Cooperative Manipulation between Humans and Teleoperated Agents

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Abstract

Robonaut is a humanoid robot designed by the Robotic Systems Technology Branch at NASA's Johnson Space Center in a collaborative effort with DARPA. This paper describes the implementation of haptic feedback into Robonaut. We conducted a cooperative manipulation task, inserting a flexible beam into an instrumented receptacle. This task was performed while both a human at the worksite and the teleoperated robot grasped the flexible beam simultaneously. Peak forces in the receptacle were consistently lower when the human operator was provided with kinesthetic force feedback in addition to other modalities of feedback such as gestures and voice commands. These findings are encouraging as the Dexterous Robotics Lab continues to implement force feedback into its teleoperator hardware architecture.

1. Introduction

The Dexterous Robotics Lab at NASA Johnson Space Center (JSC) has developed a humanoid robot astronaut assistant called Robonaut [1]. Robonaut, shown in Figure 1, is intended to be an assistant to astronauts during 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.

1.1 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 [2-7]. 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 a force-reflecting joystick for bilateral teleoperation so that the human operator now 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 human operator performance when operating in remote environments, it also has improved performance of some tasks in virtual environments [8-10].

Figure 1: Ground-based Robonaut system

1.2 Research Goals

In this experiment, we were interested to see if force feedback to a human operator would significantly reduce peak forces during a constrained motion task compared to peak forces without force feedback to the operator. In addition to force feedback, the operator was provided with voice commands or gestures from the human at the remote worksite. In Phase 1 of the experiment, a human operator 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

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2, the human operator 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 human operator.

1.3 Background

1.3.1 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 Extra-Vehicular Activity (EVA) operations requiring trained crewmembers to don External Mobility Unit (EMU) spacesuits and exit the pressurized cabin through an airlock.

Should it require 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 100ºC and shaded surfaces can plunge to -200ºC. Strict procedures are implemented 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 drifting 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.

1.3.2 The Role of Robots in Space. Today's 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 Pathfinder mission, for example, made observations and performed experiments on the Martian surface for a period of almost three 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 can 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.

1.3.3 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 deploy them from the Shuttle cargo bay. The Space Station Remote Manipulator System (SSRMS) provides ISS crewmembers 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.

1.4 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 Johnson Space Center (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 would. 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 spacewalking 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.

1.4.1 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 1). Altogether, the planned free-flyer configuration will have at least 50 coordinated degrees-of-freedom (DOFs) and physical capabilities approaching those of a human in a spacesuit. A detailed discussion of subsystem anatomy may be found in [1].

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 while posing unique thermal management problems.

1.4.2 Control System Architecture. Because 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 great 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.

1.4.3 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.

1.4.4 Human-Robot Interfaces. In its simplest form, Robonaut is a teleoperated master-slave system in which a human, the "human operator," becomes the robot master. The anthropomorphic form of the robot allows an intuitive, one-to-one mapping between 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 showed that the addition of visual and kinesthetic feedback improved the performance of human operators working a specific task with the Robonaut system [11]. Care must be taken, however, to ensure that the operator's workload in processing all of the new information does not become excessive [12].

For all its utility in the laboratory, a teleoperated system degrades quickly in the presence of communication time delay. A human operator 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 [13], 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. These time delays are expected due to system architectural bandwidth limits inherent to the space station and are unavoidable in real space application.

1.4.5 Interacting With and Through Robonaut. Humans interact with Robonaut in one of three roles: human operator, monitor, and co-worker. This interaction takes different forms depending on the configuration of the human-robot team. While the remotely located human operator 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 upon them. When a human co-worker is present at the worksite, the human operator has the opportunity to interact indirectly with the co-worker through the robot, which may be considered an extension of the human operator's own body. From the co-workers point of view, interacting with a teleoperated Robonaut is much like interacting with another human.

A haptic joystick is used for both position commands to Robonaut's arm and for force reflection. The Jet Propulsion Laboratory (JPL) FRHC is a six-DOF force feedback device. The FRHC, shown in Figure 2, has a workspace of approximately 1.25 ft^3 and is capable of producing a force of up to 9.8 Newtons (35 oz) in magnitude and a torque of up to 0.5 N-m. All data transfer between 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. The FRHC control rate was also 50 Hz.

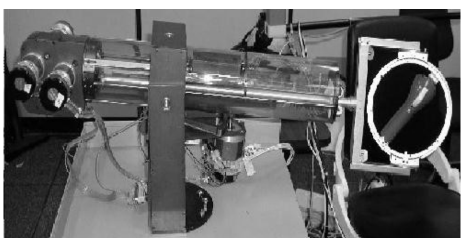


Figure 2: The teleoperation interface (Force Reflecting Hand Controller – FRHC) used in the assembly task trials with kinesthetic feedback

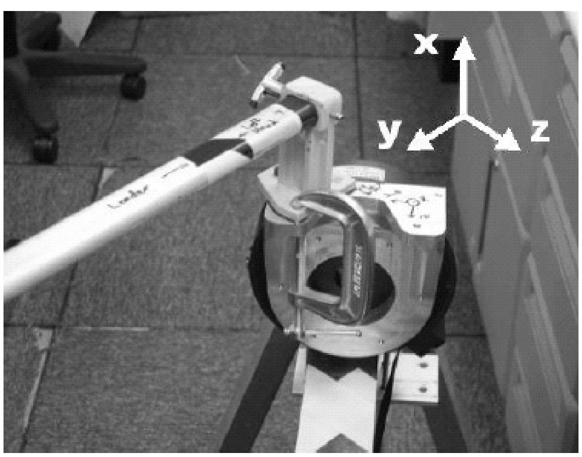


Figure 3: (top) Hardware used in the assembly task trials, force sensor axes shown

2. Methods

A simplified, hypothetical EVA assembly task featuring human-robot teaming is simulated with hardware-in-the-loop to study the human-robot interaction problem. The task is purposely designed 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.

2.1 Assembly Hardware

Three components are assembled together 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. The socket is mounted on a six-axis force/torque sensor measuring the contact forces/torques between the beam and the socket. These forces/torques are resolved about a coordinate frame centered at the beam-socket interface and oriented as shown in the figure.

2.2 Assembly Sequence

The task begins 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 arm's reach of the beam, which is initially supported at both ends. Initial conditions are controlled to reproduce the worksite between each trial and for each teaming configuration.

2.3 Description of the Human-Robot Team

The assembly team consists of one robot and three humans. One human, the co-worker, is collocated with the robot at the worksite while the other two, the human operator and monitor, are in different remote locations. For this experiment, all four participants perform their roles in the same room but interaction is artificially limited as dictated by the target task.

Several constraints are imposed on the human co-worker in order to preserve the EVA relevance of the task. Spacewalking 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, an opaque curtain was hung between the agents during the task trials (not shown in the figure). The agents were, however, allowed to communicate verbally.

The EMU encumbers the body motions of an EVA worker. Spacewalking astronauts have a restricted working envelope dictated by the EMU range of motion. The human co-worker in our task was instructed to remain stationary from the waist down during the task to prevent unrealistic physical feats. The EMU glove also degrades the tactile sensing of the wearer. The human co-worker was required to perform the task wearing heavy welder's gloves to simulate this effect. The experiment environment and remote worksite are pictured in Fig. 4.

Figure 4: The experiment environment (top, bottom) showing the human operator, the teleoperated robot, and the remote worksite agent.

2.4 Experiment Methodology

Two subjects, both experienced Robonaut operators, participated in the experiment over the course of a day. Testing was limited to two hours 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.

2.4.1 Team definition elements

The various abbreviations used to describe the teams are listed here.

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

Interaction mode
- Force only (f)
- Force and verbal (f+v)
- Force, verbal, and gesture (f+v+g)

Roles
- L = task leader (EV1)
- F = task follower (EV2)

Robonaut served as the follower and was teleoperated with force feedback to the human operator. The arm followed an overdamped impedance control law in translations only. For torque control, the arm 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 Hz 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 human operator was restricted to move slowly, and the haptic feedback lagged by approximately a quarter of a second. The system architecture was not designed with force feedback in mind, providing additional bandwidth limitations and further time lag.

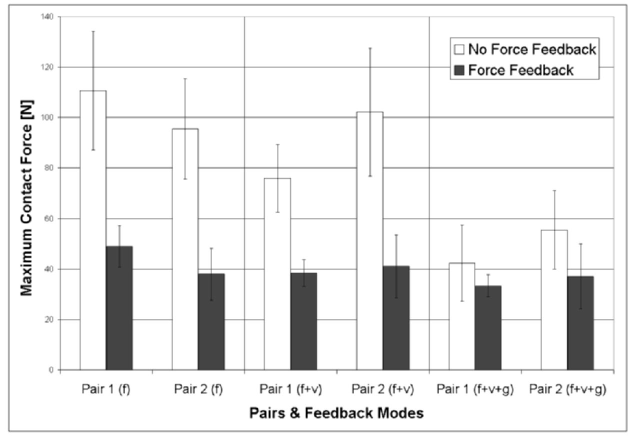
2.4.2 Data Collection. We recorded the following data during each trial: videotape of the task leader, robot wrist forces/torques, socket contact forces/torques, elapsed time, and voice communication between the two subjects. Although we recorded task time, we did not instruct subjects to perform the 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 [11].

3. Results and Discussion

Experimental results are presented in Figure 5. 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 human operator to only a visual display of the forces and torques in Robonaut's arm, peak forces ranged between 40 and 110 N. These displays were provided to via a graphical overlay human operator's visual display. 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 human operator 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 human operator) 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. Cumulative linear impulse is calculated by multiplying each measured force by its duration and then summing this across the time of task completion. 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 human operator 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



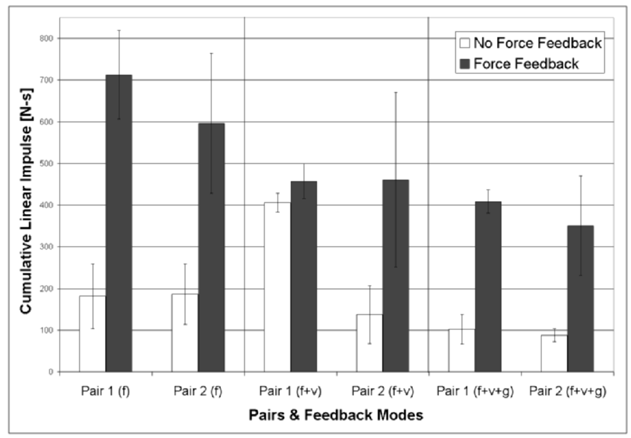


Figure 5: Maximum contact force (left) and cumulative linear impulse (right) for each pair and feedback mode

noted that task completion times were roughly the same for the force and no force feedback experiment trials.

The comparison of maximum contact force and cumulative linear impulse provides very interesting results. The increased cumulative linear impulse with force feedback shows that, on average, the forces in the receptacle are higher for longer times. However, the decreased maximum contact force with force feedback is indicative that the peak forces of contact are diminished. Therefore, although the amount of force over time increases, the force peaks that could damage equipment are reduced.

Due to the small sample size and time required for experimentation, sufficient data is not available for a full statistical analysis of the significance of the results. Therefore, an ANOVA was not performed for these experiments. However, we feel that the results here warrant further study of force feedback in the Robonaut system.

We have laid a framework for future human-robot interaction experiments. However, we need a higher fidelity simulation of EVA working conditions, including suited human subjects, realistic lighting conditions and time delay, before teaming approaches can be evaluated in the proper context.

The human-robot team should be expanded to include a mix of robotic agents of different classes. One such team might include an astronaut, an RMS, a Robonaut, and a free-flying camera such as Aercam. Teaming configurations with no humans in them should also be studied.

4. Conclusions

We conducted an experiment to evaluate human-robot teaming with varying feedback modalities to the robot operator. The task consisted of inserting a flexible beam into an instrumented receptacle. Due to the length and flexibility of the beam, the task required a two-person team. We used a human and a teleoperated humanoid robot to perform the task. Peak forces in the receptacle were consistently lower when the human operator was provided with kinesthetic force feedback versus a visual display of the forces in Robonaut's arm. This finding is consistent with finding from previous work.

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