

Feedback Strategies for Shared Control in Dexterous Telemanipulation

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ABSTRACT – Shared control represents a middle ground between supervisory control and traditional bilateral control in which the remote system can exert control over some aspects of the task while the human operator maintains access to low-level forces and motions. Our telemanipulation system includes tactile, force and motion sensors that allow the slave to regulate grasp forces and impart rolling motions to a grasped object. We describe a set of experiments designed to determine whether shared control can improve the ability of an operator to handle objects delicately and to determine what combinations of force, visual and audio feedback provide the best level of performance and operator sense of presence. The results demonstrate the benefits of shared control and the need to choose carefully the types and methods of direct and indirect feedback.

I. INTRODUCTION

The work described herein is part of a project to enhance the dexterity and sensitivity of dexterous telemanipulation (i.e., manipulation in which fine forces and motions are imparted with the fingertips). Shared control provides a framework for extending the capabilities of a traditional telemanipulation system.

A shared control telemanipulation system combines some of the autonomy of supervised systems [15] with the telepresence found in direct master-slave bilateral systems (Fig. 1). There are advantages to having the robot hand take over force regulation and object manipulation when the task is sufficiently well defined. By providing local control of forces, stiffness, and fine hand motions, the robot allows the human supervisor to focus on the task itself, concentrating on the desired motions and behavior of the grasped object or tool. Time delays and limitations in the accuracy of haptic feedback through the master become less detrimental because commands from the master are supplemented by local control to prevent unwanted slips or object damage. However, there is some concern that the operator's sense of presence will be reduced as the slave system takes more control over the interaction.

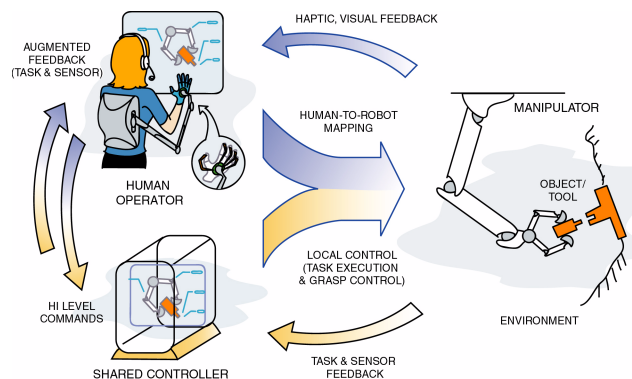


Fig. 1. Shared control concept for dexterous telemanipulation.

Moreover, there is an indication from the physiology literature [18] that without appropriate tactile cues, the human grasp force will gradually relax, leading to a divergence between conditions at the master and slave.

In the experiment discussed in this paper, the operator and the robotic hand share control of the grasp force when handling an object. To prevent accidental drops, the robot can intervene and assume control over the internal force. However, the operator maintains the ability to override the dexterous controller to release the object or grasp it tightly if desired.

Several conditions were tested to investigate some of the issues associated with shared control, including the effects of robot task intervention, indirect feedback and force feedback. In particular, we wished to determine whether task performance was improved if the operator was informed when robot intervention occurred. Additionally, because control was shared over parameters used for direct haptic feedback, different methods of force feedback were tested.

II. PREVIOUS WORK

In cases where time delay is not a significant problem, shared control offers advantages over strict supervisory control by providing the operator with direct access to

forces and motions at the slave. Many previous investigations have implemented a mix of hierarchical and shared control for telemanipulation.

Initial investigations focused on developing a framework for task-level sharing of motion trajectories for systems with moderate time delays [8][13]. Other work focused on modifying the impedance of slave-manipulators based on teleoperator commands and local sensor information [3][7].

Towards dexterous telemanipulation, Michelman and Allen [12] applied the concept of shared control to the Utah/MIT dexterous hand. Their system focused on defining and sequencing primitives for operations such as grasping an object and inserting a peg in a hole. Researchers at NASA have developed Robonaut, a humanoid robotic system with a dexterous hand and telepresence interface. The control architecture is based on “subautonomies” that combine low-level intelligence for reflexive actions and high level commands for grasp configuration [2]. While these dexterous systems demonstrate the application of a shared control framework, none specifically address the issues of haptic feedback at the fingertip level.

Of particular relevance to our experiment, Hannaford et al. [7] evaluated a six-axis generalized teleoperation system with arm/hand force feedback. Along with evaluation of the force feedback, a case was tested in which control was shared with the robot (utilizing local force/torque sensing) during a peg-hole insertion task. In this task, the operator controlled end-effector position while task-space orientation control was shared with the robot. The authors observed a reduction in task completion time and sum-of-squared forces with the addition of shared control.

III. EXPERIMENTAL SETUP

The dexterous telemanipulation system includes an arm-mounted master, a controller and a slave consisting of an industrial robot and a two-fingered hand. Although small time delays must be considered when tuning the system, the treatment of large delays is beyond the scope of this paper. In addition, the operator has direct visual and aural feedback from the slave, located across the room from the master.

A. Master System

Human finger motions are recorded by an instrumented glove (Immersion CyberGlove™) and wrist motions are recorded using a six DOF ultrasonic tracking system (Logitech Head Tracker). Calibration software developed in previous work [6] allows the telemanipulation controller to estimate the intended motions of a virtual object grasped between the operator’s thumb and index finger. The glove and tracker signals are sampled at 200 Hz and 50 Hz, respectively, and smoothed to generate motion

commands for the slave [5][16].

A cable-driven exoskeleton (Immersion CyberGrasp™) provides a single degree of freedom of force feedback at each fingertip (Fig. 2a). Additional feedback channels, including audio tones and visible LEDs on the robot hand, display state information computed by the telemanipulation controller.

B. Slave System

The slave system has a two-fingered hand with two degrees-of-freedom per finger. The hand is designed specifically for use with force and tactile sensors and therefore has a smooth back-driveable cable transmission to minimize friction and vibrations (Fig. 2b).

The robotic hand is mounted to an industrial 5-axis SCARA robotic arm. Special-purpose software allows real-time control of the robot trajectory at 63 Hz update rates via ethernet [1].

B.1 Control Framework

To accommodate the various communication rates and priorities associated with different system components, the controller was developed on a real-time operating system (QNX®) with a multi-process structure implemented on two networked nodes.

The control laws for the slave manipulator lay the foundation for implementing a shared control telemanipulation system. We are interested in both independent control of the fingers (for exploration) and coordinated control for manipulating grasped objects. Following the approach of [10] and [14], the dynamics are computed using Khatib’s operational space formulation [11], with Hogan’s impedance control [9] to specify the behavior with respect to disturbances. The impedance control loop runs at 1 kHz and the hand has a closed-loop bandwidth of approximately 10 Hz for small motions of the grasped object.

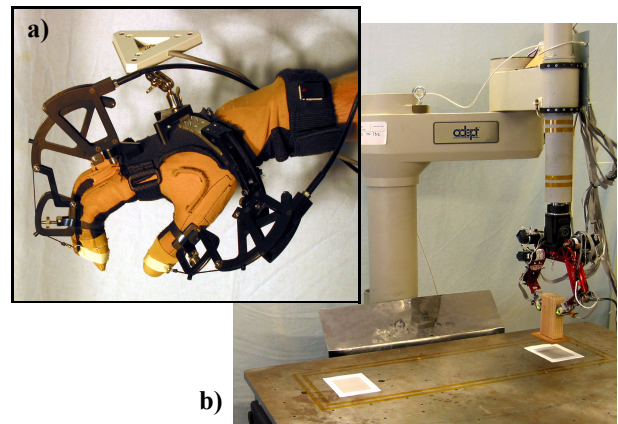


Fig. 2. a) Master interface with instrumented glove, force feedback exoskeleton, and ultrasonic wrist tracker. b) Slave system with dexterous robotic hand mounted to industrial robotic arm.

The transition between independent and coordinated manipulation is based on signals from force and tactile sensors, following the approach of Hyde [10]. For manipulation of a grasped object, the controller must first map the operator’s finger motions to the corresponding motions of a virtual object held in the hand. The controller then computes the motions required of the (non-anthropomorphic) robot fingers, including rolling kinematics, to achieve a geometrically similar motion of the actual object [5][6].

Utilizing force and tactile sensors and the kinematics of contact, the robot controller can stably manipulate an object through arbitrary small translations and rotations (i.e., until regrasping becomes necessary).

IV. EXPERIMENT DESCRIPTION

Using the telemanipulation system, operators were instructed to pick up and carry an object across the workspace and set it down on a designated target (Fig. 2b). The operators were asked to treat the object as fragile and thus to use a minimum grasp force, while taking care not to let the object drop. The object was a 0.2 Kg wood block and was moved between targets separated by 65 cm.

To assist the operator, the controller must have an estimate of the minimum grasp force. When grasping objects with their own hands, humans readily identify the minimum force required to prevent slipping and generally maintain a safety margin of 10%-30% [18]. For the robot, we estimate the minimum internal force based on *a priori* friction estimates and robot fingertip force measurements. Recall that in a multifingered grasp, the contact forces can be decomposed into f_{ext} , which balance the object weight, inertial forces and contact with the environment, and f_{int} , which produce no net resultant and can be adjusted independently to prevent slipping [17]. For a two-fingered grasp on a block that is held approximately level, the minimum internal force becomes:

$$f_{int,min} = \max\left(\frac{f_{tan,i}}{\mu_i}\right), \quad (1)$$

where μ_i is the static friction estimate for the i^{th} finger and $f_{tan,i}$ is the tangential force component, computed from the measured fingertip forces. With this information, the robot is able to regulate the internal grasp force, using a PI control law, independent of external forces on the object.

We are interested in evaluating shared control as compared to unassisted telemanipulation and in determining what kinds of feedback are most useful to the operator. Accordingly, we examined various cases in which one or more of the following conditions applied:

- direct bilateral control (baseline case) – the desired grasp force from the operator (expressed as a reduction in the virtual distance between the fingertips, following the impedance control formulation [9]) is used directly to control the grasp force on the object. The

magnitude of the measured grasp force at each finger is fed directly back to the operator via CyberGrasp.

- robot assisted control – when the desired grasp force drops below 110% of the minimum force in (1), the robot controller intervenes to maintain it at 110%, until the operator releases the object (desired grasp force < 0). When robot intervention is active, the force fed back to the user can be either the magnitude of the *actual* grasp force measured at the fingertips or proportional to the *desired* grasp force. The latter case is referred to as “reduced force feedback.”
- visual indicators – when robot intervention is enabled, LEDs on the robot hand are illuminated when the controller is actively maintaining the internal force at 110% of f_{min} .
- high audio tone – a 500 Hz warning is sounded when the object is in danger of slipping. For unassisted telemanipulation, the tone is sounded whenever the desired grasp force approaches f_{min} . If intervention is active, an audio tone is emitted when the desired grasp force approaches zero, which would trigger the robot to release the object.
- low audio tone – to discourage the user from squeezing the object too hard, a 50 Hz tone can be emitted when the desired grasp force exceeds 170% of the minimum required.

The audio and LED feedback channels create a target window in which the user can remain for safe, gentle object handling. The target windows for manipulation with and without robot intervention are depicted in Fig. 3. Note that the target window with robot intervention is wider because the desired grasp force can drop below f_{min} without adverse consequences.

The various cases tested, and the combinations of feedback associated with each case, are listed in Table 1.

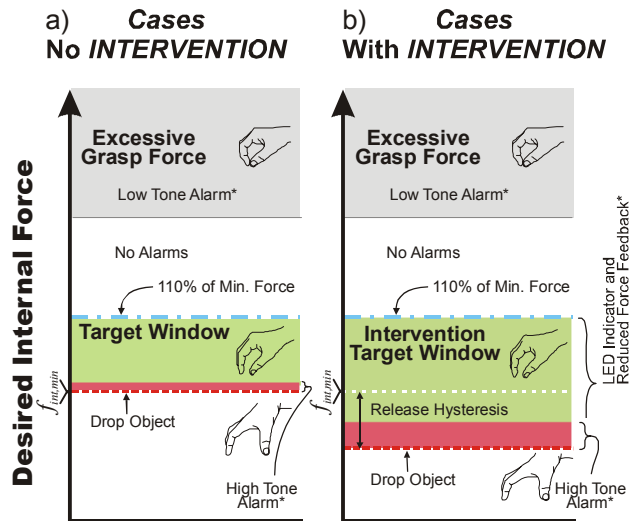


Fig. 3. Comparison plots of feedback to operator for cases with and without intervention.

Table 1. Tested effects for experimental cases.

| Aid \ Case | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|--------------------|---|---|---|---|---|---|---|
| Audio Alarms | | ✓ | | ✓ | | ✓ | |
| Robot Intervention | | | ✓ | ✓ | ✓ | ✓ | ✓ |
| LED Indicator | | | | ✓ | | ✓ | ✓ |
| Reduced Force FB | | | | | ✓ | ✓ | ✓ |

A. Procedure

A diverse set of eleven subjects, eight males and three females, was recruited for the experiments. Each subject was required to complete the experiment in two sessions. The first session was used to calibrate and adjust the human-to-robot mapping parameters (see [6]) and familiarize the operator with controlling the robotic arm and hand with visual and force feedback.

The second session occurred two to four days after the first. The subjects were re-familiarized with the system and initially instructed to perform the pick-carry-and-place task under the control case, Case 1. Prior to testing, each case was explained using a graphic similar to Fig. 3.

Subjects were asked to transport the block from target to target, using the minimum force necessary without dropping it. The task was marked a failure if the block was dropped or not placed on the target. Subjects were told that trial completion time was not considered in evaluating performance.

Each subject was asked to complete four trials for each of the seven different cases. The case order for each sub-

ject was randomized. At the start of each new case, subjects were given a single practice trial prior to the four test trials.

During the test trials, the following data were recorded at 200 Hz by the computer: time, the measured internal force on the object, the operator’s desired internal force, the calculated minimum internal force (per (1)), the intervention state, and the states of any audio alarms and LED indicators. The experimenters manually recorded failures.

V. RESULTS

The results of the tests were examined to determine which combinations of control and which forms of feedback improve task performance – in terms of minimizing the internal force and reducing failures.

Plotting key variables for each case immediately reveals some trends. Fig. 4 shows typical trials of one subject for Cases 1, 2, and 6. For every case, the measured internal force closely tracks the operator’s desired or commanded internal force, unless intervention is active. For Case 1 (direct telemanipulation), the calculated minimum internal force is also shown. This force is approximately 1.7 N, with minor variations due to vertical accelerations of the block. Most of the time, the operator’s commanded force is considerably above the minimum.

For Case 2 (alarms only), the effects of adding the audio tones are seen. Initially, the operator utilizes an excessive grasp force which is gradually relaxed until the low tone is no longer heard. The operator then uses the high tone to maintain the grasp force above the minimum requirement.

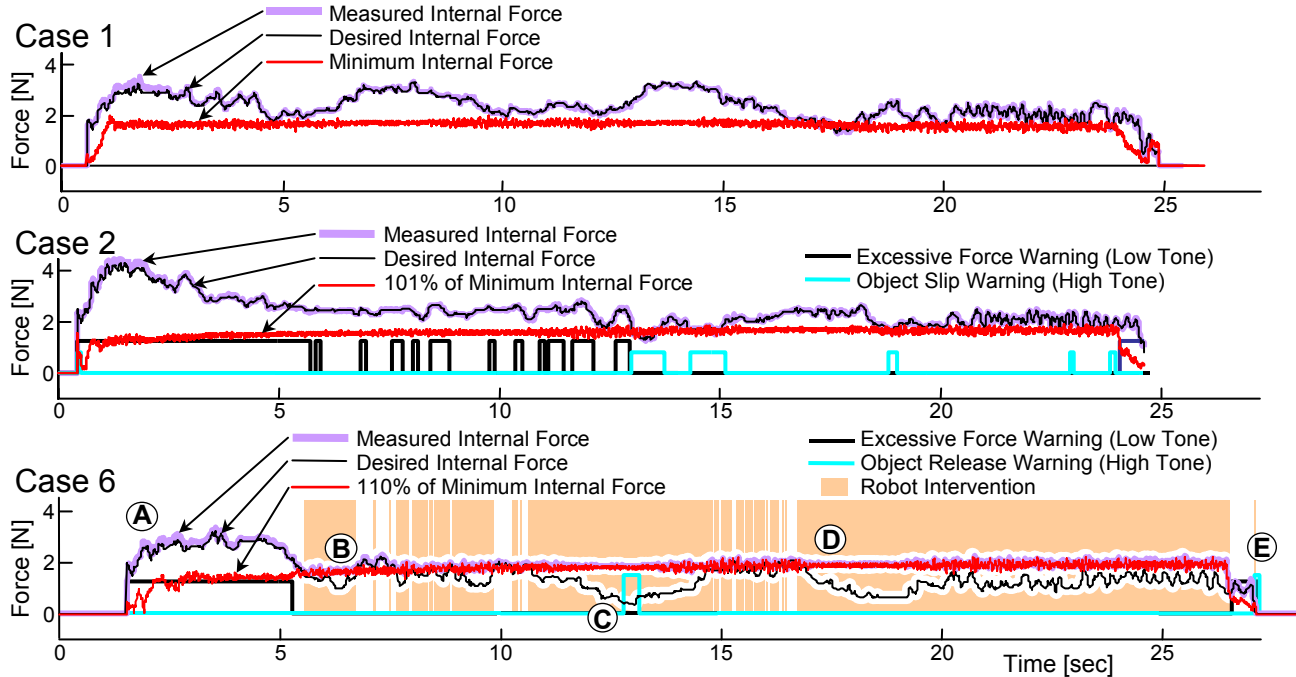


Fig. 4. Typical subject data recorded during a single task trial for Cases 1, 2 and 6.

For Case 6 (robot intervention with alarms and LEDs) a trace is plotted corresponding to the 110% threshold at which the robot assumes control of the grasp force. Not surprisingly, the measured internal force tracks this value closely. As in Case 2, the operator initially applies an excessive force (marker A) and then reduces the force, allowing the robot to assume internal force control (B). However, the operator slowly continues to relax (consistent with predictions from [18]) until the high tone alarm sounds (C) to warn that the object may be released. The operator adjusts the grasp force and lets the robot continue to intervene (D) until the object is released at the target (E).

A. Objective Data Analysis

The objective data analysis is based primarily on the measured internal force applied to the object. Since the goal is to handle the object gently, the measured internal force is a logical performance metric.

Fig. 5 shows a boxplot of the average measured internal force for each case based on an average of successful trials for each subject. There is clearly a reduction in the measured internal force when comparing all cases to the control case (Case 1). In particular, Cases 4, 6, and 7 have a distribution that is much lower than Case 1. It should be pointed out that in theory it is possible to complete the task under Cases 1 and 2 with a lower force than cases with intervention because, during intervention, the lowest force the robot can apply is 110% of the minimum. To determine if differences among the cases are statistically significant, an analysis of variance (ANOVA) was performed. A single factor, balanced ANOVA test with seven fixed effects was first run on the average measured internal force of each subject and for each case (yielding eleven data points per case with 76 DOF). The null hypothesis was the different cases have no effect on the measured internal force.

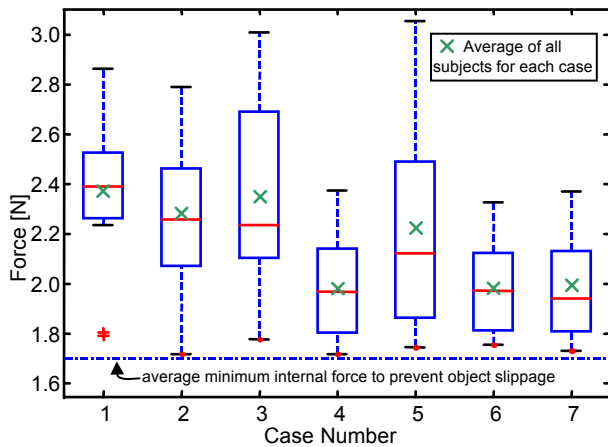


Fig. 5. Boxplot showing medians, quartiles, and outliers of subjects' averaged measured internal force applied to the object.

Table 2. Mean and standard deviation of measured internal force of all subjects for each case

| Case | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---------|------|------|------|------|------|------|------|
| Ave.[N] | 2.37 | 2.28 | 2.35 | 1.98 | 2.22 | 1.98 | 2.00 |
| Std.[N] | 0.34 | 0.30 | 0.40 | 0.21 | 0.42 | 0.18 | 0.20 |

The ANOVA test results in a p -value of 0.003 ($F(6,70)=3.71$), thus we can conclude that at least two cases have a statistically different mean.

To determine specifically which cases are different, we must apply a multicomparison procedure. For this we apply Dunnett's method, which is designed for the comparison of several effects to a control effect (Case 1) while limiting the possibility of a Type I error to the desired significance level ($\alpha = 0.05$) [4]. Applying this method, we can state with 95% confidence that Cases 4, 6, and 7 have a mean different than Case 1. From the averages in Table 2, we see a reduction of internal force on the order of 15% for these cases.

Even though subjects were informed that task completion time was not a factor, the task time may reveal information about the mental or physical difficulty associated with completing the task under the various conditions. An ANOVA test was performed using the eleven subjects' averaged trial times (excluding failures) for each case. The analysis resulted in a p -value of 0.82 ($F(6,70)=0.48$), indicating that the mean task completion times for the cases are not statistically different. While there is no improvement in task time for cases with shared control, there is importantly no increase in task time either.

Fig. 6 shows the total number of failures for each case. With eleven subjects and four trials per case, each case was attempted 44 times. The number of failures for Cases 5 and 6 are the lowest and interestingly Case 7 had the highest number of failures.

B. Discussion of Results

Taking into account the task goals and the objective performance criteria based on measured internal force, task completion time, and number of failures, it is clear that the addition of a dexterous shared controller to a traditional bilateral telemanipulation system can enhance an opera-

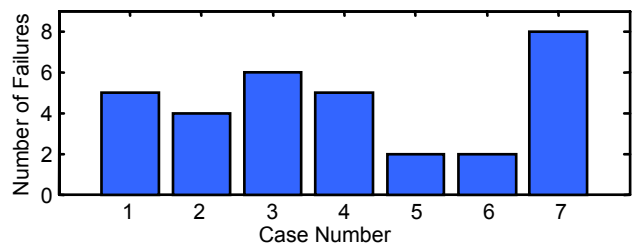


Fig. 6. Total number of failures for each case for all subjects.

tor's performance during a typical telemanipulation task.

A comparison of the measured internal force for Case 1 versus Case 2 indicates that warning the operator of a possible failure through audio feedback may be helpful. However, during preliminary testing we found that alarms could cause significant confusion for the operator if the activation levels were to set too close relative to each other. Part of the advantage of adding robot intervention is that it allows us to make the target window wider, separating the conditions associated with the high and low audio tones.

As anticipated, we found that robot intervention could improve task performance. However, the presence and type of direct and indirect feedback had a marked effect. The cases which informed the operator that the intervention was occurring (Cases 4, 6, and 7) had lower internal forces than the control (Case 1), whereas in Cases 3 and 5 (no indication of intervention), the average internal force was similar to Case 1. Moreover, if we examine the number of failures, we find that simply informing the operator that intervention was occurring, using LEDs as a visual indicator, was not adequate. The number of failures in Case 7 was four times that of Case 6, indicating that the audio alarms, particularly the high tone alarm, reduced the number of failures.

The effects of different approaches to force feedback are isolated in a comparison of Case 3 to Case 5. Neither of these cases had audio alarms or LEDs. In Case 3, the actual grasp force, based on measurements at the robot fingertips, is fed back to the operator. This force remains nearly constant when intervention is active. In Case 5, the force relayed to the operator is based upon the operator's commanded (desired) internal force. As seen in Table 2, the subjects used slightly less internal force and experienced three times fewer failures in Case 5 (see Fig. 6). While the 6% force reduction is not statistically significant, the reduction in dropped objects indicates that it is useful to feed back forces proportional to the operators' commanded internal force, even as the robot holds the actual grasp force constant. In accord with the operator's expectations, the reduction in displayed force as he opens his grasp provides an intuitive haptic cue useful for manipulation.

Based on the objective data analysis and the performance criteria, Case 6, which combines robot intervention, audio alarms, LED indicators, and reduced force feedback, provides the best overall performance compared to the bilateral control case.

In surveys conducted after the tests, subjects also generally ranked Case 6 highest in preference and ease-of-use compared to the other cases.

VI. ACKNOWLEDGMENTS

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