AIAA 2001-4593

AN EXPERIMENTAL INVESTIGATION OF DEXTROUS ROBOTS USING EVA TOOLS AND INTERFACES

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ABSTRACT

This investigation of robot capabilities with extravehicular activity (EVA) equipment looks at how improvements in dexterity are enabling robots to perform tasks once thought to be beyond machines. The approach is qualitative, using the Robonaut system at the Johnson Space Center (JSC), performing task trials that offer a quick look at this system's high degree of dexterity and the demands of EVA. Specific EVA tools attempted include tether hooks, power torque tools, and rock scoops, as well as conventional tools like scissors, wire strippers, forceps, and wrenches. More complex EVA equipment was also studied, with more complete tasks that mix tools, EVA hand rails, tethers, tools boxes, PIP pins, and EVA electrical connectors. These task trials have been ongoing over an 18 month period, as the Robonaut system evolved to its current 43 degree of freedom (DOF) configuration, soon to expand to over 50. In each case, the number of teleoperators is reported, with rough numbers of attempts and their experience level, with a subjective difficulty rating assigned to each piece of EVA equipment and function. JSC's Robonaut system was successful with all attempted EVA hardware, suggesting new options for human and robot teams working together in space.

EXPERIMENTAL SCOPE

The scope of this report is to open the readers mind to the potential of robots doing these tasks at all. The tasks selected for discussion are considered by NASA to not be robot compatible. The fact that these tasks have been considered beyond robot capability is the hypothesis that we are attacking, and we recognize that the degree of competency with which the robot functions will remain an important question worthy of continued study and debate. Therefore, the nature of this report is qualitative in that it will document EVA tools that have been successfully used by a unique and unusually advanced robotic system, and will not address the quantitative measures of force, speed, accuracy, endurance, cost and other metrics that will need to be studied for future space missions. Our belief is, first, that our ongoing work in controls, autonomy, design and human factors will soon answer these Engineering questions, and second, that the breakthroughs in dexterous robotics now occurring in NASA's labs will invite new missions that team humans and machines working together in space.

EXPERIMENTAL APPROACH

The Robonaut system, a machine built by the authors and other engineers at the Johnson Space Center, serves as the test apparatus for this study. As will be described in the next section, it is a singular and remarkable system, and is arguably the most dexterous robot built to date.

Figure 1 The Robonaut System

As a qualitative investigation, we were more interested in whether or not the robot would able to perform the EVA functions so we tested a wide assortment of tools, equipment and other EVA interfaces. A more quantitative study would likely focus on a smaller set of tools, and measure motions, forces and tasks times. These studies are now ongoing, as well as motion control research[1].

This study used both novice and veteran operators, with novices defined as having less than 100 minutes of operating time, and less than 5 attempts at any single task, tool or function of study. Some of the novices tried these EVA tools in their first minutes of experience, with literally no training. Veteran operators are constrained by the fact that the robot is very young, with no human having over 100 hours of operation with Robonaut. Typical veterans have about 10 hours of time, and 10 or more attempts at the various operations being studied.

For much of the EVA hardware, we have only allowed veterans to attempt the operations, as our training has found that teleoperation is best learned starting with simple movements and tasks[2]. We will focus primarily on those EVA trials that have both novice and veteran attempts, where the greater data set allows for conclusions to be drawn more confidently. Where we have a limited set of operators for specific trials, we will report that experience with the acknowledged smaller statistical basis. For each EVA trial, we will report the number of operators, their rough number of attempts, and deliver a fully subjective difficulty rating associated with that experience. In all cases, the EVA tools and equipment were successfully operated, but the difficulty rating of hard, medium, or easy representing the operators' success rates, speed and physiologic strain. This approach yields the reader an assessment as to whether an EVA device can be done at all by a robot, our team's confidence in our specific robot's ability to do the task, and enlightenment on new roles for robots once thought impossible in space. For each task studied in depth, we also report on particulars of the function that made it more or less hard, in the hopes of aiding other design teams.

ROBONAUT BACKGROUND

NASA is developing the Robonaut system, a highly dexterous anthropomorphic robot, now in testing at the Johnson Space Center[3, 4]. Robonaut represents the state of the art in dexterous systems, with R&D focused on multiple use tool handling end effectors, modular robotic design, telepresence control, and humanoid autonomy. The project has adopted the design concept of an anthropomorphic, EVA crew sized robot configured with two arms, two five fingered hands, a head, and a torso. Its dexterous pair of arms enables dual arm operations and its hands can work directly with a wide range of interfaces without special tooling. Its anthropomorphic design enables "intuitive" telepresence control by a human operator, with an evolving set of semi-autonomous functions that improve efficiency. As a direct result of its unique form and function, it can interface directly with EVA tools designed for the suited astronaut and can work within tight EVA access corridors. Robonaut, shown in Figure 1, has the dexterity to work with its hands, in ways that we are just beginning to explore.

System Anatomy

The gross anatomy of the system is ideally suited to work with EVA interfaces, while stabilizing on a third limb, called the 0g tail[5]. This limb, with a Worksite Interface Fixture (WIF) interconnect, can be docked similarly to the portable foot restraint that Astronauts now must setup for their own stabilization, freeing the hands for work, as shown in the Concept image of Figure 2.

Figure 2 Robonaut System Concept on Station

As shown in Figure 3, the system also has a Power Data Grapple Figure (PDGF) on its back that allows Robonaut to be pickup up by NASA's larger manipulators, such as the RMS and SSRMS. Other than these two specialized interfaces, all other interactions of Robonaut will involve the versatility that humans exhibit in the use of their arms, body and most often, hands. Instead of requiring special robot interfaces, these contacts, by design, are irregular, and require a certain degree of finesse. The upper extremities are human in scale and strength, endowed with five fingered hands, with a total of 19 DOF. Including these limbs, the tail, neck and eyes, the system has over 50 DOF. The current system has only the first 3 DOF of the 0g tail, serving as a waist joint, and for much of these trials, the eyes were fixed, for a total system mobility of 43 DOF.

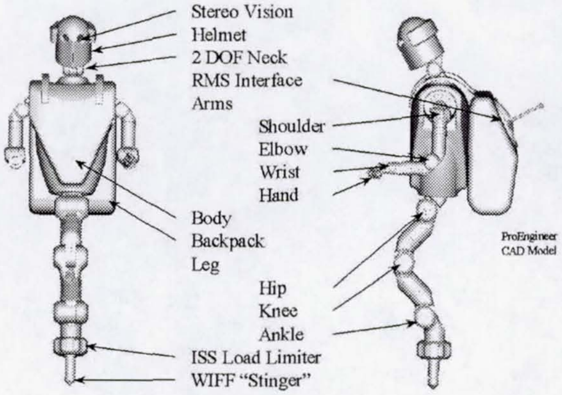

Figure 3 Robonaut Anatomy

The Robonaut system, has already demonstrated sufficient dexterity and control to handle a wide range of tools once thought impossible for robotics. As the project matures with increased feedback to the human operator and autonomy, the Robonaut system will approach the handling and manipulation capabilities of the EVA suited astronaut[6].

System Control

The Robonaut control architectures parallel the human nervous system with discrete "lobes" that are functionally distinct CPU's. These include a visual cortex for autonomous stereo vision, a thalamus for motor/sensor I/O servicing, the Robonaut brainstem that handles all motion control, and a hippocampus that is still in development. The brainstem is designed to interface to either the other autonomous lobes, or to take a numerically identical command stream from a remote teleoperator[7]. Other software products include an API for external collaborators to interface to the system, and simulation module that can be used with the same interfaces as the brainstem for software development.

The computing environment used for the Robonaut brainstem includes several state-of-the-art technologies. The PowerPC processor was chosen as the real-time computing platform for its performance and its continued development for space applications. The computers and their required I/O are connected via a VME backplane. The processors run the VxWorks real-time operating system. This combination of flexible computing hardware and operating system supports varied development activities. The software for Robonaut is written in C and C++. ControlShell, a software development environment for object oriented, real-time software development, is used extensively to aid in the development process. ControlShell provides a graphical development environment which enhances the understanding of the system and code reusability.

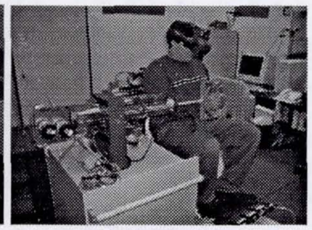

Figure 4 Cybergrasp *Figure 5 Force Feedback*

Wearing the VR gloves and helmets shown in Figure 4, an operator's hands, arms and neck are mapped directly to the Robonaut system. The immersion of the operator in the Robot's environment is achieved with the helmet displaying video from the perspective of Robonaut's head. The helmet is connected to two stereo vision cameras mounted in Robonaut's head. The sensation of immersion is furthered by the helmet's binocular displays (yielding depth perception) and the mapping of Robonaut's neck to the operator's helmet. As the operator moves the helmet, the articulated neck described in the previous section is commanded to produce similar motions of the cameras. Force feedback options include devices that put haptic forces on the operator's fingers, as shown in Figure 4, and arm forces as shown in Figure 5.

EVA Tools

NASA has a massive investment in EVA tools, well documented in the EVA Tool Catalog[8] and countless mission logs. The depth and breadth of this tool set is immense, from space versions of conventional hand tools, to specialized tools for other EVA interfaces. EVA tools similar to those found in terrestrial applications include vise grips, wrenches, hammers and scissors, with a representative set shown in Figure 6.

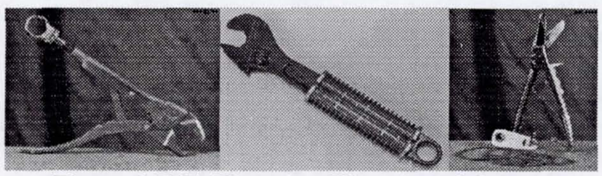

Figure 6 EVA Visegrips, Wrench and Scissors

While we recognize these from our daily lives, the modifications are important. All have been altered to include tether points, typically wide loops to which soft lines can be connected for safe handling on orbit in the 0g environment. In many case, the handles have been expanded to a larger diameter to ease the grip requirements, a feature that will be seen to improve Robonaut's handling of them as well.

More complex tools, specialized for EVA include ratchet wrenches, scoops for handling other objects, and power torque drivers, PIP pins, and hooks. Figure 7 shows examples of these specialized tools.

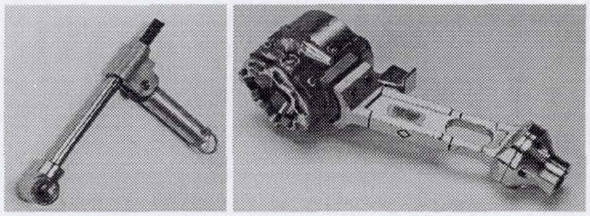

Figure 7 EVA Right Angle Drive and Square Scoop

From this spectrum of options, our study selected the EVA tether hook, acquiring an exact EVA specimen, a commercial drill that is similar to the EVA torque tool, and a commercial scoop similar to Lunar and possibly future Mars tools. These three items were tested with a group of teleoperators, of various skill levels. The skilled operators tried many other tools. The tether hook, drill, and rock scoop testing will be described in detail, with tabulated results for the other tools as well.

Tether Hook

The EVA tether hooks, shown in Figure 8, are intentionally hard to operate. Serving as the Astronaut's life line, these devices can not accidentally open, due to a design that requires two "petals" to be depressed before the gate is free to swing. When these "petals" have both been pressed, the gate can be opened due to contact, or can be articulated by pulling the trigger.

The last mode is most common, with the handle being designed to fit into the palm of the human hand, with palm and thumb pressing the petals, while the fingers pull the trigger. This compound action is complex, requires some training for humans, and meets NASA's objectives for safety. It does not meet any standard for robot compatibility, and is thus an ideal target for changing the space robotics community's perception about what is and is not robot compatible.

Of the hooks pictured, our team tested the top one with five different test subjects teleoperating the system. Experienced operators had a high (>80%) success rate in their attempts at this device, with novice operators having mixed results. Some novice operators had high and near perfect success rates on their first attempts, with others struggling through multiple attempts before getting up to high rates of success. All were eventually able to perform the tether hook task after no more than 15 minutes of practice, with operators removing it from a fixed loop on a hand rail, and grappling a swinging loop hanging from a suspended tether, often swaying gently as a pendulum. On orbit, grappling a fixed loop, such as on a hand rail or a fixed piece of equipment would be very successful, and chasing a free tether loop in 0g with the hook might even be possible.

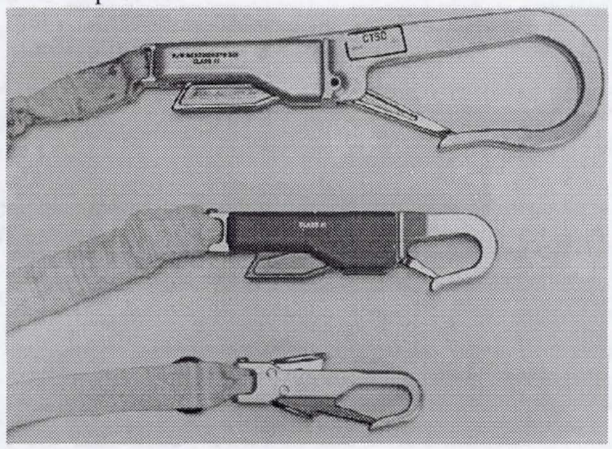

Figure 8 EVA Tether Hooks 1

Tether Hook	Subjects	Attempts	Difficulty
Novices	5	>5	Medium
Veterans	2	>30	Medium

Despite our operator's universal success rate, we still give this item a medium difficulty rating. The specific problems are all associated with the initial grasp of the object, where the robot palm must be placed accurately over the "petals" to ensure their closure, while simultaneously aligning the trigger with the ring and pinkie for its articulation. A common failure was to successfully free the "petals", but not be able to exercise the trigger. In this mode, the hook can still be engaged onto a fixed loop, much like a carabineer can be clipped on a piton. We believe that tactile sensor arrays on the palm and anterior finger surfaces would allow this alignment to be achieved even after an initial mis-grasp, producing a re-grasp sequence that humans do with great subtlety. Operators, with training, initiate this grasp slowly, carefully, and with great success using Robonaut, giving it a medium rating. Robonaut has performed this task many dozens of times.

Power Drill

EVA Hardware is often launched with bolts torqued to high levels to protect the gear from vibration. On orbit, these bolts require maintenance by EVA, first relaxing them from the high torque state, then re-tightening them to lower levels. Others tasks require installing hand rails or other gear with bolts that also must be tightened to specific torque levels. These requirements have led to the development of battery operated torque tools that are similar to rechargeable drills used on Earth. Outfitted with socket driving bits, these power tools can be used by crew to tighten and release bolts during EVA.

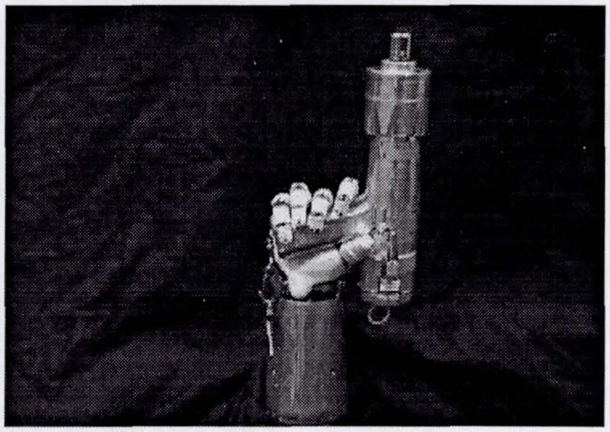

Figure 9 Robonaut Hand Grasping EVA Torque Tool

A model of an EVA torque tool is shown being grasped by the Robonaut hand in Figure 9. A commercial power drill was selected for our task trials, with its pistol grip modified to match the geometry of the EVA tool. This tool was one of the first attempted by the Robonaut system, and has logged a great number of novice and veteran trials. Shown in Figure 10, this tool was first tried when Robonaut was still a single arm system, and has more recently been attempted with the waist for coordinated reaching.

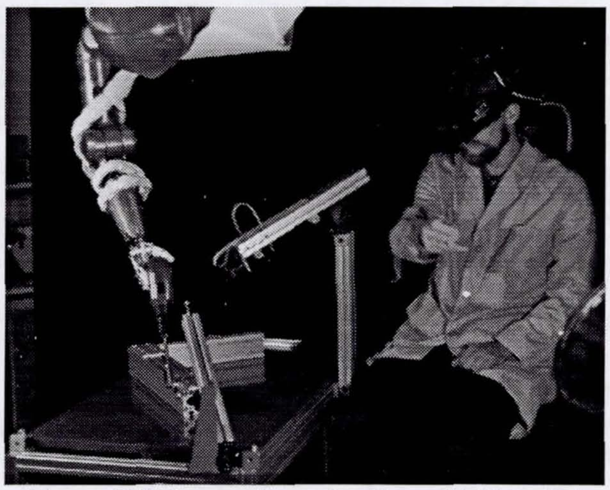

Figure 10 Robonaut Operating Power Drill on Bolt

The task trial started with the drill placed in a holster, from which the teleoperator must grasp and retrieve it. Using a 7/16 Hex driver, the tool is placed over a bare bolt head and used to tighten or loosen the bolt, then replaced into the holster.

Bolt Driver	Subjects	Attempts	Difficulty
Novices	5	>5	Medium
Veterans	2	>100	Easy

The grasp required for the drill is again a compound function. One objective is the grasping of the drill's pistol grip with the palm, thumb and all but the index finger, forming a grasp sufficient for stabilizing the drill body relative to the palm. The simultaneous objective of positioning the index finger to enable articulation of the trigger requires planning in the early stages of the grasp. A poorly formed grasp can easily bind the index finger along the underside of the drill, restricting its motion. Worse, the binding can be found after the fact, when trying to release the trigger after the action is already committed. Much of the contact with the drill is visually occluded by the drill, requiring the operator to combine his stereo depth perception with intuition about the form and function of a pistol grip shape. Robonaut's similarity to the human hand allows the operator's experience with his own hand to be exploited.

Consequently, all operators were able to do this task, usually on the first try. Subsequent attempts improved speed, reduced contact forces during constrained motion, and allowed for greater finesse in controlling drill speed. After fewer than 5 attempts, operators had high success rates, allowing us to conclude that this is an easy task for veterans. The advance planning in the early stages of the grasp gives it a medium difficulty rating for the novice operator. Notice from the table that the robot has performed this task hundreds of times.

Rock Scoop

Robonaut has demonstrated the ability to pick up and handle irregularly shaped rocks as large as 150mm across, as shown in Figure 11. Its ability to use scoops will enable future science mission that involve sample handling and collection. These tasks involve digging, scooping and pouring soil, excavating rocks from within gravel, and prying apart and sampling rock fragments that have been cracked, crushed or chipped for investigation.

Figure 12 shows Robonaut handling a commercial scoop, digging in coarse (5-10mm) gravel that resists the insertion of the tool with complex frictional forces. This task was attempted with the scoop initially left stuck into the gravel, where the operator would grasp and retrieve it, then begin digging in the gravel to expose buried rocks of a larger scale (40-50mm).

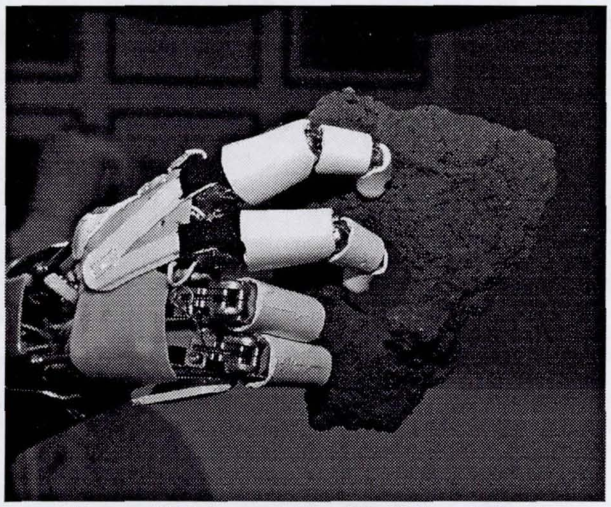

Figure 11 Robonaut Handlig Volcanic Rock

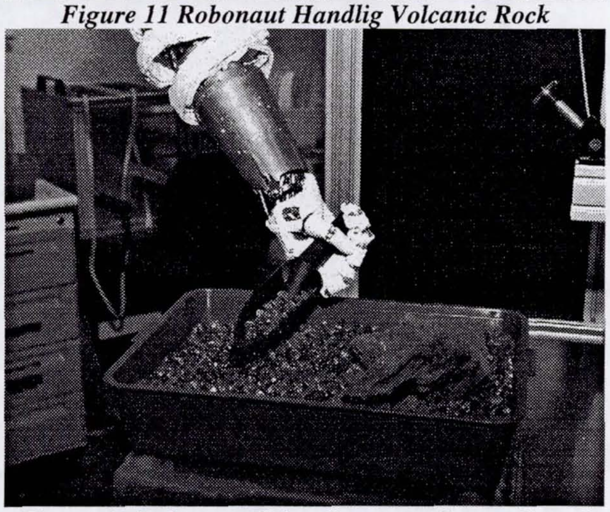

Figure 12 Robonaut Using Scoop on Coarse Gravel

These rocks, once excavated, would be picked up by the other hand, pulling them free of the gravel, and then bringing the rock near the head for a close inspection. Macroscopic features in the rock were identified, and then the sample was placed in a container (100ml plastic beaker) or the specimen was discarded, depending on the inspection results.

Rock Scoop	Subjects	Attempts	Difficulty
Novices	4	>4	Easy
Veterans	1	>10	Easy

While we have fewer attempts with this task, success rate was high, even on the first trials of novice operators. All phases of the actions were found to be very doable, with the only difficulty being the avoidance of dragging the fingers on the soil during digging with the scoop.

We believe that robots will allow geologist to explore and interact with planetary sites in a very natural way, and supervise these machine doing these tasks with a great deal of autonomy, as the work was easily done by this machine. Future inclusion of sensors into the robot, or the use of hand held instruments shared with humans would deepen the science and reduce sample sizes by working more intelligently during first contact with the materials.

Other Tools

A small number of veteran operators have attempted a much richer set of tools, ranging from EVA tools, to technician tools, to medical instruments, using the Robonaut system. We have fewer operators from which to judge these functions, and so report them with a lower level of confidence, but feel the breadth of tools attempted is still of interest.

Tool Name	Difficulty Rating
Socket Wrench	Easy
Scissors	Medium
Multi-meter Probe	Easy
Wire Stripper	Medium
Hammer	Easy
Rock Pick	Easy
Locking Forceps	Medium
Syringe	Hard
Tweezers	Medium
Arthroscopy Probe	Medium
Locking Forceps	Medium

EVA Equipment

Space walkers face an environment that challenges them in locomotion, stabilization, and manual dexterity. Where the EVA tools taxed Robonaut's ability to grasp and use hand tools, other hardware requires the robot's hands to become the tools. A J hook that an Astronaut spins by hand does not have a special tool for its articulation. It is designed for the human's (gloved) fingers to grasp it, turn it and position it. Where EVA tools might have common grips, across several devices, these other pieces of EVA equipment are often unique, and require more advanced strategy on how to handle them. The hand rail bag shown in Figure 13, requires the Astronaut to reaches into it, and extract one of many rail segments, as the crew install them on the outside of a space craft. Contact between the robot and the bag is not deterministic, with many possible points of contact along the length of the forearm as it reaches into the fabric container. The tool stanchion of Figure 14 will require a two handed grasp for it to be inserted into its socket. The crane in Figure 15 involves a mix of cranks, knobs, levers, tabs and buttons that must be articulated. The Worksite Interface Fixture Probe in Figure 16 requires another set of "petals" be pressed for release, and is designed for a human hand to wrap around it, release it, and then have a dexterous arm extract it from a socket. The pitch-yaw fitting shown in Figure 17 also has failsafe tabs that must be released by the same hand that is then applying the pitch and yaw moments that position it, then relock it on release.

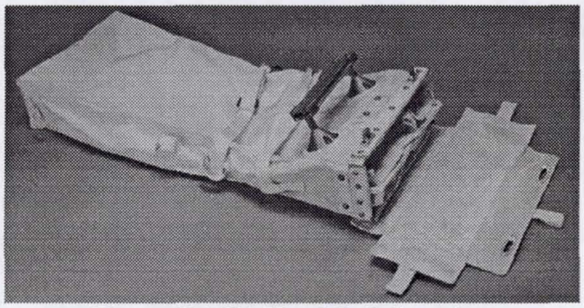

Figure 13 EVA Hand Rail Container

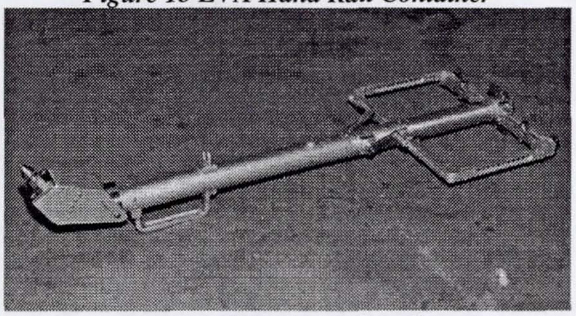

Figure 14 EVA Tool Stanchion

Figure 15 ORU Crane

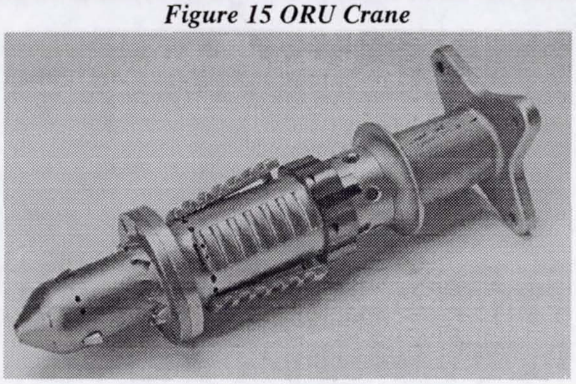

Figure 16 Active WIF Probe

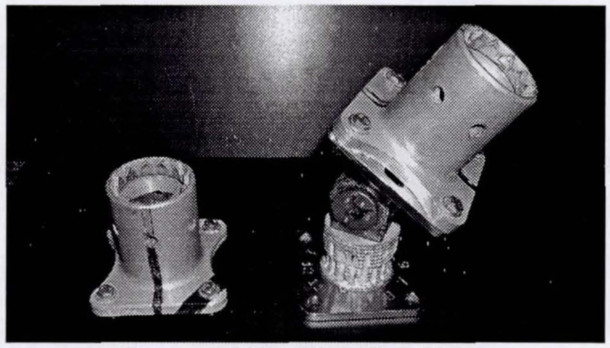

Figure 17 EVA Pitch-Yaw Fitting

For our study, we selected a soft EVA tool box, EVA hand rails, EVA electrical connectors, and EVA PIP Pins for investigation, acquiring flight hardware specimens for testing with the robot.

EVA Tool Box

The soft fabric box shown in Figure 18 is used to house tools and other equipment for launch. The container is very irregular, with a top that is more of a flap than a lid. Fastened closed by two clasps, the lip of the flap is further sealed by Velcro that is hidden from view, but firm. The flap's sides are very soft, it bends on a poorly defined seam that can not be called a hinge, and the sides of the box's body are collapsible. Items are typically suspended in foam within this box, and must be extracted from pockets within the foam.

Figure 18 EVA Tool Box

This task trial starts with the Tool Box placed on a table in front of Robonaut. The operator must first position the robot torso, by using the waist joints, to setup the various motions and views that will be needed. The operator can also handle the box, and reposition it to ease the task, but this was not allowed. For right handed operators, the left arm is pre positioned behind the box to manage the lid after release. The torso is positioned to give the head a good view of both clasps, the lid, and both arms. The right hand is then used to turn each clasp 90 degrees aligning it with an opening in the lid that is reinforced with a grommet. The right hand is then used to part the Velcro seam, grasp the flap, and peel it open. In 1g, the lid is carried over center, and drops onto the waiting left forearm, which cradles it (in 0g, the left hand would likely need to stabilize this contact on an edge of the flap). At this point, the main activity of retrieving an object from within the box can proceed, though the robot is somewhat constrained by its hold on the box flap. After extracting an object from the box with its right hand, the left arm closes the flap, and soft docks it on the box with the Velcro. Later in the EVA, the object can either be replaced, or the flap dogged down with the two clasps. This often requires a re-opening of the flap, as the imprecise seam will not align the clasps and grommets. The final task returns the clasps to the their locked positions.

Only 2 of our veteran operators have tried this task, each after they had over 20 hours of robot run time. In each case, their first experience was difficult, based primarily on strategy for setting up the task, charting the sequence of steps, and learning technique. This is similar to the EVA training experience for crew, as they confront the task, plan and learn how to execute it, and then practice those procedures. After about 5 attempts, and some strategy discussions, our veteran operators were highly successful in their reliability with the task, with low forces (<1 lb), short completion periods (<100 seconds) and low strain. We have had one novice attempt this task, and with advance coaching on technique and task sequence, was able to execute it successfully, though with several re grasps, and longer task times (~500 seconds).

Tool Chest	Subjects	Attempts	Difficulty
Novices	1	>2	Medium
Veterans	2	>10	Easy

This task is another ideal demonstration of the need for a versatile robotic system in EVA, and the potential that these new, highly dexterous robots have in serving that need. Fabric items that are irregular, and often used as compressive structure like the walls of a box, can not be easily modeled, and reactive contact requires a very light touch. In our teleoperated system, the human's cognitive skills are exploited, where visual deformations in the fabric are observed by the human, and used to perceive forces that are incredibly small (<1N). Working with soft goods like these has been successfully demonstrated, but autonomous operations with these materials will be very challenging. Tethers, blankets, caps, covers, and other fabrics are common on space craft exteriors, and EVA robots must be able to handle them.

Hand Rails

Astronauts locomote and stabilize themselves on the exterior of space craft using EVA crew handles. The cross section of these hand rails has evolved, with the latest "dog bone" profile providing a textured grip that the crew can grasp more readily, and that other EVA gear can grip. Figure 19 shows hand rails that are designed to mount on their side surfaces, and Figure 20 shows a top mount style. Both have a similar rail cross sections, with open loops where tether hooks can engage. The rigidizing tether and gripper shown in Figure 21 also grips this rail. The ability to use these hand rails for stabilization will be important for a dexterous robot working on the exterior of a space craft with few hard points. Robots will also need to be able to install these hand rails, for use by humans and robots.

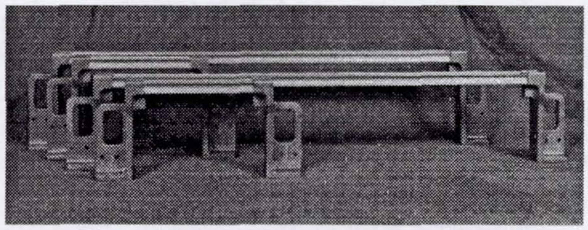

Figure 19 Side Mount EVA Hand Rails

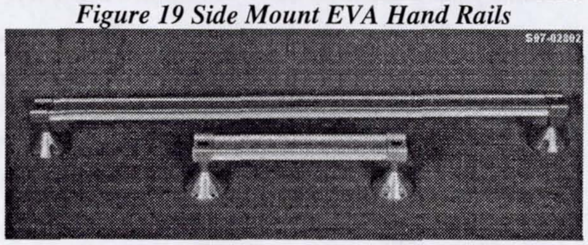

Figure 20 Top Mount EVA Hand Rails

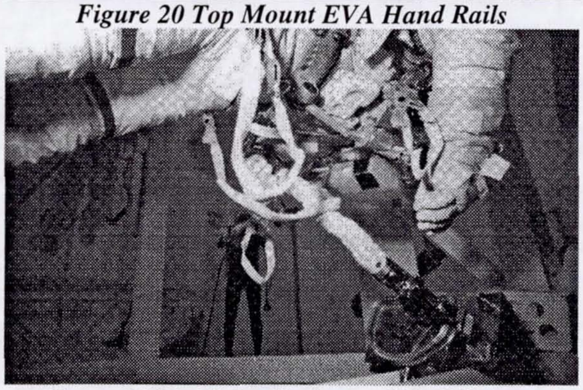

Figure 21 Rigidizing Tether and Rail Gripper

For our testing, we have combined several task sequences using hand rails segments and previously describe EVA gear. For example, we have had hand rail segments be the object that we extract from the tool box, and we have engaged tether hooks on hand rails with fixed loops. Our typical test has extracted the hand rail from a box, or taken it by hand from a human, then re grasped it, exchanging it from its right hand to its left hand, then offering it to a human, or placing it on a hook, or back in the box. In all cases, this was found to be rather easy for Robonaut.

Hand Rails	Subjects	Attempts	Difficulty
Novices	5	>5	Easy
Veterans	2	>20	Easy

The soft RTV material on the Robonaut hand, and the Kevlar/Teflon skin, ensures that the hand rails are not nicked or burred during robot handling. This is of vital importance, as any sharp burr on the hand rail could cut the glove of an Astronaut, risking a life. Typical parallel jaw grippers, or ones with metal fingers specially contoured to the hand rail cross section, would not be safe for handling this EVA equipment. Our tests with flight specimens of EVA hand rails have never damaged their surfaces. The biggest risk is similar to that posed by humans, who might hit a hand rail with a metal hand tool, or hit the rail during installation on another piece of metal structure. Periodic robot inspection of hand rails and other EVA interfaces would be advised, to protect the crew.

Figure 22 Testing of the Mini Workstation

PIP Pins

Much of the EVA equipment comes with tethers, and various pins that hold the equipment together during launch and use. These are generally referred to as PIP pins, and they come in many sizes and styles. Their common features are a long pin shaft with a ball detent, which is articulated by a button, often mounted on a T shaped handle. Most are single handed devices, designed to be grasped between the index and middle finger, with the thumb depressing the button. Figure 22 shows an Astronaut testing the Mini Workstation worn on the chest, which serves as an attachment site for tether tools. Each such interface will often require a PIP pin. Gear launched in the Orbiter Payload Bay is often secured with PIP pins, which are removed during EVA deployment of that equipment. Any robot that hopes to work with EVA hardware must be able to manage PIP pins of various styles.

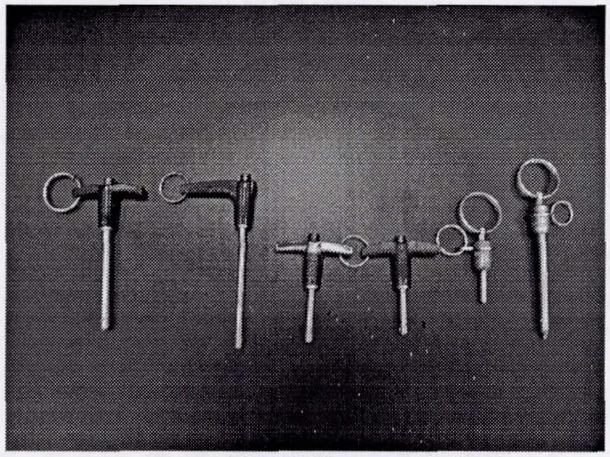

Figure 23 PIP Pins used in Study

For our study, we selected a set of 6 PIP pins for testing. Shown in Figure 23, these include 3 styles (T handle, L handle, Pull ring) two shaft diameters (3/16" and ¼"), and each with a unique length (0.75" to 2.25"). These pins were mated with sockets that were laid out on stabilizing stanchions.

The task involved grasping the PIP Pin, articulating the button, extracting the pin. Then reinserting the pin back in the hole.

PIP Pins	Subjects	Attempts	Difficulty
Novices	1	>2	Hard
Veterans	2	>10	Hard

This is a classic peg-in-hole robot control problem. Robonaut has been successful in performing these tasks, with extracting being much easier than re-insertion. The pull ring style PIP pin, a newer design, is much easier to operate, both by humans and Robonaut. Only our experienced operators have attempted this task, and the reinsertion step took the longest, and was rated as a hard task. This is not surprising, as it is also hard for a gloved Astronaut. The evolution of the pins away from the button towards the pull rings will ease this burden, but Robonaut was able to operate these small pins as is.

EVA Connectors

The last EVA interface attempted was an electrical connector, similar to those deployed on the exterior of the ISS. These connectors are used to terminate cables, which are mated to receptacles found on the exterior of space craft. The connectors are typically launched with caps covering them for protection, and the connectors have fabric boots that slide along the cable to cover the connector when installed. Robonaut was tasked with demating, then remating such a connector, with a receptacle mounted to an aluminum fixture. The connector has a linkage that is articulated with a lever and flange, that engages/disengages the electrical pins through the core of the barrel connector.

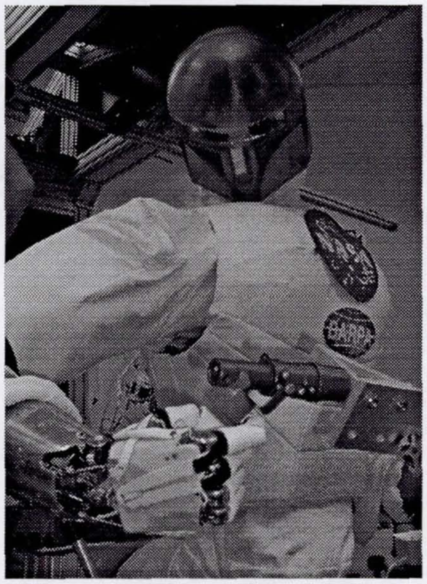

Figure 24 Robonaut Opening Latch

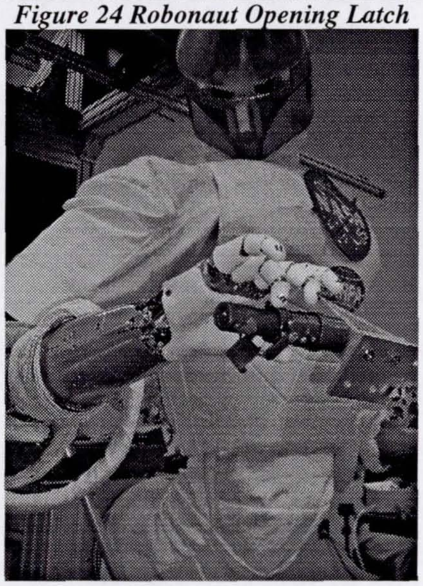

Figure 25 Robonaut Extracting Connector

Figure 24 shows Robonaut operating this lever with its right index finger. The next step is to grasp the barrel of the connector, avoiding the lever and linkage mechanisms, and twist/slide the connector free from the receptacle, as shown in Figure 25.

Like the PIP pin, the hard part is then re inserting the connector, but this is not a simple peg-in-hole geometry. The sliding engagement requires a slight twisting action that is felt more than seen. Spring loaded ball bearings provide a slight cushion, and a retaining shoulder must be aligned on each part before the balls can depress. A close up of the grasp for this is shown in Figure 26. Once soft docked, the lever is again engaged to connect the pins, requiring a large force at the end (5-10 pounds).

Electrical Connector	Subjects	Attempts	Difficulty
Veterans	1	>10	Hard

The difficulty of re-inserting this connector rates this interface as hard. Like the PIP pin, this is also challenging for humans, especially gloved humans, and slow task times must be anticipated. But these connectors, as challenging as they are, have now been done robotically.

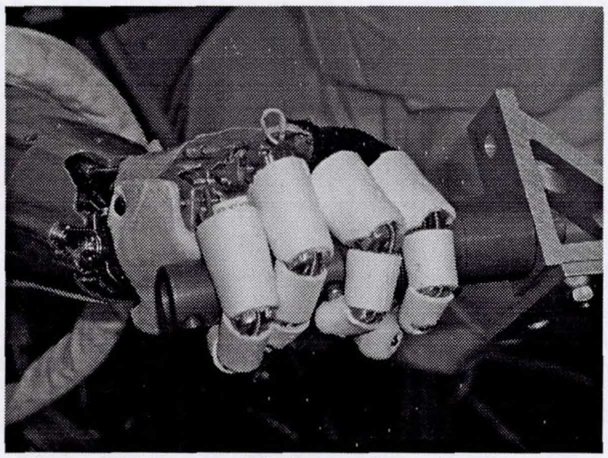

Figure 26 Closeup of Robonaut Inserting Connector

CONCLUSION

For robots to work side by side with Astronauts, they must be able to fit through the same access corridors as suited humans. They must be able to stabilize on similar hard points. They must be able to locomote to the worksite, and exploit any interfaces that are available for that purpose, managing tethers much like a mountain climber. But most importantly, once stabilized at a work site, they must then do work. They must be able to pickup and use tools, and be able to hand them and share them with human team mates. And when necessary, they must work with their fingers and skin, manipulating, holding supporting, groping, carrying, and deploying EVA equipment without leaving damaging burrs and nicks that could damage a space suit glove. While this is a great challenge, Robonaut has demonstrated that robots can work with EVA gear, and not require additional handles, targets, ports, guides, or beacons. The niche for these new machines is a compliment to the larger robots now in service on ISS and the Shuttle, and dexterous machines like Robonaut will use these systems for transport, just as humans now do in 0g.

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