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A COMPARISON OF DELAY AND BANDWIDTH LIMITATIONS IN TELEOPERATION

Dimitrios Hristu, Dimitrios A. Kontarinis, and Robert D. Howe

Division of Engineering and Applied Sciences
Harvard University, Cambridge, MA 02138 USA
howe@das.harvard.edu

Abstract: This paper compares the role of force reflection bandwidth and delay in performance of a close-tolerance peg-in-hole insertion task. The experiments used a two fingered teleoperated hand system with finger-level force feedback. Low-pass filters varied the frequency content of the force feedback signal, while circular buffers provided pure delays without altering frequency content. Task completion times and error rates decreased as force reflection bandwidth increased or delays decreased. Performance increased little above 6 Hz bandwidth or below 48 ms delay. The results suggest that high frequency information is helpful, even if delayed.

Keywords: Teleoperation, Human-machine interface, Force control, Manipulation tasks, Bandwidth measurements, Robotics.

1. INTRODUCTION

Multifingered hands promise to greatly expand the range of tasks that can be accomplished through teleoperation. These dextrous devices raise a number of issues that have not been considered in previous teleoperation research, which has focused on teleoperated arms. One of the most important issues is the force reflection bandwidth necessary to achieve adequate performance. Increasing the force reflection bandwidth of a teleoperated hand master poses difficult design challenges. An understanding of the tradeoff between force reflection bandwidth and task performance would assist in establishing design criteria for these interfaces.

There are two factors associated with force reflection bandwidth that limit the performance of a teleoperated system. One is obviously the absence of high-frequency information in the reflected force signal from the slave manipulator. This information is particularly important in contact tasks where transients due to impacts, vibrations, etc. may indicate the state of the object-hand system (Kontarinis and Howe, 1995). A concomitant factor is the increased response latency caused by the bandwidth limitation. This delayed response is evidenced, for example, in the slow rise time of the force at the master due to an abrupt force change at the slave. Pure delay of force information (with no attenuation of high frequencies) has been known to decrease performance and cause instabilities in telemanipulation for many years (Ferrel 1966). When force feedback is significantly delayed, the operator must use a "move and wait strategy" in order to avoid instability. Sheridan (1992) provides a more comprehensive discussion of the effects and implications of feedback delays. In general, completion times for teleoperation tasks have been found to increase greatly as delay increases.

Previous work on bandwidth requirements for teleoperation systems suggests that the useful bandwidth for a master-slave manipulator system should be anywhere from 1 Hz to over 500 Hz. Brooks (1990) proposes different bandwidths for the master and slave manipulators, based on the asymmetrical control and perception capabilities of human hands. In his survey of experts, Brooks reports that a 5-10 Hz maximum bandwidth is sufficient for the forward loop (from master to slave) while feedback from the slave should have a bandwidth as high as 30 Hz for proprioceptive and kinesthetic feedback, and possibly extend upwards of 300 Hz to include low-amplitude vibrations. Brooks also states that experimental data, though

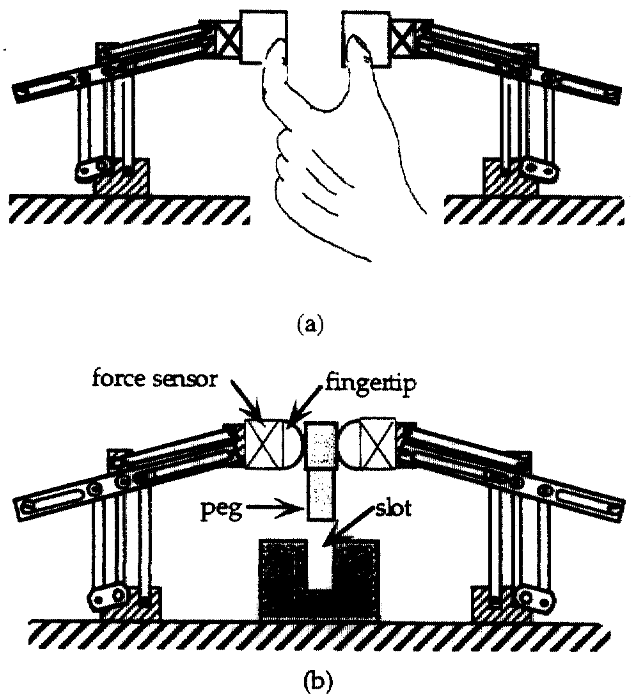

Figure 1. (a) Master manipulator with operator's hand. (b) Slave manipulator with peg-in-hole apparatus.

sparse, supports a 5-10 Hz bandwidth for maximum performance. Based on a peg-in-hole experiment, Uebel et al. (1994) report that 1 Hz was sufficient bandwidth for a slave arm manipulator. They also reported that the delay caused by the low bandwidth was problematic. Sharpe (1988) on the other hand, examining a 1 DOF wire-cutting task, proposes a bandwidth of 20-30 Hz for the slave and reports that much of the necessary sensory information was in the 5-10 kHz range, thus proposing very high frequency feedback to the master. However, subsequent work by Howe and Kontarinis (1992) found that for a planar peg-in-hole task with a two-fingered hand, little or no decrease in completion times occurred if force reflection bandwidths increased over 8 Hz. Also, for the same precision assembly task Kontarinis and Howe (1995) found that feedback of high frequency vibrations above 25 Hz did not improve performance.

Although previous work shows that task performance improves with increased force reflection bandwidth, it is not clear where the bandwidth-performance curve flattens out, so that increasing bandwidth provides diminishing performance improvement. Most important, in previous work the effects of limited frequency information and delays caused by limited feedback bandwidth have been studied together. Thus, given that low force reflection bandwidth limits performance, the question of how much of the limitation is due to the delay present in the loop and how much comes from the lack of high frequency information has not been addressed.

This paper compares the effects of force reflection bandwidth limitation and delay in the performance of close-tolerance peg-in-hole insertion, a precision manipulation task that requires good control of contact forces for successful execution. Of particuar interest is the effect on performance of limited force reflection bandwidth, as well as how much off that effect is due to delay in the system as opposed to lack of high frequency information. The next section describes the teleoperated hand system used in these experiments. The following section details the experimental design: digital low-pass filters vary the frequency content of the force feedback signal, and pure delays equivalent to the 50% rise-times of the low-pass filters isolate the effects of delay caused by the limited force feedback bandwidth from those caused by the limited frequency content of the reflected force signals. Finally, the experimental results are presented and discussed in terms of the time required for operators to complete the insertion task.

2. EXPERIMENTAL METHODS

2.1 Teleoperated Dextrous Hand System

These experiments use the dextrous teleoperated hand system we have developed for experiments in tactile and fine-force sensing and display. Most work on dextrous teleoperated hands has focused on creating lightweight master manipulators with many degrees of freedom for end-of-arm mounting (e.g. Jau 1992, Burdea et al. 1992). This presents extremely difficult design challenges, as many sensors and actuators must be located around the human operator's hand at the end of the arm. Proposed solutions often entail the use of cables or gears, which makes it difficult to accurately control the small forces and displacements that are essential for effective precision manipulation. In contrast, our system trades a limitation on the number of joints for a clean and simple mechanical design. The system has high bandwidth and large dynamic range, which permits accurate control of contact forces and small motions.

The system is designed to execute tasks that humans usually accomplish with a precision pinch grasp between the thumb and index finger. For most tasks, the operator's wrist rests on the table top and the operator makes contact with the master only at the tips of the fingers (Figure 1). Master and slave manipulators are identical two-fingered hands, with two degrees of freedom in each finger, so finger tip position or force can be controlled within the vertical plane. The workspace is roughly circular and 75 mm in diameter. Parallelogram linkages maintain a constant vertical orientation of the finger tips, which precludes inappropriate torques on the operator's finger tips as the joints rotate. The design uses brushless DC torque motors in a direct-drive configuration, resulting in low moving mass and minimal friction, backlash, and torque ripple. Two-axis strain gauge force sensors measure finger tip forces on both master and slave hands. Further details of the manipulator system design are presented in (Howe 1992).

The control computer is a 33 MFlop digital signal processor chip, which operates at a 1.1 KHz servo rate. The controller uses a conventional bilateral force reflection control scheme. The joint angles of the master manipulator are the command inputs for position control of the joints of the slave manipulator. For force feedback, the forces measured at the slave finger tips are the command inputs for force control of the master. Thus the slave follows the motions of the master and the master applies the forces measured at the slave finger tips to the operator's fingers. To maintain contact between the operator and the master manipulator when the slave is not in contact with an object in the environment, the master applies a small, continuous force in the horizontal direction against the operator's fingers.

Each finger is capable of applying a continuous tip force of at least 2 N or a maximum finger tip acceleration of at least 2.5 g in any direction in the plane. The position controller for the slave fingers has a -3 dB bandwidth of 12 Hz at 4 mm amplitude. The response is slightly overdamped, with a smooth roll off of -12 dB/octave to about 50 Hz. The force controller for the master manipulator has a bandwidth of at least 50 Hz at 0.4 N amplitude when operating against the operator's finger with a preload force of 0.7 N.

2.2 Task apparatus

The task used in these experiments is planar peg-in-hole insertion. Because this task is frequently used in robotics and teleoperation research (e.g. Hannaford et al. 1991, Uebel et al. 1994), results may be readily compared with other experimental studies and with mechanical analyses of the task (Whitney 1982). For the planar case considered here, the task becomes insertion of a round peg into a rectangular slot perpendicular to the plane of motion (Figure 1), so that only the two force components and one torque component in the plane may be generated. The peg is a ground steel cylinder 12.7 mm in diameter and 19.1 mm long, with a chamfered tip. It is attached to a cubic aluminum block 23 mm in each dimension, which provides a flat grasping surface for the slave manipulator. The hole or slot is constructed from precision ground steel machinist's parallels, with an opening width of 12.7 mm and a depth of 12.7 mm. The peg is a friction fit into the hole, with essentially zero clearance. An insertion force of at least 0.3 N is required (in addition to the 0.5 N weight of the peg), even with perfect alignment of peg and hole axes. This tight clearance emphasizes the role of force feedback in task execution. The finger tips used were semi-cylindrical in shape, with a 12.5 mm radius and consisted of soft foam core, covered with a silicone rubber skin of thickness 1.0 mm. Their stiffness was nonlinear; at a contact force of 1 N the measured stiffness was approximately 950 N/m and 200 N/m in the horizontal and vertical directions respectively. The coefficient of friction between the rubber skin and the contact area of the peg was approximately 1.0.

2.3 Force feedback filters and delays

In order to measure the effect of force bandwidth on manipulation performance, low-pass filters limited the bandwidth of the force signal relayed to the operator. These are 2-pole digital filters with switchable cutoff frequencies of 3, 6, 9, 11, 18, 22, 25, 30 and 50 Hz, installed in series with the outputs of the slave manipulator force sensors. In addition, force reflection could be disabled, leaving the operator with only visual feedback from the slave. To characterize the actual performance of the system with these filters in place, we measured the rise times for a force step at the operator-master contact, commanded from the slave force sensor output through the bandwidth-limiting filters. Table 1 shows the measured master force rise times (0 to 50%) for a 1.0 N force step applied to an operator's index finger in the horizontal direction with a 1.0 N preload force. Rise times can be affected by the impedance of the operator's finger, which can vary between individuals and with the level of muscular activation. Typical values are shown. Note that the 50 Hz filter delay time is dominated by the system latency.

In order to investigate the contribution of delay in limiting performance, a software buffer was used to delay the force information sent to the master from the slave force sensors in some experimental trials. The low-pass force reflection filters were disabled and the full bandwidth of the system

Table 1. Rise time (0-50%) for 1.0 N force step applied against a human finger tip with a 1.0 N preload.

FILTER BANDWIDTH (Hz)	MASTER FORCE 50% RISE TIME (ms)
3	98
6	48
9	30.5
11	26
18	18
22	14
25	11.5
30	9.5
50	7.4

was available. The delay was variable and the values used were arbitrarily selected to correspond to the 0–50% rise times of the filters used in the bandwidth trials (Table 1).

2.4 Experimental Procedure

The operator views the slave manipulator and peg-in-hole apparatus from a distance of about 1.5 m. In each trial, the operator begins by grasping the peg and holding it above and to one side of the hole. The operator indicates the beginning of the trial by tapping the peg against the surface next to the hole, then proceeds to insert the peg. When the peg reaches the bottom of the hole an electrical contact closes, lighting an indicator visible to the operator. The operator then extracts the peg and taps it against the surface next to the hole, indicating completion of the task. During each trial the finger tip forces and joint angles of both manipulators are recorded by a laboratory computer at a 200 Hz sampling frequency. The time interval between the taps, which appear as spikes in the force records for the trial, are used to determine the completion time for the task.

Multifingered hands promise the greatest benefit in dextrous manipulation tasks, where careful modulation forces and motions is essential. To further emphasize the role of force reflection in these experiments, the task procedure requires the operator to minimize forces while performing the task quickly, as might be required when handling a fragile object. The control computer monitors the grasp force between the fingers of the slave manipulator, and if the force exceeds a threshold of 1.8 N, a buzzer sounds, power to the motors is briefly disabled, and the trial is marked as a failure. This is intended to simulate breaking a fragile grasped object if excessive forces are applied. Operators are instructed to "perform the task quickly but avoid exceeding the force threshold." We chose to simulate breakage of the object rather than simply instructing the operators to minimize forces to create a strong incentive to avoid excessive force levels, and to provide immediate feedback when the force threshold is exceeded. This method also provided an objective measure of the operator's ability to modulate forces.

Five operators participated in these experiments; all were engineering graduate students (ages 22-27; 4 male, 1 female) experienced in the use of the system. Each operator performed ten trials at each bandwidth using low-pass filtering and another ten for its associated delay. The sequence of filters and delays was randomized and the operator did not know which filter or delay was being used each time. All trials at each bandwidth were completed before the filter bandwidth was changed, and the operator was permitted practice time to become accustomed to the system characteristics at the new bandwidth before the start of those trials. Each operator performed a total of nineteen experiments (nine filters, nine delays and one with visual feedback only).

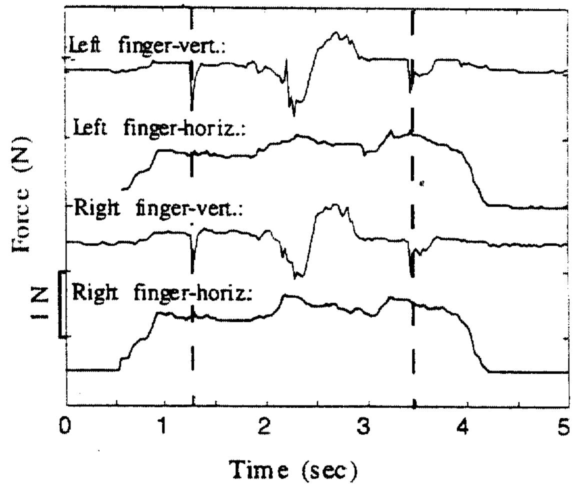

Figure 2. Typical record of finger tip forces at the slave manipulator for the insertion task. Vertical dashed lines indicate the taps which signal the beginning and end of the task.

3. RESULTS

Figure 2 shows a typical record of the finger tip forces at the slave manipulator for the insertion task with 50 Hz bandwidth force reflection. The record for the master manipulator is essentially identical. The force values in both the horizontal and vertical directions begin to increase as the peg is grasped and lifted. Next, the operator taps the grasped peg against the upper surface of the hole apparatus, producing a spike in the load force record and initiating timing of the task. The peg is then inserted into the hole and extracted. Finally, the operator signals completion of the task with another tap.

3.1 Completion times and failure rate

Figure 3 shows the mean time between taps for all subjects as a function of bandwidth and delay. The solid and dashed lines represent performance times with the low-pass filters and the pure delays respectively. Symbols indicate the mean times for all operators and the bar heights indicate standard deviation of individual operators' means. For the case reported as "visual only," force feedback was disabled and the operator controlled the task through visual observation of the peg's position only.

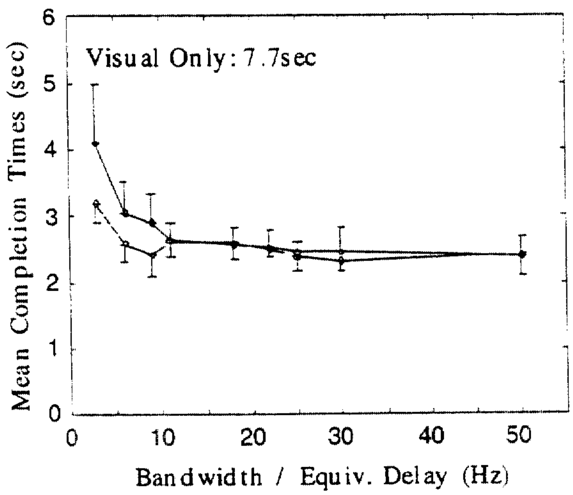

Figure 3. Average completion times for each bandwidth. The solid line corresponds to filtered force feedback, while the dashed line represents the pure-delay cases. The bars on the graph represent the standard deviation for each data point.

For the trials where force feedback was filtered, the clear trend is a decrease in completion time as the force reflection bandwidth is increased up to about 11 Hz. Operators could on average complete the task in less than half the time with 50 Hz force feedback compared with visual feedback only. The mean insertion time trials with force reflection disabled (visual feedback only) was 7.7 sec. The provision of 3 Hz force reflection reduced this to about 4.1 sec, and the completion time continued to decrease until 11 Hz, where the mean was about 2.6 sec. An F-test performed on the data for the 0, 3, 6, 9 and 11 Hz filtered cases, demonstrated significant improvement with increasing bandwidth at the F=14.1, p<0.01, r=0.88 level. Pairwise t-tests showed that the decrease in completion times between the 6 and 9 Hz cases was not significant, but the improvement from 6 Hz (and below) to 11 Hz was significant (t=1.9, p=0.05, r=0.44 minimum). From 11 Hz and on, pairwise t-tests between bandwidths showed no significant improvement (t=0.6, p=0.55, r=0.27 at best).

For the trials with pure delay, performance improved up to the delay equivalent to the 9 Hz case; an F-test on data corresponding to 3, 6, and 9 Hz bandwidth (98, 48 and 30.5 ms delay) show that the improvement in completion times is again significant (F=18.4, p=0.001, h=0.91). For delays corresponding to the 11 Hz case and upwards (26 ms or less), pairwise t-tests between different delays showed no significant improvement (t=0.8, p=0.45, r=0.25 at best).

The failure rates (percent of times the operators exceeded the 1.8 N force limit on the grasp force applied to the peg) are shown in Figure 4. The solid and dashed lines represent the low-pass filter and pure delay cases respectively. The average failure rate for the filtered feedback cases was 0.14 (14%) compared with 0.067 (6.7%) for the pure delay cases. The data showed a marked improvement at 3 Hz as opposed to visual feedback only (t=1.9, p=0.05, r=0.48). The differences between 3, 6 and 9 Hz were not statistically significant, although the mean failure rates appears to follow a decreasing trend. However, t-tests on data corresponding to pairs of bandwidth frequencies showed that there are significant differences between bandwidths below 11 Hz and those 11 Hz or above (t=2.36, p=0.03, r=0.48 minimum), implying that a bandwidth of 11 Hz provides some benefit. From 11 Hz and above, the improvement with increasing bandwidth or decreased delay is not significant.

For the pure delay cases no difference in failure rates was found with t-tests between different delays. The means for each case appear to scatter around the overall mean of 0.067. In addition, an F-test was performed to measure the improvement in failure rates between filter and delay cases; it showed a marked improvement over bandwidths of 3, 6 and 9 Hz (98, 38 and 30.5 ms delay) (F=11.8, p=0.025, r=0.87). No difference was found for frequencies over 9 Hz (delays under 30.5 ms).

Operators reported that 3 Hz force feedback (as well as its associated delay) felt oscillatory and somewhat difficult to control, but that even with these drawbacks task execution was easier than with visual feedback only. Also, operators indicated that the task was difficult and frustrating with visual feedback only, since the tight fit of the peg in the hole meant that small position errors lead to large forces and jamming of the peg. Subjectively, the "feel" of the system continued to improve with additional bandwidth or decreased delay, even at high bandwidths where performance did not significantly improve by the completion time measure.

4. DISCUSSION

These results confirm and enlarge upon previous results using the same apparatus and task (Howe and Kontarinis, 1992). Little or no improvement is seen in task performance when the force reflection bandwidth is increased above about 9 Hz. Although other researchers suggests a bandwidth of 20-32 Hz for slave-to-master feedback (Brooks, 1992), we have found that performance improvement saturates at lower frequencies.

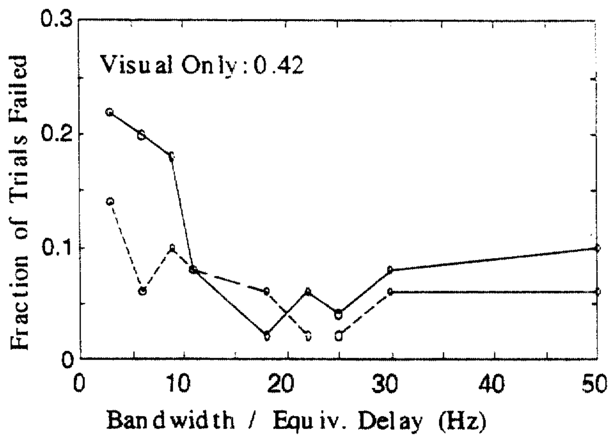

Figure 4 Mean failure rates for all subjects versus bandwidth. The solid line corresponds to filtered force feedback, while the dashed line represents the pure-delay cases.

This work, and related experiments on force reflection combined with high-frequency vibration feedback (Kontarinis and Howe, 1995), suggests that there will be no significant improvement in completion times, even if the force reflection bandwidth is increased beyond the highest tested frequency of 50 Hz. Vibration feedback is, however, beneficial in other tasks, where it can help determine the state of the hand-object-environment system; Kontarinis and Howe (1995) examined the role of vibrations in such tasks (i.e. inspecting a ball bearing for smoothness and puncturing a membrane). They found that for the peg-in-slot insertion task, feedback of vibrations above 25 Hz does not help, probably because performance is determined by the ability to coordinate forces, rather than detecting the state of the system.

In comparing performance between limited bandwidth and pure delay, there is essentially no improvement above 11 Hz bandwidth or below 48 msec delay (equivalent to the 50% rise time of the 6 Hz filter). Since 48 msec is almost twice the 50% rise time of the 11 Hz filter, it appears that high frequency information is helpful, even if it is delayed. This is particularly surprising since the rolloff rate (-12 dB/octave) of the 2-pole low-pass filter is rather slow, so force information above the cutoff frequency is attenuated and phase-shifted but is still present in the output. One potential explanation may be that to correctly use and interpret the force reflection signal at high frequencies, the amplitude and phase relationships must be unchanged. Further experiments will be required to determine the causes of the observed difference.

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