Ground-Space Teleoperation of ETS-VII Robot Arm
by Direct Bilateral Coupling under 7-sec Time Delay Condition

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Abstract
A bilateral teleoperation experiment with ETS-VII was conducted on November 22, 1999. Round-trip time for communication between the NASDA ground station and ETS-VII was approximately seven seconds. We constructed a bilateral teleoperator that is stable even under such a long time delay. Several experiments, such as slope tracing task and peg-in-hole task, were carried out. Experimental results showed that kinesthetic force feedback to the operator is helpful even under such long time delay and improves the performance of the task.

1 Introduction
Bilateral control provides important force information of the remote environment to the operator. It is well known, however, that even small communication delay may destabilize the system with conventional bilateral control methods, such as symmetric position servo and force reflecting servo[15]. Anderson and Spong[1] proposed a bilateral control law that maintains stability under the communication delay by using the scattering theory. Niemeyer and Slotine[12] studied further on this problem.

It has been assumed, however, that bilateral control would not be effective when the time delay becomes longer than about 1[sec]. For example, Kim et al.[6] described as “... However, this force-reflection technique can be utilized only up to an approximately 0.5- to 1-s communication time delay, since a long time delay in the force feedback loop causes the system to be unstable.” Hirzinger et al.[2] mentioned that “In ROTEX the loop delays varied from 5-7sec. Predictive computer graphics seems to be the only way to overcome this problem.” As Peñin et al.[14] did, we also summarized previous works on teleoperation with force-feedback under the communication time delay[5]. These previous works can be divided into two groups: (i) direct bilateral teleoperation without any models of the remote site[1][12][6][9][7][13] and (ii) model-based teleoperation with pseudo force feedback from the local model of the remote environment[8][4][16][14]. All of them conducted real experiments. Almost all works in the former group targeted time delay around 1[sec] or less than that, whereas the latter group tackled much longer delay up to 7[sec]. From this observation, it seems that when the delay time is longer than about 1[sec], the model-based approach would be the only solution. However, we have been doubtful about this “1[sec] limitation” from the following reasons:

- Some of the observations were came from using a conventional bilateral controller with which stability is not guaranteed under the time delay condition. Probably, 1[sec] would be the limitation to stabilize such an unstable system by human operators.
- Bilateral control based on the scattering theory guarantees the system stability for any time delay. However, it tends to be sticky and heavy as the delay time becomes large. Again, 1-2[sec] would be the limitation for the operator to maneuver such a system comfortably[9]. However, the scattering theory is not
the only solution to the time delay problem and some other types of bilateral controller can also guarantee the stability.

Instead of exactly drawing the limitation line at 1[sec], our claim is, in a sense, quite natural as follows: “Time delay limitation depends on the difficulty of the task. Even if the delay time becomes longer than 1[sec], some tasks could be performed by direct bilateral teleoperation.” Actually, Ferrell[3] investigated the effect of time delay longer than 1[sec] in bilateral control. Although the conducted tasks were simple positioning with force feedback, he tested the delay time up to 3[sec].

In this paper, the result of ground-space teleoperation experiment using a robot arm mounted on ETS-VII (Engineering Test Satellite No.7) is shown. The experiment was conducted on November 22, 1999. Round-trip time for communication between the NASDA ground station and ETS-VII was approximately six to seven seconds. We constructed a bilateral teleoperator based on the PD-type controller that is stable even under such a long time delay. Several tasks, such as slope tracing task and peg-in-hole task, were carried out. All the tasks were completed by the direct bilateral control even without visual information. The experimental results demonstrate that kinesthetic force feedback to the operator is helpful even under such a long time delay.

2 Bilateral Controller with Time Delay

One of the well-know approach to time delay is to use scattering transformation, which was proposed by Anderson and Spong[1]. This approach was studied further by Niemeyer and Slotine[12], who introduced the notion of “wave variable”. Besides the scattering-theory-based approach, there are several other approaches, which are less popular than the wave-variable approach. For example, Leung et al.[10] proposed a bilateral controller for time delay based on the $H_{\infty}$-optimal control and $\mu$-synthesis frameworks. Oboe and Fiorini[13] dealt with the time-varying delay problem over the Internet by using a simple PD-type controller.

We paid notice to this PD-type controller, which is shown in Figure 1. The dynamics of master and slave arms is formulated as follows:

\[
\tau_m + f_m = m_m \ddot{x}_m + b_m \dot{x}_m, \\
\tau_s - f_m = m_s \ddot{x}_s + b_s \dot{x}_s,
\]

where $x_m$ and $x_s$ denote positions of master and slave arms, and $\tau_m$ and $\tau_s$ are actuator driving forces, respectively. $b_m$ and $b_s$ represent viscous coefficients of the driving mechanism. $f_m$ is the force that the operator applies to the master, and $f_s$ denotes the force that the slave arm exerts to the environment.

The PD-type controller is given by the following equations:

\[
\tau_m = -K_m (x_m(t) - x_s(t - T_2)) - D_m \dot{x}_m, \\
\tau_s = K_s (x_m(t - T_1) - x_s(t)) - D_s \dot{x}_s,
\]

where $K_m$ and $K_s$ are position gains, and $D_m$ and $D_s$ are damping gains. $T_1$ and $T_2$ denote delay times from master to slave and slave to master, respectively.

Oboe and Fiorini[13] analyzed the stability condition of this PD-type controller under time-varying delay conditions, but their analysis contains some errors and resultant condition is not true. We assumed constant time delays in both directions and derived the stability condition using Llewellyn’s condition[11]. The derived condition is given by

\[
(D_m + b_m)(D_s + b_s) \geq \frac{K_m K_s (T_1 + T_2)^2}{4}.
\]

As the delay time becomes longer, the dumping gains should be increased, resulting in sticky feeling. Unlike the scattering-theory-based controller, however, the apparent inertia keeps constant. Therefore, this PD-type controller is expected to be still useful even under a long time delay around the range of 5-7 seconds.

3 Overview of the Experiment

3.1 Purpose of the experiment

The purpose of the experiment can be summarized as follows. Detailed contents of the experiment will be described in section 4.
1. Basic performance check of the PD-type bilateral controller under 5-7[sec] time delay condition

2. Performance check in various tasks
   (a) accuracy of force command (pushing task)
   (b) accuracy of recognizing constraint surface slope (slope tracing task)
   (c) accuracy of recognizing contact state transitions (peg-in-hole task)
   (d) accuracy of recognizing unknown constraint direction (slide handle task)

3. Consideration of psychological aspect and operator’s skill level

3.2 Experimental system

Figure 2 illustrates the task board on the ETS-VII, which contains several experimental facilities used in the experiment. Figure 3 shows the configuration of the experimental system. Figure 4(a) shows the overview of the control station. A 2-DOF force feedback joystick (Impulse Engine 2000 by Immersion Co.), which is shown in Figure 4(b), was used for the master handle.

3.3 Modified bilateral controller

The PD-type bilateral controller discussed in section 2 assumes grounded dumper at both master and slave sides. Due to the limitation of the on-board arm controller specification of ETS-VII, however, we could not implement such a grounded dumper at the slave side. Instead, we reluctantly used a compliant controller where the dumping term is relative as shown in Figure 5.

We derived stability condition for this modified controller. The derived condition is to satisfy the following inequality for all $\omega \geq 0$:

$$(D_m + b_m)D_s > \frac{1}{2} \left( \frac{K_m^2 K_s^2}{\omega^4} + \frac{K_m^2 D_s^2}{\omega^2} \right) - \left( \frac{K_m K_s}{\omega^2} \cos \omega(T_1 + T_2) + \frac{K_m D_s}{\omega} \sin \omega(T_1 + T_2) \right).$$

Unfortunately the condition is not simple like eq.(5) and we have to check the above inequality for all frequencies. Figure 6 illustrates left and right sides of this inequality with appropriate controller gains, and one can see that checking at $\omega = 0$ is sufficient. Although we found that the modified controller can be stabilized by applying enough amount of dumping gain, we could not increase the dumping gain at the master side large enough due to the hardware limitation of the master handle.

It should be noted, however, that the condition is, in a sense, conservative because it requires the passivity of the system to all passive class of environment and operator dynamics. With the maximum dumping gain available at the
master side, we have checked overall system stability by classical Nyquist diagram. Assuming certain operator dynamics and environment dynamics (free motion and hard contact), we confirmed that the overall system is stable.

4 Detailed Contents of the Experiment

In this section, each experiment task will be described in detail. During the experiment, one can see two real images taken from the shoulder camera and the hand camera as shown in Figures 7 and 8, respectively. However, these two real images were shielded from the operator’s position by putting masking boards as shown in Figure 4(a). In the following tasks, what the operator can see is only the computer screen showing telemetry force data or nothing, depending on the experimental conditions.

4.1 Pushing task

In the pushing task, the operator brings the tip of the robot arm into contact with the surface of the tracing slope shown in Figure 2. Then, he applies a rectangle force pattern 5[N]→15[N]→5[N] downwards without moving the arm. Since the force scaling factor between master and slave is five, the force pattern that the operator should actually apply is 1[N]→3[N]→1[N]. Settling time and errors were evaluated in the following three cases:

Case 1 (bilateral mode + force telemetry graph): The operator can get force feedback from the master handle. At the same time, he can monitor the telemetry force data displayed on the screen as shown in Figure 9.

Case 2 (bilateral mode): The operator must operate with force feedback alone and no visual information is provided.

Case 3 (unilateral mode + force telemetry graph): No force feedback is provided from the master handle. The telemetry force data on the screen is the only information fed back to the operator.

4.2 Slope tracing task

In the slope tracing task, the operator let the robot arm contour the sinusoidal slope, exerting a constant force (5[N]). As shown in Figure 7, a peg is attached to the tip of the robot arm. The starting point, which is not informed to the operator, was chosen among points A, B and C shown in Figure 10. The operator was asked to move the arm down to the surface, then move 150[mm] left, and move back to the starting point. Depending on the starting point, the resultant trajectory will be one of the patterns shown in Figure 11.

In order to compare the task performance in equal condition, the operators were asked to complete the task preferably in three minutes and within a maximum of four minutes. The following two cases were tried:

Case 1 (bilateral mode + force telemetry graph)

Case 2 (unilateral mode + force telemetry graph)

Completion time and force errors were evaluated. In addition, the operator had to answer which starting point was selected when he finished each trial.

Case 1 (bilateral mode + force telemetry graph): The operator can get force feedback from the master handle. At the same time, he can monitor the telemetry force data displayed on the screen as shown in Figure 9.
4.3 Peg-in-hole task

In the peg-in-hole task, the robot arm is initially placed at point D in Figure 10, 30[mm] left from the peg hole. The same peg used in slope tracing task is used again in this task. The diameter of the peg is 18[mm] and the hole has 0.4[mm] clearance. For smooth insertion, the peg tip was rounded and the hole was chamfered. The operator brings the peg into contact with the top surface, slides it horizontally until reaching the hole entrance (10[mm] below from point E), and inserts the peg into the hole. The operator was asked to avoid lateral force as much as possible when inserting the peg. He was also asked to identify the transition of the contact state, i.e., the instants when the peg starts to enter the hole and when it reaches the bottom of the hole, respectively. The following three cases were tried:

Case 1 (bilateral mode + force telemetry graph)
Case 2 (bilateral mode)
Case 3 (unilateral mode + force telemetry graph)

 Completion time, the amount of lateral force during the insertion, and accuracy of recognizing the transition of the contact state were evaluated. In fact, we were not sure if this kind of task is possible under such a long time delay.

For the above three tasks (pushing, tracing, and peg-in-hole), 2D motion of the master handle was assigned to 2D translational motion of the robot arm in the vertical plane across the contouring slope and peg holes. Arm orientation and the remaining translational component were fixed by the on-board position controller.

4.4 Slide handle task

In the slide handle task, 2D motion of the master handle was assigned to 2D translational motion in the horizontal plane including the sliding direction. To make the sliding direction unknown to the operator, a certain amount of rotational coordinate transformation around the vertical axis of the plane was introduced.

At the initial stage, the peg attached to the tip of the robot arm is already inserted in the hole of the slide handle placed at the center of the slider guide. The operator should estimate the unknown sliding direction by probing the master handle. Then, he must move the robot to the end of the slider guide, then move to the other end, and finally move back to the center. The operator was asked to avoid lateral force (perpendicular to the sliding direction) as much as possible when moving the slide handle.

To complete the task, he must estimate the correct sliding direction and recognize when he reaches the end of the slider guide. The operator should complete the task within three minutes. After the task, the operator should report his estimation of the sliding direction. The following three cases were tried:

Case 1 (bilateral mode + force telemetry graph)
Case 2 (bilateral mode)
Case 3 (unilateral mode + force telemetry graph)

Completion time, the amount of lateral force during the sliding motion, and accuracy of the estimation of the sliding direction were evaluated. Again, before we conducted this experiment, we were quite uncertain whether or not the operator can complete this task.

4.5 Skill level and other psychological factors

Due to the limited time allowed for us, most of the experiments were carried out by a single operator, who has been accustomed with the operation using the master handle. To see the effect of skill level, other two operators conducted some tasks. One is a NASDA operator, who has been accustomed with the operation of ETS-VII robot arm by NASDA’s teleoperation facilities but is not familiar with the master handle used in this experiment. The other one is a novice operator, who has not been trained with any device, but has a background of teleoperation.

To investigate psychological factors such as mental load and points of their attention during the task, operators were asked to fill out a questionnaire after the experiment.

5 Experimental Results

The experiment was conducted on November 22, 1999. Round-trip time for communication between the control station at the NASDA Tsukuba Space Center and ETS-VII, which is flying around an orbit 550[km] above, was approximately six to seven seconds. Figure 12 shows the measured delay time at each experimental unit called
Figure 14: Result of pushing task (Task 1:B+T, Task 2:B, Task 3:U+T)

Table 1: Actual starting points and declared points by the operators

<table>
<thead>
<tr>
<th>Task Condition</th>
<th>Starting Point</th>
<th>Declared Point</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Task 1 (Bilateral + Telemetry)</td>
<td>A</td>
<td>C</td>
<td>×</td>
</tr>
<tr>
<td>Task 2 (Bilateral + Telemetry)</td>
<td>C</td>
<td>C</td>
<td>○</td>
</tr>
<tr>
<td>Task 3 (Unilateral + Telemetry)</td>
<td>C</td>
<td>C</td>
<td>○</td>
</tr>
<tr>
<td>Task 4 (NASDA Operator) (Bilateral + Telemetry)</td>
<td>C</td>
<td>C</td>
<td>○</td>
</tr>
<tr>
<td>Task 5 (longer operation time) (Bilateral + Telemetry)</td>
<td>B</td>
<td>B</td>
<td>○</td>
</tr>
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</table>

“path”, corresponding the duration time (about 40[min]) when the ETS-VII is visible from the TDRS (Tracking Data Relay Satellite) on Geostationary orbit. One can see that delay time differs at each path, but does not fluctuate so much within each path. Figures 7 and 8 show the snapshots during the slope tracing task experiment.

5.1 Pushing task

Figure 13 shows two typical examples of the force response in pushing task, bilateral mode and unilateral + telemetry mode, respectively. One can see that the bilateral mode reaches the desired force more quickly and accurately than the unilateral mode. Figure 14 summarizes the result of pushing task.

5.2 Slope tracing task

Table 1 shows the estimation result of the starting points. Except Task 1, the operators including the NASDA operator could estimate the starting points correctly. The reason of failure in Task 1 would be probably due to some psychological factors, such as a stress for the first trial. It should be noted, however, that in bilateral mode the shape estimation was confident and obtained with a little movement of the handle, whereas in unilateral mode the estimation was quite uncertain and obtained after the entire movement. Figure 15 explains the reason of this observation. This figure shows typical arm trajectories (top) and force responses (bottom) in bilateral mode and unilateral + telemetry mode, respectively. In the bilateral mode, the trajectory of master handle reproduces the slope shape while in unilateral mode it is difficult to estimate the slope shape from the master handle trajectory. From the force response, one can see that sometimes the robot arm lost contact with the tracing slope in unilateral mode. It also shows tracing the slope in unilateral mode is difficult.

Figure 16 summarizes the experimental results in tracing task. The stroke in unilateral mode was reduced 20[mm] shorter than the initial plan to complete the task within the time limit. Like the pushing task, one can see that the bilateral mode keeps the desired force more accurately and complete the task faster than the unilateral mode.

It should be noted that the task performance of the NASDA operator, who used this system first time, was quite uncertain and obtained after the entire movement. Figure 15 explains the reason of this observation. This figure shows typical arm trajectories (top) and force responses (bottom) in bilateral mode and unilateral + telemetry mode, respectively. In the bilateral mode, the trajectory of master handle reproduces the slope shape while in unilateral mode it is difficult to estimate the slope shape from the master handle trajectory. From the force response, one can see that sometimes the robot arm lost contact with the tracing slope in unilateral mode. It also shows tracing the slope in unilateral mode is difficult.

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5.3 Peg-in-hole task

Figure 17 shows the arm trajectories in the peg-in-hole task. In the figure, the actual peg position when the operator judged as the starting point of the insertion is also drawn. One can see that in bilateral mode the operator could identify the transition of contact state accurately only from the force feedback information. On the other hand, the recognition of reaching to the bottom of the hole was better when using telemetry data than using force feedback from the master handle. Figure 18 shows the result of peg-in-hole task. Unexpectedly, unilateral mode gave smaller lateral force than bilateral mode. Probably the operator moved the arm more carefully in the unilateral mode. No significant difference was found in completion time.

5.4 Slide handle task

Table 2 shows the result of sliding direction estimation by the operators. In all cases, they could estimate the sliding direction with reasonable accuracies. It should be noted, however, that in bilateral mode the estimation was confident and obtained with a little movement of the handle, whereas in unilateral mode the estimation was quite uncertain and obtained after the entire movement, which is the same observation as in the slope tracing task. Figure 19 shows a typical example of the hand trajectory in the slide handle task. In the figure, the inserted rotational transformation was canceled so that master and slave trajectories coincide in the ideal situation. One can see that the operator moved the handle into a wrong direction at the beginning but shifted to the correct direction later, feeling the force feedback from the handle.

All operators including the NASDA operator and the novice operator could complete the task in bilateral mode. In unilateral mode, however, the operator could move the handle only in half way and could not complete the task within the assigned time. The NASDA operator performed only probing task to estimate the sliding direction, since we did not explain him the task procedure adequately.

Figure 20 shows the result of slide handle task. Lateral force could not be reduced in bilateral mode, because the operator exerted large lateral force when probing the sliding direction. After the direction was estimated, the lateral force was small.

5.5 Discussion

From the questionnaire survey after each task, the following observations are obtained:

- All three operators paid most attention to the force feedback from the master handle even when the telemetry force data was displayed on the screen.
- Using the kinesthetic force feedback information, the operators could recognize the shape of the contouring slope and the peg hole entrance with just a small movement. It is difficult, however, to recognize the instant of contact (e.g., when reaching the bottom of

Table 2: Sliding directions and declared directions

<table>
<thead>
<tr>
<th>Task</th>
<th>Rotational angle[deg]</th>
<th>Declared angle[deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Task 1 (Bilateral + Telemetry)</td>
<td>−75</td>
<td>−65</td>
</tr>
<tr>
<td>Task 2 (Bilateral)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Task 3 (Unilateral + Telemetry)</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>Task 4 (NASDA Operator)</td>
<td>60</td>
<td>45</td>
</tr>
<tr>
<td>Task 5 (Novice Operator)</td>
<td>60</td>
<td>45</td>
</tr>
</tbody>
</table>
the hole), due to the low position gain.

- Telemetry force data was noisy and difficult to use for shape recognition. The data should have been pass through a low-pass filter.

- Even a novice operator could complete the task, showing that no specific skill is required.

It was surprising even for us that the kinesthetic force feedback information was still useful and could improve the task performance even under such a long time delay. Of course, the task should be performed slowly and the maneuverability would be poorer than the case without time delay. However, this experiment has proven that it is still possible to complete some tasks by direct bilateral control under 6-7[sec] time delay condition.

6 Conclusion

In this paper, the result of ground-space teleoperation experiment using a robot arm mounted on ETS-VII was shown. Stability condition of the PD-type bilateral controller was derived and the controller was modified due to the limitation of on-board robot controller of ETS-VII. Several tasks, such as wall following task and peg-in-hole task, were carried out under 6-7[sec] time delay condition. All the tasks were possible by the direct bilateral control even without visual information. The experimental results demonstrate that force feedback to the operator is still helpful even under such a long time delay.

Time delay limitation depends on the difficulty of the task. Therefore, even if the delay time becomes longer than 1[sec], some tasks would be possible by direct bilateral teleoperation. This experiment is probably the first ground-space teleoperation by direct bilateral control.

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References


