Humanoids Designed to do Work

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1.0 Abstract

NASA began with the challenge of building a robot for doing assembly, maintenance, and diagnostic work in the 0g environment of space. A robot with human form was then chosen as the best means of achieving that mission. The goal was not to build a machine to look like a human, but rather, to build a system that could do the same work. Robonaut could be inserted into the existing space environment, designed for a population of astronauts, and be able to perform many of the same tasks, with the same tools, and use the same interfaces. Rather than change that world to accommodate the robot, instead Robonaut accepts that it exists for humans, and must conform to it.

While it would be easier to build a robot if all the interfaces could be changed, this is not the reality of space at present, where NASA has invested billions of dollars building spacecraft like the Space Shuttle and International Space Station. It is not possible to go back in time, and redesign those systems to accommodate full automation, but a robot can be built that adapts to them. This paper describes that design process, and the resultant solution, that NASA has named Robonaut.

Figure 1 Photo of NASA's Robonaut

2.0 Background on EVA Work

Space walking is poorly named, as it has little in common with how animals walk on Earth. Space walking is more akin to mountain climbing in scuba gear, while parachuting in a free-fall, an odd combination of effects and equipment to help people do a demanding job. Robot's are now being studied for service in this same domain, working on large scale space structures, on the Space Station, servicing science or military platforms in high orbit, or riding on the outside of a space craft in transit to Mars, the Moon or other bodies. What have we learned about working in 0g? How should machines be controlled for serving in this role? What can they do to overcome the problems that humans have faced?

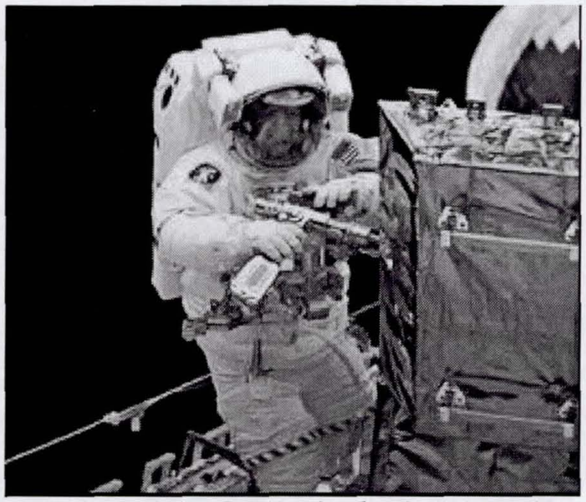

Figure 2 Photo of EVA, Shuttle Flight STS-103

NASA's name for space walking is Extravehicular Activity, or EVA. This is an all-encompassing term for any work that an Astronaut does, while working outside the spacecraft, wearing a space suit. These activities include deploying equipment that has been carried to orbit, assembling equipment, doing repairs, inspection, or simply positioning equipment for later use. This is one of the most physically demanding jobs ever performed by humans, and not without risk. It is also expensive, as EVA hours are precious, and few.

2.1 EVA Tools

Beyond the amazing advances in material science that resulted from space suit development, NASA has invested in a set of tools, equipment and interfaces to facilitate and enable EVA work. NASA has a massive investment in EVA tools, well documented in the EVA Tool Catalog[1] 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 3.

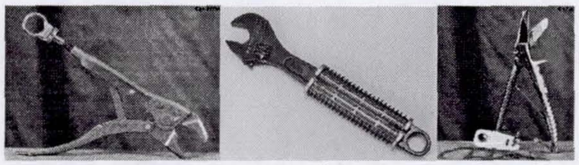

Figure 3 EVA Versions of Conventional Tools

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 micro-gravity environment. In many cases, the handles have been expanded to a larger diameter suited to the pressurized EMU (external mobility unit) glove worn by space-walking astronauts. This feature also makes the tools easier for Robonaut to handle.

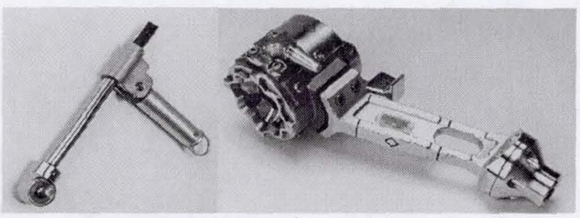

Figure 4 EVA Ratchet and Scoop Tool

More complex EVA tools include ratchet wrenches, scoops for handling other objects, power torque drivers, PIP pins, and hooks. Figure 3 shows examples of these specialized tools.

2.2 EVA Equipment

Space walkers face an environment that challenges them in locomotion, stabilization, and manual dexterity. Where the EVA tools tax a robot'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 5, requires the astronaut to reach into it and extract one of many rail segments for installation 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 6 will require a two handed grasp for it to be inserted into its socket.

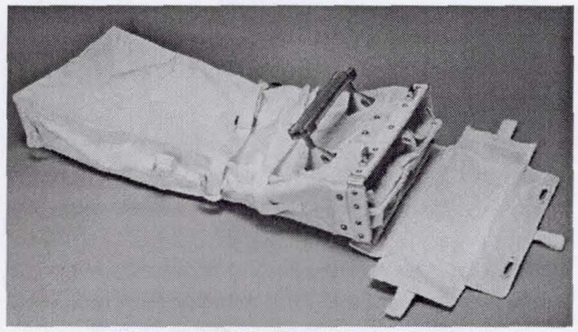

Figure 5 EVA Hand Rail Carrier

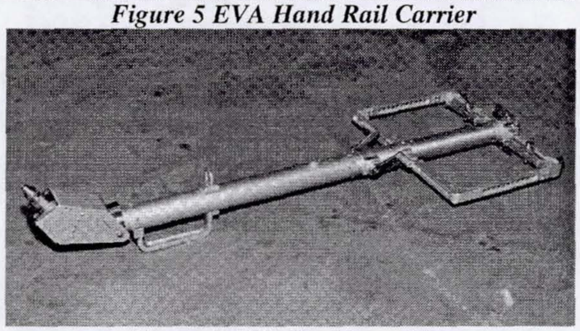

Figure 6 EVA Tool Stanchion

Figure 7 EVA Crane

The crane in Figure 7 involves a mix of cranks, knobs, levers, tabs and buttons that must be articulated. The Worksite Interface Fixture (WIF) Probe in Figure 8 requires a pair 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 9 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. The WIF socket in Figure 9 is designed to receive the probe in Figure 8.

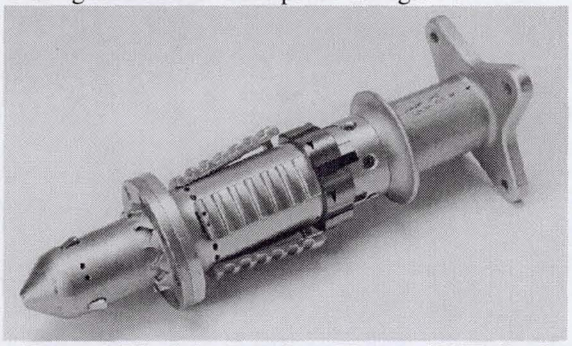

Figure 8 Worksite Interface Fixture (WIF) Probe

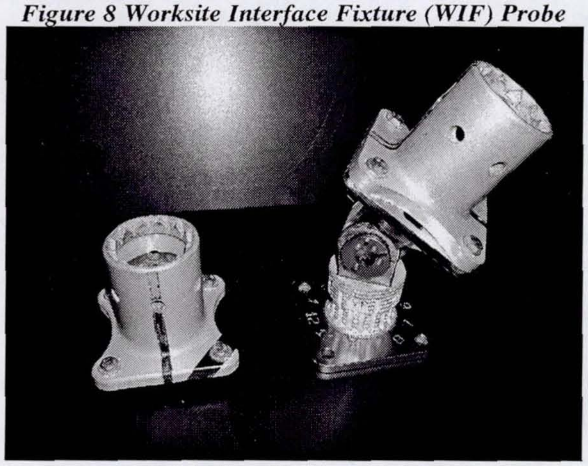

Figure 9 Pitch-Yaw Fitting with WIF Sockets

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 move 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 pick up and use tools unassisted or in cooperation with human teammates. 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. The robot can not endanger the humans that must work in the same environment, directly, or by leaving dangers behind.

3.0 Humanoid Design for EVA Work

NASA has now built a Humanoid system that meets many of these challenges. Called Robonaut, the machine has the ability to work with EVA tools and equipment, as well as perform many tasks that are beyond the realm of space walking. The following three sections describe that system's anatomy, its demonstrated ability to work with EVA tools, and its capabilities for terrestrial work. In all cases, these will be competencies that have been demonstrated with the machine, and involve the robot doing work, most often with its hands.

3.1 Robonaut 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[2]. 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 10.

Figure 10 Robonaut Concept working on the ISS

As shown in Figure 11, the system also has a Power Data Grapple Fixture (PDGF) on its back that allows Robonaut to be picked 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.

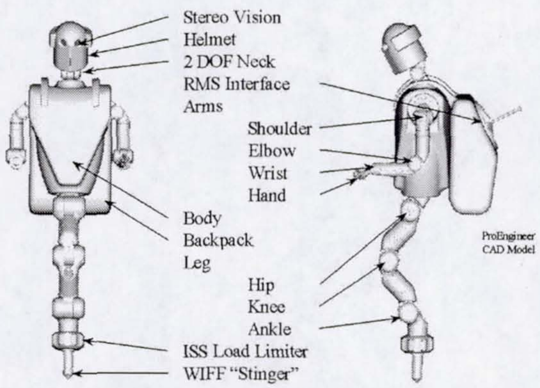

Figure 11 Robonaut Anatomy

The Robonaut system, in its current state, has already demonstrated the dexterity and control necessary to handle a wide range of tools once thought incompatible with robots. 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].

3.2 EVA Capabilities

NASA has now used the Robonaut system in a number of EVA task trials. During 1999, the Robonaut hand was used to test grasps of a number of devices[3]. These included a Torque Power tool, as shown in Figure 12.

Others grasps attempted included that of an EVA tether hook, and an EVA T-Handle, shown in Figures 13 and 14. These grasping experiments were very incomplete, as the objects had to be placed into the hand for manipulation. The fact that the hand was mounted rigidly limited the experimental options, but confirmed the hand's ability to form stable and useable grasps. The real challenge of using the robot to form those grasps itself remained.

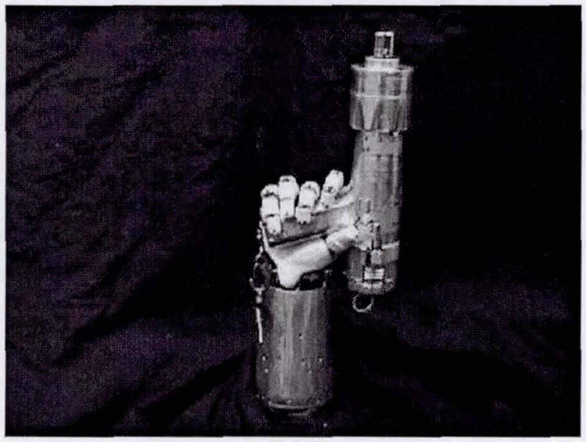
Figure 12 EVA Torque Tool

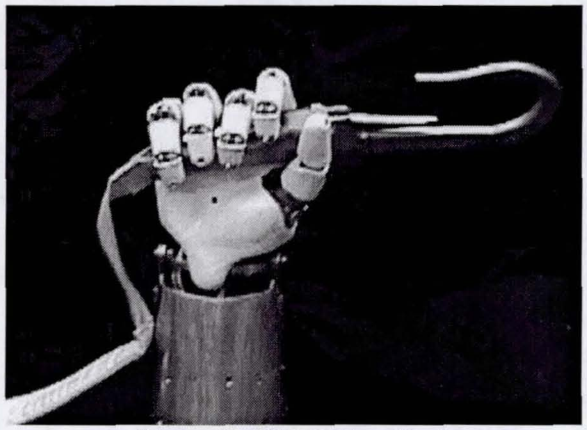
Figure 13 EVA Tether Hook

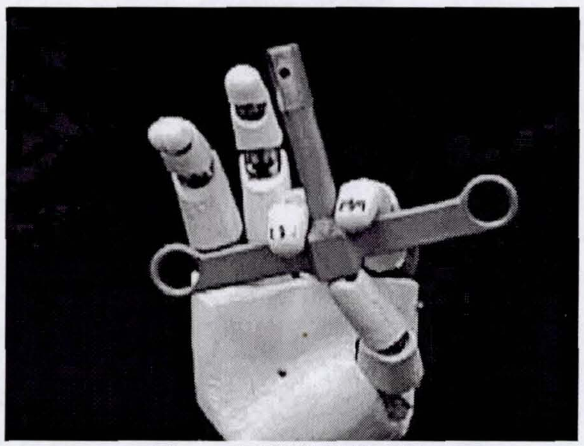
Figure 14 EVA T-Handle

During the year 2000, the hand was integrated with the Robonaut arm, as shown in Figure 14, and then used in a series of single arm tasks[4]. For the first time, the arm was able to position the hand, and help form the grasp.

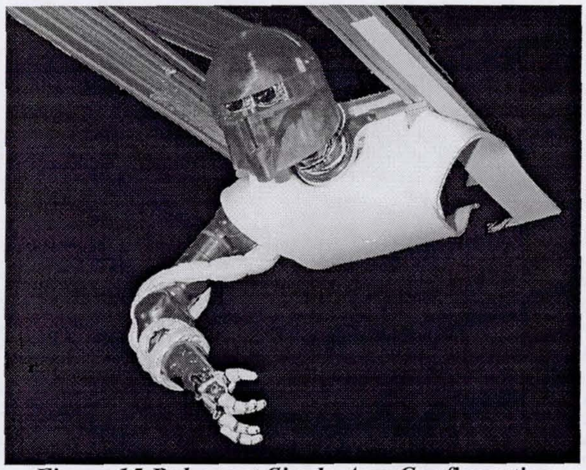

Figure 15 Robonaut Single Arm Configuration

Under teleoperator control, the system was demonstrated using torque drills, the EVA tether hook, and PIP pins, shown in Figures 16, 17 and 18. Tests with these tools were a major turning point in the system's development, for the first time being able to reach out, pickup a tool, and use it to do work. Robonaut was demonstrated performing many useful EVA jobs, including fastening bolts, putting tethers onto objects, and scooping soil with hand tools.

Figure 16 Robonaut using Torque Drill on Bolt

In the case of the torque tool (drill), the grasp shown in Figure 16 was complex, requiring four fingers to stabilize the grip of the drill, and then the index finger controlling the trigger. A job that human hands do every day, this was the first time a robot had held an object, articulated it, and used it to do work, simultaneously. Likewise with the tether hook, the grasp required both an articulation of release tabs, the stabilization of the tool, and pulling of a trigger, all while then positioning it to engage the hook on another object. This class of compound grasp, trigger articulation, and manipulation, was further compounded by contact, and often constrained motion, as the tool was used on a bolt, or slipped through a loop.

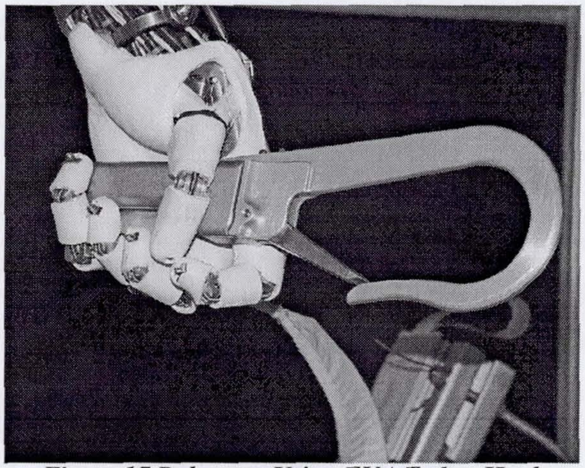

Figure 17 Robonaut Using EVA Tether Hook

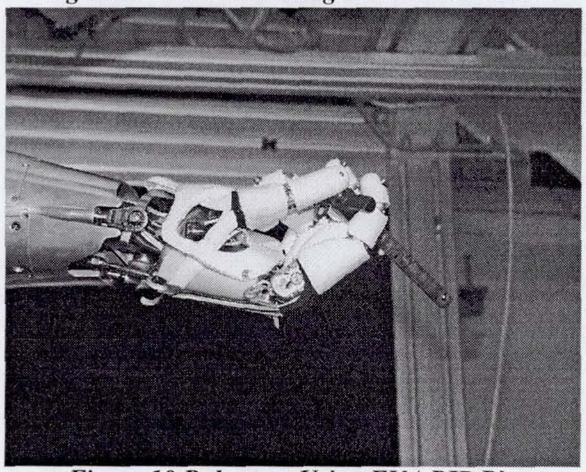

Figure 18 Robonaut Using EVA PIP Pin

In 2001, Robonaut was upgraded to a dual arm system, mounted on an articulated waist, and then tested in a series of dual arm tasks. Shown in Figure 19, this is the current state of the system.

The addition of the second limb was a major advance in the system's ability to do work. The natural grasp, re-grasp sequence was now augmented with the subtle human ability to pick up an object in one hand, in a secondary grasp, and then exchange it with the other hand, placing it in a final, primary use, grasp. For example, an object can be picked up off a work surface, or removed from a work palette, gripping the object in any grasp of convenience, often limited by the way it is presented. For a single arm system, this then requires a dexterous re-grasp, transitioning from one grasp to another, while maintaining stability and capture of the item. This would be especially difficult in 0g. With a second arm, this grasp of convenience can then be used to exchange it with the other hand, now presented for optimal grasping.

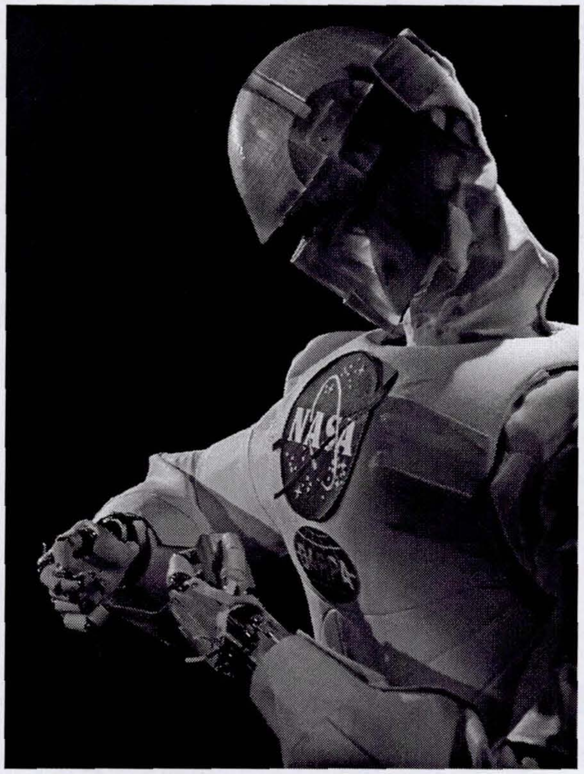

Figure 19 Robonaut as a Dual Arm System

A second class of dual arm operations is shown in Figure 19. An electronics box is held in one hand, while the other hand inserts a cable. In this case, the cable was an RJ45 Ethernet connector, with a single port transceiver as the receptacle. The teleoperator was able to hear the click that signified successful mating (using head mounted, stereo microphones) and then reverse the operation, depressing the pull-tab, and removing the connector.

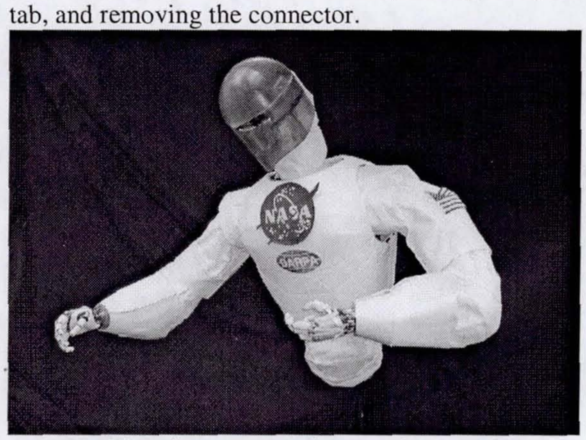

Figure 20 Robonaut Reaching with Waist Motion

The addition of the waist mobility was another major advance for the system. The ability to reposition the torso relative to the worksite is a significant capability, allowing for optimal placement of the two arms' workspaces and locating the head for optimal viewing angles. The Robonaut waist has three degrees of freedom, providing Roll, Yaw and Pitch rotations. Because of the length of the torso's spine, this rotation translates the shoulder origin frames, effectively expanding the arm workspace[5]. This motion, as shown in Figure 20, more than doubles the robot's reachable workspace, and more importantly, allows the intersection of the two arms' dexterous workspaces to be re-indexed relative to the worksite.

The last class of EVA work attempted by Robonaut to be reported here involves the use of Astronaut hand rails[6]. Much of EVA work requires that the Astronaut climb to the worksite, stabilize while doing the work, and then climb back to an airlock for re-entry into the space craft. For Robonaut to be able to work in this same environment, the machine must be able to use these same handrails and tethers for safety. The system's demonstrated competence with tethers makes this very likely, but the ability to form grasps on hand rails remains an ongoing investigation. Robonaut is now being readied for a climbing test that will measure its ability to locomote, stabilize and handle EVA crew handles, examples of which are shown in Figure 21.

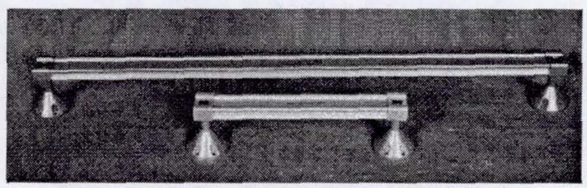

Figure 21 Examples of EVA Hand Rails

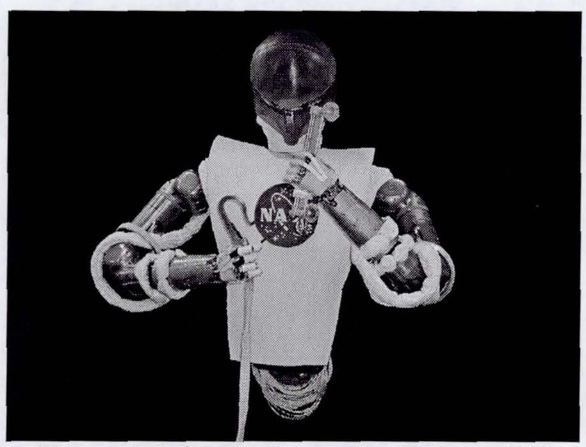

Figure 22 Robonaut Connecting Tether to Rail

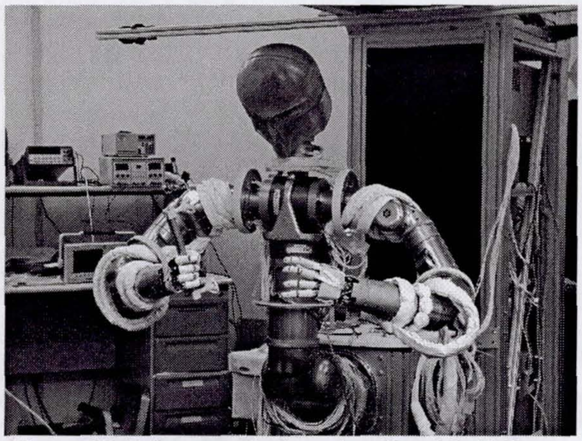

Figure 23 Robonaut Exchanging Hand Rail Grasps

3.3 Planetary Work

The experiments with the EVA tools emboldened the team to try working with more complex equipment. These devices were more similar to the tools that humans use regularly on Earth, and suggest that humanoid systems may be able to do much of the manual work now requiring human dexterity. The important commonality in these task trials is that the tools were not modified to make them robot compatible. In each case, the robot was able to use the tool or device, and perform the work, as a human might.

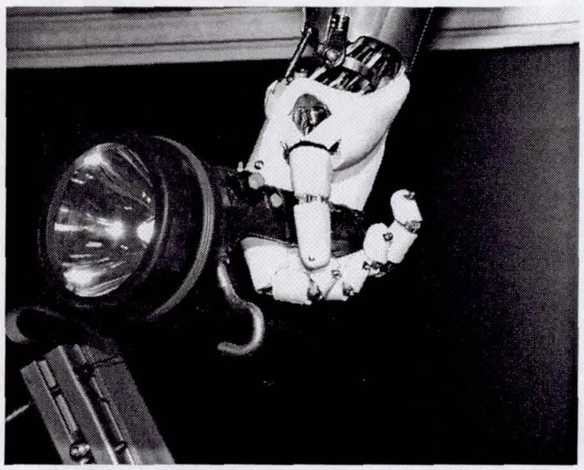

Figure 24 Robonaut Using Flashlight

The flashlight shown in Figure 24 required a number of complex actions. The device was hung from a tether, from which it had to be unhooked. The handle was grasped, and the weight lifted, and then unlooped from the hook. Once free, and while held stable, the power button was then articulated with the robot's thumb, turning it on and off. The teleoperator was then able to point and illuminate targets with this hand held device, turn it back off, and return it to its hanging tether.

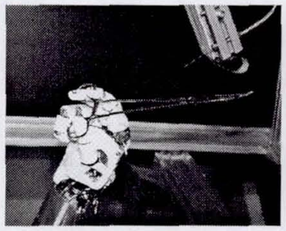

Figure 25 Forceps

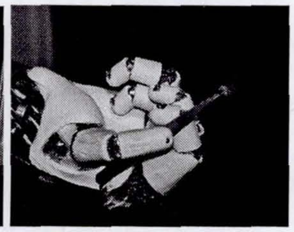

Figure 26 Tweezers

Robonaut was then used to handle a series of progressively smaller objects, from bolts, down to pebbles and small bearings. Using locking forceps, and small scales of tweezers, the system was able to pick up the objects, and place them in containers, as if taking samples. Notice the natural use of the finger loops in Figure 25, and the grasp on the side of the index finger in Figure 26.

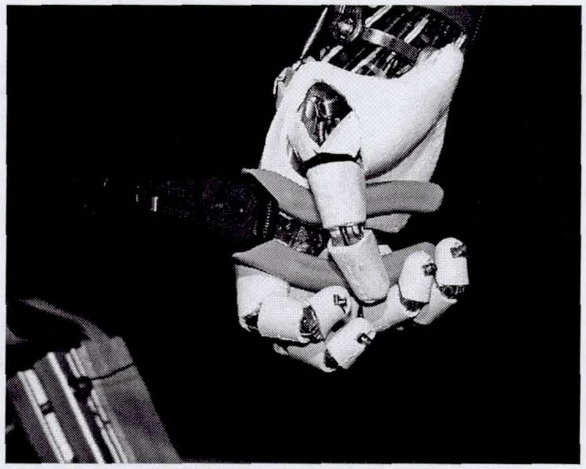

Figure 27 Robonaut using Wire Strippers

Using the same tools as electrical technicians, Robonaut is able to cut wire, and strip the insulation back for soldering. Figure 27 shows the hand holding a typical wire stripper, and a 24 AWG (Red) wire that has just been stripped.

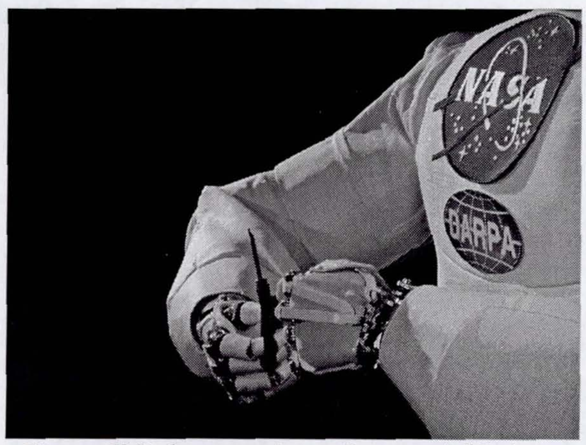

Figure 28 Robonaut using a Commercial Scissors

With similar success, Robonaut was able to use a pair of typical scissors to cut paper. The added complexity here was that the robot both held the paper, and then positioned it for cutting by the other hand. The cutting required a controlled force, out of the plane of the scissors, and then position control for the cutting action. Robonaut was able to cut thin slices of paper reliably.

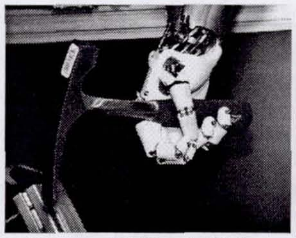

Figure 29 Rock Pick

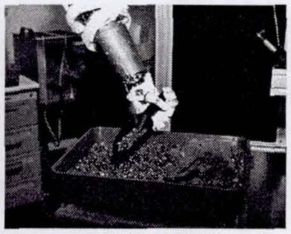

Figure 30 Hand Shovel

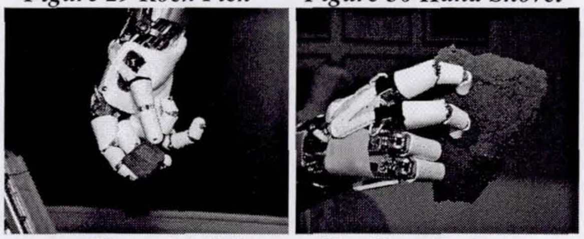

Figure 31 Robonaut Handling Rocks

The last set of task trials involved work that might be performed by a geologist. Figure 29 shows the system handling a rock pick, and Figure 30 shows a small hand shovel being used to dig in rough gravel. As a dexterous system, Robonaut has the ability to conformally grasp irregular objects, such as rocks of different shapes and scale, as shown in Figure 31.

4.0 Conclusions

NASA's work with Robonaut has shown that Humanoid systems will be able to work in an environment designed for people, without significant changes to accommodate the machines. This is of critical importance in EVA operations, where the existing investment in tools and interfaces designed for humans precludes redesign for robots. While more expensive than robots built for limited interfaces, these humanoid system will reduce facility costs, allowing them to exploit the existing conveniences provided for people, such as hand rails, buttons, latches, knobs, and tools. Overall, the Humanoid approach can reduce cost.

Extrapolating this to terrestrial settings, the cost of redesigning buildings to accommodate robots could be enormous, though for different reasons than found in space. Where redesigning spacecraft is expensive, even for a single Space Station, reconstructing buildings is expensive because of the shear numbers of them found on Earth. A robot that can fit through a standard doorway will be able to work in any building, where a substantially larger robot might be limited to out door environments, or require its own door.

But most importantly, Robonaut has shown that a Humanoid can do work. The machine has worked with EVA tools, handled typical Engineering tools, and worked with its end effectors on hand rails, tethers and hooks. This versatility promises an age when machines can slip into the human work site, seamlessly teaming with humans, without unique accommodations.

NASA will continue this development, and anticipates near term improvements in dexterity, strength, speed, sensitivity, perception, and autonomy. Work already underway will allow for these tasks to be performed merely by asking the robot, by voice, to just do it.

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