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RoboSuit: Robotic Augmentations for Future Space Suits

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ABSTRACT

Space suit design has been limited to evolutionary steps since the first pressure suit was developed in 1934. While this development process has improved the fit to the wearer, it is still common to measure the performance of a pressure suit by identifying what fraction of shirtsleeve capability it allows. Given sufficient government and commercial support, space could in the future be an expanding realm of commercial and exploration activities, including return to the moon and human Mars exploration, with requirements for extravehicular activity orders of magnitude beyond the maximum envisioned for the International Space Station era. In such an environment, the need for breakthrough technology is to make the space suit into an augmentation of the human wearer, rather than an impediment. This paper details relevant past research and several near-term approaches to the development of a “RoboSuit”: a space suit system than makes the wearer more capable than a human in shirtsleeves, rather than less. Ultimate forms of RoboSuit will include augmentations of the wearer’s sensory inputs (tactile, multispectral visual, proximity, proprioceptive, aural) and cognitive functions (knowledge bases, navigation data, adaptive task planning); however, the primary focus of this paper will be to identify approaches to augmenting physical capabilities through the incorporation of robotic manipulators as auxiliary hands and arms, or eventually the use of robotic augmentation of suit joints to provide direct human force amplification upon command.

This paper covers three evolutionary approaches to integrating robotic technologies directly into a space suit to augment current capabilities. As a first step, lightweight manipulators can be added to support systems used with the suit to provide third and fourth “hands” in performance of the EVA tasks. Results will be presented from testing this concept with existing robots in the University of Maryland Space Systems Laboratory, leading to a summary of the system which was under development to augment Hubble Space Telescope servicing productivity, prior to the cancellation of the SM-4 mission. The Hubble EVA/Robotic Utility for Logistics and Experiment Servicing (HERCULES) incorporated two dexterous robotic manipulators with interchangeable end effectors into the EVA manipulator foot restraint on the end of the shuttle Remote Manipulator System (RMS). This system can work directly as a teleoperator prior to and after crew EVAs, preparing and closing out work sites, prepositioning tools and orbital replacement units, and allowing the crew to focus on the high-dexterity tasks best suited to humans. During EVA, the manipulators would be used in direct support of the suited astronauts, carrying and positioning tool boards, transporting replacement modules to reduce translation times during EVA, and generally acting as an assistant to the crew. The detailed design of HERCULES will be described, along with analytical results showing that this system can reduce the 30 hours of baseline EVA planned for SM-4 down to 17 hours.

As the logical next step, the paper discusses migrating the robotic manipulators off of the EVA support equipment and directly onto the space suit. There are several current approaches to this manipulator-integrated space suit. The simplest is a robotic “backpack” to be worn over the portable life support system of the current extravehicular mobility unit (EMU), providing a pair of lightweight dexterous manipulators that can be used for active body restraint and stabilization, carrying tools and equipment, or actually performing assembly and servicing tasks under direct EVA control. A more ambitious version of this is the Space Construction and Orbital Utility Transport (SCOUT) concept, wherein a small pressurized spacecraft provides mobility and comfortable habitability for a single operator in extended missions. A conformal helmet/upper torso/ suit arm arrangement in the pressurized cabin allows the operator to directly interact with the work site in a similar manner to current EVA, augmented by two dexterous manipulators and a grappling arm. This system, which has been designed in detail, would be ideal for deep-space EVAs for missions or stations beyond low earth orbit.

The final system described, which can be truly called “RoboSuit”, is a more traditional space suit incorporating direct robotic torque augmentation in each joint. Starting from a rotary-joint hard suit concept such as the NASA AX-5, RoboSuit would provide selectable augmentation of each body segment, adjustable from merely canceling out joint torques or suit weight on planetary surfaces, to full force amplification for major tasks such as assembling large modules on-orbit or erecting habitats on planetary surfaces. Drawing from past SSL development of a robot-augmented EVA glove, conceptual designs and system requirements will be developed for RoboSuit, along with an overview of a logical research program to support its development.

It is anticipated that the RoboSuit approach, moving beyond

evolutionary advances in current EVA technologies, will enable a dramatic increase in space operational capabilities, positively affecting long-range NASA goals such as space science and the human exploration and development of space.

1.0 INTRODUCTION

The design of current space suits traces back in unbroken lineage to the first pressure suit, built for Wiley Post in 1934. Although many details of modern technology have advanced, the Wiley Post suit on display in the National Air and Space Museum is identical in concept and basic function to a Shuttle-era Extravehicular Mobility Unit (EMU). The fundamental concept of space suits has not changed at all with time; they are still articulated pressure-tight garments which provide life support while providing as much body mobility as possible for the wearer.

When an astronaut puts on a current-technology space suit, many of the capabilities which humans use without thinking become compromised. Movement is restricted, and a fraction of the wearer's efforts go to move the suit components rather than to perform the task. Tactile and thermal feedback is significantly reduced; the first indication that a grasp is slipping may be the sight of the object moving in the suit glove, and it is possible to grab something hot enough to place the suit glove at risk without immediate warning to the wearer. Vision is restricted by the helmet, which limits the ability to move the head to get motion parallax cues. Tools have to be specially designed to be grasped and actuated by the suit gloves. The EVA astronaut leaves behind almost all of the information tools common to interior tasks, and relies on rote training, memorization, and dedicated support from non-EVA crew members and ground controllers to get through complex procedures. It is common to train for 10 hours in high-fidelity simulations, such as neutral buoyancy, for each hour spent in actual EVA. EVA is approached with some trepidation, and is restricted to critical tasks that cannot be performed in any other manner.

Following well behind and paralleling EVA, robotics technology has advanced to allow the incorporation of robotic elements into current and future space systems. Currently, robots are limited to large, crane-like positioning systems such as the Space Shuttle Remote Manipulator System (RMS). This system is limited to grappling one complex, bulky interface, and is used for deploying, retrieving, and manipulating multi-thousand pound payloads in the close vicinity of the Space Shuttle. Even planned future "dexterous" operational systems, including the Japanese Small Fine Arm (SFA) and the Canadian Special Purpose Dexterous Manipulator (SPDM), will be limited to 2-3 specialized grasping interfaces, and are capable of performing only tasks of limited complexity and restricted kinematics. In addition, these robotic interfaces are not well adapted for grasping by pressure-suited hands, and therefore require the development and use of specialized adapter interfaces if humans have to perform a planned robotic task. There is no capability for these robots to perform a planned EVA task.

Research telerobotic systems, such as the Ranger Telerobotic Shuttle Experiment (TSX) under development in the University of Maryland's Space Systems Laboratory, represent substantial improvements over the SFA or the SPDM by incorporating interchangeable end effectors capable of adapting to EVA interfaces, and manipulator systems more closely conforming to human arm volumes and capabilities. Development simulations have indicated that Ranger is capable of performing the removal and replacement of Hubble Space Telescope (HST) orbital replacement units (ORU) originally designed exclusively for EVA operation. Current, Ranger takes as much as 10 times longer than EVA to perform any given task; it is anticipated that, when fully developed, this number might decrease to a disadvantage of only 2-3. This factor is also typical of highly experienced operational telerobotic systems in harsh earth environments, including subsea and high radiation environments.

The premise of this paper is that the amalgam of space suit and robotic technologies will result in a system with far greater capabilities than either technology alone. RoboSuits, which may come in a variety of configurations discussed in this paper, will break past the paradigm of the suit as a limiting factor on human performance, and will result in augmented performance beyond that of a shirt-sleeved human. As the final instantiations of RoboSuit are likely to be driven by evolutionary experiences, this paper is likewise organized by evolutionary steps in the synergistic combination of robotics and pressure suit technologies: first robots and suits operating in immediate proximity, then discrete robotic elements integrated directly onto the suit itself, then robotic technologies built directly into the suit.

2.0 ROBOT-AUGMENTED WORK STATIONS

From the development of the first neutral buoyancy-compatible dexterous robot in the Space Systems Laboratory (SSL), 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 (Figure 1). 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.[2]

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

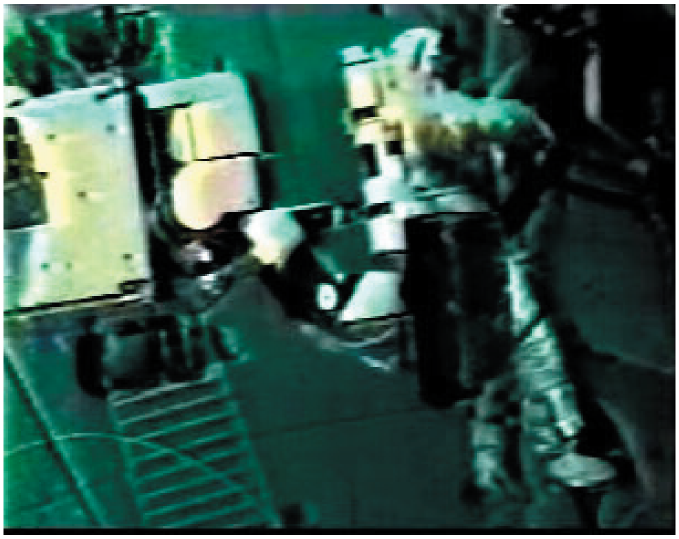

Figure 1
Beam Assembly Teleoperator acting as "third arm" for EVA subject (from video)

manipulator was developed and tested. Laboratory dexterous arm prototypes (capable of working in both 1g and underwater) are shown in Figure 2. 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.[3]

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. Servicing mission SM-4, originally scheduled for late 2004, was likely to be postponed as late as 2007. Since this was to be 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 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 had to be dropped due to insufficient EVA time.

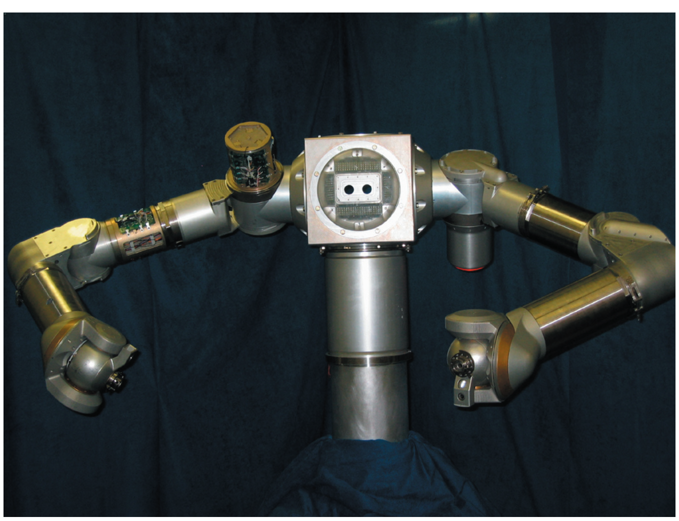

Figure 2
Ranger Spacecraft Servicing System dexterous manipulators

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 3, HERCULES would involve the modification of the MFR support structure to incorporate mounting locations for two Ranger dexterous manipulators and supporting electronics packages. The RMS would 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 4.

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

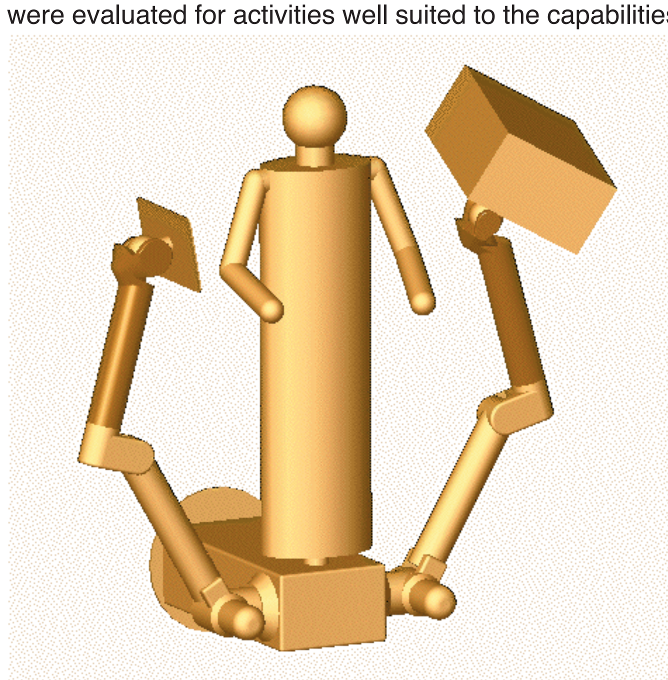

Figure 3
Robotically-Augmented Manipulator Foot Restraints

Figure 4
Laboratory test of a Robotically Augmented Manipulator Foot Restraint

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.[4]

Recently, the NASA administrator announced that SM-4 would be canceled due to safety concerns following the loss of Columbia. While HERCULES will not be realized for Hubble Space Telescope servicing, it should be noted that the relative improvement in EVA performance should hold true in similar operational applications, such as maintenance of the International Space Station. Efforts are underway in the Space Systems Laboratory to identify HERCULES-type systems which are applicable to ISS, and to analyze past EVA operations to obtain an estimate of time savings from the use of robot-augmented manipulator foot restraints for future ISS external operations.

3.0 SUIT-INTEGRATED ROBOTIC APPENDAGES

A drawback to the HERCULES paradigm for EVA/robotic collaboration is that the robotic manipulators are left behind when the EVA crew egresses the manipulator-mounted foot restraints. For worksites where RMS access is restricted or infeasible, the HERCULES-type system does not offer any help.

One next step would be to directly integrate the robotics into the suit; this is generally assumed to take the form of manipulators mounted to the portable life support system backpack, which would provide a stable mechanical mount for reacting manipulator loads cleanly into the suit system. To provide the EVA crew with the option of having robotic augmentation or not, a similar approach is the use of an external frame which mounts to the PLSS backpack, on which the robotic elements are mounted. One conceptualization of this is shown in Figure 5, based on the original manned maneuvering unit, and using the MMU hand controllers for robot command inputs as well as flight control. Such a system would provide robotic arms capable of carrying tools or orbital replacement units, providing body restraint in the absence of fixed or portable foot restraints, and performing high force or precision assembly operations infeasible for unaided EVA.

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

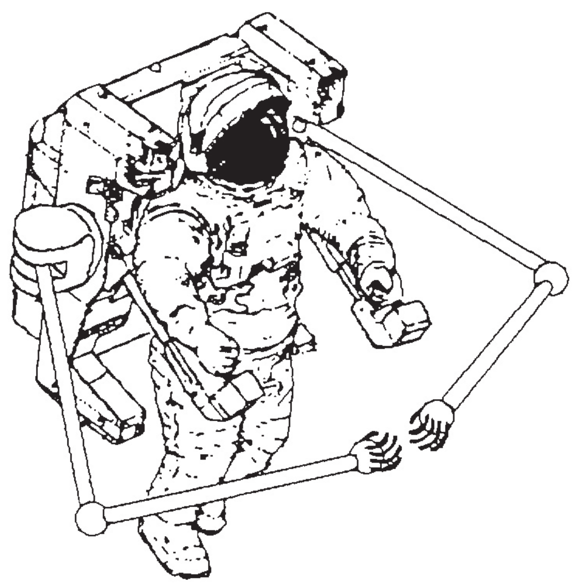

Figure 5
Robotic manipulators integrated into PLSS backpack/Manned Maneuvering Unit

a fresh look at an alternative future of EVA in the spring of 2003. The primary mission for Gateway station was 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 dexterity of human hands, was also a critical design requirement.

The new deep-space EVA paradigm which resulted is SCOUT: Space Construction and Orbital Utility Transport. As shown in Figure 6, 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,

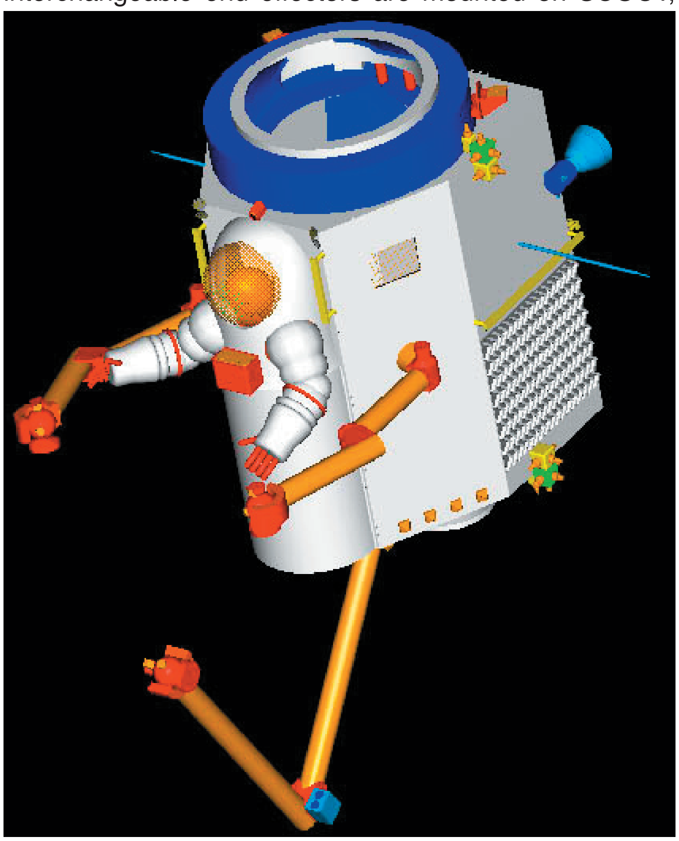

Figure 6
Space Construction and Orbital Utility Transport (SCOUT)

and are 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 7, 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.

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

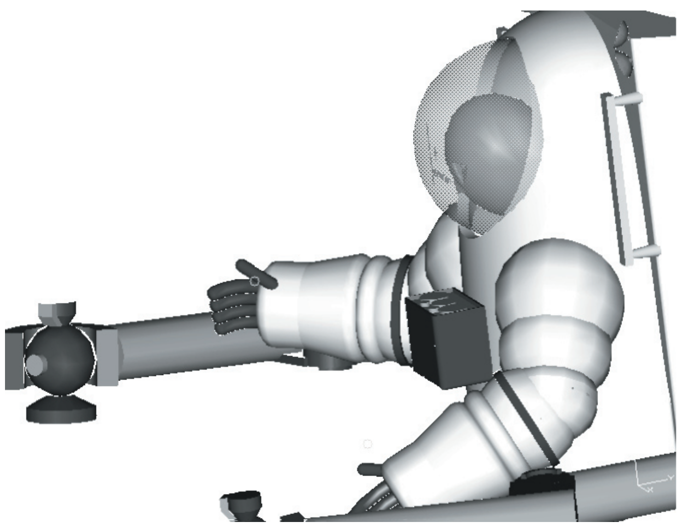

Figure 7
Closeup of suit and robot arms and helmet configuration of SCOUT

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 require the station to be operated without onboard intervention and monitoring during the period of preparation, EVA, and post-EVA clean-up.

4.0 ROBOT-AUGMENTED SUITS

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 primarily 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 Figure 8.

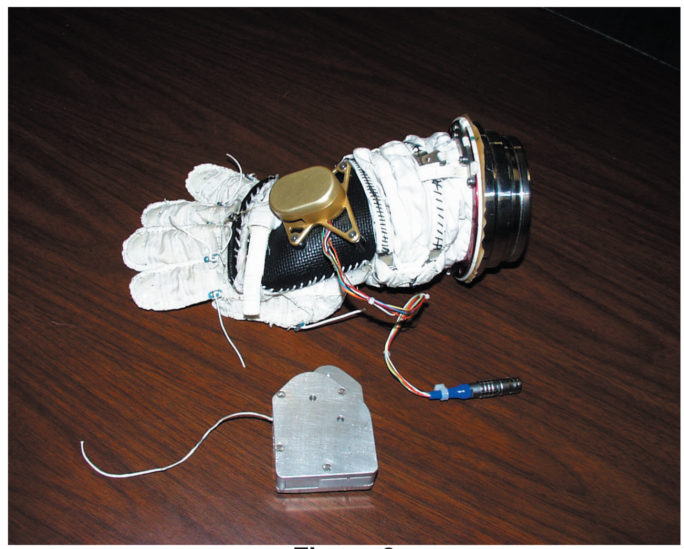

Figure 8
2nd generation power-assisted glove
(first generation actuator in foreground)

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, according to a torque model based on current MCP position. 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 true RoboSuit – 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.

What would the critical features of a RoboSuit be? While the focus of the paper thus far has been on actuation via robotic technologies, it is important to realize that sensing is probably the most near-term human augmentation to be built into future space suits, as sensory amplification does not create the safety implications that actuation augmentation does.

Augmented sensor systems will provide the suit wearer with a wealth of data currently unavailable. In this way, an astronaut will be able to create and maintain better situational awareness, as well as gain important data sources for scientific inquiry. Within each of the following categories, suit integration approaches (based on current sensor technologies) need to be assessed, and the best approach(es) incorporated into the RoboSuit reference design. Sensor systems for potential RoboSuit integration include:

Kinematic data - The RoboSuit could measure the wearer's body position, through instrumentation of body joint positions. This data might be used for gestural input, as well as basic biomechanical data collection. Monitoring gait data on planetary excursions, for example, could provide early warning of fatigue or possible musculoskeletal damage.

Biomedical data - Basic noninvasive measurement of heart rate, respiration, temperature, and blood oxygen concentration could provide critical data on the health of the wearer, and would be used by the suit monitor system to advise the astronaut when rest breaks should be taken, and when sufficient recovery has taken place to resume nominal activities.

Workload data - Measurement of oxygen uptake and CO_2 production in the suit life support hardware would provide direct measurements of metabolic workload, allowing assessment of task performance and monitoring of crew fatigue.

Electromyographic data - EMG sensors placed noninvasively on the wearer's skin would provide basic data on muscle signatures, and would enable direct monitoring of fatigue onset in critical muscle groups.

Tactile sensing - perhaps one of the greatest drawbacks of space suit use is the degradation in tactile feedback. Despite the incorporation of rubber fingertip grips, little tactile data is available to today's space suit wearer. To overcome this limitation, the RoboSuit might pair tactile sensors on the outside of the glove fingertips, with tactile excitation systems internal to the gloves directly against the wearer's fingertips. In this way, tactile data would be rerouted past the mechanical impediment of the suit glove, and more detailed information could be available to the suit wearer from this enhanced sense of touch.

Thermal data -As mentioned previously, the heavy insulation on current suit gloves restricts the ability of the crew to assess surface temperature by feel. There has been ongoing concern that some surfaces on International Space Station are hot enough to damage the gloves, and might be inadvertantly grasped during EVA. Thermal sensors integrated into the RoboSuit gloves could provide proximity and contact sensing of temperature, with feedback to the crew through either voice synthesis or direct (limited) heaters on the hands.

Proximity sensing - One of the problems of bulky pressure suits is the lack of proprioceptive feedback to the wearer, and resultant lack of awareness of proximity to exterior constraints. In the Apollo lunar module, astronauts broke off critical switches and circuit breakers with their suits and backpacks as they maneuvered in and out of the tight constraints of the vehicle. To overcome this limitation, RoboSuit could incorporate distributed proximity sensors, based on technologies such as infrared reflectance or capacitive sensing. This data would be provided to the wearer by tactile stimulators in the suit on corresponding parts of the wearer's body.

Navigational data - For a number of reasons, navigational data is one of the most important categories for operations. Uses for this data range from the simple desire not to get lost, to accurate data logging of sample collection locations, to integration with the data management system for such purposes as synthetic vision or computer data overlays on the wearer's visual field. For these purposes, several types of navigation may be identified. *Global navigation* provides data on the astronaut's position relative to the space station or surface habitat, and does not require particularly fine resolution (~10 m). *Local navigation* would be used to accurately project data based on rover-mounted instruments on the astronaut's visual field, and requires highly accurate (~1 cm) relative positions between the astronaut and the sensor platform. In either case, this data should represent a complete state vector: position, attitude, and the corresponding rates.

Engineering data - Although it is perhaps the most mundane of data, it is important for the astronaut to understand the functional status of the suit, science instruments, and other support systems such as rovers and other forms of supporting robotics. Collection, logging, and presentation of this data is critical to providing a high performance work environment without sensory overload.

Visual system amplification - As vision is the highest bandwidth of any human sense, it is correspondingly the most critical in EVA operations. For this reason, multiple data streams are best provided to the RoboSuit wearer via visual means. The most critical design implication of this is the provision of high resolution head-mounted (or head-slaved) stereo graphics images without interfering with the wearer's direct vision of the outside world. Given this display technology, a number of visual representations can be made to the wearer. These might include external area sensors (synthetic aperture radar or laser scanning systems), expanded visual range (infrared and/or ultraviolet), multispectral imaging, or false-color presentation of data. Human vision may be expanded through the use of telescopes for distance vision, microscopes for close-up vision, or distance maps to local terrain features. The visual display system can be used for communications, or for real-time training or mentoring.

Binaural sensing - For Mars exploration, the presence of even the highly attenuated Mars atmosphere provides the potential for the use of normal binaural hearing in localizing amplified sounds. Even in vacuum applications, synthesized aural feedback can be used to great effect as an alternate to the highly-subscribed vision system. For example, a microphone mounted on a robot picking up generated noises through body conduction has proven to be one of the most sensitive instruments for monitoring robotic operations, and alerting the operator to early indications of impending failures.

Science sensors - A number of science instruments could be integrated into the RoboSuit for augmenting the capabilities of the planetary field geologist. Telescopes and microscopes were mentioned previously. Spectrographic data can be collected and presented, although some spectroscopy systems require data collection times incompatible with EVA operations. Non-imaging sensors, on the boot soles for example, can continuously monitor local surface properties such as resistance to penetration, and collected data could be used in conjunction with navigational data and other science instruments to automatically generate data maps of the explored regions.

Of greater difficulty than sensory augmentation is actuator augmentation. This might begin, as in the case of the power glove, with pure *augmentation* (using the actuators to minimize the force and power required to actuate suit joints), and ultimately lead to the capability for force *amplification* (making the output force arbitrarily larger than the wearer's input force.) Ultimately, this will require a robotic actuator for each degree of freedom of the suit.

A number of potential approaches exist for implementing this power suit concept. The final form of the design will be dependent on future developments in high torque, low power actuators. Short of these breakthrough developments, though, the University of Maryland has attempted to develop a notional concept for a force-augmented RoboSuit which could be constructed today to enable this research, and to allow subsequent operational evaluation of the system.

The development platform chosen was the NASA Ames AX-5 experimental space suit (Figure 9). This suit configuration is ideally suited for power amplification, as it is an all-"hard suit" design, and all joints articulations are provided by multiple single-degree-of-freedom rotary actuators.

The current design approach is to develop and implement robotic assistance actuators on each rotary joint of an AX-5-type suit. Design goals are to keep the actuators low in volume, mass, and power required. Some interesting challenges with this approach include routing power and control wiring for distal actuators (such as the wrists and hands) across multiple proximal rotary joints, and developing a controller with sufficient sophistication to handle the suit forward and inverse kinematics, given that

Figure 9
NASA Ames AX-5 Experimental Space Suit

the suit actually has more degrees of freedom than the human wearer.[5]

It should be noted that there are a lot of intermediate applications of powered suits, short of the full-up force augmented RoboSuit described here. For instance, selected joints (such as the glove MCP joint described earlier) might be augmented to relieve specific problems with astronaut fatigue in EVA operations. Leg joints for a microgravity suit might be designed with brakes or variable friction mechanisms, to allow free motion when maneuvering, but providing the wearer the option to "lock out" the legs to provide additional stability without fatigue when in foot restraints. Even if the full powered suit concept never comes to fruition, the technologies described will enable a host of new capabilities to improve EVA performance while reducing crew physical and mental workloads.

CONCLUSIONS

Modern-day space suits are unquestionably one of the great feats of engineering. As others have described them before, they are self contained personal spacecraft that have to take human form, surrounding the body as closely as possible without bearing on it directly, and moving with very low friction as the wearer moves inside. For all the achievements of space suit design over the decades, though, the fact remains that the current space suit paradigm is that of a passive envelope which is moved by the muscle power of the human inside. The unaugmented system (human + suit), by definition, can ultimately only asymptotically approach the capabilities of a human in shirtsleeves.

This paper addresses technological approaches for a paradigm shift: using robotics and advanced electronics integrated into the suit to augment and extend the capabilities of the wearer. By adding additional hands and arms, either to the work site or to the suit itself, additional sensors, displayed in a natural and intuitive way to the operator, or robotic torque augmentation to the joints of the suit itself, the RoboSuit concept embraces the concept of the space suit as an *active* partner to the wearer, making the total system *more* capable than the human alone.

REFERENCES

1 Lillian D. Kozloski, *U.S. Space Gear - Outfitting the Astronaut* Smithsonian Institute Press, 1994.

2 D. L. Akin, J. C. Hedgecock, and E. A. Sorenson, "Experimental Results of Integrated EVA/Telerobotic Work Sites" *NASA Space Operations and Robotics Workshop*, Houston, Texas, July 1989

3 Gardell G.Gefke, Craig R.Carignan, Brian J.Roberts, J.Corde Lane, "Ranger Telerobotic Shuttle Experiment: Status Report" *SPIE International Symposium on Intelligent Systems and Advanced Manufacturing*, Newton, Massachusetts, October 2001.

4 David L. Akin, Brian Roberts, Kristin Pilotte, and Meghan Baker, "Robotic Augmentation of EVA for Hubble Space Telescope Servicing" AIAA-2003-6274, *AIAA Space 2003 Conference*, Long Beach, CA, Sept. 2003.

5 Gary L. Harris, *The Origins and Technology of the Advanced Extra-Vehicular Space Suit*, AAS History Series, Vol. 24, Univelt Publishers, 2001.