0g Climbing- The Challenge of Walking in Space

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Abstract

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 freefall- an odd combination of effects and equipment to help people do a demanding job. Robots are now being studied for service in this same domain, working on large scale space structures like 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 destinations. What have we learned about climbing in 0g? How should machines be controlled for serving in this role? What can they do to overcome the problems that humans have faced?

In order to move about in this environment, a robot must be able to climb autonomously, using gaits that smoothly manage its momentum and that minimize contact forces (walking lightly) while providing for safety in the event of an emergency requiring the system to stop. All three of these objectives are now being explored at NASA's Johnson Space Center, using the Robonaut system and a set of mockups that emulate the 0g condition. NASA's goal for Robonaut is to develop the control technology that will allow it to climb on the outside of the Space Shuttle, the Space Station, and satellite mockups at JSC, enabling the robot to perform EVA task setups or serve as an Astronaut's assistant.

Robonaut System Overview

The requirements for interacting with ISS crew interfaces and tools provided the starting point for the Robonaut design, which has shown promise in working in the 0g environment more generally. Anatomically, the robot closely resembles the form of a suited EVA astronaut except that it only has one leg instead of two (Fig. 1). This is because legs are used very differently in a microgravity environment than they are on Earth. An astronaut typically does not use her legs for much while floating or climbing around. It is only when she straps her feet side-by-side into a portable foot restraint (PFR) that she can use her legs to position her body and react forces exerted while working. Robonaut carries a WIF stinger on the end of its leg and can plug into the same WIF sockets used to hold the PFR at ISS worksites. Once anchored, the 7 DOF leg will be able to position the robot with superhuman strength and accuracy into configurations that a suited human would find impossible.

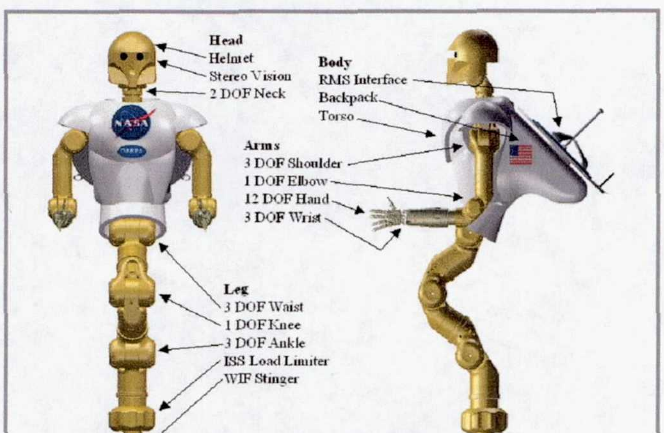

Figure 1. Robonaut Anatomy with Skins Removed

The five-fingered Robonaut hand is designed to work with EVA tools and hardware used by suited astronauts. Both power and dexterous grasps are required for manipulating these items. Certain tools require single or multiple finger actuation while being firmly grasped. Up to 25 lbs of force and 30 in-lbs of torque are required to remove and install EVA ORUs[1]. Recesses designed for the EMU glove can be as small as 8 inches in diameter to a maximu m depth of 18 inches[2]. To meet all of these requirements, two 12 DOF hands (right and left) were built (Fig. 2). Each hand has a dexterous work set consisting of two 3 DOF fingers (index and middle) and a 3 DOF opposable thumb. Each also has a grasping set consisting of two single DOF fingers (ring and pinkie) and single DOF cupping palm.

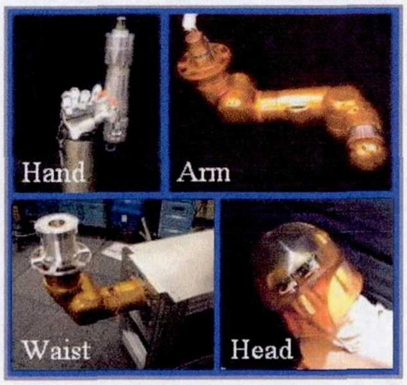

Figure 2. Robonaut Subsystems

The Robonaut head does not contain a brain but is actually a sensor-pointing platform riding on a 2 DOF neck. A pair of independently verging camera eyes mounted in the head provides stereo vision for human teleoperators and autonomy systems. Each eye can be independently zoomed via remote commands. An infrared sensor mounted below the eyes measures the temperature of surfaces in the robot's vicinity. A low-power laser pattern is projected onto these surfaces for sensor targeting and proximity estimation.

The 5 DOF Robonaut arms are made up of revolute joints from the same family of modular joints making up the leg and neck. In this family, all joints fall into one of two kinematic categories, designated roll and pitch, with proportionately scaled strength and size. The arm terminates at the forearm, which houses all of the motors driving the hand and supports a 2 DOF wrist assembly. The resulting 7 DOF arms feature large, overlapping dexterous workspaces useful for manipulating tools.

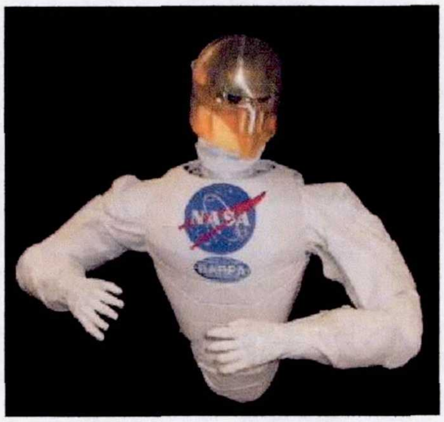

Figure 3. Ground-based Robonaut System, Summer 2001

Traditionally, unintended physical contact between a robotic manipulator and its environment is treated as a failure and drastic measures are taken to limit the consequences. A robot is typically shut down when the controller detects a collision and then it waits helplessly for a human to resolve the problem. Humans, on the other hand, are adept at managing contact forces and routinely use them to great advantage, as when carrying bulky items. Because Robonaut's manipulator workspaces overlap and because the robot will work in cluttered environments, frequent contact is expected and must be tolerated, even exploited through judicious use of the robot's various sensors. For added protection, the body is covered with a custom-fitted fabric skin designed to contain electrical wire harnesses while keeping foreign material out of the mechanical joints. The torso section also features a subcutaneous layer of foam padding designed to absorb impact energy while permitting contact forces to build up gradually.

Figure 4. Teleoperation Interface

Although the challenges of designing robots for space and terrestrial applications are very different, a ground-based Robonaut system was built at JSC to develop and test control strategies. On Earth, the robot is encumbered by gravity and does not have sufficient strength to stand on its single leg. For this reason, only the waist joints appear in the ground-based system (Fig. 3). The focus, nevertheless, remains fixed on eventual orbital deployment, severely limiting the selection of materials, motors, and electronic components while posing unique thermal management problems.

Robonaut is currently a teleoperated master-slave system in which a human becomes the robot master. The anthropomorphic form of the robot allows an intuitive, one-to-one mapping between master and slave motions. Within minutes of donning the teleoperation interface, consisting of a stereo vision HMD, instrumented gloves, and posture tracking sensors, even a novice operator can control the robot to interact with the environment in simple ways (Fig. 4). To enhance the operator's sense of immersion, or telepresence, additional feedback is provided in the form of kinesthetic, tactile, and auditory cues. Using this interface, experienced teleoperators have demonstrated an impressive degree of finesse and dexterity while working with a wide assortment of both EVA and conventional tools.

Robonaut System Specifications

Subsystem	**Description**	**Data**
Hand	finger force, closing	5 lbs at fingertip
	finger force, holding closed	5 lbs at fingertip
	finger force, opening and holding open	light, spring-powered return
	finger speed, unloaded opening and closing	10 in/sec at fingertip
Arm	joint torque, stall	600 in-lb
	joint speed, unloaded	25 deg/sec
Leg	joint torque, stall	2400 in-lb
	joint speed, unloaded	10 deg/sec
General	reach, fingertip to fingertip	94 in
	weight	175 lbs
	Idle power consumption	0.25 kW
	Average power consumption	0.40 kW
	Max power consumption	0.60 kW

For all its utility in the laboratory, a teleoperated system degrades quickly in the presence of time delay. A human teleoperator can deal with a limited amount of time delay by slowing down her motions, effectively compressing the effect. But even a perfectly immersive interface becomes useless if the time between command and confirmation is more than a few seconds. Such time delays are expected when communicating with Earth-orbiting spacecraft and cannot be avoided when commanding a space robot from the ground. A better strategy is to develop autonomy modes that enable the robot to perform simple tasks on its own, without continuous, real-time command streams. Concurrently, the teleoperation interface must be modified to promote the human from robot master to robot supervisor. The master-slave strategy, supplemented with predictive displays and a shared control architecture, would then be reserved for only the most challenging tasks requiring human intervention.

Robonaut Capabilities

The ability to move and work like an EVA astronaut is what distinguishes Robonaut from other space robots. Experiments with a wide variety of tools have demonstrated the machine's considerable mechanical dexterity. Successful tests have been performed with EVA tether hooks, PIP pins, power torque tools, electrical connectors, cable ties, and toolboxes. The robot can also work with conventional tools like forceps, wire strippers, rock scoops, syringes, and flashlights. From a robotics standpoint, some of the most impressive demonstrations involve velcro, rope, webbing, and other softgoods that would frustrate conventional robotic grippers.

Figure 5. Robonaut Manipulating an EVA Electrical Connector

A spacewalking astronaut moves around a space structure much like a rock climber moves over a vertical wall. She is always secured to the structure by at least one tether and climbs from point to point using EVA handrails. Getting from point A to point B requires careful path planning because handholds are limited. Every tool that the astronaut is carrying must be tethered to the EMU so it won't float away if dropped. Like a rock climber, an astronaut must also control reaction forces and torques to avoid undesired rotation. Experiments with a climbing mockup have demonstrated that Robonaut can complete a simple traverse across several ISS handrails, even while managing a cable or tether (Fig. 6). Moreover, the robot's compact design enables it to reach all worksites accessible to a suited crewmember.

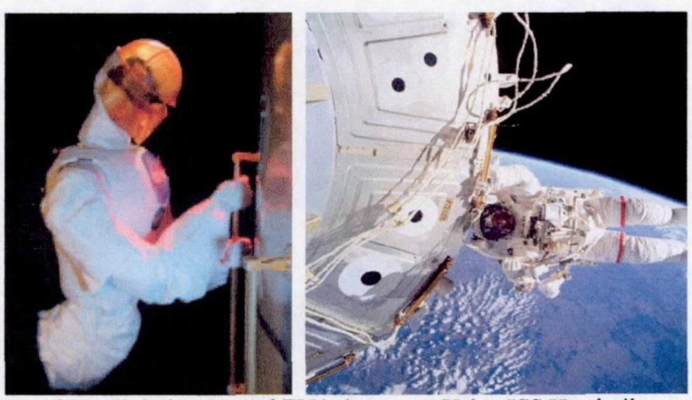

Figure 6. Robonaut and EVA Astronaut Using ISS Handrails

Despite all the similarities between Robonaut and its warm-blooded cousin, it must be acknowledged that robot workers will not be replacing humans anytime in the near future. By the same token, humans make poor substitutes for robots in certain limited roles. Asking a human to stand perfectly still for 2 days while supporting a bulky piece of space hardware is unreasonable but Robonaut can do so indefinitely, with absolutely no power consumption! And robots are unparalleled at repetitive positioning tasks, especially those requiring constant velocity or high accuracy. One such task that could be performed completely autonomously is spacecraft surface inspection for micrometeoroid damage.

As noted earlier, Robonaut's dexterous workspace greatly exceeds that of a suited crewmember due, in large part, to the articulating leg. By coordinating motions of the leg with other limbs, interesting redundancy solutions may be exploited, allowing the robot to reach around obstacles in its workspace. Leg motions could also be used to minimize contact forces exerted while climbing on delicate structures. With a different end effector, the leg could even be used as a third arm to hold a workpiece steady. Figure 7 illustrates the possibility of pairing two very different robotic systems in complementary roles to offer new capabilities.

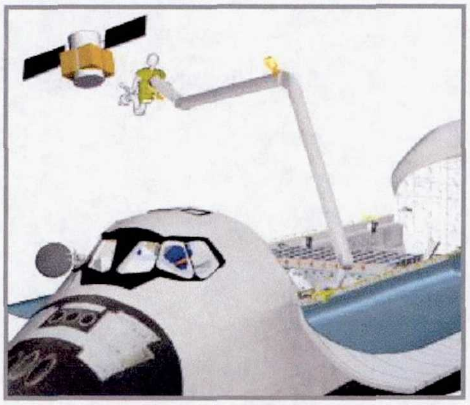

Figure 7. Robonaut Riding SRMS in Three Arm Configuration

Designing the 0g Gait

Early in the development of the Robonaut system, requirements for 0g climbing were investigated and used in bounding the system design. Superficially, this required that the system fit within EVA access corridors, and have a hand that could fit in the recess of an EVA crew handle. More importantly, the system needed to have the ability to exert adequate forces for locomotion, and have sufficient control authority to minimize reactions on a structure over which it is climbing. Figure 8 shows a visualization tool [6] developed to give designers insight into load and arm design choices.

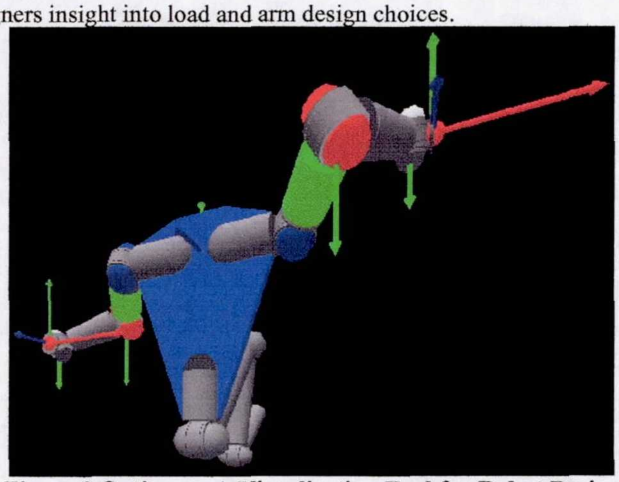

Figure 8 Optimus: A Visualization Tool for Robot Design

In addition to kinematic and strength analysis, this tool also simulates manipulator thermodynamics, modeling heat transfer mechanisms of conduction, radiation, solar insolation, and Earth albedo, combined with internal generation of heat, and transient thermal increases in temperature [6]. Figure 9 shows a simulated run of the program. The graphs at the top show arm joint thermal histories, and arm joint position histories for a simple linear climb down a row of EVA hand rails. The program allows for general hand rail length, and hand rail spacing, but these variables can quickly produce infeasible gaits, where the stride length of the robot is inadequate to span a gap.

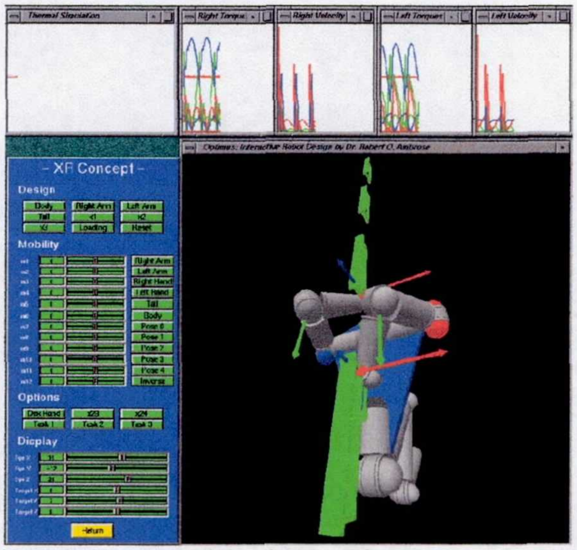

Figure 9 Simulated Climbing Run for a Linear Traverse

The dual arm system, representing Robonaut, uses its two upper arms to climb, with its tail either stowed, or carrying a payload. The RGB vectors shown in the figure on the endpoints of the arm represent a strength ellipsoid, or a graphical representation of the arm's stength in the three principal directions [7]. As the arm moves through its workspace, these vectors grow and shrink, displaying strength. Furthermore, as the designer selects different joint actuator options from a database, these vectors also change to display the impacts of those choices on strength.

Unlike rolling, climbing implies the reciprocating motion of limbs, conserving linear and angular momentum as a system, with internal impulses between limbs, and external impulses imparted on the ground. Early Space Walking experiments with Astronauts demonstrated the instability of this momentum management problem in the frictionless environment of 0g, problems with tether management, and the advantages of slow, deliberate motions. Our first objective is the momentum modeling of a bifurcating [7] system to enable gait synthesis that optimizes torque, velocity, heat, and electrical power, while maintaining steering and stopping margins. One specific innovation towards this end is the investigation of multi-limb systems in which payloads are isolated from the climbing robot's body by a separate serial chain, expanding momentum management options. The model shown in Figure 10 represents Robonaut, climbing with two arms while towing a payload with its tail.

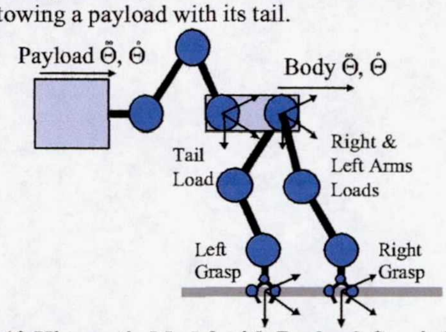

Figure 10 Kinematic Model with Payload Carried by Tail

The second objective, minimizing contact force, is motivated by the need to avoid damaging lightweight, fragile space structures while climbing across them. One fundamental difference between 0g climbing and terrestrial walking is the dimension of the contact load. The grasping contact used in 0g climbing may be modeled with a full six axis wrench (3 forces and 3 moments) at the grasp point. The walking contact, meanwhile, depends heavily on friction and can only support those components of the contact wrench that arise from compressive forces developed between the foot and the ground. Should the walker attempt to exert a wrench outside of these bounds, the walking contact will be lost. Examples of such a condition are leaning forward too far over one's feet and attempting to run on ice. Robotic grasp contacts will be formed with full spatial dexterity, theoretically allowing a robot to move its body along a trajectory with only one arm.

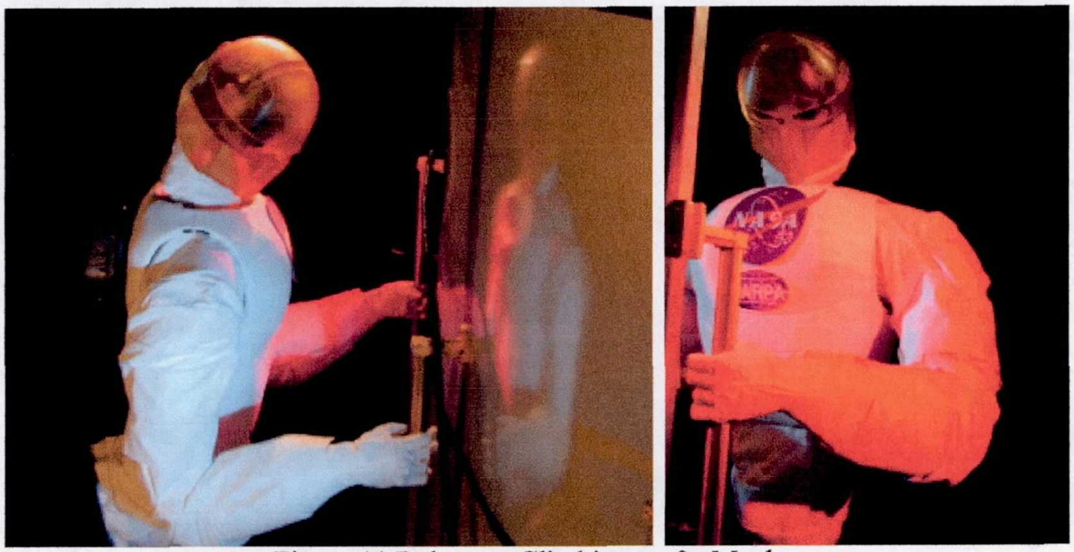

Figure 11 Robonaut Climbing on 0g Mockup

An additional innovation now being studied is the use of multiple contact points (two-handed climbing) to reduce applied torques that can damage delicate structures. Robonaut is shown in Figure 11 moving its body while over-constrained in a dual arm grasp. Internally, impulses must be optimized to reduce contact loading by absorbing the reciprocating momentum in self motion, much like a cat uses its tail for steering. The bifurcating chain structure, carrying payloads away from the body, allows for an optimization that will minimize hand forces at all phases of gait. Except when making dynamic moves of the system's C.G. (starting, stopping, and steering) these climbing forces can be zeroed during straight line motion. During dynamic moves, the self motion and momentum management will minimize the reaction loads in amplitude and frequency content, yielding a system that walks lightly and efficiently, while moving the body and payload at or near constant velocity.

Positioned in the two handed pose shown in Figure 12, the robot has the ability to apply a moment to its body that is the cross product of the wrist forces and the vector between each grasp. While these forces may be small, the larger the hand spacing, the greater the leverage, allowing for powerful starting, stopping and steering maneuvers. It is expected that the robot would start from this stance, execute steering actions while passing through such a pose, and stop (land) in the same two-point stance. The two-handed stance is referred to as a parallel phase because the closed chain looping between the arms has two paths to ground, one along each arm. In contrast, the second pose shown in Figure 12 is a serial stance, found when the robot advances one hand to a new grasp point. In this case, the moment that can be applied to the robot's body is limited by either the wrist torque, strength of the hand, or the structural limits of the hand rail. The vectors on the ends of the arms represent manipulator strength ellipsoids [7] that are linked to the actuators, fixed arm geometry (D-H parameters), Cartesian pose of each arm's point of resolution, and any self motion available within the chains.

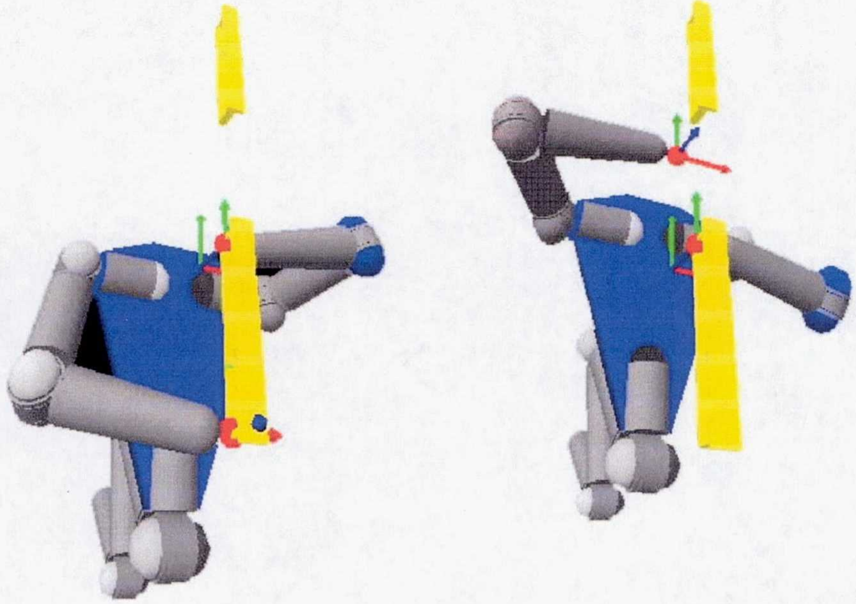

Figure 12 Two Handed Climbing (Parallel & Serial Phases) Using Hand Rails

Natural climbing gaits will include a fluid mix of serial and parallel phases of motion, with the body's C.G maintaining smooth and constant velocity as the arms walk beneath it. Depending on speed and grasp point availability and their density, the percentage of time spent in the parallel phase can be maximized to enhance the system's ability to respond to emergency stop conditions and minimize reaction moments.

Figure 13 Climbing Sequence with Two Handed Gait Using Hand Rails

The tail shown folded in Figure 13 can be used to carry payloads, which can be further isolated from the reciprocating motion of the arms to maintain smooth motion. The tail can also apply small impulses between the payload and body to balance the momentum of the climbing arms, much as people swing their arms while walking. This is a key feature of the bifurcating chain's dynamics that will be used to optimize contact forces on the spacecraft or structure over which the robot is climbing.

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