Feature

Haptic feedback applications for Robonaut

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Keywords

Aerospace industry, Tactile sensors, Robotics

Abstract

Robonaut is a humanoid robot designed by the Robotic Systems Technology Branch at NASA's Johnson Space Center in a collaborative effort with Defense Advanced Research Projects Agency. This paper describes the implementation of haptic feedback into Robonaut and Robosim, the computer simulation of Robotonaut. In the first experiment, we measured the effects of varying feedback to a teleoperator during a handrail grasp task. Second, we conducted a teleoperated task, inserting a flexible beam into an instrumented receptacle. In the third experiment, we used Robonaut to perform a two-arm task where a compliant ball was translated in the robot's workspace. The experimental results are encouraging as the Dexterous Robotics Lab continues to implement force feedback into its teleoperator hardware architecture.

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Industrial Robot: An International Journal
Volume 30 · Number 6 · 2003 · pp. 531–542

DOI 10.1108/01439910310506800

Introduction

The Dexterous Robotics Lab at NASA Johnson Space Center (JSC) has developed a humanoid robot astronaut assistant called Robonaut (Ambrose *et al.*, 2000). Robonaut, shown in Figure 1, is intended to be an assistant to astronauts during extra-vehicular activity (EVA) tasks, and is teleoperated by a remote human operator. While Robonaut has some autonomous capabilities as of this publication, including object recognition and move to grasp functions, the work discussed in this report focuses only on teleoperation tasks with the robot and computer simulation.

Prior work

Studies have shown that force feedback in a teleoperator system improves performance of the operator in terms of reduced completion times, decreased peak forces and torques, and decreased cumulative forces and torques (Draper *et al.*, 1987; Hannaford *et al.*, 1991; Hill, 1979; Kim, 1991; Massimino and Sheridan, 1992; Williams *et al.*, 2002). For this reason, the Robonaut team is very interested in implementing higher fidelity force feedback in their telemanipulation system. Currently, the only mode of haptic feedback available to the operator is vibrotactile feedback through pager motors mounted in a sensing glove. We implemented two force-reflecting joysticks so that the teleoperator can have three or six degrees of force feedback (forces only or forces and torques) during operation of Robonaut. Prior work has shown that just as force feedback can improve teleoperator performance when operating in remote environments, it also has improved performance of some tasks in virtual environments (Dennerlein, 2000; Millman, 1995; Wall and Harwin, 2000).

Research goals

This project involves one experiment with a teleoperation controlling Robosim, and two multi-phase experiments using Robonaut controlled by a remote operator. In the Robosim experiment, users were asked to perform a "handrail task", 12 times. In each trial, the subject was presented with one of the three feedback conditions (no feedback, visual feedback to indicate collision, or force feedback upon collision). The second experiment involved assembly of a strut.

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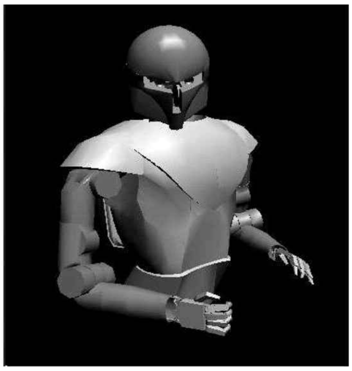
Figure 1 Ground-based Robonaut system (left) and Robosim (right)



In Phase 1 of the first experiment, a teleoperator completed the task with full force feedback to one arm via the force reflecting hand controller (FRHC) six degree-of-freedom (DOF) joystick. In Phase 2, the teleoperator taught Robonaut to complete the task autonomously with voice commands, gesturing commands, and force feedback information. Results of these tests were compared to prior experiments with a numb teleoperator. The third experiment involved grasping and translating a beach ball. In Phase 1 of the second experiment, the compliant ball was handed to Robonaut, and the teleoperator grasped the ball with a two-handed grasp on each side of the ball. The teleoperator used force feedback, felt via two FRHCs, to successfully translate the ball in the workspace without dropping or squeezing the ball. In Phase 2, the teleoperator taught Robonaut to translate the beach ball autonomously with voice commands, gesturing commands, and force feedback information.

Background

The role of humans in space

The International Space Station (ISS) is the largest and most complex space structure ever flown. Each phase of the ISS lifecycle, with the exception of final de-orbiting, depends heavily on human labor with activities ranging from the exotic to the mundane. The planned human workload, already well underway, calls for a significant amount of direct physical interaction with ISS hardware during assembly, deployment, maintenance, research, and repair operations. Some of these are intra-vehicular activity (IVA) operations taking place in the carefully controlled environment found in the ISS cabin. Others are EVA operations requiring trained crewmembers to don external mobility unit (EMU) spacesuits and exit the pressurized cabin through an airlock.

If it requires a spacewalk, even a seemingly trivial task instantly becomes both hazardous and complex. Accidents or malfunctions can quickly turn deadly in the vacuum of space, where sunlit surfaces can heat up to 100°C and shaded surfaces can plunge to −200°C. Strict procedures are practiced to ensure that a space-walking astronaut is always secured with at least one lifeline in the event that the astronaut loses his/her grip while climbing and begins to drift away from the spacecraft. Flight hardware design requirements prohibit sharp edges and corners to avoid puncturing spacesuits. Background radiation levels can be orders of magnitude higher outside earth's protective atmosphere and there is always the remote risk of a micrometeoroid/orbital debris (MMOD) impact. Because of the inherent risk and expense, EVA time is a precious resource used sparingly. Cost estimates range as high as $100K per astronaut-hour of EVA time. Nevertheless, EVA operations are unavoidable, especially when critical equipment fails unexpectedly.

The role of robots in space

Nowadays, robotic explorers are pushing back the frontiers of the solar system and will soon extend our reach even farther. Because they can accept high levels of risk, robotic space missions offer ever-expanding capabilities at decreasing cost. The highly successful Mars Path-finder mission, for example, made observations and performed experiments on the Martian surface for a period of almost 3 months at a cost comparable to a single Space Shuttle flight (about $250M).

Robots built to work in space have several advantages over their human counterparts. These machines far exceed the physical capabilities of humans in limited roles demanding precision, strength, and speed. They are not dependent on perishable consumables or pressurized cabins and can withstand extreme environmental effects including temperature and radiation. They may even be able to continue functioning at reduced capacity in the event of serious damage. Most importantly, robots are expendable machines that can be repaired or replaced when they fail.

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Human-robot teaming in EVA operations

When comparing humans and robots, it is only natural to differentiate between the types of work suited to each. But what happens when the work demands the complementary strengths of humans and robots? Such scenarios are common in the EVA world of precisely machined and mated components cluttered with umbilical cables, thermal blankets, and storage bags. An EVA human-robot team combining the information-gathering and problem-solving skills of human astronauts with the survivability and physical capabilities of space robots is proposed as a compromise designed to increase productivity.

Astronauts already use teleoperated robots, built by the Canadian Space Agency (CSA) to assist them in EVA operations. The space shuttle's robotic arm, or shuttle remote manipulator system (SRMS), is used to capture and position large orbiting payloads or to retrieve them from the Shuttle cargo bay. The space station remote manipulator system (SSRMS) provides ISS crew members the ability to reconfigure the station by moving functional modules from one docking port to another. These robots excel in instances where high strength, long reach, and coarse positioning capability are required. They are well suited to large-scale construction and deployment tasks. Maintenance work, in contrast, requires a much finer degree of control and greater dexterity than either arm can offer. To meet this need, CSA has developed the two-armed special purpose dexterous manipulator (SPDM) to perform some very well-defined servicing work, like replacing failed orbital replacement unit (ORU) modules in precisely located receptacles found on the outside of the ISS.

Robonaut

Recognizing the opportunity to augment human presence in space with cost-effective machines, the Automation, Robotics and Simulation Division (AR&SD) at NASA's JSC is collaborating with the Defense Advanced Research Projects Agency (DARPA) to develop a humanoid robot called Robonaut.

Unlike other space robots, Robonaut is designed specifically to work with and around humans. The robot's considerable mechanical dexterity allows it to use EVA tools and manipulate flexible materials much like a human astronaut. About the same size as the EMU spacesuit, Robonaut can go wherever a suited astronaut can. By meeting these requirements, the Robonaut project leverages NASA enormous investment in tools, procedures and workspaces for space-walking astronauts. Aboard the ISS, robotic astronauts like Robonaut could perform routine chores, assist humans in more complex tasks, and be available for emergency EVA operations in minutes, instead of hours.

Robonaut system morphology

The requirements for interacting with ISS crew members, interfaces and tools provided the starting point for the Robonaut design. Anatomically, the robot closely resembles the form of a suited EVA astronaut except that it has only one leg instead of two (Figure 2). Altogether, the planned free-flyer configuration will have at least 50 coordinated DOF and physical capabilities approaching those of a human in a spacesuit. A detailed discussion of subsystem anatomy may be found in Ambrose *et al.* (2000).

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

Figure 2 The teleoperation interface used in the assembly task trials with kinesthetic feedback

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while posing unique thermal management problems.

Control system architecture

As Robonaut is a humanoid designed to work with and in near proximity to humans, the interface between the robot and the various humans in the system is central to the high-level control system design.

The fundamental control methods for Robonaut are Cartesian position control of the arms and joint position control of the hands. A two-tiered force accommodation approach is used to handle external forces. For relatively small forces, Robonaut uses an impedance control law. In this control mode, the arm acts as a mass-spring-damper, complying with external forces, but returning to the original position if the load is relieved. For loads exceeding a user-defined threshold, the arm transitions into a damping control law, where the arm moves at a velocity proportional to the applied load.

Although designed for safety, the force accommodation control laws can also be tools for performing work. For example, when attempting to place a peg into a hole, the impedance control law may be stiff in the direction of insertion and compliant in the off-axes. This allows the manipulator to apply forces in the insertion direction without building up forces in the other axes. Damping control is effective in multi-agent tasks, where the robot follows a teammate's lead by moving to minimize loads.

System capabilities

A wide array of tools and interfaces, both EVA and conventional, have been successfully handled in the course of testing the Robonaut system's capabilities. Many of these have been utilized or manipulated to complete demonstration tasks of varying complexity. Some of the more interesting tasks are well beyond the capabilities of conventional robotic systems. One example is unzipping a conventional backpack and searching through the contents.

Human-robot interfaces

In its simplest form, Robonaut is a teleoperated master-slave system in which a human, the "teleoperator", becomes the robot master. The anthropomorphic form of the robot allows an intuitive, one-to-one mapping between the master and slave motions. To enhance the operator's sense of immersion (telepresence), additional feedback may be provided in the form of visual aids and kinesthetic, tactile, and auditory cues. Williams (2001) showed that the addition of visual and kinesthetic feedback improved the performance of teleoperators working a specific task with the Robonaut system. Care must be taken, however, to ensure that the operator's workload in processing all of the new information does not become excessive (Rochlis, 2002).

For all its utility in the laboratory, a teleoperated system degrades quickly in the presence of communication time delay. A human teleoperator can deal with a few seconds of time delay by slowing down his/her motions, effectively compressing the effect, or by adopting a move-and-wait strategy, thereby allowing the feedback to catch up (Ferrell, 1965), but these techniques are only useful for non-contact tasks or when interacting with a very compliant environment. Significant time delays are expected when communicating with space robots and, depending on the magnitude, varying degrees of autonomy are required to deal with them.

Interacting with and through Robonaut

Humans interact with Robonaut in one of the three roles: teleoperator, monitor, and co-worker. This interaction takes different forms depending on the configuration of the human-robot team. While the remotely located teleoperator and monitor exchange mainly information signals with the system, the co-worker is actually present at the worksite and can interact with the robot in a direct, physical manner. Robonaut is equipped with force and tactile sensors to sense these physical stimuli as well as motors to act on them. When a human co-worker is present at the worksite, the teleoperator has the opportunity to interact indirectly with the co-worker through the robot, which may be considered as an extension of the teleoperator's own body. From the co-workers' point of view, interacting with a teleoperated Robonaut is like interacting with another human.

A haptic joystick is used for both position commands to Robonaut's arm and for force reflection. The visual overlays are also available for the teleoperator through the helmet-mounted display. The Jet Propulsion Laboratory (JPL) FRHC is a six DOF force feedback device. The FRHC, shown in

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Figure 2, has a workspace of approximately 1.25 ft^3 and is capable of producing a force of up to 9.8 N (35 oz) in magnitude and a torque of up to 0.5 N m. All data transfer between the Robonaut and the FRHC occurs at 50 Hz, significantly less than typical haptic systems. Despite this limitation, force feedback is stable due to filtering and scaling of the output forces.

Robosim software

Robosim is a graphical simulation of Robonaut currently under development in the JSC Dexterous Robotics Lab. The simulation has many uses such as the testing of new control algorithms before applying them directly to the hardware in order to minimize the possibility of damage to Robonaut. Robosim is also designed for use as a training tool for Robonaut teleoperators. If operators can learn the dynamic response of the robot and feel comfortable utilizing it via Robosim, training time on the actual robot can be decreased and movements that would cause excessive forces or damage to the hardware are less likely to occur. The simulation uses the Interactive Graphics, Operations and Analysis Laboratory (IGOAL) Enigma modeling software, developed at JSC, to create a simulation of Robonaut and its worksite. The simulation code controls the display graphics, display functions, drawing routines and operational limits.

One of the primary differences between the Robonaut and Robosim, the software equivalent of Robonaut, is the lack of availability of contact force information in the simulated environment. For the experiments with Robosim, simulated contact forces were calculated based on a collision detection and force model algorithm implemented in Visual C++ for the purpose of force reflection to the teleoperator. With this capability, the operator feels forces when controlling Robosim similar to those that would be generated when operating Robonaut.

Experiment 1: haptic interaction with Robosim

We present a comparison of the effects of various modalities of sensory feedback during a simulated teleoperation task. Subjects were asked to complete a move-to-grasp task, contact a handrail, and return to a home position. During contact, subjects were asked to make contact with the handrail, yet avoid excessive forces that would be generated by exaggerated collision between the Robonaut hand and a handrail. Performance, measured in terms of peak forces during contact, was compared for three experimental conditions.

Experimental design

Each subject was asked to perform a single teleoperation task, referred to as the "handrail task", 12 times. In each trial, the subject moved to one of the four colored handrails (orange, pink, green, or purple) with one of the three feedback conditions (no feedback, visual feedback to indicate collision, or force feedback upon collision). The handrails were placed at the same orientation in order to avoid joint limits and singularity conditions of the Robonaut arm. Additionally, Rochlis (2002) showed that target orientation and approach direction were not significant for reaching tasks with Robonaut.

Subjects

Ten right-handed subjects, one female and nine male, all with some experience as teleoperators of Robonaut or Robosim, were tested. Subjects were seated in the teleoperator chair wearing the head mounted display. The FRHC was placed at their right side such that they could reach the entire workspace of the device with their right arm, yet the FRHC could not collide with the subject during testing. Figure 7 shows a test subject seated at the FRHC.

Experiment details

The handrail task was divided into the following subtasks.

(1) The robot arm will start from a predefined position.
(2) Located in front of the robot arm will be the four handrails, each having a unique color.
(3) When the test conductor identifies a handrail color, move robot arm to the location of handrail with that color.
(4) Align robot hand for grasping the handrail.
(5) Move robot hand to handrail so that the palm makes contact with the handrail, avoiding collision with other handrails in the workspace.
(6) Return robot hand to starting position, again avoiding collisions with other handrails.

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Several random sequences were generated for the experiment. Numbers were drawn from a hat to determine which sequence would be presented to each subject. A subject was presented with each handrail-feedback combination once during the experiment (12 trials per subject). Results were then tabulated across subjects.

Collision detection and force modeling

Enigma, the 3D modeling software used to create Robosim and the handrails for the simulated worksite experiments, includes collision detection and minimum distance routines. For the handrail task, minimum distance calculations were performed between the palm of the right arm and each of the four handrails and the home target. Enigma function calls return the closest object to the palm in the workspace and the distance between the two closest points on the object surfaces. The minimum distance routine returns a minimum distance of zero once a collision has occurred. For the visual feedback case, knowing a minimum distance of zero was sufficient to give a visual cue to the operator. For the force feedback case, the degree of overlap between the two objects was needed in order to calculate forces of interaction. Upon collision, the two closest points (one on the palm and the other on the handrail) were captured and stored in memory. At each subsequent time step, the collision point on the handrail was transformed to the current palm coordinate frame. With both points in the palm coordinate frame, it was possible to calculate a vector between the two points, and the distance of separation along each axis of the palm coordinate frame. A simple spring model of the surface, with a stiffness of 50 N/cm, was used in these experiments. The force along each axis of the palm was calculated as the spring stiffness times the distance of separation between the original collision points. The FRHC receives palm force data, which are converted to the necessary joint torques for display on the FRHC PC. Although more complex spring-damper models of surfaces are often used in haptic feedback, prior work by O'Malley and Goldfarb (2002) and Richard and Coiffet (1999) has shown that simplified and low-fidelity force feedback is sufficient for simple manipulation and perceptual tasks. For the no feedback and visual feedback cases, forces were still calculated, but the emergency stop on the FRHC was depressed so that forces were not commanded to the device.

Experiment 2: cooperative assembly task trials

A simplified, hypothetical EVA assembly task featuring human-robot teaming is simulated with hardware-in-the-loop to study the human-robot interaction problem. We purposefully designed the task to require more than two hands and, therefore, multiple agents so that meaningful interactions can take place. A long structural beam, too awkward for one agent to handle alone, is to be inserted into a fixed socket and pinned in place.

Assembly hardware

We assemble three components in this task, as shown in Figure 3. There is a fixed socket, a lightweight 12 ft (3.7 m) structural beam, and a mating pin that locks them together. We mounted the socket on a six-axis force/torque sensor measuring the contact forces/torques between the beam and the socket. We resolve these forces/torques about a coordinate frame centered at the beam-socket interface and oriented as shown in the figure.

Assembly sequence

We begin the task with both agents (robot and co-worker) situated at the worksite. One agent, the leader (EV1 in NASA terminology), is near the fixed socket and the other agent, the follower (EV2), is located 10 ft (3.1 m) from the socket. Both agents start the task within arms reach of the beam, which we initially support at both ends. We control initial conditions to reproduce the worksite between each trial and for each teaming configuration.

Description of the human-robot team

The assembly team consists of one robot and three humans. We collocate one human, the co-worker, with the robot at the worksite while we place the other two, the teleoperator and the monitor, in different remote locations. For this experiment, all four participants perform their roles in the same room, but we limit interaction artificially as dictated by the target task.

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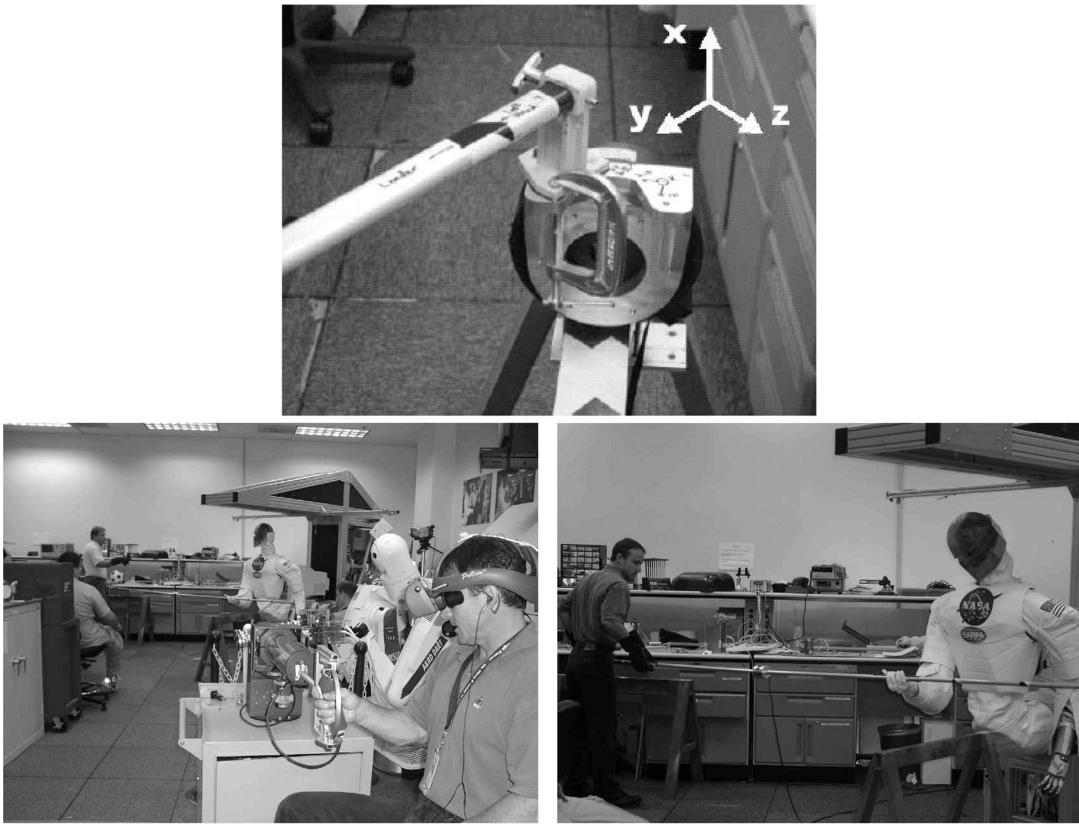
Figure 3 Hardware used in the assembly task trials, force sensor axes shown, and the experiment environment



We place several constraints on the human co-worker in order to preserve the EVA relevance of the task. Space-walking astronauts have a very limited field-of-view restricted to the window in the EMU helmet, which does not swivel with neck motions. In general, two astronauts working side-by-side on an EVA cannot see each other. They are unable to communicate through body language or gestures and cannot anticipate each other's actions through observation. By necessity, EV1 and EV2 communicate almost exclusively by radio, employing very methodical handshaking to confirm mutual understanding. To minimize unrealistic interactions, we asked EV1 and EV2 to look only at the local work environment, not the other participant. We allowed, however, the agents to communicate verbally. The EMU encumbers the body motions of an EVA worker. Space-walking astronauts have a restricted working envelope dictated by the EMU range of motion. Therefore, we instructed the human co-worker to remain stationary from the waist down during the task to prevent unrealistic physical feats.

Methodology

Two subjects, both experienced Robonaut teleoperators, participated in the experiment over the course of a day. Testing was limited to 2 h to reduce effects due to human subject fatigue. To reduce the effects of learning, we conducted a practice run between team reconfigurations to familiarize the subjects with their new role in the experiment. Three trials of each configuration were conducted.

Team definition elements

Subjects

- H1 = human subject 1
- H2 = human subject 2

Interaction mode

- Force only (f);
- force and verbal ($f + v$); and
- force, verbal, and gesture ($f + v + g$).

Roles

- L = task leader (EV1); and
- F = task follower (EV2).

Robonaut served as the follower and was teleoperated with force feedback to the teleoperator. The arm followed an overdamped impedance control law in translations only. For torque control, the arm

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was driven by the mechanism/joint controller stiffness. In addition to these control modes, the forces into the impedance control law and those commanded to the hand controller were filtered with a critically damped second order low pass filters with cutoff frequencies of 125 and 1 Hz, respectively. Robonaut's Cartesian controller was further restricted to allow motion in translation only. Because of the filtering required to maintain stable haptic interaction, the teleoperator was restricted to move slowly, and the haptic feedback lagged by approximately a quarter of a second.

Data collection

We recorded the following data during each trial: videotape of the task leader, robot wrist forces/torques, socket contact forces/torques, elapsed time, and voice communication between the two subjects. Although we recorded task time, we did not instruct subjects to perform the task rapidly.

Performance metrics for the assembly task included task success, task completion time, maximum contact force/torque, and cumulative linear/angular impulse. Task success describes the degree to which a team was able to meet all task objectives. Task completion time reflects how efficiently resources were used in accomplishing the task. Maximum contact force/torque quantifies the risk of hardware failure or damage due to excessive momentary peak loads at the beam-socket interface. Cumulative linear/angular impulse quantifies the risk of hardware failure or damage due to excessive wear and tear as a result of extended contact at the beam-socket interface (Williams, 2001).

Experiment 3: two-armed manipulation

In this task, the teleoperator translated a compliant ball in the workspace. In the forces only case, the teleoperator moved the ball to trace a square in the workspace. In the force and verbal case, the teleoperator translated the ball according to the verbal commands from the task leader. Finally, in the force, verbal, and gestures case, the task follower responded to both the verbal and gesture cues to determine how to manipulate the ball in the workspace. The environment is shown in Figure 4. One teleoperator served as the task follower and operated either with filtering on or off. When filtering was on, Cartesian position commands and force feedback commands were filtered with low-pass filters with a cut-off frequency of 1 Hz, intended to reduce operator-induced instabilities during the translation task.

Team definition elements

Interaction mode

- Force only (f);
- force and verbal ($f + v$); and
- force, verbal, and gestures ($f + v + g$).

Force control

- Filtering on; and
- filtering off.

Results and discussion

Experiment 1: haptic interaction with Robosim

The calculated forces of interaction between the handrail and the palm of Robonaut were recorded for each trial, regardless of the mode of feedback to the operator. These results were averaged across subjects, handrails, and feedback modalities, and are shown in Figure 5.

Force feedback did not significantly improve performance, in terms of limiting peak force magnitudes during a grasp task, for this experiment. It is conjectured that the task relied heavily on visual feedback in order to align for a grasp, and that the simplified force model required a noticeable collision between the palm and the handrail in order to generate forces of a magnitude that could be felt by the operator through the FRHC. Because subjects were expecting force feedback during specified trials, they seemed to generate exaggerated collisions so that they could feel the force of the collision through the FRHC. In the no feedback case, they relied on the visual display of the simulated environment only and were able to align with the same amount of peak force generation as in the force feedback case. Should the task have involved obscured view handrails, it is likely that force feedback would contribute to lower peak forces during contact than in a no feedback case since the subjects would have limited visual cues during the task. Another observation during testing was that the force felt by the operator depended on the geometric configuration of the FRHC. For example, if the subject was extended near the end of the stroke of the FRHC when contacting a handrail, the forces felt smaller

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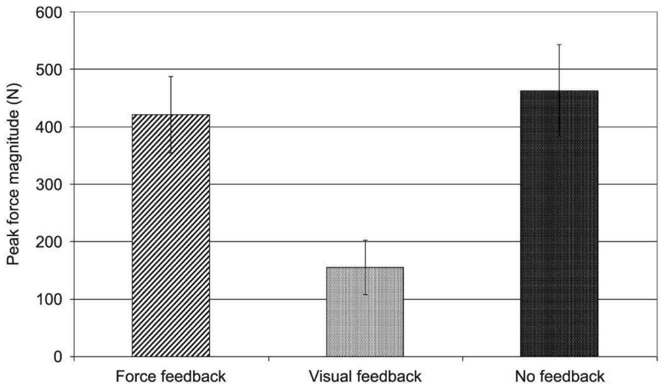
Figure 4 Robonaut holding ball, teleoperator driving Robonaut, and task leader gesturing the desired location of the ball

Figure 5 Overall peak force magnitudes for each feedback mode



than if they were in the center of the workspace. The phenomenon could be merely due to the limited range of motion near the workspace extents such that the subjects were unable to generate enough deflection between the palm and the handrail and therefore the calculated forces were limited in magnitude. Another possible explanation is that the FRHC has some un-modeled non-linear behavior that is not accounted for in the force to torque transformation. These issues should be investigated prior to additional testing with the FRHC and Robosim.

Experiment 2: cooperative assembly task trials

Experimental results are shown in Figure 6. The most significant result is the comparison of maximum contact force in the beam receptacle across pairs and feedback modes. In the case of no force feedback, where we limited the teleoperator to only a visual display of the forces and torques in Robonaut's arm, peak forces ranged between 40 and 110 N. As we added additional feedback modes, such as verbal cues and gesturing, peak forces tended to decrease. In fact, in the case where visual force information, verbal cues, and gestures were all employed, peak forces were roughly half that of the other non-force feedback trials. In the force feedback cases where we used the FRHC, peak forces were quite consistent and ranged between 30 and 50 N. Standard errors were much smaller for the force feedback case. This is a significant result due to the fact that large forces in the receptacle are transferred to the robot during constrained motion and contact, leading to larger loads on the hardware. It is apparent that when the teleoperator has kinesthetic information regarding the contact forces, we see a significant reduction in peak forces. Differences in the roles played by each subject (task leader or teleoperator) are insignificant for this comparison.

We also present cumulative linear impulse data for the pairs and feedback modes. This measure captures the net force over time that is sensed in the beam receptacle. It provides an understanding of both the force magnitudes during the test and the time of task completion. For the experiments described here, the cumulative linear impulse was greater when the teleoperator was provided with force feedback. Additional feedback modalities (voice and gestures) led to a decrease in cumulative linear impulse for the force feedback cases, but not significantly. It was noted that task completion times were roughly the same for the force and no force feedback experiment trials.

Experiment 3: two-armed manipulation

Experimental results are presented in Figures 7-10. Figure 7 shows the force magnitude versus time for two of the experiment trials. In Trial 6, the operator had force feedback to both arms and the filtering was active. In this case, it is easy to see the point of contact and release of the ball at 200 and 850, respectively, on the time scale. For these

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Figure 6 Maximum contact force (left) and cumulative linear impulse (right) for each pair and feedback mode

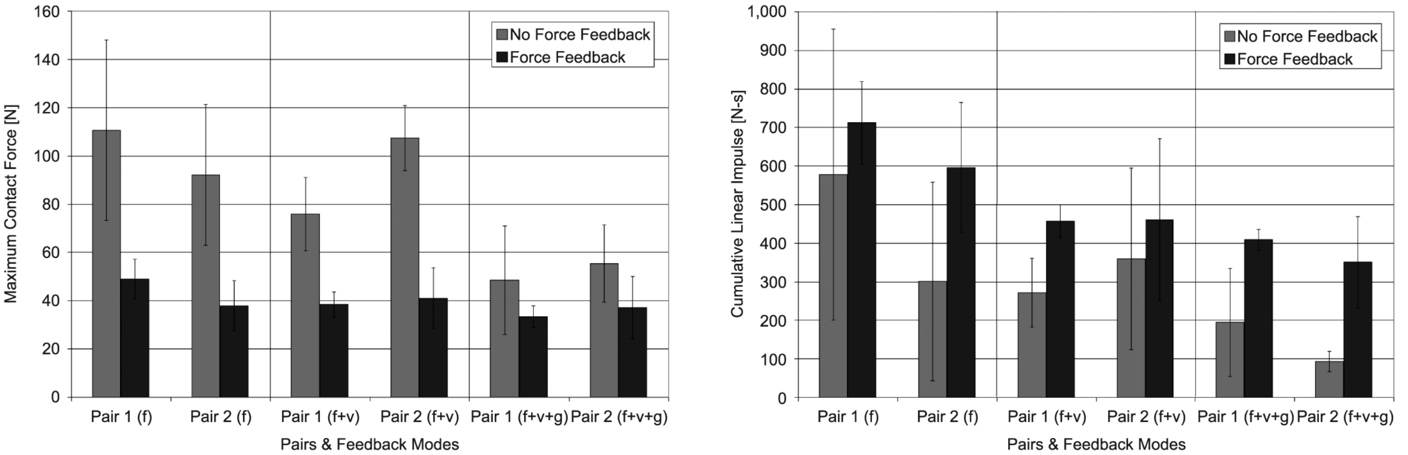


Figure 7 (left) Trial 6 – force feedback to both arms, filtering active (right) Trial 15 – force feedback to right arm only, filtering inactive

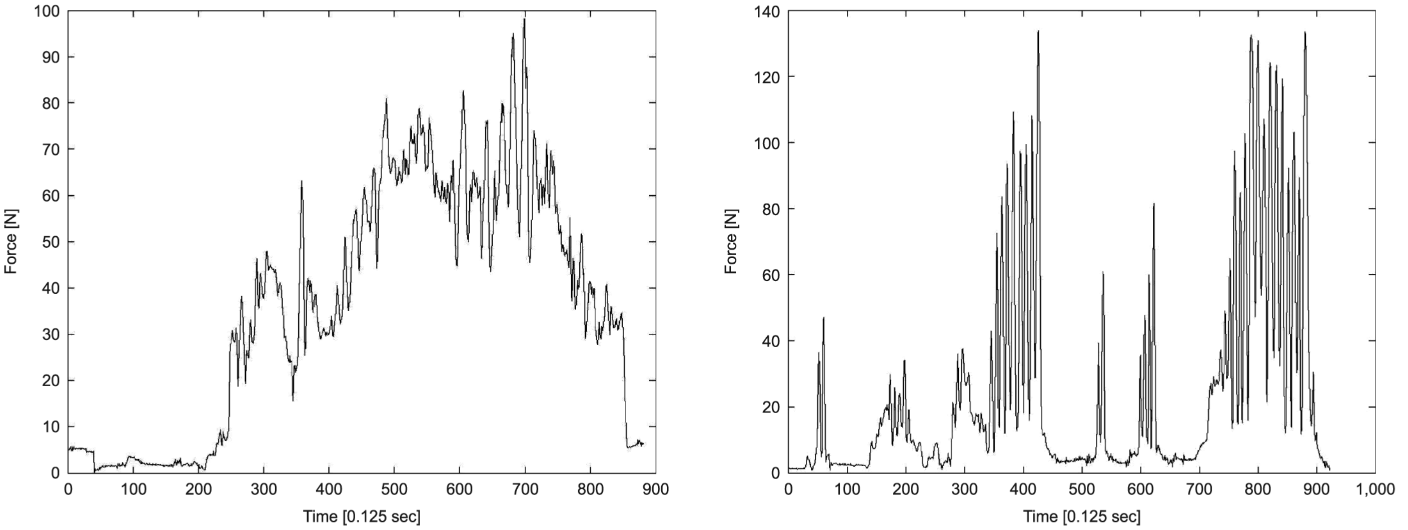
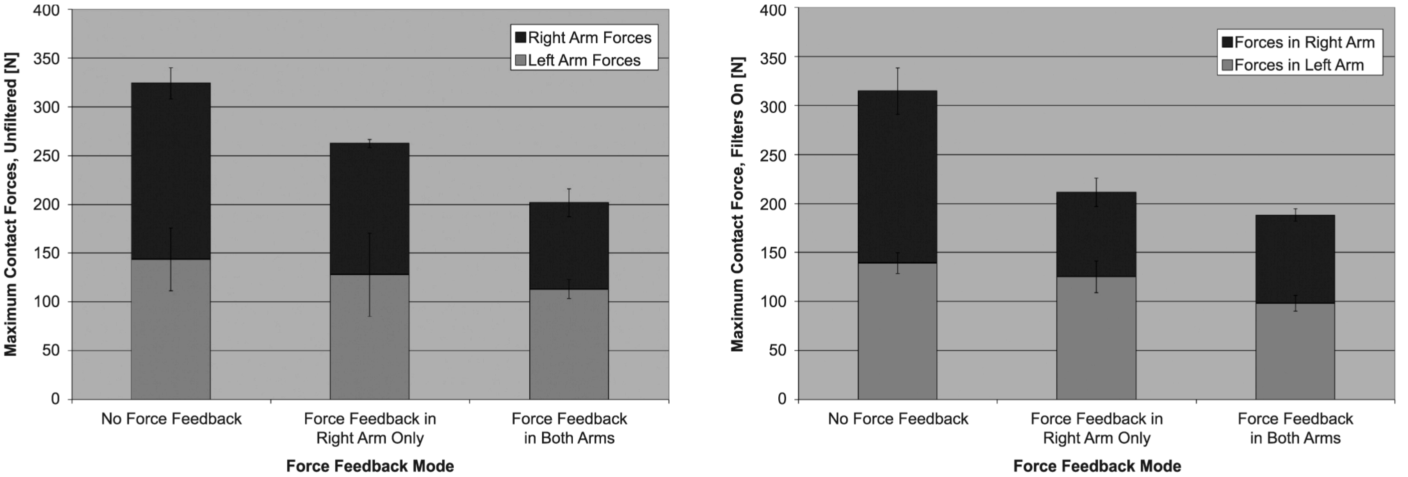


Figure 8 Maximum contact forces for right and left arm without (left) and with (right) filtering. Note the decrease in peak contact force as the level of force feedback to the teleoperator is increased



experiments, the time scale corresponds to the sample number, and sampling occurred at approximately 8 Hz. In Trial 15, the operator had force feedback only to the right arm, and the filters were not active. In this trial, the ball was dropped several times. Here, the operator-induced instabilities are easily picked out, as are the ball drops and grasps.

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Figure 9 Cumulative linear impulse for the unfiltered (left) and filtered (right) cases

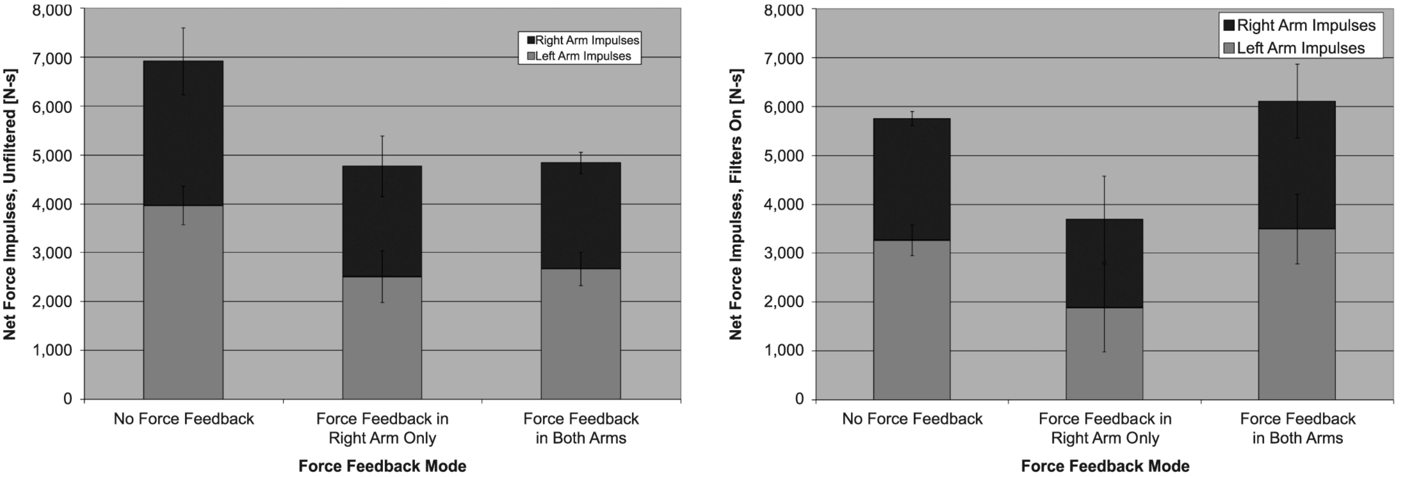

Figure 10 Cumulative linear impulse divided by trial time for the unfiltered (left) and filtered (right) cases

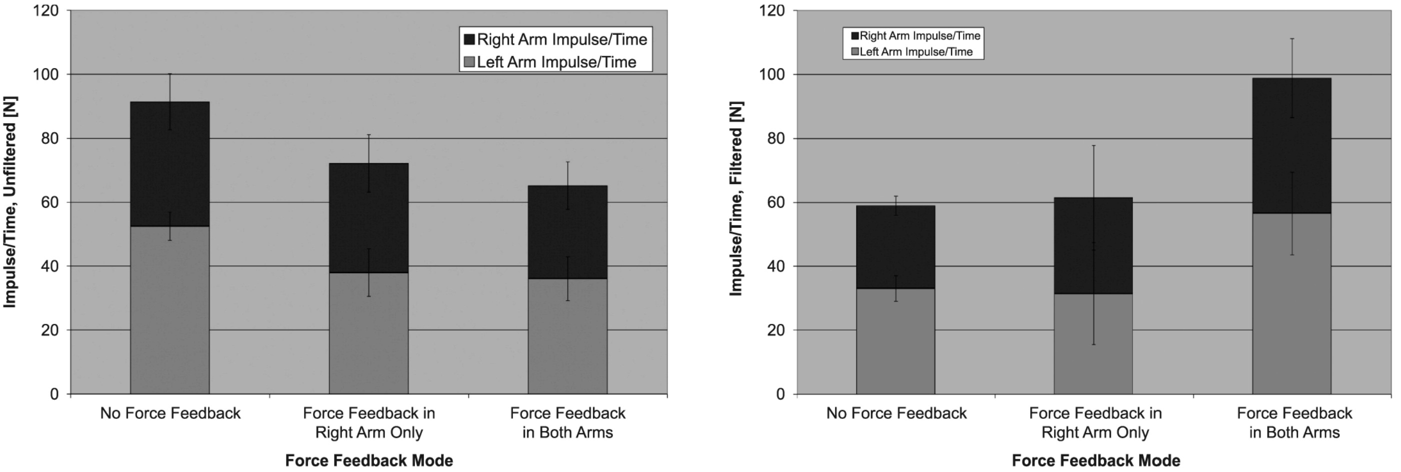

Figure 8 shows the maximum contact forces in Robonaut's wrists during the ball task. Here, the decrease in peak forces with the addition of force feedback to the teleoperator is easily recognized. Figure 9 shows the cumulative linear impulse for the unfiltered and filtered cases. In the unfiltered case, the CLI decreases with an increase in force feedback to the operator. It is hypothesized that this trend indicates the presence of oscillatory motion for the unfiltered trials that resulted in an increase in the number of ball drops. As a result, the ball was grasped for a shorter period of time and the duration of the trials was generally shorter. For the filtered case, we see no significant trends in the CLI based on feedback mode to the operator. In these cases, there were no noticeable oscillations and therefore the trial length varied randomly. It should be noted that the duration of the trials was not controlled during the experiments, and therefore this comparison is only presented for the interest of the reader. Future experiments should be tightly controlled if strong conclusions about the effects of feedback mode on CLI are to be drawn.

Finally, Figure 10 shows the CLI divided by total trial time for the unfiltered and filtered cases. These graphs aim to remove the variability due to trial length that were seen in Figure 8. Here, we see a strong trend of decreasing normalized CLI as force feedback increases in the unfiltered case, for the same reason (increasing oscillations) described earlier. In the filtered case, we see increasing normalized CLI as force feedback mode increases, indicating that the teleoperator was able to grasp the ball for longer portions of the trials. Again, these tests should be repeated with strong control over the task duration.

Industrial Robot: An International Journal
Volume 30 · Number 6 · 2003 · 531–542

Conclusions

We conducted three experiments with varying feedback modalities to the robot teleoperator when interacting with both Robosim and Robonaut. Although the expected result for Experiment 1, that force feedback would improve performance in simulated teleoperation, was not observed, a great deal of knowledge was gained with regard to the architecture and system configuration necessary to display kinesthetic feedback via the JPL Force Reflecting Hand Controller to a teleoperator of Robosim, the simulated equivalent of Robonaut. In the second task, the operator worked with a human team member to insert a flexible beam into an instrumented receptacle. Peak forces in the receptacle were consistently lower when the teleoperator was provided with kinesthetic force feedback versus a visual display of the forces in Robonaut's arm. The third task involved a teleoperator manipulating a ball around the workspace with a two-armed grasp. The operator was provided with varying degrees of force feedback (none, one arm only, two arms) and both filtered and unfiltered cases, where the position commands to the robot and the force commands to the teleoperator were filtered to reduce the effects of operator-induced instabilities. The filters were effective in reducing these oscillations, and force feedback helped to reduce peak forces in Robonaut's wrists. Conclusions about cumulative linear impulse are difficult to draw since the task duration was not closely controlled.

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