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Robotic Capabilities for Complex Space Operations

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ABSTRACT

This paper reviews the many potential applications of robotics technology to current and future space operations, with particular emphasis on the experience base of the University of Maryland Space Systems Laboratory. A pedagogy is presented wherein space operations are broken down into the following areas: docking, assembly, inspection, maintenance, assistant, and training. A brief description of each area shows requirements for specific robotic capabilities to accomplish or improve the current performance of these tasks. Specific examples are presented based on relevant Space Systems Laboratory experience in each area, drawn from two decades of research with seven major integrated robotic test beds, along with extensive experience in human-robotic cooperation.

INTRODUCTION

For the last 25 years, the Space Systems Laboratory (SSL) has been exploring the application of advanced telerobotic technologies to space operations. The focus of the laboratory has been to develop and test systems capable of performing complex end-to-end on-orbit tasks in a neutrally buoyant environment, as well as to perform integrated testing of humans and robots working cooperatively in the simulated space work site. This work has led to the development of a number of integrated robotic systems, including:

- Beam Assembly Teleoperator (BAT), a structural assembly system
- Multimode Proximity Operations Device (MPOD), an orbital maneuvering vehicle simulator
- Stewart Platform Augmented Manipulator (SPAM), a fixed-base positioning system
- Supplemental Camera and Maneuvering Platform (SCAMP), a free-flying camera platform
- SCAMP Space Simulation Vehicle (SSV), a high fidelity neutral buoyancy simulation of vehicle space flight dynamics
- Ranger Telerobotic Flight Experiment (RTFX), a robotic prototype testbed for satellite inspection, maintenance, refueling, and orbit adjustment

These systems have demonstrated such capabilities as the telerobotic rescue of incapacitated extravehicular activity (EVA) astronauts, cooperative satellite servicing, and robotic refurbishment of the Hubble Space Telescope. Currently, the SSL is developing the Ranger Telerobotic Shuttle Experiment, a space shuttle-based experiment to demonstrate dexterous robotic on-orbit satellite servicing, in anticipation of a launch in 2003. With over twenty years of experience in developing and operating these systems, the lessons learned from thousands of Space Systems Laboratory test operations form an illustrative background for a discussion of future robotic roles in space operations.

RELEVANT SSL BACKGROUND

The Space Systems Laboratory is focused on experimental research aimed at understanding and improving space operations. In existence since 1976 and located at the University of Maryland (UMd) since 1990, the SSL is a world-class center for advanced research into space human factors and telerobotics. The underlying paradigm of the SSL is to develop and test complete systems, fully capable

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of performing complex space tasks end-to-end in the underwater environment as the best long-term simulation of weightlessness available on Earth. Current research in the SSL is focused on space robotics, extravehicular activity and space suit design, space human factors and bioinstrumentation, space applications of automation and artificial intelligence, and theory and application of adaptive nonlinear control. The SSL currently has four robotic systems either in development or under test, including a telerobotic flight experiment being developed for NASA for flight in 2003. Due to its emphasis on high fidelity experimental simulation and full-scale testing, one of the unique capabilities of the SSL is to perform integrated testing of humans and robots working cooperatively in a space work site.

The University of Maryland Neutral Buoyancy Research Facility (NBRF) is one of only two such operational laboratories in the United States, the other being the Neutral Buoyancy Laboratory used for flight crew training at the NASA Johnson Space Center (JSC). Shown in Figure 1, the UMd NBRF is the only neutral buoyancy facility dedicated to basic research, and the only one in the world to be located on a college campus. About 150 tests per year use the 50-foot diameter, 25-foot deep-water tank for underwater simulation of the space microgravity environment.

To develop state-of-the-art robotic systems requires a corresponding committment to facilities. The Space Systems Laboratory includes a mechanical parts fabrication area, with computer-controlled mill and lathe and a fused deposition rapid prototyping machine. A space-flight certified electronics laboratory allows internal fabrication and testing of electronics, and a class 100,000 clean room is currently in use for the fabrication of the Ranger Telerobotic Shuttle Experiment.

Figure 1
SSL Personnel, Robotic Systems, and Neutral Buoyancy Research Facility

The basic tenet of the SSL from its inception has been to maximize the involvement of students, at all levels, in the research activities of the lab. Currently 21 graduate students are performing research in the SSL, with 30 undergraduates employed part time and involved integrally in the research projects. One of the 3 faculty, 11 full-time staff, or a graduate student mentors each incoming undergraduate. Challenged to apply and continually improve their engineering skills, after several academic terms of involvement a typical undergraduate assignment might be to develop a new system for one of the robots. The undergraduate would design the components using CAD/CAM software in the lab, fabricate the components in the machine shop, assemble and test their system, integrate it to the robot, and (frequently) dive with the robot while the system is evaluated in realistic space operations. The goal of the SSL is to make this type of hands-on experience, incorporating all of the steps of engineering development from design and fabrication through integration and testing, available to as many students as possible within limited SSL resources.

PROJECT DESCRIPTIONS

Since the first robotic system design began in the Space Systems Laboratory, a large number of systems have been brought through development and operations testing. These have ranged in scope from single-student term projects to multi-million dollar flight hardware development projects. To fully review SSL robotic systems would take many times the allowable space in this paper; even to fully describe the major systems would not leave any room for results and discussions. The larger robotic systems that form the basis for many of the results discussed herein are presented in a concise reference form in Table 1. As results are discussed, references are given to publications with more information; these also have more complete descriptions of the relevant robotic systems and results. While not specifically discussed to as great a degree, Table 1 also summarizes the two major development projects currently underway in the Space Systems Laboratory. As MARS Suit and Ranger NBV II near operational status, they will provide a quantum increase in the ability of the SSL to perform cutting-edge research on human-robotic cooperative teams in space operations tasks.

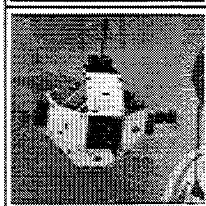
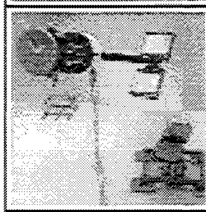
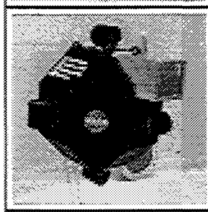
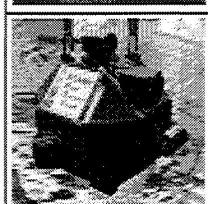
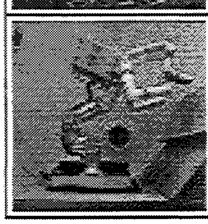
Vehicle/System	Project Title	Capabilities/Applications/Accomplishments	Ops Period
	**BAT** Beam Assembly Teleoperator	6DOF mobility base; 5DOF dexterous assembly manipulator; modular task-specific automation Telerobotic assembly of STS 61-B EASE structure Demonstrated rescue of incapacitated EVA subject; cooperative EVA/robotic HST servicing; advanced control station human factors testing	1984-1997
	**MPOD** Multimode Proximity Operations Device	6DOF mobility base; cockpit for onboard control Role of human sensory modes in free-flight control Performed onboard and remote-controlled docking; maneuvering and berthing of large masses; testbed for nonlinear adaptive control; demonstration of concept for Astronaut Support Vehicle	1986-1999
	**SPAM** Stewart Platform Augmented Manipulator	3DOF positioning arm with interchangeable links; 6DOF Stewart platform wrist for fine positioning Simulation of Shuttle Remote Manipulator System Implementation of innovative water hydraulic system; multirobot control coordination; application of parallel-actuator wrist mechanisms for fine control	1989-1994
	**SCAMP** Supplemental Camera and Mobility Platform	6DOF mobility base; stereo video + closeup image Free-flying camera platform operations Remotely commanded visual survey and inspection; close interactions of EVA and free-flying robots; first robotic system in JSC tanks; first demo of robotic ISS inspection; advanced control modes	1992-
	**Ranger TFX** Telerobotic Flight Experiment (Neutral Buoyancy Vehicle I)	6DOF mobility base; 2x7DOF dexterous arms w/ interchangeable end effectors; 6DOF camera positioning arm; 7DOF grappling arm Telerobotic servicing, assembly, and maintenance EVA/dexterous robotic cooperation; HST and ISS servicing tasks; coordinated arm/body control	1995-
	**SCAMP SSV** SCAMP Space Simulation Vehicle	6DOF mobility base; color video camera; 3-axis gyros, accelerometers, magnetometers; docking hardware Cancellation of water drag effects for flight dynamics Model-referenced vehicle flight control (realistic AERCAM dynamics); adaptive control of unknown docked payloads; autonomous docking	1997-
	**MARS Suit** Maryland Advanced Research/Simulation Suit	Underwater simulation of EVA pressure suit; scars for advanced controls and displays Research on cooperative EVA/robotic operations Under development; planned research on immersive VR simulation environments, suit integration w/ robot control systems, EVA/robot symbiosis	2002-
	**Ranger TSX** Telerobotic Shuttle Experiment (Neutral Buoyancy Vehicle II)	6DOF positioning leg; 2x8DOF dexterous arms w/ interchangeable end effectors; 7DOF camera positioning arm; full capabilities of flight unit Telerobotic servicing, assembly, maintenance, ops Under development; planned simulation and training for Ranger TSX flight, advanced robotic ops	2002-

Table 1
Summary of Major SSL Space Operations Research Systems

REQUIRED ROBOTIC CAPABILITIES

Current and future space operations will require robotic capabilities that span a wide spectrum of complexities and levels of difficulty. While this spectrum could be broken down in a number of different ways, Figure 2 shows a breakdown of needed capabilities based on the general categories of space operations to be performed. *Docking* allows a robot to attach and to move about a worksite. A robot can be used for the *assembly* of complex structures from parts without requiring EVA resources. Once a complex structure is built, it may need to undergo routine *inspection* to make sure everything is working correctly. When a problem is found, a robot may be able to perform simple *maintenance* tasks. A more complex procedure could well require human operations, but could still use a robot as an *assistant* to the human, both to increase task performance and provide increased safety. Finally, the ability to provide high-fidelity *training* for the operators of these robotic systems will increase the effectiveness of the other capabilities.

Docking

Before a robot can interact with the worksite, it first must successfully attach itself to the target spacecraft. Rudimentary docking capabilities for vehicles have been in existence since the 1960's, although the United States still relies on human pilots for operational rendezvous and docking maneuvers.

The Multimode Proximity Operations Device (MPOD), shown in Figure 3, was designed with symmetric mass and shape properties to allow for easier open loop control during docking. Testing included comparisons of onboard and remote control of MPOD [21]. Adding closed loop functionality improved docking performance, including

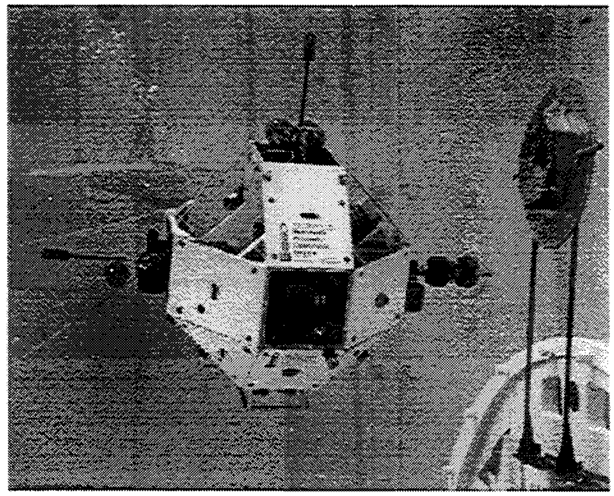


Figure 3
MPOD in Docking Approach

attitude hold [23] and a full three-dimensional positioning sensor suite [17]. The further inclusion and testing of three different closed-loop attitude controllers (a well tuned PD controller, a nonlinear controller, and adaptive controller) facilitated easier docking [16]. A high gain PD controller was the most accurate, but was observed to cause pilot induced oscillations. Analysis showed that a rational intelligent agent acting as a pilot, coupled with a well behaved high-performance vehicle, can also result in an unstable system [15]. Autonomous trajectory following allowed the vehicle to approach and dock with minimal operator effort [11].

The Beam Assembly Teleoperator (BAT) was designed to assemble the same EASE structure that was flown on shuttle mission STS 61-B in late 1985. In parallel with the unrestrained EVA subjects during the EASE experiment on that mission, BAT was designed to assemble the EASE structure while free-flying, rather than

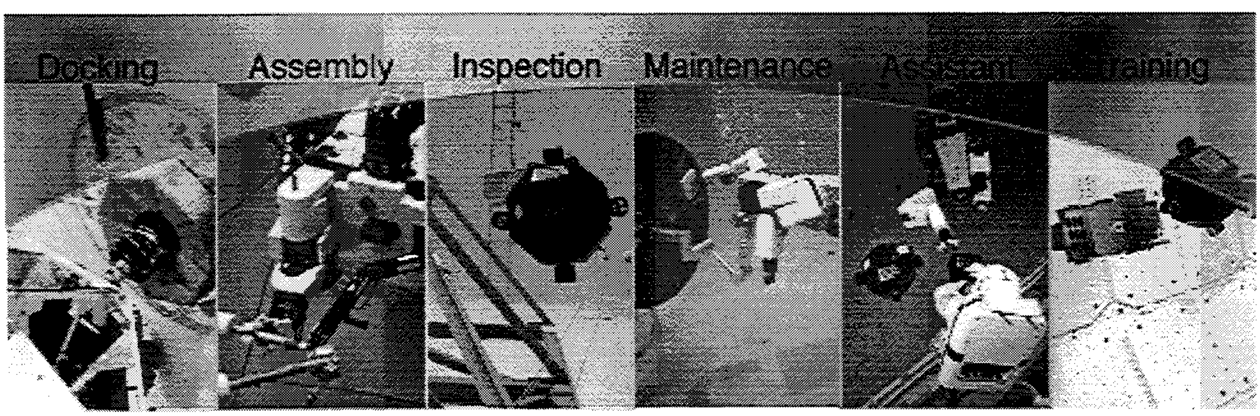


Figure 2
The Spectrum of Space Operations Requiring Advanced Robotic Capabilities

being externally positioned or restrained. During its assembly task (Figure 4), BAT was required to grapple to each component to be assembled, carry it to the work site, grapple to the work site, and attached the new component. At least 21 docking maneuvers were thus required to build a simple tetrahedron truss structure. Although successful with extensive testing, it was found that the flight dynamics of this vehicle made the free flight to grapple task challenging. Free flight to grapple took 33.9% of total assembly time.

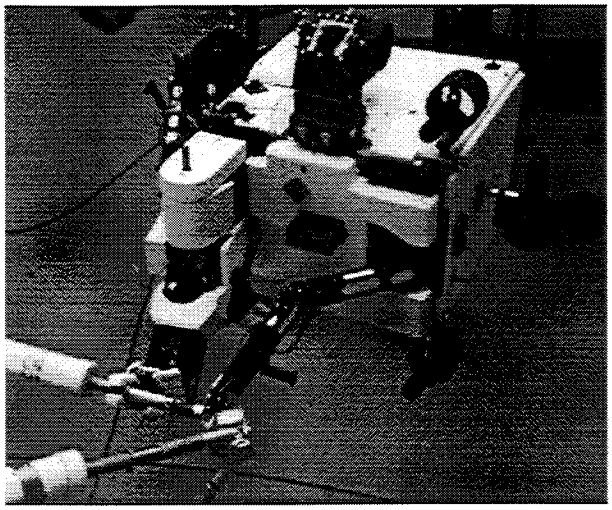


Figure 4
BAT Completing EASE Structure

The Ranger Telerobotic Flight Experiment (TFX) Neutral Buoyancy Vehicle (NBV I) was also designed to provide free-flight mobility. From free-flight, Ranger successfully grappled to an EVA handrail. This was the first demonstration that complex (and relatively massive) robotic systems could interface to existing EVA infrastructure, rather than requiring dedicated robotic interfaces. As a further extension of this demonstration, Ranger successfully maneuvered itself hand-over-hand along EVA handrails, in a manner exactly analogous to astronaut mobility.

Large robotic manipulators are used currently for mating two massive components together, as in the use of the Space Station Remote Manipulator System (SSRMS) to berth modules to the International Space Station (ISS). While this is a highly controllable system for the actual docking, it does not provide for transport of the modules beyond the physical reach limitation of the manipulator. If a module is to be mated to ISS, it must be delivered by a system capable of performing the orbital maneuvering and proximity operations, such as the space shuttle. The SSL was tasked in 1994 to examine the possibility of robotic station assembly without shuttle involvement. In simulations at the NBRF, MPOD demonstrated the capabilities required to approach and dock to a large module (a simulation of a Topaz nuclear power source), then maneuver with it to dock to a commercial space

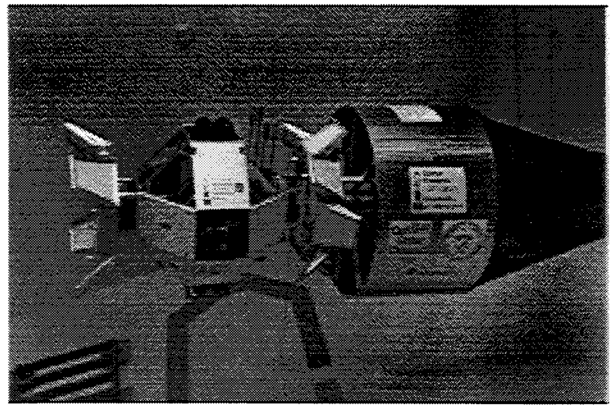


Figure 5
MPOD Maneuvering Topaz Module

platform mockup. Figure 5 shows MPOD with the Topaz mockup attached approaching the space platform docking fixture.

Robotic vehicles differ from existing spacecraft in that they do not necessarily dock merely to attach to the worksite. A free flying robot may use a manipulator to dock to a hard point atthe work site, similar to an astronaut positioning themselves into foot restraints. Once attached, the grappling manipulator can move the vehicle into a working configuration, in a manner similar to a leg. In current plans, ISS will be partially serviced by the Canadian Special Purpose Dexterous Manipulator (SPDM). The SSRMS will grapple SPDM and transport it to the work site, and will provide coarse positioning for the system. However, current plans are for SPDM to use one of its two dexterous arms to grapple locally to the work site to react forces. SSL experience with this type of multirobot interaction dates back to BAT and the

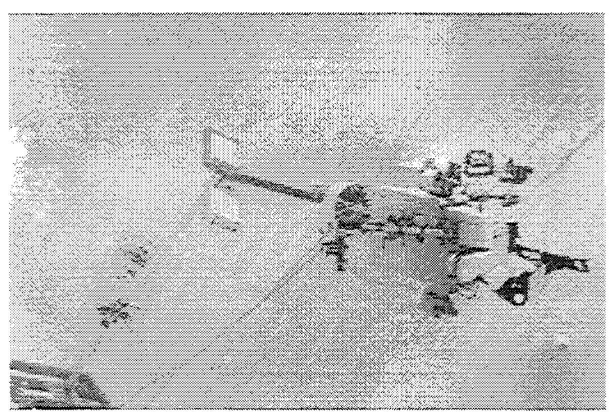


Figure 6
SPAM Positioning BAT

Stewart Platform Augmented Manipulator, or SPAM, as in Figure 6. SSL experience indicates that it is essential for the positioning manipulator (whether a crane-type manipulator, like the SSRMS, or a positioning leg or grapple arm) must be fully integrated into the control architecture of the dexterous arms. Although the Ranger dexterous manipulators set a new standard for singularity-free work space, space servicing tasks typically require far more volume than the standard work envelope of a single arm. By having the positioning leg autonomously reposition Ranger's body to prevent approach to work space limits, the overall effect is the provision of nearly unlimited dexterous work volume without increasing the operator's workload.

Assembly

In-space assembly is one of the most interesting categories of tasks for a number of reasons. From the researcher's point of view, assembly involves the manipulation of large masses, which minimizes the perturbing effects of water drag in neutral buoyancy simulation. On-orbit structural assembly has been shown to allow much higher packing factors. As a result of the EASE-ACCESS experiments on STS 61-B, the Space Station *Freedom* structural truss was baselined for EVA assembly. It was found later that the structural assembly was the easiest of the problems to overcome; the problem of routing and verifying utilities (fluids, power, data, etc.) drove the use of pre-integrated truss segments for the International Space Station. However, in-space assembly will be an enabling technology for many of the future space goals, including large-aperture telescopes and advanced space platforms.

Figure 4 shows the Beam Assembly Teleoperator completing an assembly of the EASE structure. Performing over 200 hours of assembly in its operational lifetime, BAT also completed an early version of the NASA Langley structural connector and a modular coupler (Vought Corp) [3]. BAT provided many lessons on how to design and operate a teleoperator. A novice operator using BAT assembled a full EASE structure in 89 minutes. This compared to an inexperienced space suited subject taking 71 minutes to perform the same task [1]. In a separate research effort, the method by which the manipulator was controlled was shown to have only a minor effect on assembly performance. A mechanical cartesian position input device was favored over a pair of joysticks or direct joint control [22].

BAT was also used to examine robotic capabilities for Space Station truss assembly. Figure 7 shows BAT assembling a cubical truss representative of the planned Space Station *Freedom* keel structure. These tests were done by BAT alone, and in cooperation with EVA subjects. Test results demonstrated the limitations of BAT's capabilities for full cooperation with humans, as the disconnect in performance time (BAT was approximately 20% as fast as an EVA subject in assembling the truss structure) prevented the research team from finding task allocations that did not have a substantial waiting period on the part of the EVA subject. This proved to be one of the driving forces behind the Ranger design requirements in later years.

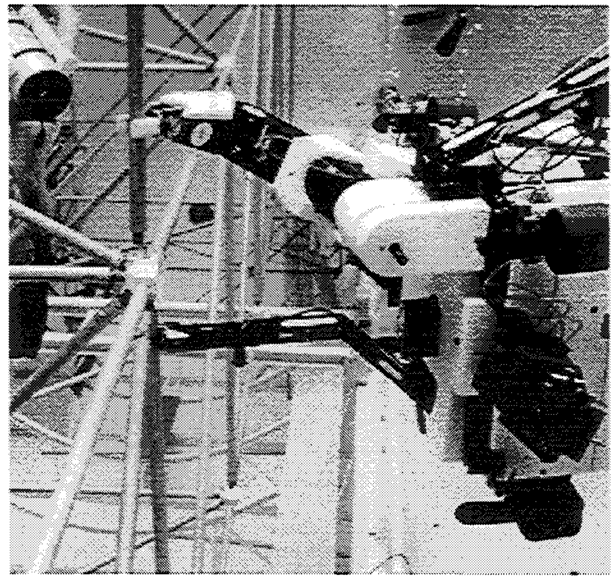


Figure 7
BAT Assembling Space Station Truss

In tests at the NASA Marshall Space Flight Center (MSFC), Ranger NBV I demonstrated its capability for assembly by erecting the EASE structure. To avoid the performance losses shown by BAT in free-flying assembly, Ranger was grappled by the shuttle Remote Manipulator System (RMS) simulator, which provided mobility and positioning thoughout the assembly process. In tests planned for the end of 2001, Ranger NBV I will be used to investigate robotic assembly of Next Generation Space Telescope primary mirror segments.

Inspection

Once a complex structure is in place, the need arises to maintain it at full operating capacity. ISS will require routine monitoring of the structure to find and repair components damaged from corrosion, micrometeorite strikes, and equipment malfunction. An automatically or remotely controlled robot could replace EVA for the mundane task of routine inspection. A robot can also provide an additional view of an astronaut and/or robot working on a task. This can assist in verification that a task is being done according to procedure, as well as increase ground and intravehicular activity (IVA) personnel situational awareness.

With over 300 hours of testing, SCAMP has been used in many situations to provide an additional camera view. In SSL test operations, SCAMP is commonly used to provide situational awareness for both surface observers and operators of other robotic systems.

SCAMP has demonstrated a number of representative space inspection tasks [4]. It easily identified several types of labels at different distances and orientations. SCAMP found all simulated structural faults; however, some false positives were later identified as weld points, bolts, and bolt holes. SCAMP has also been used to verify alignment of a docking task [12]. A study found that high zoom caused the operator to lose situational awareness [24]. Operators preferred a wide angle view, even though moderate zooming yielded superior performance. Although it caused no significant difference in task performance, operators preferred stereo video over the monoscopic view.

During test operations at NASA MSFC, SCAMP was remotely controlled from a high school in Florida, NASA JSC, and the University of Maryland. Testing showed that the effect of controlling SCAMP with various, fixed time delays of less than 1 second was not statistically significant. However, as delays increased over 1 second, a resulting linear increase in completion time and subjective task difficulty occurred. Operating with variable time delay (between 0.1 s - 5 s) negatively affected performance. Subjects claimed to prefer a longer fixed delay over the variable delay.

SCAMP has successfully monitored EVA crew, including flight crew training for STS-80 at the JSC Weightless Environment Training Facility (Figure 8). In conjunction with other robots performing a task[4, 23], SCAMP assisted in aligning a task component, identifying a positive grasp on a component, and verifying the condition of hardware. SCAMP was also used to follow an EVA subject during motion. If the target could move faster than SCAMP, tracking became difficult. A vision based controller for tracking was implemented on SCAMP, which alleviated this problem [13].

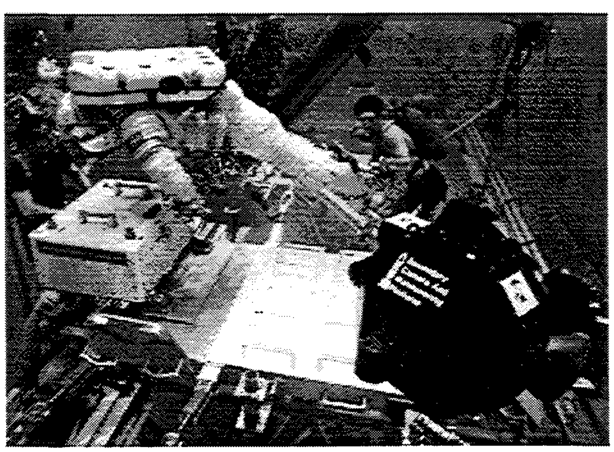


Figure 8
SCAMP Monitoring EVA Training at JSC

Maintenance

One of the most challenging requirements for robotic design is maintaining a spacecraft on-orbit. A maintenance task may begin by requiring the previous capabilities: docking to the target spacecraft, using assembly capabilities to replace an orbital replacement unit (ORU), and inspecting the result. However, unlike assembly, maintenance will probably not be repetitive, but will instead require a number of different tools, interfaces, and procedures. Planned servicing can be designed to accommodate robotic systems; however, experience on-orbit indicates that the most important maintenance tasks will probably not be ones that were planned for preflight. Since spacecraft are assembled by humans on the ground, maintenance tasks call for human-scale robot components for reaching into constrained spaces, human levels of strength and dexterity, and human-equivalent visual accuity.

Although designed specifically and solely for EASE structure assembly, BAT was used to examine the potential roles for robots in spacecraft servicing. This was primarily accomplished using the same high-fidelity mockup of the Hubble Space Telescope (HST) used to train the flight servicing mission crews. In initial testing, BAT was used to investigate telerobotic servicing of the HST Wide Field/ Planetary Camera (WFPC), and the changeout of HST batteries. To facilitate this testing, BAT was modified with a shorter left arm to bring the work site into a better work envelope for the dexterous right arm, and a power tool was added for actuating bolts. The power tool was grasped in the hand of the right arm and remotely controlled.

These tests demonstrated the potential for robotic servicing, even on a spacecraft as complex as HST. BAT was able to actuate the J-hooks used for mechanical restraint of ORUs, and successfully unzipped and rolled back thermal blankets over the HST spares launch restraints. However, many of the interfaces proved to be more difficult than BAT could accomplish [14]. To perform an end-to-end battery changeout, J-hooks at the bottom of a 4-inch diameter, 12-inch-deep cylindrical recess had to be reliably opened and closed. This was not possible within the restrictions of a 5DOF manipulator and a fixed-base pan/tilt camera unit for operator feedback. The lack of force-torque sensing limited the available dexterity below the level where reliable operational procedures could be performed by the robot alone.

BAT tests of HST servicing were essential in developing the design requirements for the Ranger systems. BAT did validate the basic assumption, originated in systems analyses of robotic servicing performed for NASA MSFC by the SSL in 1978 and 1980: robotic systems should be designed to perform servicing using standard EVA interfaces. This provides maximum flexibility for the overall servicing program, while allowing flight hardware to be designed to a single, well-understood and time-tested interface standard. This demands that the robot be capable of stocking and using a variety of tools and specialized interfaces to make up for the lack of anthropomorphic dexterity. Since one of the major problems with BAT operations was its inability to grasp the power tool rigidly enough to allow tool tip control, Ranger was designed around the concept of interchangeable end effectors. Like EVA crews, Ranger carries a tool box to perform specific servicing tasks. The fact that they are not identical tools to the EVA set is far less important than the fact that they fit on the same task interfaces, and allow the same servicing procedures to be followed.

In Ranger servicing tests to date, Ranger NBV I has grasped H-handles, EVA handrails, and HST door handles. It has actuated J-hooks, electrical connectors, and performed an end-to-end replacement of an ISS fluids ORU. These tests were performed under both local control (simulating local IVA control of a flight system) and remotely via satellite video link and low-speed phone lines for command uplink. In neutral buoyancy preparation for the Ranger Telerobotic Shuttle Experiment (TSX) flight, NBV II will perform numerous repetitions of the removal and replacement of both an ISS Removable Power Control Module and an HST Electronics Control Unit. As neutral buoyancy mockup hardware becomes available, it is planned to use Ranger NBV II to develop a data base on a variety of spacecraft servicing tasks and interfaces.

EVA Assistant

With ISS as a data point, it would appear that a limited dexterous robotic system such as SPDM will allow the robotic performance of about 30% of the planned servicing tasks. As the robot becomes faster and more capable, the optimum distribution of tasks becomes more heavily weighted on the robotic side. However, there is a clear case here of diminishing returns; the investment required to go from a robot capable of 50% of the tasks to one capable of 90% is probably only a small fraction of the cost required to go from 90% to 98%. In fact, the last few percent of capability may always require the presence of a human on-site. If the human is accepted as available, the obvious question to be asked is what level of robotic capability is optimal - that is, what are the tasks the robot does best, and how does the robot make the human faster, better, and more safe? Even with fairly rudimentary capabilities, robots could be used to position an astronaut, pass needed tools, handle large components, setup the worksite for the astronaut, and clean up afterwards. With a robotic assistant, the astronaut's workload can be shorter and easier. The human is used for the complex, dexterous task for which he or she is best suited; the robot does the easy, repetitive, simplistic tasks that are a waste of the human's valuable time. The SSL has been actively researching concepts for human-robotic cooperation over the past 15 years.

During the initial tests of BAT performing HST servicing, it became clear that BAT's design limitations precluded most end-to-end HST tasks. The majority of test time on the system became investigations of how BAT might serve as an assistant to the EVA crew. BAT and an EVA subject collaborated in the replacement of the HST WFPC. BAT, attached to the RMS, provided accurate position control for the massive object; the EVA crew moved about to locations that provided optimum vantage points for ensuring that the camera was on the right track (Figure 9), and monitored the insertion process to make sure that optical surfaces were not damaged or dislocated. During battery replacement tasks, BAT removed the old ORUs and replaced them with new batteries, allowing the EVA

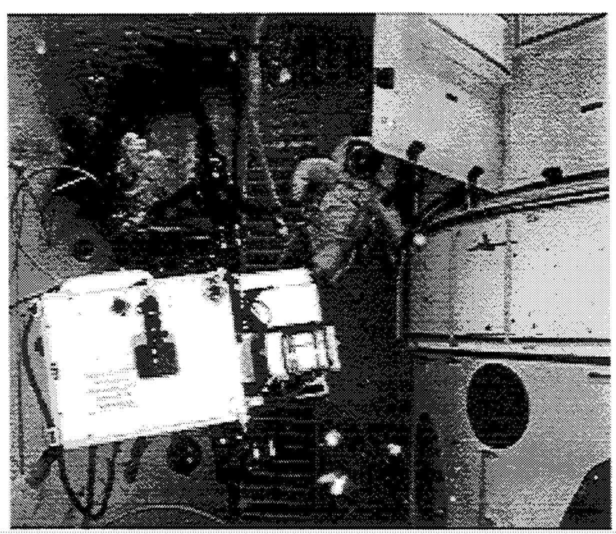


Figure 9
BAT and EVA Subject Remove HST WFPC

crew to remain on-site and devote more time to the delicate removal and installation process.

In later HST tests, a combination of Ranger, RMS, SCAMP, and EVA operations were used to perform end-to-end ORU changeouts. Ranger, maneuvered by the RMS, opened the access panel to the HST instrument ring. Ranger then emplaced a portable foot restraint for the EVA subject. At this point the EVA subject arrived at the site, and immediately began the removal of the ORU itself. When the unit was detached, the EVA subject passed it to Ranger, monitored by SCAMP (Figure 10). While the instrument bay was empty, SCAMP performed a free-flight close inspection of the interior to allow the remote operators to assess its condition. Ranger gave the crew a

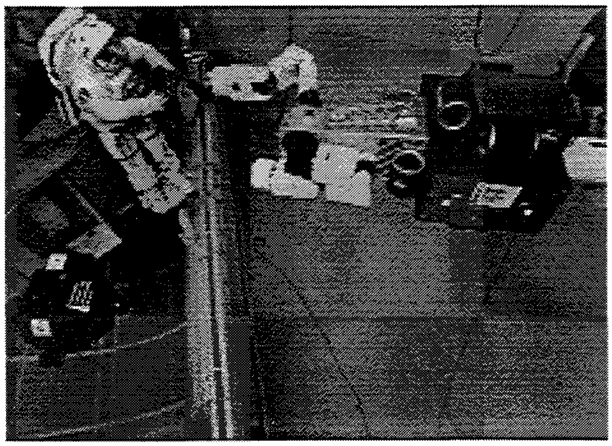


Figure 10
Ranger Receives ORU from EVA Subject, Monitored by SCAMP

new ORU, and left to stow the removed unit while the new one was installed. Following the ORU installation, the EVA subject left the work site. Ranger closed and latched the bay door. SCAMP inspected the door J-hooks, and reported one which the Ranger operator had purposely incorrectly tightened. Ranger corrected the closeout error and removed the foot restraints.

Having a robot act as a helper for the EVA crew is an obvious near-term application for robots in space; it is by no means the only one. The undersea community uses diver support vehicles to excellent advantage. These vehicles transport saturation divers, under pressure, to their work site, and then support them (typically through lighting, video monitoring, and umbilical-supplied air and hot water) during operations. As a parallel concept, an Astronaut Support Vehicle (ASV) might take ISS crew on an extended-duration mission to a co-orbital asset, then support them during EVA servicing in-situ. This concept was demonstrated by the SSL using MPOD as the ASV,

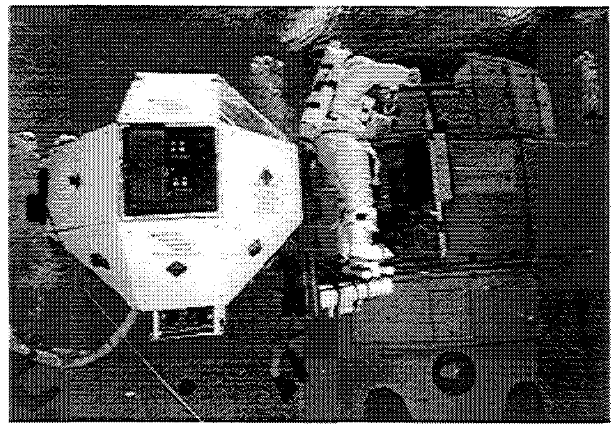


Figure 11
MPOD as Astronaut Support Vehicle Servicing Hubble Space Telescope

which also provided a stabilized work platform for EVA foot restraints mounted to the vehicle exterior. Figure 11 shows the ASV concept used for HST servicing operations.

Looking farther downstream, the SSL feels strongly that the ultimate form of space operations will be that of a human-robot symbiosis: that by adding robotic capabilities directly to the human's pressure suit, the overall system will become maximally effective at performing the required tasks. A small first step in this direction came during initial BAT testing. As more and more cooperative scenarios were tested, it became clear that the robot could be highly beneficial as a "third hand" to assist with the servicing tasks. BAT was mounted to the RMS, and then docked using the fixed left arm to the EVA backpack (Figure 12). At this point the RMS could be used to position and stabilize the EVA/BAT combination at the work site, where the human became a "smart dexterous

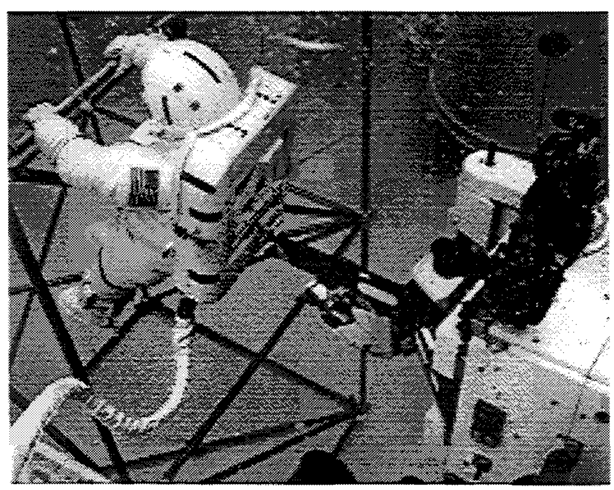


Figure 12
BAT Grappling EMU Backpack

end effector" for the RMS. As components were removed, they were simply handed to BAT's dexterous right arm for stowage, and tools were passed back and forth from BAT to the EVA subject. Although BAT kinematics were far from ideal for this application, the overall concept worked quite well, and will be extended using Ranger and the MARS suit simulator described in Table 1.

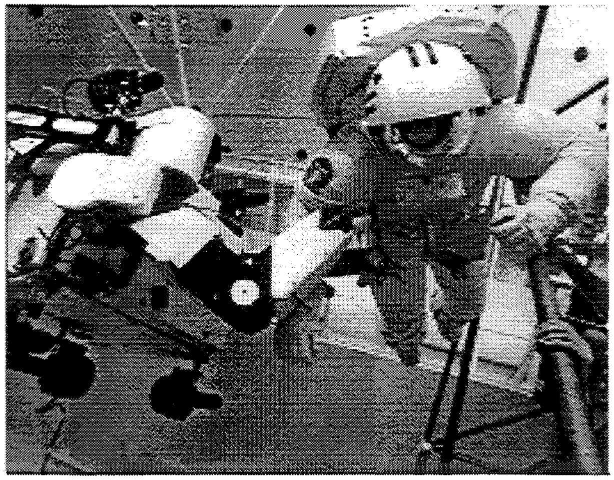


Figure 13
BAT Demonstrating EVA Rescue

Ultimately, the human/robot partnership must provide both greater performance and a greater degree of safety than an EVA-only scenario. Figure 13 demonstrated BAT grasping an EVA subject who is pretending to be incapaciated. These tests demonstrated the ability of a remotely controlled system to rescue a stranded or incapacitated EVA crew, and return them to the shuttle or ISS airlock.

Training

As robotic vehicles become more prevalent, the ability to train human operators will become more important. Training systems can be used to simulate a variety of conditions, which can be changed quickly and easily, to allow for diverse training. These specialized systems, used to help operators learn different strategies of teleoperation, will strengthen the advantages of human-robot cooperation.

Robotic systems are currently used, in conjunction with immersive head-mounted displays, to train EVA crews for manipulating large masses in microgravity. While these systems are quite good, there are limitations that will become more adverse with time. Body responses learned in a gravity environment will be inappropriate in microgravity. As crew resident times on-orbit increase with ISS operations, ground-based training will be so far in the past as to be ineffective when the actual procedure needs to be performed. The SSL has used its robotic systems to validate concepts for both neutral buoyancy and in-orbit haptic training. By simulating contact dynamics using manipulators, astronauts can be trained prior to flight in realistic dynamic environments. Recurrent training can occur during flight to keep the human's responses properly trained for the operational applications.

Similarly, the SCAMP SSV system was designed to be a high-fidelity simulation of actual flight dynamics for an AERCAM-type vehicle. By using SSV in the JSC NBL, future flight crews can experience realistic flight dynamics for free-flying camera platforms in parallel with training the EVA crew on the tasks to be monitored. The ultimate effect of these advanced robotic systems is to eliminate the undesirable dynamics of the underwater environment, and produce optimal training for future astronauts.

CONCLUSIONS

As time goes on, the demand for space operations increases dramatically. Operational approaches which worked 10 or 20 years ago are increasingly proving inadequate to current and future demands for increased capabilities. One of the most productive responses to this increase in requirements is to utilize the capabilities of the telerobotics field to augment and enhance astronauts on-orbit.

Experiences in the Space Systems Laboratory over the last two decades have provided a wealth of data, summarized only very briefly in this paper, applicable to expanded capabilities for complex space operations. SSL experiments have demonstrated the capability of free-flying mobility vehicles to dock with and maneuver large payloads. Dexterous robots have been used to assemble space structures, service and repair satellites, and maintain space platforms. These results have broken free of the prevailing wisdom that robots are only suitable for tasks which are specialized with a single standard interface, and instead have demonstrated that dexterous robots can be designed to use standard EVA interfaces and perform standard EVA tasks.

Robotic systems have shown themselves to be ideal partners for humans in extravehicular operations. Working in close conjunction, human/robot teams have serviced the Hubble Space Telescope and assembled space station structures. Robots have been used to go for tools and hardware, hold an astronaut in position, or rescue them if things go wrong. As experience grows, it will become unthinkable for humans to perform operations in space without their trusty sidekicks – advanced dexterous robots. Ultimately, the distinction between a robot and a space suit will drop away, and robotically-augmented humans in space will approach (or even surpass) the capabilities of a shirt-sleeved human on Earth.

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