Robonaut: A Robotic Astronaut's Assistant

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Abstract

The Robotics Technology Branch at the NASA Johnson Space Center is developing robotic systems to assist astronauts in space. One such system, Robonaut, is a humanoid robot designed to approach the dexterity of a suited astronaut. Robonaut currently has two dexterous arms and hands, a three degree-of-freedom articulating waist, and a two degree-of-freedom neck used as a camera and sensor platform. In contrast to other space manipulator systems, Robonaut is designed to work within existing extra-vehicular activity (EVA) corridors and use the same tools as space walking astronauts. Robonaut is envisioned as working with astronauts in space performing a variety of tasks including: routine maintenance, setting up and breaking down work sites, assisting crew members during EVA, and serving in a rapid response capacity.

1. Introduction

The requirements for extra-vehicular activity (EVA) on-board the Space Station Alpha are expected to be considerable. These maintenance and construction activities are expensive and hazardous. Astronauts must prepare extensively before they may leave the relative safety of the space station, including pre-breathing at space suit air pressure for up to 4 hours. Once outside, the crew person must be extremely cautious to prevent damage to the suit. To perform the necessary work outside of the spacecraft, NASA has a long history and large investment in developing tools, procedures and workspaces for space walking astronauts.

Certain pieces of the Space Station Alpha are designed robotic system serviceable. The Canadian Space Agency's Special Purpose Dexterous Manipulator (SPDM) was developed for this purpose such system. To be serviceable by the SPDM, worksites have been designed to have different approach corridors than EVA and specialized interfaces.

While specialized worksites for robotics system have been very successful in a variety of industries, including space, the Robotic Systems Technology Branch at the NASA Johnson Space Center is taking a different approach to building service robots for space; developing robots to work with existing EVA tools, at existing EVA worksites. Robots of this nature will reduce the load on EVA crew by performing routine maintenance, assisting crew members before, during, and after EVA, and serving in a rapid response capacity. Robonaut, a robot of this class, is currently being designed and built at NASA JSC.

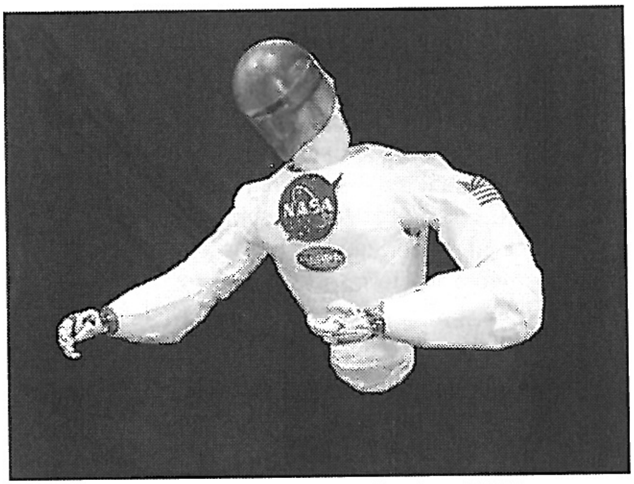

Figure 1. Robonaut - Spring 2001

2. Robonaut System Overview

The focus of the Robonaut team has been in the design and construction a dexterous upper extremity. However, Robonaut has recently transitioned from a single hand and arm with a fixed shoulder to a dual limbed upper body with an articulating three degree-of-freedom (DOF) waist. This results in a total of 43 DOF dexterous robot.

While working during EVA, crew members typically place both legs into a portable foot restraint. In its space configuration, Robonaut uses the same interface with a single seven DOF leg. The end effector of this leg uses the same interface as the crew's foot restraints and plugs into sockets around Space Station. Having a leg provides Robonaut with the ability to anchor itself at worksites and provides a great amount of body mobility once anchored. Figure 2 shows a representation of Robonaut in its space configuration.

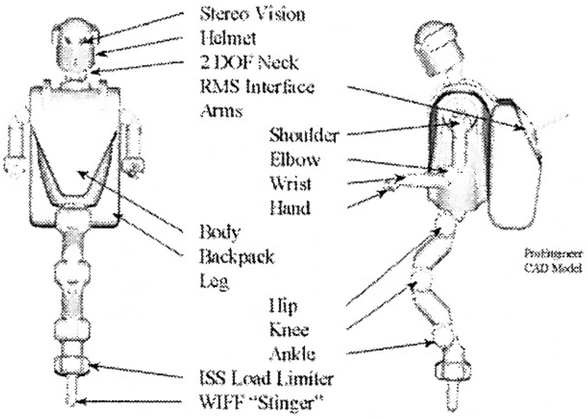

Figure 2. Robonaut in 0g Configuration

Beyond having the correct anatomy to work with EVA equipment, the Robonaut system is designed with space operations in mind. During the design phase, the ability to work in space was considered for nearly every aspect, including materials selection, thermal endurance, lubricants, avionics, and computer selection.

Robonaut is currently a teleoperated system. The anthropomorphic form of Robonaut allows a very intuitive mapping between human and robot. By incrementally augmenting the teleoperation capabilities, the goal is to lighten the teleoperator's load by transitioning to a more supervisory role.

2.1. Hands

The requirements for interacting with planned space station EVA crew interfaces and tools provided the starting point for the Robonaut Hand design [1]. Both power and dexterous grasps are required for manipulating EVA crew tools. Certain tools require single or multiple finger actuation while being firmly grasped. A maximum force of 20 lbs and torque of 30 in-lbs are required to remove and install EVA orbital replaceable units (ORUs) [2].

The Robonaut hand has a total of 14 DOF. It consists of a forearm that houses the motors and avionics, a 2 DOF wrist, and a five-finger, 12 DOF hand (Figure 3). The forearm, which measures four inches in diameter at its base and is approximately eight inches long, houses all fourteen motors, 12 associated circuit boards and the wiring for the hand.

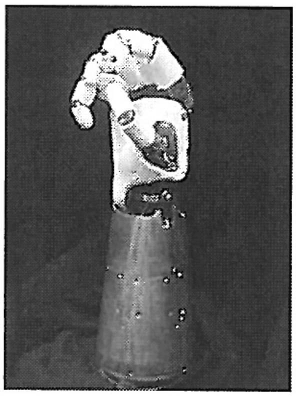

Figure 3. The Robonaut Hand

The hand itself is consists of two sections: a dexterous work set used for manipulation, and a grasping set which allows the hand to maintain a stable grasp while manipulating or actuating a given object. This is an essential feature for tool use [3]. The dexterous set consists of two 3 DOF fingers (index and middle) and a 3 DOF opposable thumb. The grasping set consists of two, single DOF fingers (ring and pinkie) and a palm DOF. All of the fingers are shock mounted into the palm.

In order to match the size of an astronaut's gloved hand, the motors are mounted outside the hand, and mechanical power is transmitted through a flexible drive train. Past hand designs [4] have used tendon drives that utilize complex pulley systems or sheathes, both of which pose serious wear and reliability problems when used in the EVA space environment. To avoid the problems associated with tendons, the hand uses flex shafts to transmit power from the motors in the forearm to the fingers. The rotary motion of the flex shafts is converted to linear motion in the hand using small modular leadscrew assemblies. The result is a compact yet rugged drive train.

Overall the hand is equipped with forty-two sensors (not including tactile sensing). Each joint is equipped with embedded absolute position sensors and each motor is equipped with incremental encoders. Each of the leadscrew assemblies as well as the wrist ball joint links is instrumented as load cells to provide force feedback.

2.2. Arms, Neck and Waist

Robonaut has four serial chains emerging from the body: two upper arms for dexterous work, a neck for pointing the head, and a leg for stabilizing the body in micro gravity. These chains are all built with common technology, best described as a family of modular joints, characterized by size and kinematic motion type. There are three torque ranges, from 10 ft-lbs to 200 ft-lbs, and two motions types, roll and pitch. Other scales have been built for thermal vacuum testing, but are not included in the currently integrated system.

A software design tool, with visualization shown in Figure 4, was developed at JSC for use in trade studies of kinematic arrangements [5], strength [6] and thermal analyses [7]. Using a database of drive train components, optimized sizing of the manipulator joints was achieved with identification of thermal endurance [8] and task workspace suitability [9]. Of particular interest is the choice of a bifurcating system, where a central, and articulated chain, here the segment from ankle to body, splits into two independent upper arms. This waist mobility has been shown to complement the dexterity of a dual arm system, by allowing the intersection of the two arm's dexterous workspaces to be repositioned around a work site. This enables the use of smaller, closely configured arms to perform dexterous manipulation over a large resultant workspace. Figure 1 shows the coordination of a waist bending motion with an arm's reach, expanding the arm's reachable workspace. The intersection of the arm's dexterous region is a toroidal space centered on the line of action passing through the two shoulders, which is then in turn swept by the waist motion for a spherical dexterous workspace of the full system, shown schematically in Figure 5.

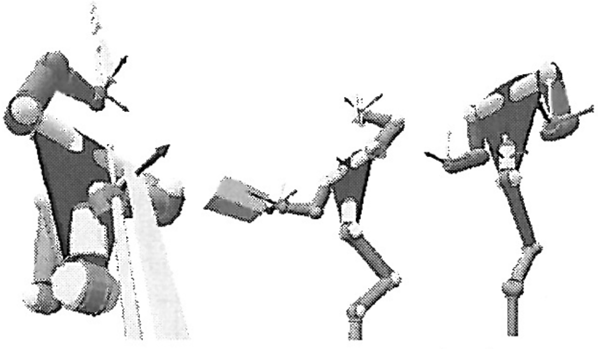

Figure 4. Arm Design Visualization Tool

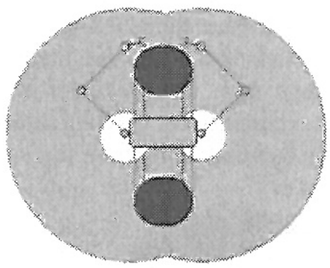

Figure 5. Dexterous Workspace of Robonaut Arms with Waist Motion

2.3. Body

The Robonaut torso consists of an aluminum endoskeleton covered by a protective outer integument. The endoskeleton terminates in a mounting flange for each robot limb, providing convenient locations for six-axis load cells used to measure external forces affecting the robot (Figure 6). When the distal end of the waist is held fixed, it becomes a leg capable of repositioning the body. In this configuration, the torso sensor measures external forces acting on the arms, the head, and the outer shell. When contact occurs, all three load cells may be used to distinguish self-collisions and estimate the contact location. This information is useful in handling incidental contacts that often occur in unstructured environments.

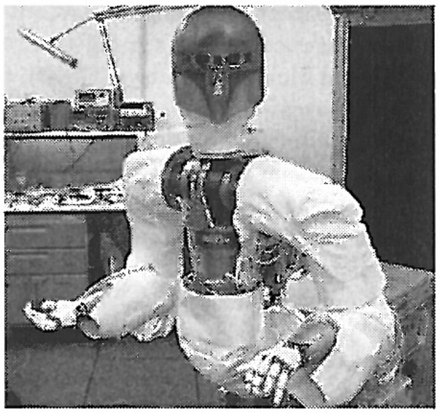

Figure 6. The Robonaut endoskeleton

Covered in a soft outer layer, the outer shell was produced in sections by first laying up dry carbon fiber fabric on a female mold and then injecting it with resin in a vacuum forming process. Both the torso and backpack are split into front and back halves to permit easy access to internal electronics (Figure 7). The outer shell protects the robot in two ways. First, it hides electronic components and wire bundles which would otherwise present a serious entanglement hazard. Second, it softens impact through a combination of a padded jacket and a floating suspension. Much like the human ribcage, the outer shell hangs from the backbone of the robot. In response to an external force, the shell deflects elastically while gradually building up reaction force.

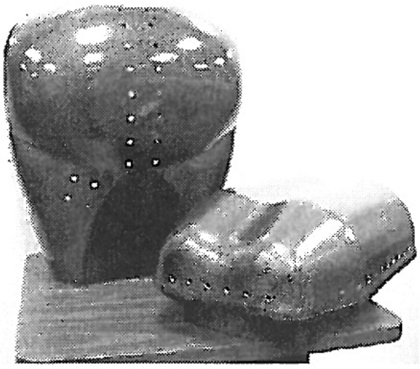

Figure 7. The Robonaut outer shell

2.4. Telepresence

Because Robonaut is anthropomorphic, a master-slave relationship where the operator's motions are followed by the robot is a very intuitive approach. The goal of telepresence control is to provide an intuitive, unobtrusive, accurate and low-cost method for tracking operator motions, communicating them to the robot, and providing the operator feedback about the state of the robotic system. Some of the component technologies currently used in Robonaut's telepresence system are shown in figure 8. They include Head Mounted Displays (HMD), force and tactile feedback gloves and posture trackers.

Virtual reality display technology is used to visually immerse the operator in the robot's workspace. Stereo visual feedback is provided to a HMD by Robonaut's stereo head cameras. The HMD provides a view into the robot's environment, facilitating intuitive operation and natural interaction with the work site.

Controlling Robonaut's hands is made possible by mapping the motions of the teleoperator's hands onto the robot's hand motions. Finger tracking is accomplished using commercially available glove based hand pose sensors. The forces imparted on Robonaut's fingers can be displayed to the teleoperator by means of an exoskeleton worn by the teleoperator. Arm, torso and head tracking is accomplished with the use of magnetic based posture trackers.

Figure 8. Components of a Teleoperation System

Future telepresence control will address new methods that will significantly improve safety and performance of teleoperated human-scaled dexterous robots during in-space operations. These methods must allow the natural and unencumbered control of anthropomorphic robots, while minimizing training and maximizing robot performance. These new technologies have the potential to provide any telepresence interface with real-time operator tracking and audio-visual task feedback. Crew members will take full advantage of Robonaut's high performance only if operation is made easy and safe.

2.5. Avionics

The objectives for the Robonaut avionics have been to develop motor control and sensor processing integrally packaged within the actuators and local structure. The focus of the first generation avionics development was to integrate the low-level motor control co-located with the actuators. This was most challenging in the hand and wrist mechanisms where 14 actuators are packaged within the volume of the forearm. Single and three-axis hybrid power drivers, three-axis FPGA motor controllers, and flexible circuit packaging was used to produce compact integrated actuator modules with only power and data connections required. The FPGA based motor controller provides motor commutation, PWM control, velocity and control, and position feedback. A hybrid motor driver performs the translation of logic level control signals, gate drive of the high and low side MOSFETS of the three phase power bridge, which source and sink motor phase current. For the Robonaut hand, the hybrid driver is housed in a conformal flexible circuit board, which wraps around a triple motor pack as shown in Figure 9.

The Robonaut hand/wrist module currently contains 42 sensors for feedback and control, 28 of which are analog and require signal conditioning and digitization. The arm, head, and waist modules contain up to 9 sensors per actuator resulting in over 100 sensors to be sampled. Additionally there are five 6-axis force/moment sensors installed on Robonaut, which enable not only end-point forces to be resolved, but mid-point forces as well. The initial data acquisition system (DAS) used by Robonaut is a commercially available, compact, ruggedized system capable of sampling the hundreds of sensors distributed throughout the Robonaut system. This data is packetized in an IRIG format PCM data stream, which is sent to the controller CPU.

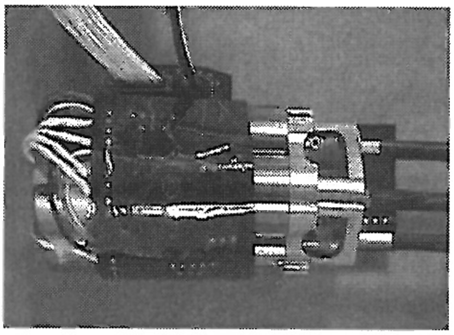

Figure 9. Motor Triple Pack

2.6. Controls Design

The Robonaut control system design philosophy is inspired by the human brain anatomy. The human brain embeds some functions, such as gaits, reactive reflexes and sensing, at a very low level, in the spinal cord or nerves [10]. Higher functions, such as cognition and planning take place in other parts of the brain.

Within the Robonaut control system, the functions analogous to the very low level functions in the brain are referred to as the brainstem. The brainstem contains the joint and Cartesian controllers for the 43 DOF, sensing, safety functions, and low-level sequencing.

Using the brainstem approach allows higher-level functions to operate independently of the low level functions. This allows the Robonaut system to implement a variety of control methods ranging from teleoperation to full autonomy with the brainstem unaware of which higher-level control system is being used. An application programmer's interface (API) separates the brainstem from the higher-level systems. This standard interface allows systems to both monitor and modify the state of the Robonaut brainstem.

As a humanoid robot designed for the purpose of working with humans in space, safety is the central to Robonaut's control system. By embedding safety systems at a low level in the brainstem overall safety and performance are improved [11].

The computing environment for Robonaut utilizes the PowerPC processor. This processor was selected for both performance and its heritage in space flight. The processor's and I/O connect across a VME bus and use the VxWorks™ real-time operating system. Robonaut's brainstem software is written using the Controlshell™ development environment. Controlshell provides a graphical interface that enforces object-oriented design and the re-use of code. The flexibility and performance of these systems make for an exceptional controls development environment.

2.7. Simulation

A simulation of Robonaut was developed to bridge a gap between operations and development activities. The simulation serves as a safe alternative for testing control algorithms, grasping algorithms, path planning, etc. As a robot under development there will be periods when the Robonaut hardware is unavailable. During these periods, development may continue using the simulation. Additionally, many users from industry and university sites desire access to Robonaut for research and testing. A simulation that matches the dynamics and appearance of Robonaut allows initial development by these remote developers prior to testing on Robonaut

The simulation uses Enigma, a JSC developed graphics package, for real-time animation. Figure 10 shows the results of the simulation displayed on an Enigma animation. The simulation is capable of animating at or near real time on PCs with a minimum refresh rate of 15 Hz.

Uses for the simulation are continuing to expand. Currently, new control algorithms for various appendages, grasping techniques, path planning, etc. are being developed using the simulation.

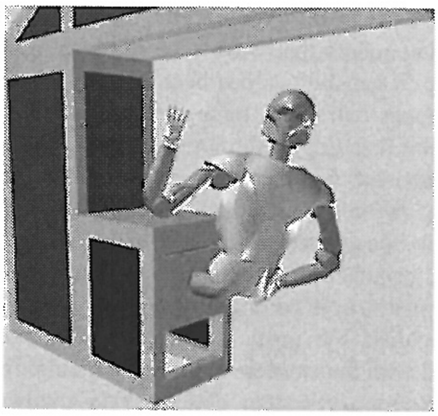

Figure 10. Robonaut Simulation/Animation

3. Task Experiments

Robonaut can perform a wide variety of space, surface and, tool usage tasks. Space tasks include tether hooks used as lifelines by astronauts during EVA and power drills representing torque tools. Surface tasks include scooping gravel and transferring it into containers. Robonaut also can work with a wide variety of tools, including wire strippers, socket wrenches, and flashlights.

Adding a second arm/hand and waist has added another dimension to Robonaut's capabilities. Instead of receiving tools from a human in a very limited range, Robonaut is now capable of picking up tools at one area and re-positioning its waist to operate at the worksite. The addition of the second arm and hand allows for Robonaut to perform two-handed tasks. For example, Robonaut has worked with EVA handrails, network cables, and soft goods boxes. Robonaut performing two-handed tasks is shown in Figure 11.

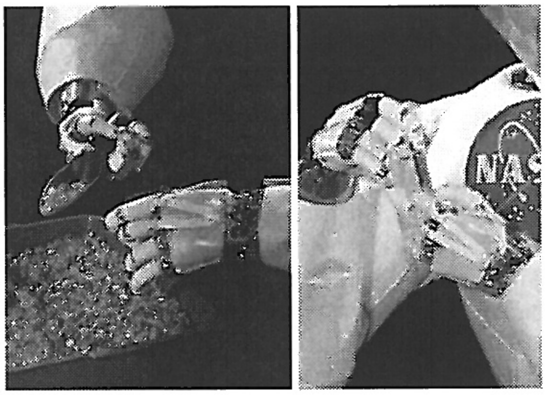

Figure 11. Two-handed tasks

4. Conclusions and Future Challenges

Robonaut is an anthropomorphic robot project focused on building robots that work with humans in space. A large step in capabilities has been achieved by adding a second upper extremity, torso, and waist. Adding the waist is the first step towards mobility for Robonaut. In space, Robonaut will have the ability to move through a variety of methods, including being transported by the Shuttle or Space Station Remote Manipulator Systems, climbing, or attached to a free flyer. Another intriguing mobility platform is adding a Robonaut upper body to a rover, yielding the great dexterity of humanoid robot combined with the extreme mobility of mobile robots.

The Robonaut system continues to evolve. New avionics are currently being designed that will be embedded near actuators and sensors and will reduce the volumetric requirements for data acquisition and computation. Teleoperation advances continue through improved feedback to the operator and better method of tracking the operator's position. As the simulation continues to grow in fidelity, the Robonaut team will be able to work with outside researchers to test more automation software that will help move from the teleoperation towards supervisory control. Initial advances in shared autonomy are also underway, including human tracking, object recognition, and automated grasping. The head also continues to evolve as a sensor platform, adding more sensing and better vision.

Improvement in the technologies will continue to move Robonaut towards its goal of assisting astronauts perform work in space.

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