Evolution of the NASA/DARPA Robonaut Control System

M. A. Diftler
Automation and Robotics Dept.
Lockheed Martin
Houston, Texas 77058
diftler@jsc.nasa.gov

R. Platt, Jr.
Department of Computer Science
University of Massachusetts
Amherst, Massachusetts 01003
rplatt@cs.umass.edu

C. J. Culbert, R.O. Ambrose
Robotics Technology Branch
NASA Johnson Space Center
Houston, Texas 77058
cculbert, ambrose@ems.jsc.nasa.gov

W. J. Buethmann
Hernandez Engineering, Inc.
Johnson Space Center
Houston, Texas 77058
bluethmann@jsc.nasa.gov

Abstract

The NASA/DARPA Robonaut system is evolving from a purely teleoperator controlled anthropomorphic robot towards a humanoid system with multiple control pathways. Robonaut is a human scale robot designed to approach the dexterity of a space suited astronaut. Under teleoperator control, Robonaut has been able to perform many high payoff tasks indicating that it could significantly reduce the maintenance workload for human's working in space. Throughout its development, Robonaut has been augmented to include new sensors and software resulting in increased skills that allow for more shared control with the teleoperator, and ever increasing levels of autonomy. These skills range from simple compliance control, and short term memory, to, most recently, reflexive grasping and haptic object identification using a custom tactile glove, and real-time visual object tracking.

1 Introduction

The requirements for extravehicular activity (EVA) on-board the International Space Station (ISS) are 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.

Future human planetary exploration missions may involve habitat construction and maintenance, geological exploration, material's processing, launch and landing preparations, scientific instrument manipulation, and other tasks that expose the humans to dangerous or risky environments.

The Robotic Systems Technology Branch at the NASA Johnson Space Center (JSC) is currently developing robot systems to reduce the EVA and planetary exploration burden on astronauts and also to serve in rapid response capacities. One such system, Robonaut, a humanoid robot, is capable of interfacing with external space station systems that have only human interfaces and working with the same human rated tools designed for all NASA missions.

Humanoids are a relatively new class of robots. One of the most well known is the self-contained Honda Humanoid Robot [1] which is able to walk and even climb stairs. In the area of upper body capability several prototypes have been built that are designed to work with humans. One of the first, Greenman [2], showed the benefits of a human teleoperating a humanoid robot. WENDY (Waseda Engineering Designed sYmbiont) [3] has a full upper torso on a wheeled base and is a prototype for a possible domestic humanoid. Several humanoids have been designed specifically to explore human-robot interaction. MIT's Cog [4] and Vanderbilt's ISAC [5] are both remarkable platforms for such work.

These are all impressive devices, but are still prototypes and of course evolving. Unlike natural evolution, researchers from around the world are experimenting with different techniques to improve their humanoids. Fukuda, *et. al.*[6], provide an excellent survey of anthropomorphic robot evolution and suggest three characteristics that are most important towards making a better humanoid: human like motion, human like intelligence, and human like communication.

Initially the NASA/DARPA Robonaut achieved these human like characteristics solely through a human teleoperator directly controlling the system. Through an incremental process, more of the skills necessary to achieve the human like capabilities necessary to perform EVA tasks are being reproduced within the Robonaut's control system. These skills combine new software and sensors and form the basis for both shared control and autonomy.

Figure 1: NASA/DARPA Robonaut

2 NASA/DARPA Robonaut System

The requirements for interacting with planned space station EVA crew interfaces and tools provided the starting point for the Robonaut design. The NASA/DARPA Robonaut shown in figure 1 is equipped with two seven degree of freedom arms, two dexterous five finger hands [7], a two degree freedom neck and a head with multiple stereo camera sets, all mounted on a three degree freedom waist to provide an impressive work space. The limbs can generate the maximum force of 20 lbs and torque of 30 in-lbs required to remove and install EVA orbital replaceable units (ORUs) [8].

Figure 2: Robonaut – Astronaut size comparison

Robonaut's hands are very human like and are able to actuate many of the astronaut tools. Figure 1 shows the prototype Robonaut operating a tether hook which is used by crew to tether themselves and their tools. As shown in figure 2, this highly anthropomorphic robot is smaller than a suited astronaut and is able to fit within the same corridors designed for EVA crew.

3 Teleoperation

Robonaut's initial and still primary control mode is teleoperation. Actually, an immersive version of teleoperation, telepresence is the chosen technique. Using a collection of virtual reality gear, the human operator immerses himself into the robot's environment making control extremely intuitive. The operator wears a helmet with stereo screens, stereo headphones, and a microphone linked directly to the robot's stereo cameras, stereo microphones, and speaker, respectively. From a sensory standpoint the human operator's "presence" is shifted to the robot. (Figure 3)

Four Polhemus™ trackers provide data to control the arms, neck, and waist, providing very human like motion. Fully instrumented Cybergloves™ are worn on both hands to control the fingers. The mapping between human and robot is relative, permitting the operator to maintain a more comfortable pose while controlling the robot's limbs.

Figure 3. Telepresence gear

Numerous human rated tasks have been performed under teloperator control. Figure 4 shows Robonaut tying a knot, demonstrating the ease with which a human's ability to work with soft flexible materials can be transferred through the telepresence control system. Similarly a human operating Robonaut can even thread a nut onto a bolt. These are difficult tasks for a robot and will likely stay within the class of teleoperator controlled functions for some time to come.

Other tasks that are relatively easy to perform under direct human control are good candidates for more shared control and automation. Figure 5 shows Robonaut moving along the outside of a simulated Space Station module by grasping hand rails in succession. Through a combination of computer vision and haptic algorithms (described later) this task will, in the near future, either be supervised by a human or performed autonomously. While more difficult to completely automate, the operator workload for the electrical connector installation can be reduced by using grasps and arm motion primitives, and force control.

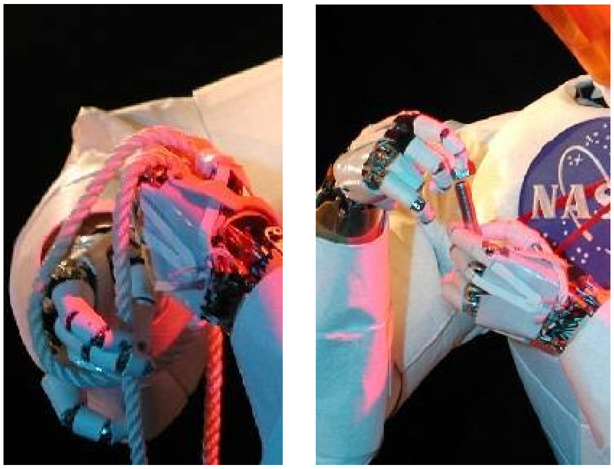

Figure 4. Robonaut tying a knot (L) and threading a nut onto a bolt(R).

Figure 5: Robonaut moving along a Space Station (L) and locking down an electrical connector (R).

The telepresence control paradigm combines the best of two worlds: the durability of a robot designed to work in the extremes of space, and the flexibility of a human mind immersed in the robot's environment. Most importantly, the human is able to quickly develop and test time savings control strategies that form the basis for shared control and automation

4 Shared Control

While direct teleoperation is an excellent control mode, it is not the most efficient technique for all operations. By intelligently moving part of the control over to the robot in the form of low level skills and functions, operator workload can be significantly reduced for many tasks. The Robonaut control system responds to voice commands that activate and deactivate the following example skills that are a subset of what is currently available.

4.1 Compliance Control

Teleoperations systems passing forces directly back to the operator have their advantages. At the Johnson Space Center teleoperators have experimented with a variety of force feedback devices with varying results. But even when a force feedback device is used, local compliance control at the robot is very useful.

By controlling the stiffness [9] of the Robonaut arms, assembly forces are substantially reduced and the teleoperator does not need to be as precise during constrained motion since the robot is moving to reduce forces that are a result of misalignment. Reductions in task time and operator workload have been achieved with the addition of compliance control for the tasks shown in figure 5.

4.2 Hand Primitives

Using the techniques developed for the NASA DART robot [10] as a starting point, a set of hand primitives have been developed and are now available for Robonaut. These primitives simplify the operator's hand motions for specific grasps: pinch, tether, spherical, splint, and drill. The spatial configuration of the fingers is modulated by the human operator and mapped into one of these primitive grasp geometries. The teleoperator uses only a few human joints to control all 12 hand joints, resulting in a decreased workload. For example, the drill primitive freezes the command to all of Robonaut's fingers except the trigger finger. In this way, the teleoperator can relax his human fingers while Robonaut maintains a firm grasp on the drill. Similarly, in spherical grasp mode the robot's fingers are spread apart, but the human maintains a comfortable hand pose while manipulating an object.

5 Autonomy

In keeping with the biological theme that is at the basis for developing humanoids, automated functions developed for Robonaut are distributed into various control system nodes that are analogous to the human brain's anatomy. The lowest level functions include: actuator control, motion control, safety, compliance control, tactile sensing, etc…, and are part of Robonaut's brainstem. Higher level functions such as vision, memory, and grasping are located in other parts of Robonaut's brain and are described below. All communication between the distributed control system nodes passes through a well defined Application Programmer's Interface (API) which is analgous to a brain's thalamus.

5.1 Short term memory

Robonaut has a short-term memory structure analogous to the mammalian hippocampus. Developed by colleagues at Vanderbilt University, this data structure, called the Sensory Egosphere (SES), provides an egocentric view of objects within the robot's world [11]. Any aspect of Robonaut's distributed control system may use the API to access the SES to recall where within the egocentric sphere an object was last identified. Objects include tools or humans recognized using vision systems, the robot's limbs using the data stream coming from the robot, or even values manually inserted into memory.

One application of the SES involves giving the robot a hint when searching for objects in its workspace. After having recognized a tool, the vision system (described later) will write the tool's coordinates onto the SES. If the robot is later asked to retrieve that tool, the sequencing system will as first step, command the robot to look where it has last seen the tool.

In addition to the implementation described in [11], the Robonaut implementation of the SES has an object database attached to the short-term memory structure. This allows additional, non-spatial information about the object to stored in a data structure that is similar to medium to long-term memory. The information stored within the object database can be as large as necessary. It could include relatively simple data such as how to pre-shape a hand before grasping a wrench or more complex information such as detailed geometric data about that same wrench.

Although the examples presented within are relatively basic, the concept of an information resource shared between all processes on a distributed, autonomous robot could be expanded to serve as both a central data repository and a data fusion agent.

5.2 Reflexive Grab

Human grasping relies heavily on tactile feedback to grasp and manipulate an object[12]. Unfortunately, it is currently impossible for a haptic device to reproduce this kind of cutaneous and proprioceptive feedback for a teleoperator. This forces teleoperators to rely on limited haptic and visual information to execute a grasp. As a result, ways to enable the teleoperator to engage fine autonomous grasp control when the arm is brought near a graspable object are needed. One way to implement autonomous grasp control is through the use of controllers which optimize a grasp quality error function[13].

The first implementation of semi-autonomous grasp control on the Robonaut platform relies on a new tactile glove, shown in figure 6. This glove is instrumented with 19 moderate resolution force sensors. Each finger joint is equipped with one sensor, and the thumb has multiple sensors to distinguish between the different thumb contacts that can be achieved. Three sensors are strategically located across the palm that are very useful for determining contact when making tool and power grasps. In addition to providing good tactile data, the glove is rugged and designed to protect the sensors, provide excellent gripping surfaces and take the abuse associated with doing a wide range of EVA and planetary tasks.


Figure 6: Robonaut tactile glove


Figure 7: Reflexive grasp of a wrench

A "grab reflex" located in Robonaut's cerebellum commands the fingers to autonomously close when tactile stimulation is detected on the glove's palm sensors (figure 7). Upon contact with the object, the fingers continue to apply force. This is similar to the distal curl reflex observed in human infants. On Robonaut, the teleoperator moves the robot arm until the palm contacts the object. At this point, the reflexive grab is automatically engaged. The teleoperator assesses the resulting grasp and decides if a regrasp is necessary. In initial test, Robonaut teleoperators report this grab reflex is particularly useful when grabbing handrails.

5.3 Haptic Exploration

Humans depend on a wealth of tactile and proprioceptive feedback in grasping and manipulation. There appears to be an interesting relationship between the type of information that humans have access to and a set of ``exploratory procedures" that people commonly use to extract object properties. Evidence suggests that each member of the set of exploratory procedures is specifically designed to engage a particular sensory modality[12]. For example, humans use lateral motion of the finger to extract texture information, unsupported holding to extract weight information, and enclosing to determine the overall shape of an object.

Robonaut's cerebellum now contains an automated function similar to this "enclosing" exploratory procedure that is being used to examine the interaction between haptic sensing with the tactile glove and arm/hand control. In this procedure, the Robonaut hand probe along the surface of a handrail in order to extract object location and pose (figure 8). This currently happens without the aid of visual information.

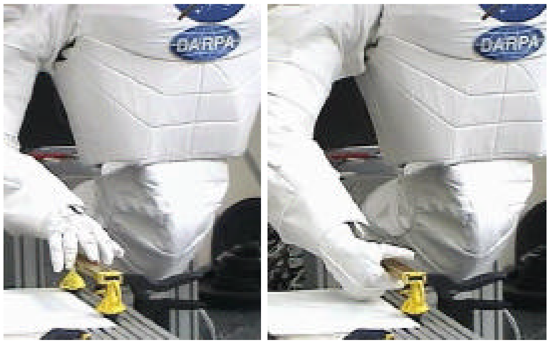

Figure 8: Probing (L) Grasping (R)

At the beginning of the enclosing exploratory procedure, the Robonaut arm is initially placed in contact with the object. The hand grabs the handrail using the reflexive grab described in the last section. Glove sensor information is combined with hand proprioceptive information to produce an estimate of where contact between the hand and handrail occurred. The forward kinematics of the hand/arm system is evaluated to determine the location of the contact points in the global coordinate frame. This set of contact points is used to make an initial 'guess' at the handrail location and orientation. Next, this guess is tested by displacing the hand along the surface of the handrail, and executing a re-grasp. Contact points are again estimated and projected into the global coordinate frame. Finally, if data acquired during the second probe corroborates data from the first probe, the hand executes a reach and grab to the estimated handrail location and orientation.

5.4 Visual Cortex

In any autonomous system, the availability of high quality sensing is a key component to success. While the sensor modalities vary, it is often high quality vision sensing that ties the system together. Within Robonaut, this is the case.

Following the biological analogy, Robonaut's vision system is referred to as the visual cortex. The visual cortex is an appearance-based template-matching algorithm operating on stereo depth information used to track the pose of objects, such as wrenches and humans[14]. Bandpass and thresholds are applied to the images, yielding a simple binary profile of objects within a specific depth-of-field (figure 9). The resultant binary image is then iteratively matched against large sets of binary templates. Each template depicts the profile of the object at a slightly different scale or orientation.

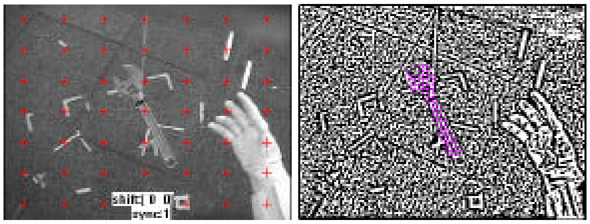

Figure 9: Wrench and hand: greyscale (L), binary (R)

The visual cortex currently tracks wrenches, screwdrivers and humans in real-time, with more tools in the works. Although the system can currently track tools that are grasped with minimal occlusion, it performs best if the tracked objects are spatially isolated. Future plans include the relaxation of this constraint by adding the ability to track tools as a composite of parts. Taking this approach, it may be possible to track objects that are partially occluded, even by a human holding the object.

Although a very sophisticated system, the visual cortex has a minimal interface to other processes. It takes only two commands; track an object by name and stop tracking. Once the vision system begins tracking it attempts to identify the object within its field of view. After identifying the object, it begins sending the object's position and orientation in the robot's base frame through the Robonaut API.

The processes most interested in the results of the object tracking are the SES (described above) and the cerebellum. The SES uses the vision results to map the object's location into the robot's short term memory, where it could then be looked at further by other processes designed to extract information from the SES. The cerebellum is an eye-hand coordination process that is currently being upgraded to combine the results of visual object tacking and the above haptic algorithms to enhance Robonaut's ability to identify an object's orientation and then successfully grasp it.

The visual cortex has also been useful in a learning experiment conducted with colleagues from Vanderbilt University. In this experiment, a teleoperator performed the task of reaching out and grasping a wrench several times. The learning system then identified the key components to the motion of grasping the wrench. After the "how to" was determined, the wrench was placed in another location. The visual cortex then provided the "where to" information for the wrenches current location. The learning system then played the learned trajectories back with the grasp position determined by the visual cortex.

6 Summary

The three different control strategies presented above: teleoperation, shared control, and automation, are designed to provide flexibility. These strategies combine together to form a general distributed control model shown in figure 10. Within this framework, a teleoperator can directly control Robonaut or a simulated Robonaut while learning algorithms collect data to build skills. Later the teleoperator can utilize these learned skills or pre-programmed skills in a shared control mode, reducing operator workload. In another mode, the teleoperator and/or a human working directly with Roboanut can monitor the system as it autonomously performs subtasks that have already been mastered, and then intervene when the system indicates it needs assistance.

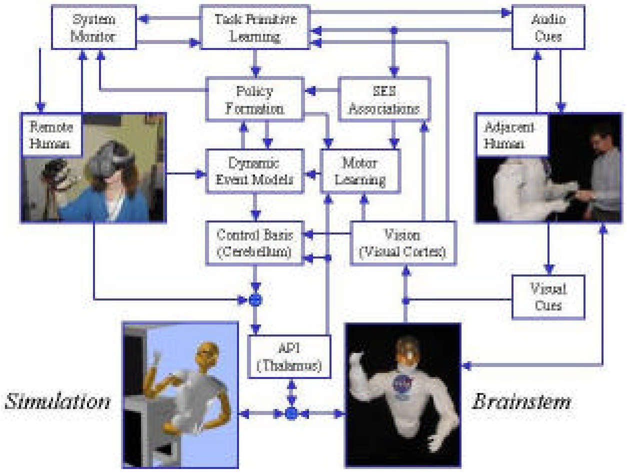

Figure 10: Distributed control

7 Future Work

Robonaut's control system is continuing to evolve. Additional and improved sensors and algorithms will lead to new skills that will give both Robonaut teleoperators and humans working directly with Robonaut more capability and options in performing space based and planetary activities.

Acknowledgement

This work is sponsored by NASA and the Mobile Autonomous Robot Software (MARS) program in the DARPA Information Processing Technology Office (IPTO)

References

1. Hirai, K. *et al.*, The development of Honda Humanoid Robot. *Proceedings of the IEEE International Conference on Robotics and Automation*, Leuven, Belgium, 1321-1326, 1998.
2. Shimamoto, M.S., TeleOperator/telePresence System (TOPS) Concept Verification Model (CVM) Development, in *Recent Advances in Marine Science and Technology, '92*, Saxena, N.K., ed., Pacon International, Honolulu, HI, pp. 97-104.
3. Morita, T., Iwata, H., Sugano, S., Development of Human Symbiotic Robot: WENDY. *Proceedings of the IEEE International Conference on Robotics and Automation*, Detroit, MI, 3183-3188, 1999.
4. Brooks, R.A., Breazeal, C., *et. al.*, The Cog Project: Building a Humanoid Robot, *Computation for Metaphors, Analogy, and Agents.* C. Nehaniv (ed), Lecture Notes in Artificial Intelligence 1562. New York, Springer, 52–87, 1999.
5. Peters, R. A., et. al., A Software Agent Based Control System for Human-Robot Interaction. *Proceedings of the Second International Symposium on Humanoid Robot*, Tokyo, Japan, 1999. (page #)
6. Fukuda, T., et. al., How Far Away is "Artificial Man"?, *IEEE Robotics and Automation Magazine*, 7(3), 66-73, 2001.
7. Lovchik, C. S., Diftler, M. A., *Compact Dexterous Robotic Hand*. US Patent 6,233,644 B1, June 2001.
8. Extravehicular Activity (EVA) Hardware Generic Design Requirements Document, *JSC 26626*, NASA/Johnson Space Center, Houston, Texas, July, 1994
9. Whitney, D., Quasi-static assembly of compliantly supported rigid parts, Journal of Dynamic Systems, Measurement and Control, 104(March), 65-77,1982.
10. Li, L., Cox, B., Diftler, M., Shelton, S., Rogers, B., Development of a Telepresence Controlled Ambidextrous Robot for Space Applications. *Proceedings of the IEEE International Conference on Robotics and Automation*, Minneapolis, MN, 1996.
11. Peters, R. A., Hambuchen, K. E., Kawamura, K., Wilkes, D. M., The Sensory Ego-Sphere as a Short-Term Memory for Humanoids, *Proceedings of the IEEE-RAS International. Conference on Humanoid Robots*, Tokyo, Japan, pp. 451-459, 2001
12. Mackenzie, C. and Iberall, T., The Grasping Hand. North Holland, Amsterdam, 1994.
13. Platt, R., Fagg, A., Grupen, R., Nullspace composition of control laws for grasping, *Proceedings of the IEEE-RSJ International. Conference on Intelligent Robots and Systems*, Lausanne, Switzerland. 2002.
14. Bluethmann, W., Huber, E., *et al.*, A Robot Designed to Work with Humans in Space, *Autonomous Robots*, 10(6), December 2002.