# Human-Robotic Cooperative Teams for Advanced Space Operations

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### *Abstract*

Flight and research experience to date indicates that teams of robots and humans will provide significantly greater productivity and capabilities than either system working alone. This paper details research developments in the University of Maryland Space Systems Laboratory on three different approaches to human/robotic interaction in the space environment. In each of these, the human performing EVA is brought into closer interaction with the robotic system, with the ultimate conceptual goal being a symbiotic relationship between the human and the robot. In the first, a robotic actuator was integrated into a space suit glove, enabling hitherto unavailable dexterity without a penalty in crew fatigue. This "power glove" project paves the way for advanced robotic suit augmentation, including fully powered suits. In the second, advanced dexterous robot manipulators were integrated into the shuttle manipulator foot restraints, providing direct robotic capabilities for worksite preparation and closeout, and assisting the EVA crew during human operations. Results indicate productivity enhancements ranging from 60% to 400%, depending on the details of the tasks performed. In the last, a single-person spacecraft was designed for space operations, incorporating both robotic manipulators and space suit arms. The system is capable of zero-prebreathe EVA and extended mission operations, while providing greater protection for the crew and reducing the number of crew necessary to conduct safe external operations.


### *Introduction*

Over the past forty years of human space flight, the ability to assemble, repair, or otherwise perform direct physical manipulation of the space work site has rested almost entirely with extravehicular activity (EVA): astronauts in space suits performing "space walks". Advances in space robotics have created the ability to augment or supplant some EVA operations with robotic ones, although no funding has yet materialized to develop these dexterous robotics systems from laboratory or ground-based simulations to flight-ready systems.

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It is the purpose of this paper, however, to look beyond simple applications of robotics, to the use of robotics and humans in direct contact in the same work site. As will be shown, the most relevant data currently available indicates that the most effective way to perform advanced operations in space is to team humans and robots together directly, and let each do those tasks to which they are best suited.

The University of Maryland (UMd) Space Systems Laboratory (SSL) has been performing research into human/robotic interactions in the EVA worksite for twenty years. Building on an extensive database of EVA capabilities and limitations, based on neutral buoyancy simulation and with flight validation from the STS 61-B mission, early developments of dexterous robots were used to better understand how robots and humans could interact effectively and safely. The Beam Assembly Teleoperator (BAT) was the first integrated robotic system developed for neutral buoyancy simulations. Although BAT was designed solely for structural assembly, and thus lacked many features of value in spacecraft servicing, it was used for both purely robotic and cooperative EVA/robotic servicing of Hubble Space Telescope. The EVA/robotic cooperative mode proved to be a significant improvement in the overall servicing time as compared to EVA alone, or to purely robotic operations.

In the 1990’s, NASA funded the SSL to develop a highly capable robotic system for dexterous servicing, Designed with the goal of being as capable of a human in a space suit, the Ranger Telerobotic Flight Experiment program led to the development and testing of the Ranger Neutral Buoyancy Vehicle (NBV), which was used extensively for testing of both pure robotic and EVA/robotic cooperative activities. This system demonstrated the capability of a robot to install and adjust EVA portable foot restraints, to open access panels, and to do all the other support tasks necessary for EVA servicing (Figure 1). The EVA subject then arrived at the scene and performed the highly dexterous servicing tasks, assisted by Ranger (Figure 2). When this subset of tasks was accomplished, the EVA crew moved on to other assignments while Ranger removed servicing support equipment and closed out the work site.

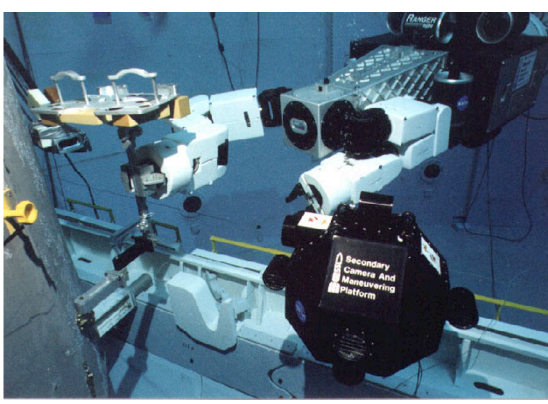


Figure 1: Ranger Installing Portable Foot Restraints in HST Socket

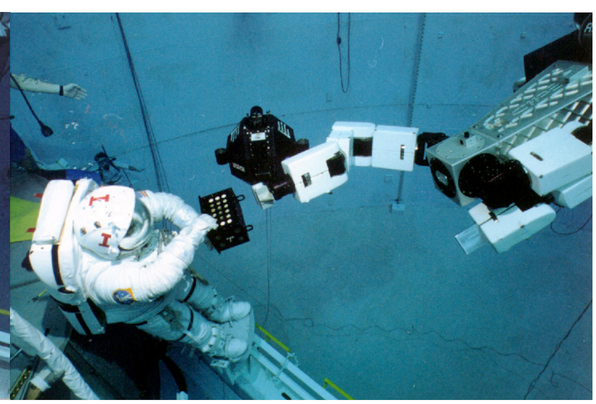

Figure 2: Ranger Receiving ORU from EVA Crew

Despite the success of these tests, there clearly was a greater degree of integration possible between the EVA human and the robotic system. The focus of this paper is on three projects in the SSL which aim at directly integrating robotic capabilities into the EVA worksite simultaneously with the astronaut. This level of human/robot cooperation might be more properly termed a *symbiosis*: a total integration of human and robot to achieve capabilities beyond the reach of either system alone.

***Direct Robotic Augmentation: The Power Glove***

Among the great unsolved challenges of space suit glove design is that of the metacarpophalangeal (MCP) joint. Running along the “knuckles” of the hand, the MCP joint is critical to a number of standard grasps. However, since this is a large joint, it has so far proven impossible to design a passive MCP articulation into the glove which has low enough torque requirements to be useful. As a result, grasping in pressure suits is accomplished through individual articulation of the proximal interphalangeal (PIP) joints of the fingers. This is a weaker and more fatiguing grasp, but one which can be implemented in glove design without unacceptable joint torque requirements.

In collaboration with ILC-Dover, the UMd SSL undertook the challenge of designing a robotic assist mechanism for the hand MCP joint. Based on glove safety issues, no part of the mechanism could intrude on the palm side of the hand, to ensure no degradation in the already limited tactile feedback. No sensors could be placed inside the glove, and no part of the robotic assist mechanism could penetrate the pressure bladder. All external components had to fit on the back of the glove, and provide useful access in the current established glove envelope as specified in NASA Standard 3000. Finally, the glove had to be operable, even with degraded performance, in the event of a robotic system failure.

In response to these requirements, ILC-Dover fabricated a glove with an MCP articulation. The restraint layer incorporated a conformal composite plate on the back of the hand, and a matching bar along the distal side of the MCP joint. The glove was designed so that the MCP joint was biased in the closed (flexed) position by glove pressure. The University of Maryland designed a miniature robotic actuator which mounted on the plate on the back of the glove and provided actuation force to the MCP bar via a cable drive system. Two generations of these gloves were manufactured, as shown in Figures 3 and 4.

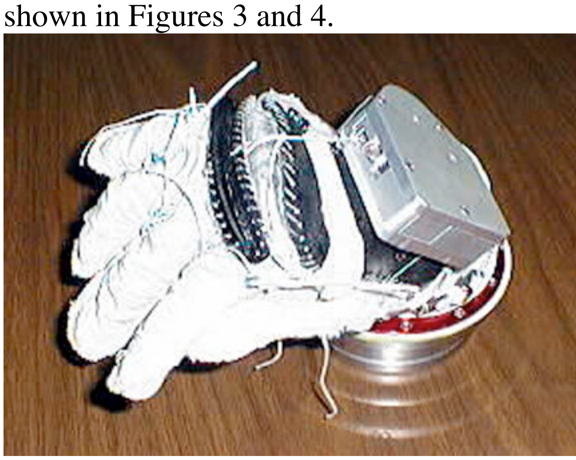

Figure 3: Robot-Assisted Space Suit Glove (Mark I Configuration)

Figure 4: Robot-Assisted Space Suit Glove (Mark II Configuration)

Through the use of adaptive control techniques, a detailed nonlinear model was developed for joint torque as a function of MCP deflection. The control system for the robotic actuator was designed to null out the inherent torques of the glove joint, in response to current MCP position according to the torque model. This approach proved highly effective, reducing the required force for actuating the MCP joint from 16 pounds (passive) down to an average of 12 ounces (active). The system was tested in partial pressure glove boxes, and demonstrated its ability to reduce the rate of fatigue onset and improve operability of the glove.

This research points the way to new applications of robotics in EVA operations. Other body joints, such as wrists, elbows, and shoulders could also be modified to incorporate robotic assistance for joint motions. Once reliable and robust powered suit joints are available, it is a short distance to force augmentation for activities requiring high strength, such as establishing a planetary surface base. Indeed, the far-term vision for this research is the *SuperSuit* – a system which will make the astronaut *more* productive than they would be in a shirtsleeve situation, and which, in the extreme case, is capable of autonomously returning an unconscious or otherwise incapacitated astronaut to the safety of the habitat.

***Synergistic Robotic Assistance: HERCULES***

From the development of the first neutral buoyancy-compatible dexterous robot in the Space Systems Laboratory, substantial test activity focused on examining possible roles for robotic interaction with EVA subjects. In a rudimentary first test of EVA/robotic symbiosis, the Beam Assembly Teleoperator was “mounted” to the backpack of an EVA subject, so that its single dexterous manipulator could reach around the subject’s right side and provide a “third hand” for Hubble Space Telescope servicing operations. This proved to be a highly productive operating mode, although the details of integrating the robot with the pressure suit in a more formal (and flight-qualifiable) way were not resolved.

Over the past several years, the SSL developed the Ranger Telerobotic Shuttle Experiment, which was intended as a first flight demonstration of highly dexterous robotics for space operations. As part of this development process, a highly capable and adaptable dexterous manipulator was developed and tested. Laboratory prototypes (capable of working in both 1g and underwater) are shown in Figure 5. Over 70% of the hardware for a flight-qualified pair of these manipulators had been completed by the SSL at the time the program was canceled due to NASA budget limitations in 2002.

With the loss of the shuttle Columbia in February, 2003, the Hubble Space Telescope servicing program at NASA Goddard Space Flight Center also faced new and substantial challenges. With a change in policy on shuttle flights, there will now be no HST recovery flight at the end of its mission. The next servicing mission, SM-4, was planned to be flown in late 2004, but now could be postponed as late as 2007. Since this is the last planned mission for maintenance and upgrades of the telescope, the five assignable EVA days were already oversubscribed with spacecraft servicing tasks. With the real possibility of one or more EVA days dedicated to routine tile inspections, and the probable addition of a task to add a deorbit system to HST, a number of high-priority science system upgrades might have to be dropped due to insufficient EVA time.

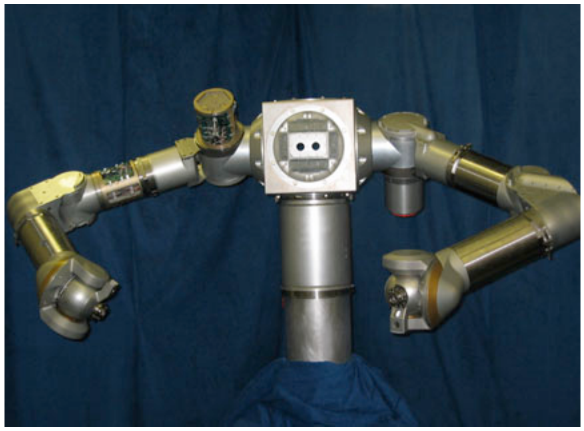

Figure 5: Ranger Dexterous Manipulators in Laboratory Testing

Recognizing the potential synergy in these two problems, the engineering teams at the SSL and GSFC began to look for ways to use the nearly completed dexterous manipulators at UMd to augment and increase EVA performance on SM-4. Based on past experience with BAT as a "third hand", the SSL suggested incorporating one or both Ranger dexterous manipulators on the platform for the shuttle remote manipulator system (RMS) manipulator foot restraints (MFR). This would allow the robot arms to serve as additional hands for the EVA crew, or to carry and position tool boards and replacement parts. This concept was christened the Hubble EVA/Robotic Cooperative Utility and Experiment Servicing system, or HERCULES.

As conceptualized in Figure 6, HERCULES will involve the modification of the MFR support structure to incorporate mounting locations for two Ranger dexterous manipulators and supporting electronics packages. The RMS will provide mobility around the HST servicing site, which encompasses the entire payload bay and the telescope unit rising out of it. The manipulators are capable of assisting the astronaut during the EVA, and performing robotic activities outside of EVA times, under ground control. This approach was mocked up in the laboratory using a Ranger development arm and Skylab-era space suit, as shown in Figure 7.

Based on a wealth of experience with EVA/robotic interactions, and the evidence of development trials for the Ranger arms, the detailed EVA plans for SM-4 were broken down into tasks and subtasks. Each of these were evaluated for activities well suited to the capabilities and limitations of the Ranger arms, and further divided into tasks which must be performed in conjunction with the EVA, and tasks which could be done prior to or after EVA operations. This analysis indicated that a single-manipulator version of HERCULES could cut 6:50 (6 hours 50 minutes) off of the 30 hours of baseline EVA, and that a dual-arm HERCULES could save 13 hours. This would allow the completion of the nominal SM-4 EVA plan in three EVA days, rather than five.

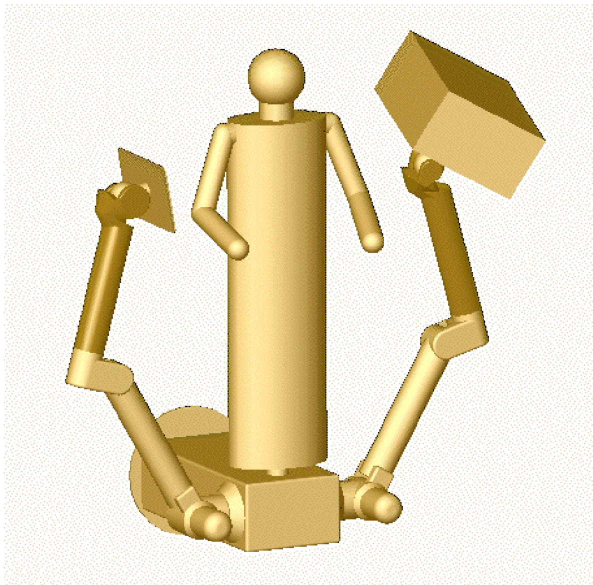

Figure 6: HERCULES Concept

Figure 7: HERCULES Proof-of-Concept Testing in Laboratory Environment

***Human/Robot Amalgam: SCOUT***

For almost forty years, the concept of extravehicular activity has been synonymous with space suits. The paradigm of the conformal, articulated space suit made largely of soft goods, however, is not the only valid one; as we leave low earth orbit and extend human presence deeper into the solar system, it may well not be the optimal one. With the increased radiation flux of deep space, potential for greater travel distances and mission durations, and focus on large space structures assembly and maintenance, there are a number of EVA requirements that call for a fresh approach.

Starting from the NASA vision of a "Gateway" station at the Earth-Moon L1 point, the University of Maryland took a fresh look at the future of EVA in the spring of 2003. The primary mission for Gateway station is to assemble and maintain large space structures for science purposes, such as the James Webb Space Telescope and Terrestrial Planet Finder. These sensitive optical structures are best assembled far from the Gateway habitat to prevent contamination; the UMd team assumed that the EVA crew would have to transit a kilometer each way to "commute" to work. Requirements were also set for the presence of Ranger-class dexterous robotic manipulators on or about the suit, but it was assumed that direct human access to the worksite, to facilitate the use of the dexterous human hands, was also a critical design requirement.

The new deep-space EVA paradigm which was arrived at is SCOUT: Space Construction and Orbital Utility Transport. As shown in Figure 8, SCOUT is a development of the manned autonomous work station concept, or "man-in-a-can". The 2000-kilogram, single-person spacecraft has dual propulsion systems for mobility to and from, as well as around the work site. A hydrazine system provides efficient propulsion in non-sensitive regions, maximizing commonality with the base station propulsion systems. A nitrogen cold-gas propulsion system serves as a backup to the hydrazine system, and is used in contamination-sensitive regions such as in the vicinity of optical surfaces.

A pair of Ranger-class dexterous manipulators with interchangeable end effectors are mounted on SCOUT, and used for operations requiring large forces, fine control, or augmented manipulation, such as mating two large masses together. A third, longer manipulator is provided on the lower end plate of SCOUT, and used as a grappling and positioning manipulator for local attachment to the work site. The SCOUT hull also includes a conformal region resembling a traditional space suit hard upper torso and helmet. By moving into this volume, shown in an expanded view in Figure 9, the SCOUT operator can use a pair of “hard suit” arms (based on the NASA Ames AX-5 experimental space suit) with standard space suit gloves to perform tasks manually where advantageous. The system also incorporates control modes to facilitate cooperative use of both suit and robot arms, such as compliant force control or master-slave manipulator response to control inputs made in the suit arms.

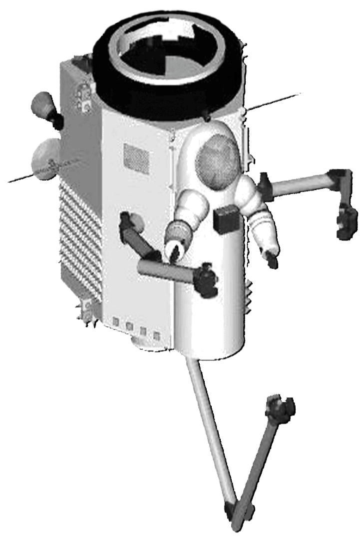

Figure 8: SCOUT Concept

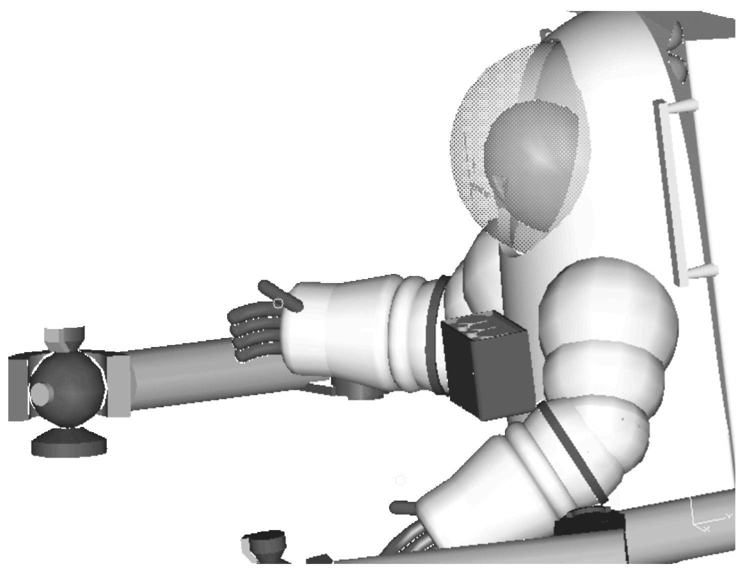

Figure 9: Close-up of Space Suit Torso, Helmet, and Arm Assemblies

The basic SCOUT sortie is 11 hours long, allotting a full eight hours of operations at the work site, while making it easier on the crew by providing break times in the extended workday. An hour is also allotted for translation to and from the work site each day. Maximum survival duration in SCOUT in contingency mode is 27 hours without resupply.

To maximize operator safety, an emergency “bail-out” system was designed for SCOUT. In the event of an emergency which necessitates an immediate egress, a small package on the bottom of SCOUT can be inflated to become a “one-size-fits-all” fabric space suit, with propulsion system similar to the NASA Simplified Aid For EVA Rescue (SAFER) system in use currently. This allows an autonomous rescue capability for SCOUT, and makes single-unit sorties practical.

One of the critical SCOUT requirements was to limit crew involvement in pre-sortie checkout and post-sortie maintenance to a total of no more than one hour. This led to the adoption of an 8.3 psi cabin atmosphere, allowing crew ingress and start of operations with no requirements for prebreathing for denitrogenation. A SCOUT docking module has also been designed, which supports docking and maintenance of two SCOUT pods for long-term space-based operations. Since SCOUT is designed for immediate operation on demand, single-pod sorties are allowed, relying on the combination of emergency bailout and immediate availability of the second unit on "ready alert" to ensure crew safety regardless of failure mode.

A second unit was also developed for SCOUT operations support. The Extended Mission Pallet (XMP) is designed to interface with NASA transport vehicles in the Gateway development scenario, to allow SCOUT to be used for supporting crew transfer between Gateway station and other high-priority work sites, such as lunar orbit or geostationary orbit. The XMP can provide power and consumables to support two pods for up to two weeks, and will (in conjunction with the NASA transport vehicles) extend human presence throughout cis-lunar space.

Although designed for the Earth-Moon L1 location, a brief operations analysis has shown a high utility for SCOUT on International Space Station. EVA assembly and maintenance tasks performed on ISS as two-person EVAs, and requiring a third person to provide positioning via the Space Station Remote Manipulator System (SSRMS), could easily be performed by a single SCOUT vehicle through the use of suit arms, dexterous manipulators, and grappling arm. SCOUT cabin atmospheric pressure was chosen to ensure safe zero-prebreathe operations from ISS, eliminating almost all EVA preparation time currently required. This single-person EVA capability would be especially valuable today in a Soyuz-only crew rotation mode, where the long-duration crew is limited to two people, and EVAs are performed only if urgently needed for the survival of the crew or the station.

***Conclusions***

Whether a miniature robotic actuator to make a glove move with less effort, or a 2000 kg "work pod", robotics will play a critical role in augmenting and extending human capabilities in space. Two decades of research in the University of Maryland Space Systems Laboratory have repeatedly demonstrated that teams of humans and robots, fully integrated into a single work site, are far more productive than either system working alone. The systems discussed in this paper, which represent the far end of the spectrum in terms of the degree of robot integration into the human EVA system, will decrease glove actuation force by a factor of 20, increase Hubble servicing productivity by 75%, and allow ISS EVA operations which currently require three dedicated crew to be done by one. Given the dramatic benefits of human/robotic cooperation, it is ironic that so little programmatic attention has been given to developing these technologies in laboratory simulations and flight demonstrations, and making them a cornerstone of routine space operations.