motion. This is a case of uncommanded motion caused by a failure in the system specification, rather than being a system runaway. In this case, the
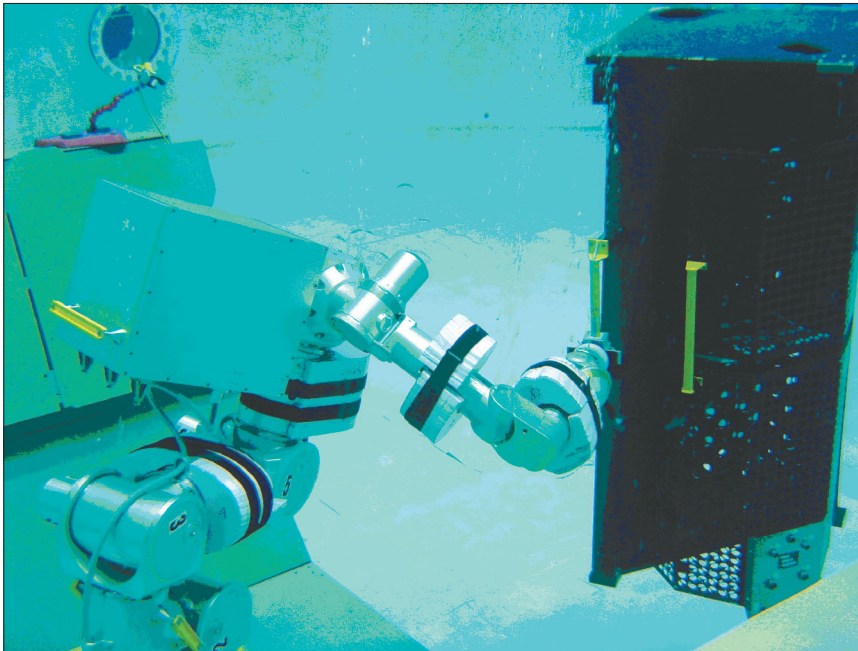
Figure 3. Ranger operating in the University of Maryland Neutral Buoyancy Research Facility.

autonomous safety system lets the motion occur so long as the vehicle is operating away from its workspace boundaries. The safety system only takes action when a potential hazard could occur, in this case only when the manipulator violates a work-

space boundary.

Finally, poor power supplied to an LPU held the LPU in reset, preventing it from safing the local motors, resulting in uncommanded motion. This runaway occurred in a development system configuration that did-

Figure 4. Cooperative removal of a Hubble Space Telescope electronics control unit mockup.

n't have working PMUs. In the fully deployed system, both DMU computers would have identified an LPU that was not communicating correctly. In turn, they would have safed the arm, which includes instructing the redundant PMUs to remove power from the arm's motors. This would have prevented the uncommanded motion from occurring. The total time elapsed from the LPU being held in reset to the PMUs removing power is less than 30 ms, a number determined through theoretical analysis and verified through hardware testing.

Roadmap to autonomous operation

Providing semiautonomous or ultimately autonomous control to any manipulation-based space robotic platform such as Ranger will offer a multitude of possibilities for servicing and construction activities. In the short term, the equivalent of a first-generation flight management system for space-based operations must be provided as a supplement to the software safety system to free ground controllers of the stress associated with managing each detailed motion of each manipulator.

Consider for example the removal of an ORU secured by several bolts. With strictly teleoperated control, a ground operator commands each continuous six-DOF end effector trajectory with time-delayed video feedback, a task that exacts a significant toll in a relatively short time period. For Ranger, the implementation of a predictive display GUI, shown in Figure 6, mitigates the effects of time delay, a strategy that has great potential given the high-precision controller present on Ranger to ease workload for Earth-orbiting operations with communication delays on the order of seconds.[4]

However, even small joint position errors can cause discrepancies in end-effector motion that is magnified over time, particularly when the attachment between the robotic servicer and spacecraft isn't perfectly rigid. As time delay increases to the order of minutes, as would be the case for Earth-based control of robots in orbit around Mars, the accuracy of the predictive display might also degrade, and the operator must additionally correct for these errors.

As a bridge between teleoperation and fully-autonomous control, consider a task "remove bolt 2." Initially, the manipulator is directed to "proceed to bolt 2," specifically a position near but not exactly on the bolt. Beyond capabilities already available
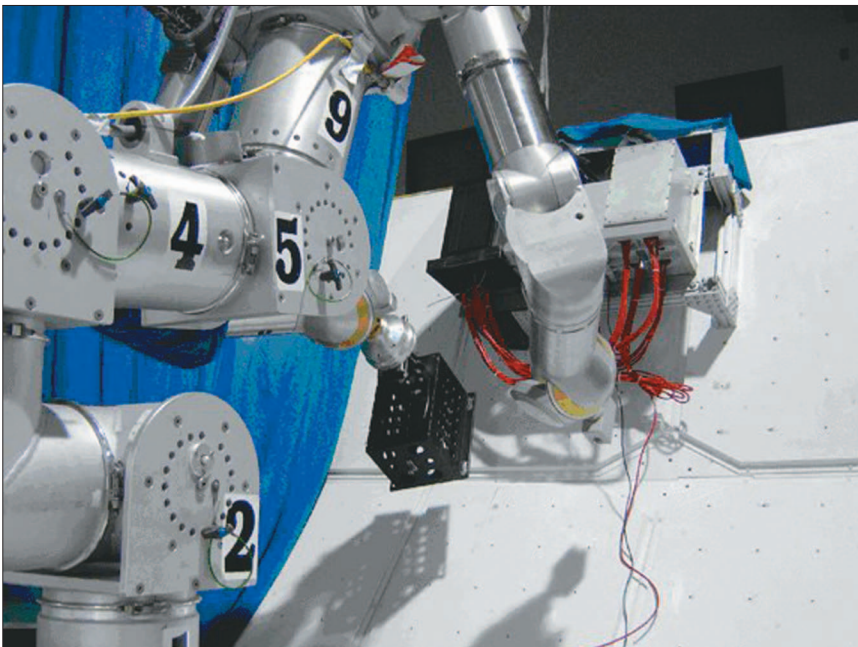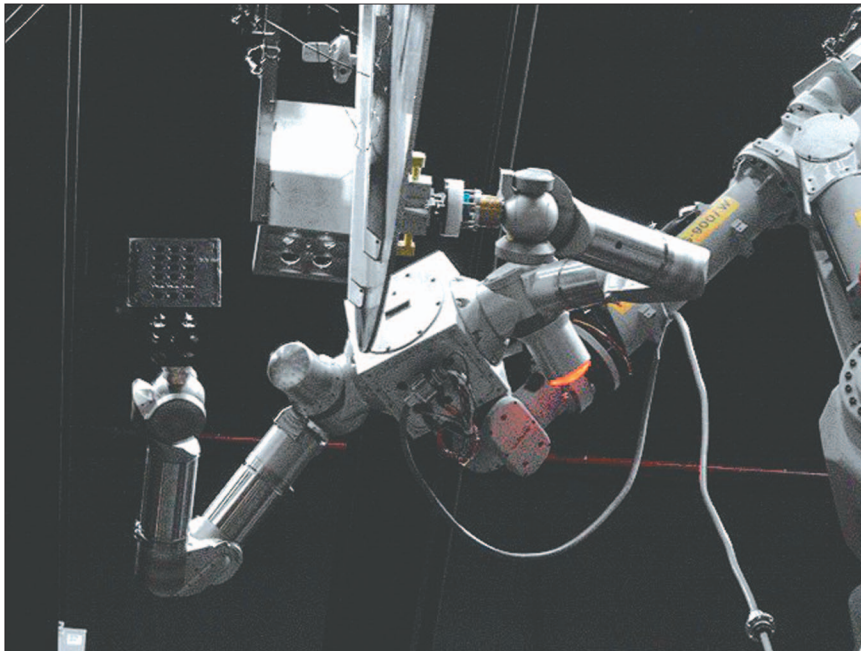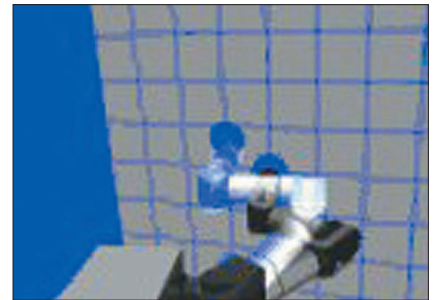
Figure 5. A suspended Ranger removing a Hubble Space Telescope electronics control unit mockup at the Naval Research Laboratory's Proximity Operations Testbed.

Figure 6. Display of predictive and commanded manipulator positions.

on Ranger, this action requires a computer model of the ORU/fastener geometry and knowledge of the manipulator position (grapple/attachment point) relative to the spacecraft. It doesn't require extensive relative navigation, however, because the manipulator is controlled to sufficient precision (0.25 inches) to prevent collision at close proximity to the bolt.

The "proceed to bolt 2" directive would be achieved autonomously, giving the controller a break during motions not requiring extremely precise relative navigation. Such autonomy is possible with current Ranger hardware given automatically generated six-DOF end-effector paths built from a standard spline-based curve fit to the "bolt 2" locale.[5] As with teleoperation mode, the autonomous safety system can interact with the joint trajectory guidance module to guarantee the computed trajectory follows a collision-free path. The human controllers

would then teleoperate the final precision operation to actually place the tool tip on the bolt. This semiautonomous mode of operation will reduce direct operator control from 100 percent to a small fraction of the total operation time without necessitating additional sensing technology.

As technology matures and we gain more experience with space robotic operations, we can then work toward a fully-autonomous operational mode that requires accurate relative navigation techniques ranging from machine vision to laser scanners to ensure successful completion of contact tasks such as bolt removal or insertion. We can also facilitate autonomous operation by deploying spacecraft designed to accommodate robotic servicing, moving beyond the model where fasteners (such as hex-head bolts) mimic those found in mechanisms on Earth.

A significant amount of neutral buoyancy testing with Ranger is underway to study the tasks and procedures required to robotically service HST. Although the current baseline is
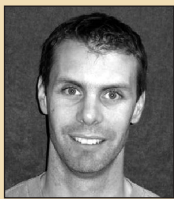
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to conduct most of the robotic servicing via teleoperation, neutral buoyancy testing will enable quantitative assessment of Ranger manipulation accuracy during all phases of servicing that will enable the definition of "autonomous" versus "teleoperated" regions in close proximity to the spacecraft structure. Conducting these evaluations will let us study the same task—removing and inserting a camera from the telescope—as it's conducted via teleoperation, supervised autonomy, and full autonomy.

Extending this work even further, SSL has teamed with Woods Hole Oceanographic Institute (WHOI) to develop technologies enabling autonomous planetary sample collection by merging NASA-supported robotics technologies with advanced autonomous undersea vehicles. Earth-based evaluation of these autonomous sampling capabilities will involve a new, more compact manipulator derived from Ranger software and hardware technologies that can withstand 5,000-meter seawater depths. We will integrate this manipulator to an autonomous underwater vehicle being developed by WHOI. The resulting fully autonomous system will sample hydrothermal vent areas under the Arctic Ocean. This mission requires full autonomy as tethered or high-bandwidth wireless communication under the Arctic icecap isn't an option.

Some early tests will be done by using existing Ranger manipulators to autonomously grasp targets, both in 1-g and in the Maryland neutral buoyancy facility. Sea trials will be accomplished by mounting the deep-sea arm on a piloted WHOI vehicle such as Jason II that provides extensive real-time feedback to the vehicle operator while manipulator sampling tasks take place autonomously. As this mission develops, the team will move the manipulator to an untethered WHOI AUV named SeaBED and will enhance vision, thermal, and potentially laser-based relative navigation technologies for autonomous sampling tasks that'll be transferable to space-based applications where robots are tasked with building, repairing, or refueling the spacecraft that will monitor and support missions on Earth, the Moon, Mars, and beyond. ◼

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