Robonaut: NASA's Space Humanoid

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TO MEET THE DEXTEROUS MANIPULATION NEEDS OF FUTURE MISSIONS, NASA IS DEVELOPING ROBONAUT, AN ASTRONAUT-SIZED ROBOT WITH TWO ARMS, TWO FIVE-FINGERED HANDS, A HEAD, AND A TORSO. ROBONAUT IS ADVANCING THE STATE OF THE ART IN ANTHROPOMORPHIC ROBOTIC SYSTEMS, DEXTEROUS ROBOTIC HANDS, MODULAR ROBOTIC SYSTEMS COMPONENTS, AND TELEPRESENCE CONTROL SYSTEMS.

OVER THE YEARS, NASA HAS experimented with humanoid robots, mainly to use with space hardware and tools designed for astronaut use. In 1973, the Johnson Space Center built a robot with two arms, grippers, and stereo head cameras mounted on a movable base. More recently JSC's Dexterous Anthropomorphic Robotic Testbed has found that astronaut tasks once thought impossible for robots can be performed with multifingered robotic hands.

NASA's latest effort in humanoid robotics is Robonaut, shown in Figure 1a. With a human form and scale, Robonaut can use many astronaut tools and can work in the same tight corridors as astronauts. This is an important accomplishment in humanoid systems, but it is even more significant considering NASA's need for a system that can operate in the extreme environments of space. To meet this challenge, the Robonaut team focused on the upper body, designing an arm and hand offering greater dexterity, strength, sensing abilities, and thermal endurance than any other system packaged in human form.

Robonaut's mission

Robonaut is the first anthropomorphic robot possessing the fine motion and force–torque control required for dexterous tasks needed in space environments. For example, Robonaut could help assemble and service space science satellites in orbits beyond the Space Shuttle's reach, or it could handle long-duration exposed payloads on board the Shuttle or International Space Station. Robonaut could complement the work of larger robots or serve as an astronaut's assistant during space walks. We are designing it to provide humanlike capabilities in a broad variety of environments.

Unlike humanoid robots now being developed for entertainment or as technological curiosities, Robonaut will actually perform work. Starting with this practical goal, we have built a robot that can use tools and science instruments, work with soft materials such as Velcro and thermal insulation, and perform other tasks that current robots cannot handle. Although now possessing only one arm, Robonaut has passed a series of task trials, including those using extra-vehicular activity (EVA) tools, geologic tools, and medical instruments.

In its final form, shown in Figure 1b, Robonaut will look much like an astronaut. During EVA, astronauts generally keep their legs together, with their feet inserted in a foot restraint. Robonaut recreates this stabilized position with a single leg and uses a "stinger" identical to the one on the foot restraint to interface with the space vehicle.

Through a combination of teleoperation and

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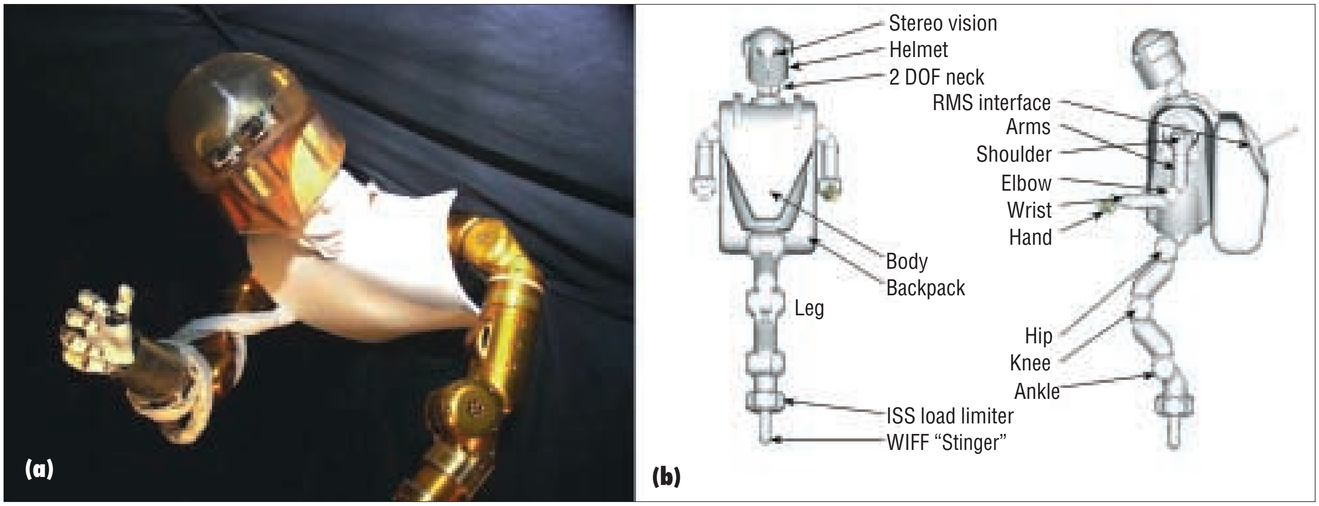

Figure 1. Robonaut's (a) upper body and (b) full anatomy, showing its single leg.

automation, Robonaut will be able to do a select set of astronaut tasks. It will act more as an assistant, handling lower-skilled work and saving human EVA time for more valuable tasks. In higher orbits, however, or in ships bound for Mars or orbital locations beyond our current reach, Robonaut will be the preferred choice for dexterous manipulation.

Robonaut is notable both for its collection of world-class subsystems and for the quality of its system integration. We are making technological achievements in each of the robot's main subsystems—hands, manipulators, head, avionics, control software, and teleoperator's interface.

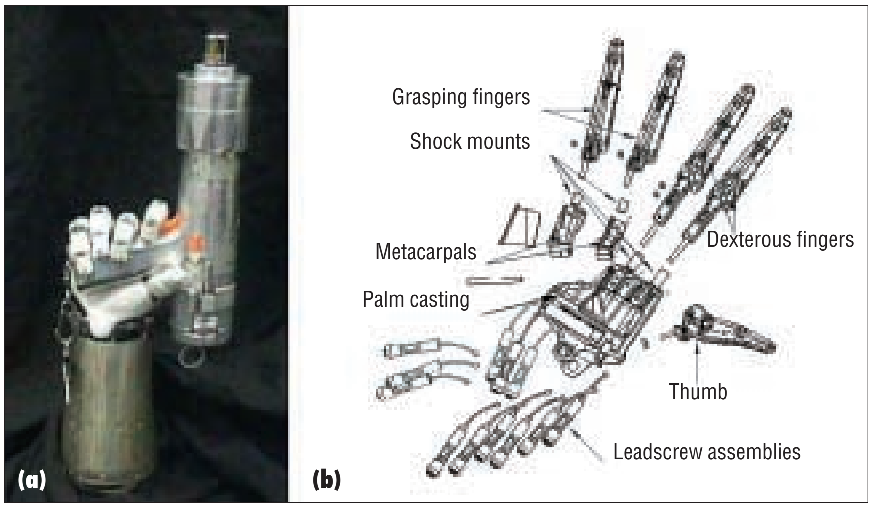

Figure 2. Robonaut's (a) hand, holding a space torque tool; (b) hand parts, showing the dexterous and grasping sets.

Hand design

In the past two decades, engineers have developed many dexterous robotic hands that can grasp and manipulate various objects.[1,2] They have designed several grippers for space use and have tested them in space,[3] but we have yet to use a dexterous robotic hand for EVA. Robonaut's hand is one of the first developed explicitly for EVA use and is the closest in size to a suited astronaut's hand.[4] Its technology is based on 12 years of cutting-edge work at JSC's Automation, Robotics, and Simulation Division.

Robonaut's hand, shown in Figure 2a, will fit into all the same places as a gloved astronaut's hand. With a total of 14 degrees of freedom, the hand consists of a forearm, a two-DOF wrist, and a 12-DOF hand with five fingers. The forearm, which is four inches in diameter at its base and about eight inches long, houses all 14 motors, 12 separate circuit boards, and all hand wiring. We designed joint travel for wrist pitch and yaw to meet or exceed that of a human hand in a pressurized glove, and we sized hand and wrist parts to provide the strength needed for EVA work.

As Figure 2b shows, the hand is divided into a dexterous set used for manipulation and a grasping set used to maintain a stable grasp while manipulating an object—both needed for tool use.[5] The dexterous set consists of two three-DOF fingers—index and middle—and a three-DOF opposable thumb. The grasping set consists of two one-DOF fingers—ring and pinkie—and a one-DOF palm. All fingers are shock-mounted in the palm, giving the hand rugged grasping options.

Robonaut's hand stands apart from others in its design for space work. All component materials meet out-gassing restrictions, preventing contamination that could interfere with other space systems. Parts made of different materials are toleranced to perform acceptably under the extreme temperature variations of EVA. Brushless motors ensure long life in a vacuum, and all hand parts use proven space lubricants.

Robonaut's hand is approaching the capabilities of a gloved astronaut, and we have demonstrated its use with a large set of EVA tools, conventional hand tools, and even medical instruments. We are now working to add tactile sensing and other features for improved control. A second-generation hand under development will employ a new linear drive system, reducing hand size and weight while providing significantly higher performance.

Arm design

The Robonaut arm is approximately the size of a human arm, with similar strength and reach but with a greater range of motion. It is capable of fine motion, has a high-bandwidth dynamic response, includes redundancy and safety features, and can endure the

Figure 3. Robonaut's upper extremity.

Figure 4. Robonaut head, neck, and camera subsystem.

thermal conditions of an eight-hour EVA. The five-DOF arm mates with the 14-DOF hand and forearm, producing the 19-DOF upper extremity shown in Figure 3. All of Robonaut's other manipulators use the same technology as the arm, resulting in a modular family of joints.

We developed the arm's dense packaging of joints and avionics using the mechatronics philosophy—combining mechanicals, electronics, and software to make intelligent machines. Its endoskeleton houses a thermal-vacuum-rated motor, a harmonic drive, a fail-safe brake, and 16 sensors for each of the five upper joints. The arm's small size, one-to-one strength-to-weight ratio, high density, and thermal vacuum capabilities make it state of the art in space manipulators.

To make the dense packaging possible, we developed custom lubricants, strain gauges, encoders, and absolute angular position sensors. A series of synthetic fabric layers will cover the manipulators, forming a skin that protects against contact and thermal damage. We have tested two of these joints in JSC's thermal vacuum chamber, and they performed well in temperatures from –25 C to 105 C. The new lubricants that make this possible are a major breakthrough in harmonic drive technology.

In designing the arm, we used custom software to size and select components,[6] evaluate strength requirements, and simulate thermal endurance for specific task timelines.[7] We also used custom analysis techniques to design the arm (and other Robonaut parts) for zero-gravity applications, where load sharing and compliance require an understanding of serial, parallel, and bifurcating chain kinetics.[8]

We are now exploring arm requirements for advanced applications, such as climbing in zero gravity and integration with surface mobility systems, such as rovers. We also plan to investigate new manipulator technologies, including linear actuators and sleek inline packaging. Our new development objectives include reducing the forearm length to improve wrist and hand motor packaging and reducing the overall weight.

Head and neck design

Robonaut's current head and neck are early prototypes. The head, shown in Figure 4, holds two small color cameras that deliver stereo vision to the operator's virtual reality display, providing depth perception. The cameras' spacing equals typical human interocular spacing, with a fixed verge at arm's reach. We are now investigating new optics for a wider field of view, ways to enhance depth perception by giving the teleoperator better verge control, new cameras that are insensitive to solar light, and ways to integrate a stereo computer vision system.

The articulated neck lets the teleoperator point Robonaut's head. Like the arms, the neck's endoskeleton is covered with a fabric skin, which is fitted into and under the helmet. Using a helmet is unusual in robotics, where cameras are typically mounted on exposed pan-tilt-verge units, but we felt we needed a rugged design to protect the cameras in cluttered environments.

The design of the neck joints is similar to that of the arm joints, using the same real-time control system. The neck joints' kinematics is based on a pan-tilt serial chain, with the first rotation about Robonaut's spine, and then a pitch motion about a lateral axis. The pitch motion axis does not pass through the camera lenses, but is instead three inches below them. This offset allows the cameras to translate forward, letting Robonaut see down over its chest.

Avionics design

For avionics, our objective has been to develop motor control and sensor processing that are integrally packaged within the actuators and local structure. The primary focus of first-generation avionics development has been to integrate multiaxis hybrid power drivers, embedded-logic motor controllers, and packaging technology, producing compact integrated actuator modules needing only power and data connections.

The motor controller, based on a field-programmable gate array, provides motor commutation, pulse width modulation control, velocity and current control, and position, velocity, and current feedback. The hybrid motor driver translates logic-level control signals, serves as the gate drive of the high- and low-side metal-oxide-semiconductor field-effect transistors of the three-phase power bridge, and provides motor-phase sourcing and sinking using the MOSFETs and ultra-fast recovery flyback diodes. The hybrid driver is rated to deliver 2 amps continuously at 28 Vdc from –55 C to +125 C, measures $2.88'' \times 0.8'' \times 0.175''$, and is housed in a conformal flexible circuit board that wraps around a triple-motor pack, as Figure 5 shows.

Next-generation avionics will incorporate a recently developed radiation-tolerant application-specific integrated circuit, which can be fabricated at commercial semiconductor foundries. A radiation-hardened hybrid power stage will integrate with the ASIC to provide a fully functional three-axis motor controller/driver. The integration of these fundamental components of motor control will provide intelligent actuators that perform signal and power processing integral to their electromechanical structure. This greatly reduces external components, reducing volumetric requirements, and simplifies the

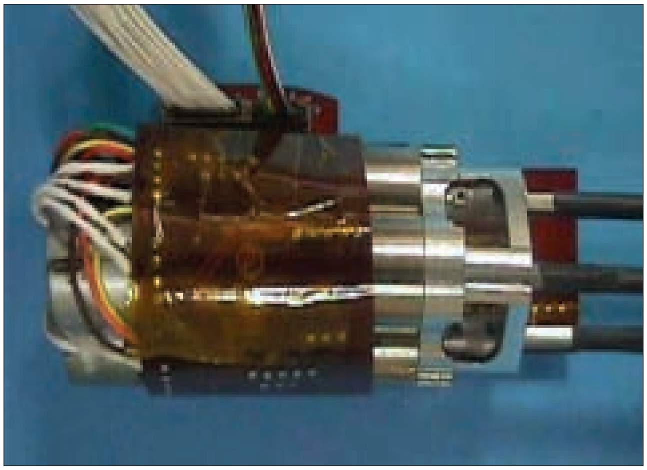

Figure 5. Triple-motor pack.

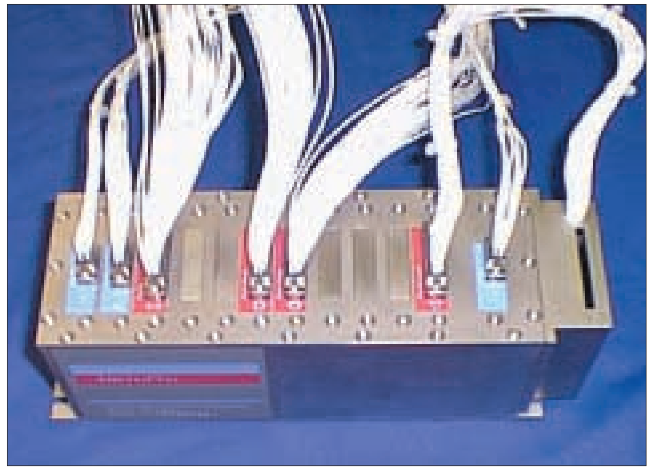

Figure 6. The data acquisition system.

interface to the motors. The first-generation design has reduced the wire count from 400 to 250, with the majority of these being motor power wires.

The Robonaut hand and wrist module contains 42 sensors for feedback and control, 28 of which are analog and require signal conditioning and digitization. The arm module contains an even greater number of sensors with similar requirements. Handling this large data stream is made more difficult by the need for small packaging, which limits overall electronics volume and geometry, both in the limbs and in the body.

The first-generation data acquisition system shown in Figure 6 is compact, rugged, and commercially available, and can sample the hundreds of sensors distributed throughout the Robonaut system. To meet the challenge of embedding the DAS, we have been prototyping mixed-signal ASICs, which provide signal conditioning and A/D conversion and can be both distributed throughout the system and embedded close to the sensors. These prototypes have shown the potential for a truly distributed DAS capable of processing the numerous Robonaut sensors.

Control design

The Robonaut control system must

- provide safe, reliable control for 43-plus DOF using data from 150-plus sensors;
- be controllable through direct teleoperation, shared control, and full autonomy;
- maintain performance in a harsh thermal environment; and
- execute at the required rate on available computing hardware.

We cannot meet these challenges using only classical robot control methods. To fully realize Robonaut's capabilities, we will need advances in control theory in the areas of grasping, force control, intelligent control, and shared control.

For Robonaut's development, we will need both safe functionality under teleoperator control and high-level partial or fully autonomous control incorporating artificial intelligence and machine vision. The resulting system will be able to make safety decisions and provide reflexive actions—such as force control and basic grasping—at a low level. This architecture makes the control system inherently safe and enables the research and development of teleoperation and machine intelligence.

To allow this safe interaction, we are developing the overall control architecture around subautonomies—each combining controllers, safety systems, low-level intelligence, and sequencing, and each acting as a self-contained peer system that interacts with other peers. For example, Figure 7 shows the force controller subautonomy. One integral part of it is the force safety system, whose limits are controlled by the force sequencer, which configures the subautonomy for the selected force mode. When the safety system detects a problem, an input reaches a design criterion, or a mode change occurs, the force sequencer handles an orderly configuration change of the force control subautonomy. The force sequencer decides the mode of the joint control system required to implement the force mode and sends it to the joint control subautonomy.

Robonaut's computing environment includes several state-of-the-art technologies. We chose the PowerPC processor for the real-time computing platform because of its performance and continued development for space applications. A VME backplane connects the computers and their required I/O. The processors run the VxWorks real-time operating system. We are using C and C++ to write Robonaut's software.

For Robonaut's development, we are using ControlShell, an object-oriented, real-time software development environment. ControlShell provides a graphical development environment that enhances the understanding of the system and code reusability. We are also using JSC's Cooperative Manipulation

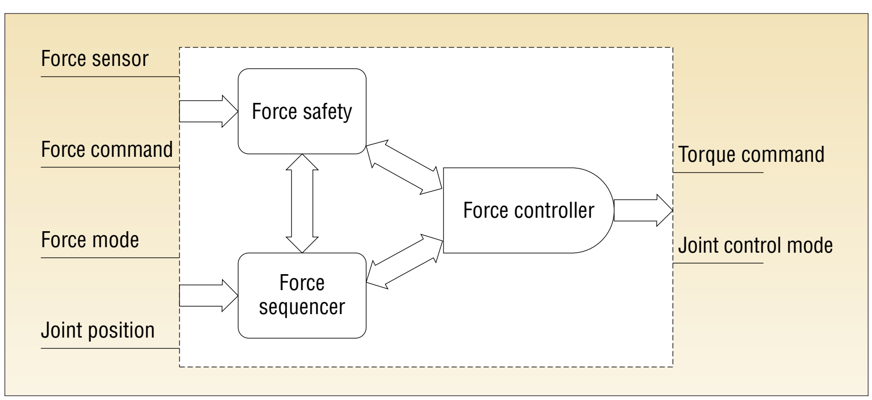

Figure 7. Force controller subautonomy, showing the decision-making, safety, and control processes.

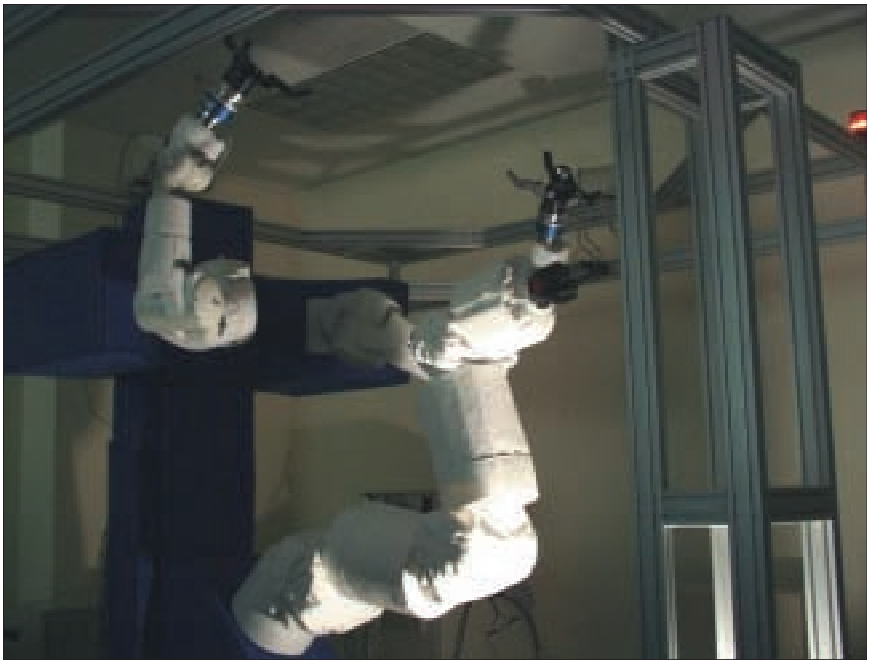

Figure 8. JSC's Cooperative Manipulation Testbed is a three-manipulator system used to prototype and develop advanced control systems for use in space. Control techniques and software developed on CMT enhance the capabilities of systems such as Robonaut.

Testbed facility, shown in Figure 8, to develop and test software and control strategies.

Robonaut's control system currently supports teleoperative control of the right extremity and the head, with subautonomies for Cartesian control, motor control, and teleoperation. We are now testing on CMT prototypes of the force control and multiarm control systems, which we will shift to Robonaut as sensors and mechanisms become available.

While teleoperation is the initial mode, the Robonaut control system is fully sensate and will execute commands regardless of origin. We will be able to add higher-level autonomous functions using an application programming interface for Robonaut, with interfaces for higher-level computing and reasoning systems. Our goal is to give Robonaut's supervisor a combination of autonomous and telepresence control modes to accomplish complex tasks.

Teleoperator interface

Robonaut's teleoperator interface uses new methods and algorithms to significantly improve robot safety and performance during space operations, such as the use of a torque tool (see Figure 9a). We've achieved this goal using

- an intuitive mapping of the human operator to Robonaut's anthropomorphic design;
- unencumbering telepresence equipment;
- text and graphical advising capabilities, including status, warning, and safety information, for robot operators;
- an immersion environment for the operator that maximizes situational awareness;
- voice recognition for operator commands; and
- feedback devices that give the operator natural cues for force and contact.

Wearing the virtual-reality-based telepresence gloves and helmet shown in Figure 9b, an operator's hand, arm, and neck map directly to the Robonaut system. Sensors in the gloves determine finger positions and send commands to the Robonaut hand. Six-axis Polhemus sensors on the operator's helmet and wrist generate neck and arm commands.

Robonaut's human scale and form make it possible for teleoperators to apply their own experience, training, and instincts. Using the system now in development at JSC, novice operators have become proficient in less than five minutes. An orthopedic surgeon, who had never operated the robot before, was able to competently handle medical instruments within minutes.

Figure 9. (a) Robonaut under teleoperation and (b) VR gear used to control Robonaut.

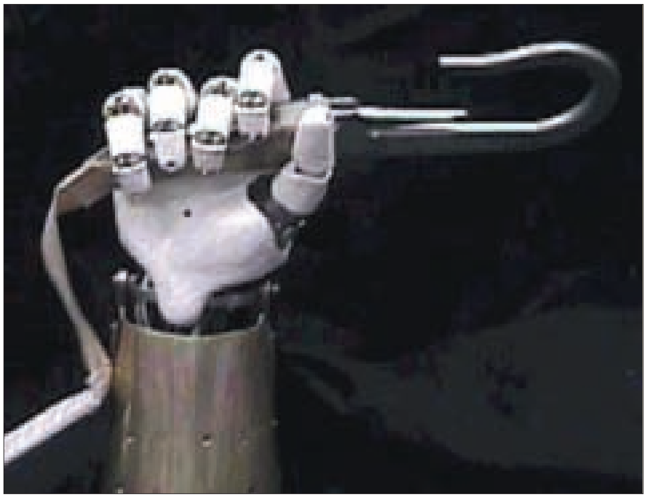

Figure 10. Robonaut unlatching a locking tether hook.

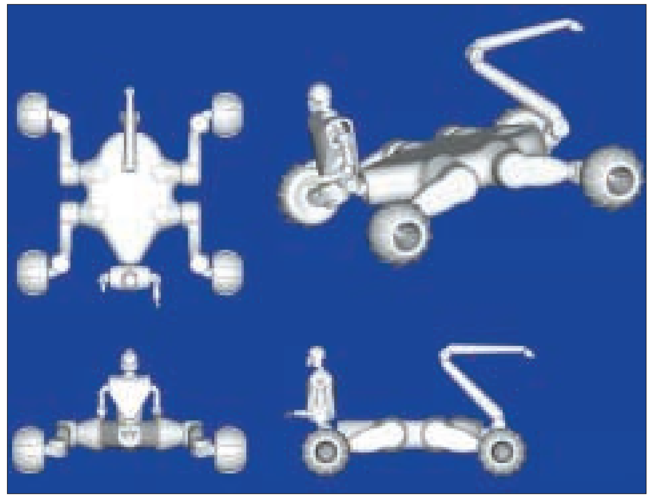

Figure 11. The centaur concept, where the Robonaut attaches to a rover.

Much of Robonaut's dexterous work will involve force-controlled manipulation, where small motions produce significant force and torque. Humans can easily handle this work, but robot operators don't receive the same feedback. The Robonaut project will integrate new force and tactile feedback devices to give the operator natural cues to the system's force amplitude and direction. These devices include tactile displays and haptic force feedback, which will provide intuitive and effective closed-loop control.

Task testing

We have begun testing the Robonaut system in representative tasks, including those for applications in space, geology, and medicine. For example, Figure 10 shows Robonaut unlatching a locking tether hook used to secure objects in zero gravity—a task requiring complex manipulation. Geologic operations, such as digging, require significant strength and the ability to handle multiple tools, including scoops, drills, and picks. Medical tasks require fine positioning and dexterous movement to operate complex tools, such as the arthroscopic wand. These diverse tasks show Robonaut's flexibility. We will continue working to quantify operator workload, build capabilities for complete end-to-end tasks, and develop new operational methods to best utilize the Robonaut system.

ROBONAUT IS A WORK IN PROGRESS, but the JSC team is committed to developing a series of Robonaut systems, with new generations outfitted for a spectrum of missions. The zero-gravity servicing system, configured with a single leg, has been the team's primary focus. This configuration seems ideal for outside work on the International Space Station, the Space Shuttle, high-orbit science or military platforms, or a Mars-bound spacecraft.

One intriguing configuration, shown in Figure 11, attaches Robonaut to a rover, resembling the centaur, a mythical creature with the upper torso of a man and lower torso of a horse. This design would be well suited for planetary operations, habitat building, work with humans in exploration, or rescue and recovery.

Our work now, though, is to continue developing Robonaut's subsystems. In arm and hand designs, we are pushing the state of the art in packaging, strength, and sensor count. We are making avionics smaller and better integrated, which will lead to a true mechatronic design. We are moving the control system beyond teleoperation to shared or fully autonomous control. We are making the teleoperation interface even more intuitive. The common denominator for these technologies is the dexterous upper-body system, our initial focus. We will continue to advance its dexterity while investigating lower-body options for new missions. ■

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