Effects of Translational and Gripping Force Feedback are Decoupled in a 4-Degree-of-Freedom Telemanipulator

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Abstract

Many high-degree-of-freedom haptic devices and teleoperator systems either do not have grippers or do not provide force feedback in the gripper degree of freedom (DOF). The purpose of this work is to determine the effect of gripper force feedback in relation to Cartesian (translational) force feedback on the execution of telemanipulation tasks. We developed a system for adding an additional DOF of grip force feedback on a 3-DOF Phantom haptic device master, as well as 6-DOF force/torque sensing on each "finger" of a coupled gripper on a Phantom haptic device slave. The internal (grip) and external (translational) forces were measured as users performed a soft peg-in-hole task with various DOFs of force feedback: (1) full force feedback, (2) translational force feedback only, (3) grip force feedback only, and (4) no force feedback. Results show that the level of force applied in the translational and gripping DOFs are decoupled for a 3-DOF telemanipulator with added grip force feedback. This is likely due to the decoupled dynamics of internal and external hand forces.

1. Introduction

An ideal telemanipulator would provide perfect transparency, so that the operator would feel as if he or she was manipulating the environment directly. Such a system would require sensing and display of all degrees of freedom (DOF) of tactile and force/torque information to the user. Due the current state of tactile devices and the difficulty of adding them to force-reflecting masters, "perfect transparency" is often described as perfect impedance reflection. If the slave tracks the master exactly, the system must provide force/torque feedback via the master device that is equal to the force/torque applied to the environment by the slave in every DOF.

While the desire for complete force/torque feedback in telemanipulators is apparent, it is not always practical. It would require either perfect dynamic modeling of the slave robot (for position-exchange control), or force sensors in each DOF of the slave device (for position forward/force feedback control). It would also require the master device to have actuators in each DOF that map its motion to that of the slave. Durable, accurate force sensors and backdrivable, responsive motors (both needed for good force reflection) can greatly increase the cost of the telemanipulator, making it prohibitively expensive to incorporate full force feedback in many systems.

Current surgical telemanipulators do not provide full force feedback to the user. Force sensor size, sterilization, and bio-compatibility limit the feasibility of complete force sensing on the slave robot in the operating environment. On the slave of the da Vinci Surgical System (Intuitive Surgical, Sunnyvale, CA), disposable tools are used. Incorporating commercially available 6-DOF force/torque sensors would more than triple the cost of these tools. More importantly, no current commercial 6-DOF force/torque sensor is small enough to integrate into the 10mm-diameter tools. There has been important preliminary research on force-sensing grippers for surgical robots [4], but these systems are far from clinical implementation. The master device of the da Vinci also lacks an actuator on the gripping DOF, making it impossible to display gripping force feedback.

Often, when full force feedback is not achievable, partial force feedback is provided by reducing the number of force sensors used on the slave device or the number of actuators on the master. Semere, et al. [9] found that removing axial force feedback from a 3-DOF haptic device during specific tasks did not significantly affect the level of force that users applied to the remote environment in the removed DOF. These results indicate that, with partial force feedback, users may be able to discern the amount of force they are applying in DOFs in which they do not have force feedback. Whether this applies for external (translational) and internal (grip) forces in telemanipulator is unknown. In this study, we hypothesize that users will adjust the level of grip force they apply in a telemanipulator that has only

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translational force feedback compared to a telemanipulator with no force feedback. Additionally, we test whether the addition of grip force feedback on a telemanipulator significantly affects the level of force applied in the translational DOFs.

2. Related Work

Partial force feedback in a telemanipulator results in sensor/acuator asymmetry. Barbagli and Salisbury [1] examined sensor/actuator asymmetries in haptic devices for virtual environments. For telemanipulators, sensor/actuator asymmetries occur when the number of sensors on the slave device are not equal to the number of actuators in the master device. A common sensor/actuator asymmetry in telemanipulation uses a 6-DOF positioning, 3-DOF force-feedback Phantom haptic device (Sensable Technologies, Woburn, MA) to control a 6-DOF slave robot, e.g. [2, 3, 14].

While sensor/actuator asymmetries in telemanipulators are routinely used, many issues arise. First, the partial force feedback can be unrealistic and cause the telemanipulator to lose transparency. In manipulators designed for specific tasks, the effect of this can be minimized by placing force sensors in the most important degrees of freedom. To guide such designs, Saha et al. [8] investigated the DOFs with maximum magnitude and variance of applied force/torque during tasks performed with the da Vinci surgical system. However, asymmetries in a generic telemanipulator can cause unusual force/torque sensations during some tasks. Second, our previous work [12] has shown that telemanipulators with sensor/actuator asymmetries are not passive. Passivity is often used to guarantee the stability of a telemanipulator and further research on the effects of sensor/actuator asymmetries on telemanipulator controllers is needed.

3. Gripping Mechanisms for the Phantom

In order to study the effects of grip and translational force feedback in a simple teleoperator, we developed a system for adding grip force feedback to a pair of Phantom Premium haptic devices. The 4-DOF teleoperator with gripper consists of two Phantoms (model 1.0 for the master and 1.5 for the slave) and two custom gripping attachments (Fig. 1). This significantly modifies our earlier design [11].

3.1. Gripper Design

The gripper is designed to mount the largest weight of the gripper mechanism (the motor) as close as possible to the kinematic base of the haptic device. In another mechanism for adding grip force feedback to Phantom devices [1],

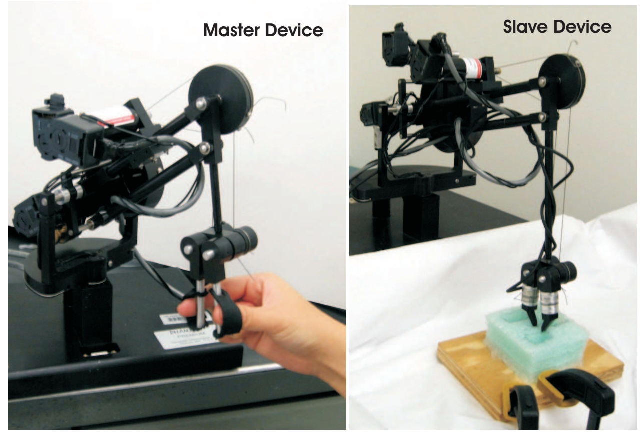

Figure 1. 4-DOF Telemanipulator. The telemanipulator consists of two Phantom haptic devices with added gripping mechanism.

the weight of the motor is at the distal end of the device. The location and the larger counter-weight required for that device significantly adds to the effective inertia of the Phantom and limits transparency. In our mechanism, these effects are still present, but reduced.

Many other haptic devices exist that incorporate gripping forces. The FREG [7], SPIDAR-G [5], and Tholey's 7-DOF device [10] are just a few. Many more incorporate independent, dexterous fingers. Few, however, allow researchers to create a gripping telemanipulator using a common haptic device.

As shown in Fig. 1, the end of the gripper mechanism for the master and slave devices are slightly different. The master device has adjustable straps to attach the haptic device to the user. In the slave device, two ATI Industrial Automation Nano-17 6-DOF force/torque sensors are added into grippers to measure forces and torques that occur between the slave manipulator and the environment.

3.2. Kinematic Integration

Our gripper design couples the movement of the gripper to that of the DOFs of the Phantom haptic device. Fig. 2 provides the definitions of the variables used in the following kinematic equations. The position of the gripper is thus a function of the added motor position and the Phantom joint position:

$$\theta_g = 2\frac{r_6}{r_7}\left(\frac{r_4}{r_5}\theta_4 + \frac{r_2}{r_3}\theta_3 - \frac{r_2}{r_3}\theta_2\right). \qquad (1)$$

Also due to the coupling, the force applied between the grippers is dependent not only on the added motor 4, but also on motors 2 and 3 of the Phantom. The Jacobian that

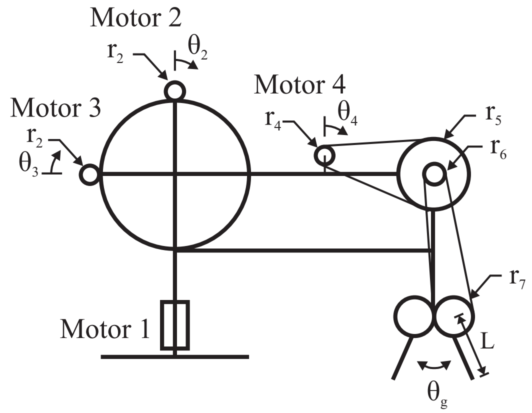

Figure 2. Schematic of Phantom device with gripper. A side-view schematic shows the structure of the gripping mechanism.

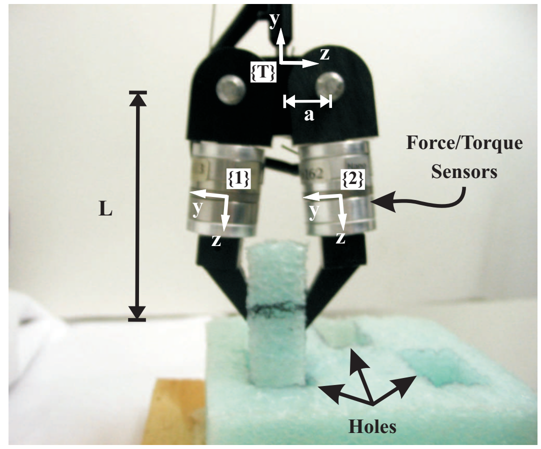

Figure 3. Slave Gripper. A detailed view, including frame definitions, of the slave gripper with integrated force/torque sensors.

relates the motor torque of the 4-DOF device to the force applied between the grippers is

$$J = \begin{pmatrix} 0 & -\frac{2r_6 r_2 L}{r_7 r_3} & \frac{2r_6 r_2 L}{r_7 r_3} & \frac{2r_4 r_6 L}{r_5 r_7} \end{pmatrix}. \quad (2)$$

Using this Jacobian, it is possible to calculate the torque to command to motors 2, 3, and 4 that will output a desired force of the grippers:

$$\begin{pmatrix} \tau_1 & \tau_2 & \tau_3 & \tau_4 \end{pmatrix}^T = J^T F_g, \quad (3)$$

where τ_i for $i = 1, 2, 3, 4$ are the motor torques of motor i, L is the length of the gripper, and F_g is the desired internal force at the gripper degree of freedom. Thus, τ_1, τ_2, and τ_3 are added to the the motor torque values necessary for the translational forcing of the device, while τ_4 is commanded to motor 4. Thus, the translational force and gripper force are commanded simultaneously.

3.3. Grip Force Feedback

Two 6-DOF force/torque sensors are used to measure the force applied at the slave device (Fig. 3). Therefore, the 12 DOFs of force/torque sensing must be reduced to the desired 4 DOFS of the manipulator. Of the 4 DOFs of the manipulator, the 3 translational DOFs are external forces and the grip force is an internal force of the system.

If F_1 and F_2 are the sensed forces on sensors 1 and 2, respectively (Fig. 3 provides frame definitions), the resulting translational and grip force of the manipulator can be calculated using the adjoint transformation, following the notation of [6]. The wrench of the force/torque sensors, ${}^T F_1$ and ${}^T F_2$ can be transformed from the $\{1\}$ and $\{2\}$ frames, respectively, to the $\{\mathrm{T}\}$ frame by

$$\begin{aligned} {}^T F_1 &= Ad^T_{g_{1T}} \, {}^1 F_1, & (4) \\ {}^T F_2 &= Ad^T_{g_{2T}} \, {}^2 F_2. & (5) \end{aligned}$$

At frame $\{\mathrm{T}\}$, the designation of internal and external forces is important. External forces act on the telemanipulator in a summing fashion. That is, if a translational force is sensed by both sensors, the sum of those signals is the total translational force on the slave device. However, for the gripping (internal) force, the net force on the telemanipulator is zero. Thus, to obtain the force applied to the environment by the grippers, the signals must be subtracted.

The resulting translational force, f, in frame $\{\mathrm{T}\}$ is

$$f = \begin{pmatrix} -f_{1x} - f_{2x} \\ \sin(\frac{\theta_g}{2})(f_{1y} - f_{2y}) - \cos(\frac{\theta_g}{2})(f_{1z} + f_{2z}) \\ -\cos(\frac{\theta_g}{2})(f_{1y} + f_{2y}) - \sin(\frac{\theta_g}{2})(f_{1z} - f_{2z}) \end{pmatrix}.$$

The torque from the gripper, τ_g, about the x axis in frame $\{\mathrm{T}\}$ is

$$\begin{aligned} \tau_g = & \left(L + a\sin\left(\frac{\theta_g}{2}\right)\right)(f_{1y} - f_{2y}) \\ & + a\cos\left(\frac{\theta_g}{2}\right)(f_{1z} + f_{2z}) - \tau_{1x} + \tau_{2x}. \end{aligned}$$

The terms with scalar a are needed because the center of rotation of the each gripper is not in line with frame $\{\mathrm{T}\}$. The sensed torque in the y and z axes of frame $\{\mathrm{T}\}$ are ignored since there is no actuation in those degrees of freedom.

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4. Experiment

The purpose of this experiment is to evaluate how partial force feedback influences user performance during manipulation tasks. The study is designed to test the following hypotheses:

Hypothesis 1: Grip Force with Translational FF $\neq$ Grip Force with No FF. (a) The average applied gripping force to the slave environment with translational force feedback will be significantly different than the average applied gripping force to the slave with no force feedback. (b) Additionally, the time to complete the task will be significantly different with the addition of translational FF.

Hypothesis 2: Translational Force with Grip FF $\neq$ Translational Force with No FF. (a) The average applied translational force to the slave environment with gripping force feedback will be significantly different than the average applied translational force with no force feedback. (b) Additionally, the time to complete the task will be significantly different with the addition of gripping force feedback.

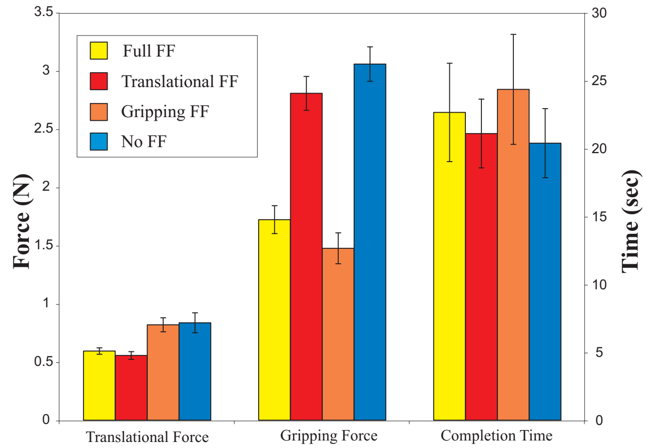

Figure 4. Average applied force and completion time for 5 subjects. Applied translational forces were only affected by force feedback in the translational DOFs. Similiarly, applied grip force was only affected by feedback given in the gripping DOF. No significant difference are observed between task completion time under various force feedback conditions.

4.1. Methods

Five subjects, all right-handed, were asked to perform a simple manipulation task with the 4-DOF telemanipulator. The task was to grasp a rectangular foam "peg" and insert it into rectangular holes in a foam block. Video feedback of the slave device and task environment was presented to subjects using a computer monitor.

During each trial, the subject grasped the peg and inserted it into the block to a specified depth. The subject then removed the peg and placed it into a different hole, again to the specified depth. Finally, in a third hole, the subject inserted the peg entirely. (See Fig. 3 for hole locations.) The trial finished when the user inserted the peg such that the top surface of the peg and block were even. The peg was approximately 35 mm $\times$ 25 mm $\times$ 12 mm in size and the users were required to insert the peg into the foam 23 mm (marked on the peg with a black line – see Fig. 3). The clearance between the peg and each hole was approximately 1 mm.

Each subject was presented with four different force feedback conditions: (1) Full force feedback, (2) Translational force feedback only, (3) Gripping force feedback only, and (4) No force feedback. Conditions (2), (3), and (4) were created by eliminating force feedback in some or all of the DOF of the master haptic device. Each subject repeated the four conditions in a random order five times. Position, velocity, applied force/torque, and time were recorded during each trial.

A position forward/force feedback control scheme was used, with the appropriately tuned gains to provide the highest stable teleoperator stiffness. The proportional and derivative gains on the position forward controller for the translational degrees of freedom were 0.16 N/mm and 0.003 N-s/mm, respectively. The proportional and derivative gains on the position forward controller for the gripping degree of freedom were 0.41 N/mm and 0.0006 N-s/mm, respectively.

Prior to the start of the trials, subjects were given unlimited amount of time to practice the task with all four feedback conditions. No subject took more than five minutes to practice. Subjects were instructed to use the least amount of force possible during the task (as if they were manipulating delicate tissues), but they were also instructed that time was an important factor.

4.2. Results

Analysis of variance (ANOVA) was performed with two factors, subject and condition, to determine if the factors significantly affect the variables of interest. The subject factor was included to reduce the effect of variability between subjects on the evaluation of the conditions. Comparisons between pairs of conditions were performed using Tukey's test at a 95% confidence level. ANOVA revealed that force feedback does significantly affect the average applied translational force and the average applied gripping force (both $p < 0.0001$), but does not significantly affect the completion time ($p = 0.144$).

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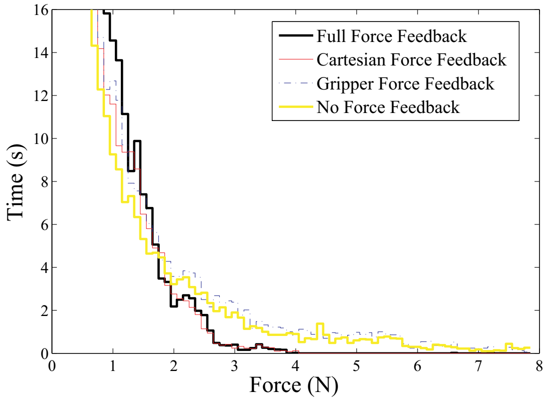

Figure 5. A histogram of all users' translational forces shows that when translational force feedback is given, no user applied more than 4 N. When no force feedback or gripping force force is given, users applied significantly higher forces.

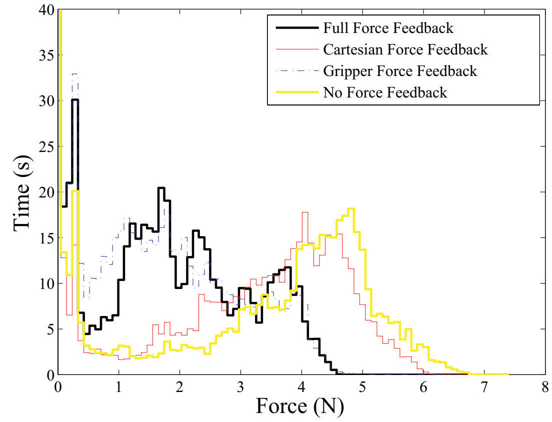

Figure 6. A histogram of all users' grip forces shows that when grip force feedback is given, no user applied more than 5 N. When no force feedback or translational force force is given, users applied much higher gripping forces.

Hypothesis 1: Grip Force with Translational FF $\neq$ Grip Force with No FF. Hypothesis 1a suggests that translational force feedback affects the applied grip force when there is no grip force feedback. However, Tukey's tests show that there is no significant difference in the average applied gripping force with or without translational force feedback. Fig. 4 illustrates the average translational and grip force applied for each condition. Hypothesis 1b states that the time to complete the task with translational force feedback will be significantly different than the no force feedback condition. However, no significant difference between the completion time exists. Therefore, Hypothesis 1 is not supported. The addition of translational force in a 3-DOF telemanipulator does not significantly affect the amount of applied grip force.

Hypothesis 2: Translational Force with Grip FF $\neq$ Translational Force with No FF. Hypothesis 2a asserts that gripping force feedback will affect the amount of translational force applied when there is no translational force feedback (Fig. 4). However, Tukey's test showed no significant difference between the amount of translational force applied between the two conditions. Hypothesis 2b suggests that the completion time for the two conditions are significantly different, but the data shows no significant difference in time.

Figures 5 and 6 show histograms of the translational force and gripping forces used across all of the five subjects. The histograms show that the presence of one type of feedback (e.g. gripping force feedback) does not significantly affect the applied forces in the other degrees of freedom (e.g. translational). In Fig. 5, with translational force feedback (regardless of presence of gripping force feedback), users do not apply more than 4 N of force. However, in both the no force feedback and grip-only force feedback conditions, the histogram shows the user applying much higher forces during the trials. A similar result is seen in Fig. 6 with the gripping force.

Our results are not surprising in the context of experiments by Wagner and Howe [13], which demonstrated that the dynamic interplay of force feedback and the human arm affects task performance. If the dynamics of the DOF(s) lacking force feedback are coupled to the dynamics of the DOF(s) with force feedback (which is not the case for internal and external hand forces), we would expect the DOFs with force feedback to have more impact on forces in the DOFs which lack force feedback. Thus, a larger question in higher-DOF telemanipulators with partial force feedback is the interplay between forces and torques in the device. Many telemanipulators provide 3-DOF force display but allow users to position a 6-DOF robot. Thus, users can impose a torque on the slave environment without direct feedback on the amount of torque applied. However, this torque is often felt by the user as an applied translational force. Future work will investigate if this type of force information is enough to discern applied torques in the environment while performing manipulation tasks.

Subjects did appear to use grip force feedback to regulate the amount of force applied to the peg such that they operated closer to the minimum force required to maintain a no-slip condition. When grip forces were being feedback to the user, almost every user, at some point, would slip off the peg while trying to remove the peg from a hole. When gripping forces were not being feedback to the user, this action did not occur.

5. Conclusions

This paper presents a 4-DOF telemanipulator using two Phantom haptic devices with attachable gripper mechanisms that is capable of force feedback in 4 DOFs. The kinematic relationship and Jacobian necessary to control the gripper degree of freedom is given. We also describe the necessary equations to obtain the 4-DOF force/torque information from force/torque sensors mounted in the grippers.

Using this telemanipulator, we have tested how partial force feedback affects the forces applied in the DOFs in which no force feedback is provided. Specifically, Cartesian (translational) force feedback alone does not provide users with enough gripping force information in procedures where grip force should be minimized. Also, grip force feedback cannot provide sufficient Cartesian force information in tasks where translational forces should be minimized. Thus, force feedback in translational degrees of freedom and gripping degrees are decoupled with respect to the ability to regulate force. In situations where both Cartesian force feedback and gripping force feedback should be minimized, the need for full force feedback is apparent.

Further research on partial force feedback is necessary. Little is known about users' ability to adapt to the unusual force feedback created by the sensor/actuator asymmetries. More work on controller design must be completed to ensure the stability of telemanipulators with sensor/actuator asymmetries – an issue of great importance for surgical telemanipulators. Future work will include investigation of energy observers and environment modeling to reduce the negative effects of partial force feedback to the user and ensure stability of the telemanipulator.

Acknowledgments

This work is supported by a National Defense Science and Engineering Graduate Fellowship, the National Institutes of Health (R01 EB002004), the Whitaker Foundation (RG-02-911) and the National Science Foundation (IIS-0347464).

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