Telepresence Control of the NASA/DARPA Robonaut on a Mobility Platform

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Abstract
Engineers at the Johnson Space Center recently combined the upper body of the National Aeronautics and Space Administration (NASA) / Defense Advanced Research Projects Agency (DARPA) Robonaut system with a Robotic Mobility Platform (RMP) to make an extremely mobile humanoid robot designed to interact with human teammates. Virtual Reality gear that immerses a human operator into Robonaut's working environment provides the primary control pathway for remote operations. Human/robot interface challenges are addressed in the control system for teleoperators, console operators and humans working directly with the Robonaut. Multiple control modes are available for controlling the five fingered dexterous robot hands and operator selectable depending on the type of grasp required. A relative positioning system is used to maximize operator comfort during arm and head motions. Foot pedals control the mobility base. Initial tasks that include working with human rated tools, navigating hallways and cutting wires are presented and show the effectiveness of telepresence control for this class of robot.

Categories & Subject Descriptors:
C.0 [Computer Systems Organization]: General - Hardware/software interfaces; C.2.0 [Computer-Communications Networks]: General - Data communications; H.1.2 [Information Systems]: User/Machine Systems - Human factors, Human information processing; H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems - Artificial, augmented, and virtual realities; H.5.2 [Information Interfaces and Presentation]: User Interfaces - Input devices and strategies, Interaction styles, Theory and methods;

General Terms
Design, Experimentation, Human Factors

Keywords
Humanoid robot, telepresence, teleoperation.

INTRODUCTION
Humanoid robots offer great potential for assisting humans with a variety of tasks. By definition, they are designed to perform an ever increasing set of tasks that are currently limited to people. Tasks that currently require people to work in dangerous arenas are perfect candidates for humanoid robots. In addition, the humanoid robots need to be mobile to be effective. A dexterous robot is of no use if it cannot get to the work site. To this end, NASA and DARPA are jointly pursing the development of humanoid robots for use in the hazardous environments of low earth orbit (LOE) and planetary operations.

Humanoids are a relatively new class of robots. One of the most well known is the self-contained Honda Humanoid Robot [3], which is able to walk and even climb stairs. A recent development by Kawada is the impressive human scale HRP-2 [4] that can lie down and then stand back up again. In the area of upper body capability several prototypes have been built that are designed to work with humans. One of the first, Greenman [10], showed the benefits of a human remotely operating or teleoperating a humanoid robot. WENDY (Waseda Engineering Designed sYmbiont) [7] 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 [2] and Vanderbilt's ISAC [8] are both remarkable platforms for such work.

Figure 1: Robonaut Unit B

This human-robot interaction is critical to the effectiveness of any humanoid, and as seen in previous work, there are two parts to the interaction, remote control and direct interaction. NASA explored the remote control of an early human like robot, DART [5] using a telepresence system. The promising results from this control technique became the basis for remote operations of the first Robonaut [1] prototype. The more complex Robonaut requires additional interfaces for both the human teleoperator controlling the robot and the console operator who initializes and monitors the various robotic subsystems. By combining an efficient mobility platform and Robonaut, the interaction between the robot, human teammates, and a world designed for humans introduces new issues that are explored here.

NASA/DARPA ROBONAUT

The NASA/DARPA Robonaut Unit B, shown in the Figure 1, is equipped with two seven Degree Of Freedom (DOF) arms, two dexterous five finger hands [6], a seven DOF stabilizing leg, and a three DOF neck and head with multiple stereo camera sets, to create a highly capable robot with an impressive work space. Robonaut Unit A is similar to Unit B except that it has a three DOF waist instead of the seven DOF leg of Unit B. Robonaut Unit A, as shown in the Figure 2, is smaller than a suited astronaut and is able to fit within the same corridors designed for EVA crew.

Figure 2: Robonaut Unit A – Astronaut size comparison

Visible in the figures are Robonaut's hands. These hands were designed to mimic a human hand in size and dexterity. In fact, Figure 3 shows the operation of an EVA tether hook. Prior to Robonaut and its immediate predecessor DART no other robot was capable of operating this hook. The tether hook is one of the first objects our novice teleoperators learn to open.

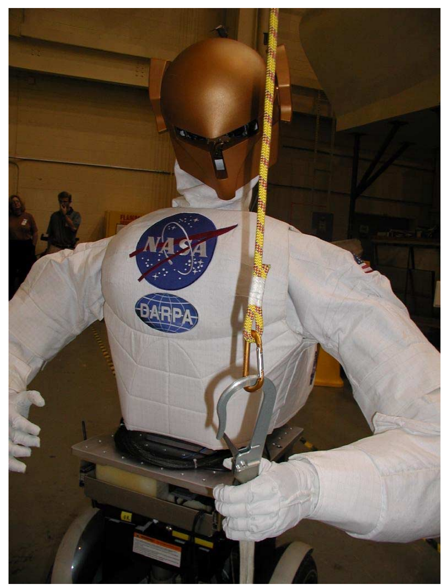

Figure 3: Robonaut with Tether Hook

SEGWAY™ RMP

The Segway™ Robotic Mobility Platform (RMP), as shown in Figure 4, is a derivative of the Segway™ Human Transporter (HT). The HT was designed to be a two wheeled motorized vehicle for transportation. It is capable of traversing a multitude of terrains. DARPA commissioned Segway™ to develop a computer-controlled version capable of balancing large payloads. This became the Segway™ RMP. The RMP is controlled via computer. Velocity and turning rate are the primary controls. When these values are set to zero, the RMP will hold position even when external forces are applied. One of these very special devices was delivered to NASA – JSC.

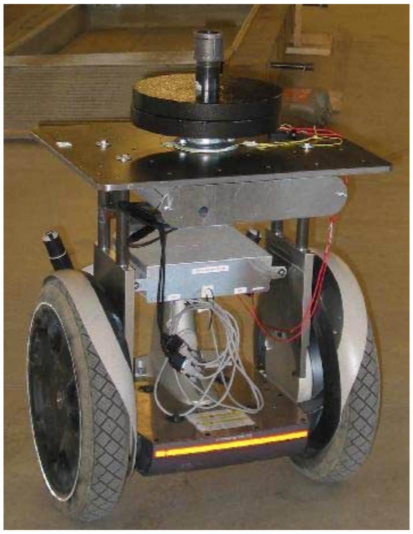

Figure 4: Segway RMP

ROBONAUT ON THE RMP

Once at NASA, the RMP was tested extensively to determine its capabilities. Control software was tested and the stock hardware was modified to suit the needs of Robonaut. A battery power distribution system was added and training wheels were added for initial development and testing. One shortfall of a two-wheeled platform is its inability to stay upright if drive power is severed for any reason. The training wheels prevent this failure mode from causing damage to its robotic payload.

The leg of Robonaut Unit B, except for a single roll joint, was removed in preparation for mounting on the RMP. This joint provides a single waist DOF and allows Robonaut to pivot on top of its mobile platform providing more flexibility to the teleoperator. Figure 5 depicts this DOF. Robonaut combines human like dexterity with low profile mobility making for an impressive and capable humanoid.

ROBONAUT TELEPRESENCE

Robonaut is a 45 DOF robot. How is it controlled? Robonaut works in a master/slave configuration. Robonaut follows the motions or controls of its master, the human teleoperator. The teleoperator is located remotely from the actual robot. Robonaut Unit A has actually been controlled from Washington, DC, USA while the robot was still located in Houston, Texas, USA. This exercise demonstrated that the teleoperator might be in the next room or across the globe. Other than logistical or time delay reasons, the teleoperator's location is immaterial to the robot being controlled. During the DC test, time delays over 0.5 seconds were experienced. These posed no problems for the teleoperator. The teleoperator slowed his motion to compensate for the delay. Obviously, this approach would not work for longer delays. Future research is required. It is assumed that a combination of autonomy and teleoperation will be implemented to compensate for long delays. Various autonomy modes are being investigated on Robonaut Unit A by several universities and research groups.

Robonaut is manipulated through a variety of interfaces. Most are chosen for comfort, ease of egress, and to minimize external hindrances with the physical environment. Therefore, any sort of exoskeleton type hardware was immediately dismissed. The operator dons a myriad of virtual reality (VR) hardware to fully immerse and become Robonaut. The VR gear utilized on Robonaut consists of a helmet, gloves, body tracking and foot pedals. Everything but the foot pedals are visible in Figure 6. All of this equipment works in concert to give the operator the illusion of actually being the robot in a comfortable fashion. This also provides the added benefit of creating a very intuitive interface that is easy for novice operators to understand and utilize.

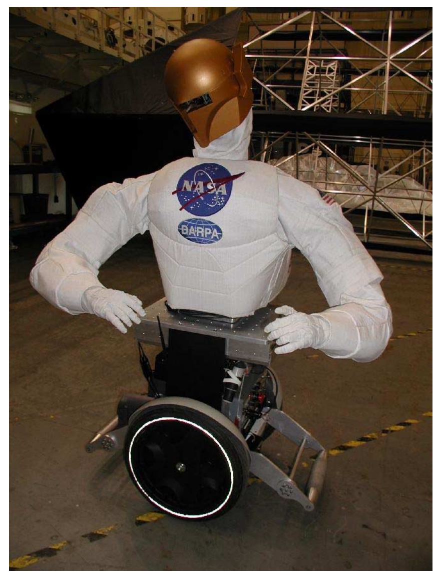

Figure 5: Robonaut Waist Motion

Robonaut has two cameras mounted in its head. By feeding the images to a VR helmet, the teleoperator perceives a stereo view of the world from the perspective of the robot. This view is key to the effectiveness of the teleoperator. By using the sense of depth gleaned from stereo images and lighting, the operator develops an understanding of the environment. In fact, the images are so compelling that operators have been known to jerk their feet back in response to falling objects nearby the robot. This is usually an amusing situation considering the operator is nowhere near the robot. This state of immersion is highly desirable when controlling Robonaut. When immersion occurs, the operator no longer considers the robot a separate entity. It is now part of his/her body, which increases productivity.

Figure 6: Telepresence Hardware

Since Robonaut is now mobile, wireless video is mandatory. Trailing a cable behind the robot is unacceptable and dangerous. The team investigated transmitting the two video cameras signals via Ethernet but image quality, reliability, resolution and time lags prohibited its use. Instead, two video transmitters were installed on Robonaut. A ground station located near the teleoperator receives the signals and pipes the images to the VR helmet displays.

Body tracking of the teleoperator was accomplished through the use of Polhemus™ [9] hardware. Polhemus™ is a six DOF tracking system. The position and orientation of four sensors are measured relative to a base station. The teleoperator wears a head sensor, sensors on the back of each hand, and a chest sensor. Robonaut is controlled via Cartesian commands, which are measured relative to a body centric coordinate frame. Since Robonaut and the human body are very similar, the custom designed software for reading the Polhemus™ sensors was configured in much the same way. The head and arms are measured relative to the chest sensor. This has an added benefit of allowing the teleoperator to move around in the chair and not affect the relative position of the arms and head. From a comfort standpoint, this is very much appreciated by the teleoperators.

Another highly useful feature of the custom software is the ability to “freeze/thaw” and “index” the extremities. Freeze and thaw are fairly obvious in their use. Use of these commands controls whether the robot will listen to the control command or ignore it. By freezing an extremity, the teleoperator can relax the human extremity without affecting Robonaut posture. The thaw command not only starts the robot receiving control commands, but it implies an “index” of the extremity. Indexing simply computes the delta difference between the actual robot position and the command position computed by the Polhemus™ sensors at the time of the thaw. The delta is applied to the Polhemus™ command before being sent to Robonaut.

Indexing allows the teleoperators physical arm to be in a different position relative to the robot’s arm. Here is a simple example. Consider that the teleoperator is straining their neck to look down and the position is uncomfortable. By freezing the robot neck, positioning his/her own head to a more comfortable position, and then thawing allows the teleoperator to look straight ahead while the robot is looking down. Indexing is also useful for the arms. Robonaut can hold an uncomfortable position indefinitely, but the human cannot. Indexing to a more relaxed position reduces strain and fatigue on the human, thus increasing comfort.

It is important to note that the idea of indexing can be applied to any sensor system. It does not have to be a Polhemus™. This method has been readily applied to other sensor systems such as Phoenix Technologies, Inc. VZ3000™ optical tracking system.

Voice is used to control the freeze/thaw of extremities of Robonaut. Voice control is used extensively by the teleoperator. In addition to controlling freeze/thaw, the teleoperator can control camera views, zooming, autonomy modes and a myriad of other functions. Voice control allows the teleoperator more control of his environment and less dependence on additional operators.

The Virtual Technologies, Inc (VTI) Cyberglove™ tracks finger motion. The Cyberglove™ consists of a tight fitting glove with embedded strips of metal located at various joints on the human hand. These metal strips change resistance as they are bent. This change in resistance is converted into an angular measurement by the Cyberglove™ hardware. Cybergloves™ are available in 18 and 22 sensor versions. Knowing these angles is useful, but they still have to be mapped to the Robonaut hand. Typical mapping techniques attempt to map a sensor to a joint. The Cyberglove™, due to variations in teleoperator hand size and fit of the gloves, creates inaccuracies in the mapping.

A novel method has been implemented in the glove software to alleviate mapping discrepancies. The glove sensor angles are measured as normal, but are now applied to a virtual hand. The joints are defined based on VTI documentation [11]. A forward kinematics solution provides the Cartesian position of each fingertip. This becomes the input to an inverse kinematics algorithm specific to the Robonaut robotic hand. The result is a joint space solution, which is sent as a command to the Robonaut hand. The algorithm performs the mapping in the Cartesian space of the hand. By doing so, the mapping becomes generic to the human and the robotic hand being used. Also, calibration offsets can be computed in Cartesian space and applied to the finger coordinates before inverse kinematics is computed for the final joint space solution. Based on empirical data from several operators this method has provided better mapping of the human hand to the Robonaut hand. Natural human finger motions translate readily into robot space and provide a more natural feel for the teleoperator. Fine motor control is enhanced. Variations in hand size pose little problem to this algorithm. Extremely small hands do require adjustment of the virtual hand to more closely match the human hand. A result of this algorithm is shown in Figure 7 where a prototype optically tracked glove was being tested. Note how well the fingers of the human hand in the black glove match those of the robotic hand in the white glove. Better finger matching using Cartesian control has lessened the awkward finger positions sometimes required to operate the previous mapping system.

Figure 7: Cartesian control using prototype optical glove

Since the teleoperators hands and upper body are instrumented for control of 43 DOF, the only part left un-instrumented is the feet. The feet control the 2 DOF mobility of Robonaut. CH Products ProPedals™, see Figure 8, flight simulator foot pedals control the base of Robonaut on the RMP. Initially a tank style foot pedal control was implemented. Tank steering is where the travel of the pedals is centered. Pressing both feet forward would cause forward motion. Both back would cause reverse movement. One forward, one back would cause turning. This method was problematic based on the hardware. The foot pedals on a flight simulator are not centered in their travel. They are more like the pedals on a car or aircraft. The foot pedals are sprung in one direction. They also move fore and aft about a central pivot just like the rudder pedals on an airplane. Therefore, tank steering was physically impractical.

Other methods were implemented using various types of control, but were quickly dismissed for various reasons. One method even used the concept of shifting gears from forward to reverse like a toggle switch, but the teleoperator quickly became confused as to which mode they were in. This created safety issues and was quickly rejected.

Figure 8: CH Products ProPedals™

The final method involved using the pivoting of the foot pedals to control yaw like a set of aircraft rudder pedals. Unlike an airplane, the right pedal was depressed to control velocity much like the gas pedal on a car. The left pedal was used to control forward and reverse. Pedal up equated to forward velocity. Pedal depressed equated to reverse velocity when the gas pedal was activated. The teleoperator easily adapted to this method of mobile base control and quickly gained fine control over base placement. It was interesting to note that during some complex tasks involving the hands and arms, the teleoperator would tense up his/her feet causing slight motions in the mobility base. Once noticed or warned of the unwarranted motion, it quickly ceased. The ability to freeze the base was implemented to lessen this problem. By doing a freeze, the teleoperator load was lowered allowing him/her to focus more on the task at hand. Once the task was completed, motion base activities could resume. This mode was left to the discretion of the teleoperator.

ROBONAUT CONTROL CONSOLE

The other side of telepresence for Robonaut is the console operator. The console operator is responsible for running the Robonaut control software. The console operator performs a variety of other tasks, including calibrating and homing the robot, monitoring the health of Robonaut, and arbitrating robotic control to the teleoperator.

The control software for Robonaut runs in a real time operating system that has a text-based interface. To alleviate typing control commands, windows based GUIs were created. Control GUIs were created for the head, both arms, both hands and the waist. These are illustrated in the

Figures 9 and 10. Each GUI contains a main dialog that displays the modes and states of the different body parts. Also each appendage has its own control dialog that is orientated around the main dialog. Its position corresponds to its location relative to the robot, i.e. the head is on top, the left arm is on the left, etc. There is also a GUI to control the Segway RMP. Note that while the dialogs initialize in the default configuration, the console operator is free to move these GUIs into any preferred configuration.

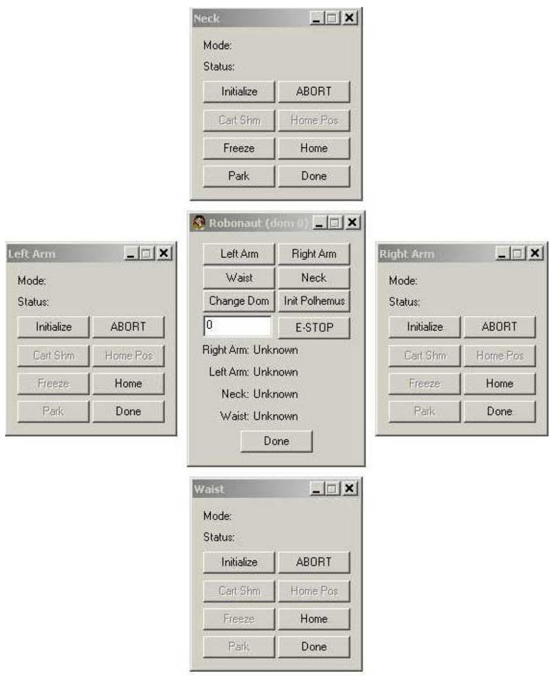

Figure 9: Console Operations Body GUI

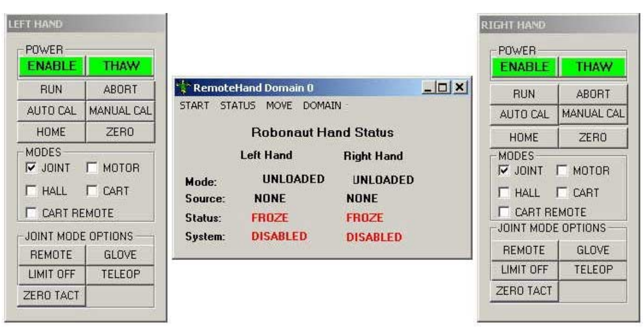

Figure 10: Console Operations Hand GUI

LESSONS LEARNED

There were many lessons learned throughout the Robonaut/RMP project. While single person teleoperation of Robonaut on the Segway RMP was always a requirement, it turned out to be a simple task. To date only four people have operated Robonaut on the RMP. All considered the increase in workload to be minimal. The combination of input devices allowed for an intuitive controllable interface to the robot. Robonaut becomes a natural extension of the human teleoperator. Freezing and thawing of extremities and the mobility base through the use of voice, is a must for teleoperation. Without it, human physical limitations are reached rapidly and fatigue becomes a factor.

Adding mobility to Robonaut added a whole new level to the operating environment. No longer does the table have to come to Robonaut. Robonaut can go to the table. To date, Robonaut has picked rocks and tools off tables, followed people through buildings, navigated tight confines, and a myriad of other tasks. Its operating environment has expanded dramatically. Every day new tasks are being attempted that were not thought of before. Our teleoperators commented that the added mobility was excellent. Instead of an external human deciding the correct presentation of a tool or object, the teleoperator could decide which approach was best for him/her and then execute the motion. This is not possible on a stationary platform. It should be noted that this expanded mobility would not have been possible without the wireless connections to video and Ethernet. If the robot had been tethered, a number of tasks would have been impossible. The wireless systems have caused problems, though. By going wireless, interference by other transmitters and physical barriers becomes problematic. The wireless operating environment should be considered when selecting locations.

Integration with the Segway™ RMP has been a useful learning experience. New techniques are being developed to reduce operator workloads and enhance mobility. One such area is the RMP balance mode. While the Robonaut/RMP is balancing, there are inherent dynamic challenges to overcome. First off, imparting vertical forces such as pressing on a table or lifting a cart can cause instabilities in the balance control algorithms. Basically, when in this mode, the Robonaut/RMP robot tries to balance itself, but is unable because of constrained motion. When this occurs, the balance control tries even harder to balance, which it cannot do, and eventual powers off. Since this only occurs during constrained and typically stationary tasks, it would be desirable to turn off the balance mode, and then turn it back on once the task was complete. This mode is currently being discussed with Segway™.

Secondly, moving the arms causes slight shifts in the mobility base due to balance. The arm motion causes slight shifts of the CG, which in turn causes the base to move correspondingly to maintain balance. Therefore, when fine motor control is desired, arm motions must be kept to a minimum to keep the base stationary. Currently the team is investigating the possibility of canceling out the motion of the base from the arms. By reading the stability gyros inside the mobility platform, the unwanted arm motion could be cancelled out.

Thirdly, the Robonaut on the RMP is constantly creating slight motions of the base to maintain balance. Initially, the team anticipated that this would cause vestibular problems with the teleoperator. This has proven not to be the case. The various teleoperators have shown no signs of motion sickness while operating Robonaut. Even so, the team is currently looking at canceling out the motion of the base to stabilize the head camera views. The team is considering future image processing and autonomy work, which would be simplified by stable camera views.

CONCLUSIONS

Robonaut on the Segway RMP has proven to be a highly adaptable and robust robot capable of many complicated tasks. Its range of operation has been significantly enhanced by the addition of the mobility base. The NASA engineering team is still exploring the boundaries of Robonaut's operational capabilities with its newfound mobility.

It is surprising how easily Robonaut is teleoperated. It was initially thought that the teleoperator might suffer from control overload, but this has not been the case. In fact, teleoperation of Robonaut is quite natural and intuitive. The only "unnatural" interface is the foot pedals. Control of the foot pedals, though, is learned in a very short period of time and becomes second nature. Complicated driving and arm motion tasks are routinely performed with minimal effort.

Using a single teleoperator has created no problems in the operation of Robonaut. Relative position sensors and indexing added to teleoperator comfort. Cartesian control of the hands reduced strain on the physical hands and allowed a more natural, comfortable pose. Anticipated motion sickness due to the balance mode of the Segway™ has not occurred. Immersion into the Robonaut environment is readily achieved.

Overall, Robonaut on the Segway RMP has proven to be a robust and highly adaptable system. The team has learned much from moving into the world of mobile robotics and will continue to learn more as they expand the capabilities of this remarkable system.

ACKNOWLEDGMENTS

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

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