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Sliding Mode Control of Bilateral Teleoperation Systems with Force-Reflection on the Internet

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Abstract

In [1], it was shown that a regular sliding-mode controller is difficult to be used in bilateral teleoperation systems with varying time delay in that its nonlinear gain should be set based on the worst time delay. As an alternative to the regular sliding-mode controller, a modified sliding-mode controller was proposed to compensate the varying time delay and to guarantee its nonlinear gain to be independent of the magnitude of the time delay. In this paper, the validity of the proposed control scheme proposed is demonstrated by a series of experiments with a 1-dof master/slave teleoperation system. In the experiments, it is shown that the proposed controller effectively compensates the effects of the varying time delay even when the magnitude of the delay, i.e., RTT (Round-Trip Time) in the communication line becomes as large as 4.0 s, while the performance of the regular sliding-mode controller deteriorates, especially with a large value of the force scaling factor.

1 Introduction

The capability of force-feedback and force-reflection in teleoperation systems can improve their performance considerably. A solution to the difficulty in stably controlling such a bilateral teleoperation system when there exists a constant communication time-delay between the master and the slave was suggested based on the network transmission theory and passivity [2].

Currently, more and more computer networks such as the Internet are being used as the communication channel of bilateral teleoperation systems due to the fact that those with computer networks are easier to implement and have higher flexibility than those with a some kind of dedicated private communication channels. However, one problem associated with computer networks is that the communication time-delay between the master and the slave is not only significantly large but also keeps *changing* depending on the network conditions, which could make the overall system unstable.

Anderson and Spong [2] pointed out that even a small *constant* time delay can make bilateral systems unstable and certainly degrade the operator's intuition and performance. Several control methods have been proposed to overcome the stability problem associated with a varying time-delay. Kim et al. [3] used force reflection and shared compliant control to increase the maximum force reflection gain. And they reported that low-pass filtered force reflection combined with compliance control enables force reflection gains of up to two or three for dissimilar master/slave system. Oboe and Fiorini [4] presented a design environment for the identification, control design, and test of a telerobotic system connected to the Internet. They also proposed a quasi-optimal estimator to compensate small data losses. Brady and Tarn [5] discussed a description of the delays inherent in communication channels and presented a state space model taking into account the time-varying nature of the delay. But the proposed architecture is just unilateral. Yokokohji et al. [6] proposed a control scheme based on wave variables to minimize the performance degradation due to varying time delay. But, their method does not maintain the passivity rigorously, i.e., the entire system may be unstable.

In general, sliding-mode control is a good solution to guarantee stability robustness, in our case, to the varying time-delay between the master and the slave. In a regular sliding-mode controller, however, the sliding condition requires that its nonlinear gain should be determined depending on a function that implicitly depends on the time delay, and external forces exerted at the slave as well as scaling factors [1]. Thus, it is necessary to estimate or measure the varying time delay between the master and the slave, the maximum difference in contact force exerted on the slave, and scaling factors in order to use the regular sliding-mode controller. However, it is not so easy to measure the time delay between the master and slave precisely and on-line. Moreover, the nonlinear gain becomes very large as the scaling factors increase and/or the maximum difference in contact force becomes large, which may lead to actuator saturations and excessive input chatterings.

In this paper, a control method, so called modified sliding-mode control, based on the sliding-mode control but with a slight modification to the structure of the communication system, is introduced. Its advantage is that its nonlinear control gain can be selected *independent* of the time delay between the master and the slave. Its stability as well as performance is investigated with experiments.

Section 2 describes the dynamics of the bilateral teleoperation system and the Internet protocol used in this paper. Section 3 summarizes the impedance controller for the master and the regular and modified sliding controller for the slave with a local compliance capability. Experiments with a single dof teleoperation system and their results are shown in Section 4, followed by conclusions in Section 5.

2 Network and Dynamic Models

For the bilateral teleoperation, the information on the slave force only is sent to the master, while the information on the position, velocity and force of the master and slave are transmitted to the slave. The information exchanges are done by a communication protocol such as TCP, UDP, and ICMP. In this paper, the TCP is used as the Internet protocol in order to prevent abrupt changes in the data, which could occur in UDP, using its *error recovery* and *reordering* capability.

The dynamics of the single dof master/slave system are modeled as a mass-damper system as follows:

$$M_m \ddot{x}_m + B_m \dot{x}_m = u_m + f_h \quad (1)$$
$$M_s \ddot{x}_s + B_s \dot{x}_s = u_s - f_e \quad (2)$$

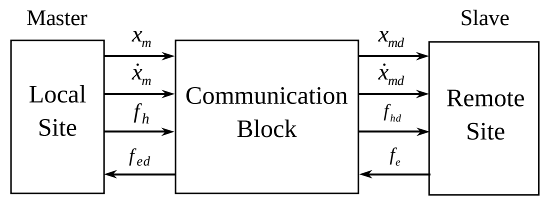

Figure 1: A block diagram of bilateral teleoperation.

where x and u denote position and torque; M and B denote mass and viscous coefficient; subscript 'm' and 's' denote the master and the slave, respectively; f_h is the force applied at the master by the operator, and f_e is the force exerted on the slave by its environment.

3 Controller Design

In this section, two control schemes for the master and the slave to use delayed position and force information are explained: impedance control for the master and sliding-mode control for the slave.

These controllers are designed based on a typical position-force teleoperation. The force-controlled master device reflects to the human operator the contact force between the slave and its environment while the position-controlled slave follows the trajectory of the master.

3.1 Delayed Signals and Scaling Factors

A bilateral teleoperation system can be represented by a diagram with 3 blocks as in Fig. 1. In Fig. 1, x_{md}, $\dot{x}_{md}$, and f_{hd} are the position, velocity commands and the operating force, respectively, transmitted from the master to the slave. Using the Internet as the communication line, the time delay between the master and slave varies differently with the direction as well as the network condition. Thus, the related signals at the communication block can be represented by

$$x_{md}(t) = x_m(t - T_1(t)) \quad (3)$$
$$\dot{x}_{md}(t) = \dot{x}_m(t - T_1(t)) \quad (4)$$
$$f_{hd}(t) = f_h(t - T_1(t)) \quad (5)$$
$$f_{ed}(t) = f_e(t - T_2(t)) \quad (6)$$

where $T_1(t)$ is the time delay of the signal flowing from the master to the slave, and $T_2(t)$ is the time delay of the signal flowing in the opposite direction. Note that these delays vary with respect to time t.

These delayed signal out of the communication block is then scaled down or up with some factors. Using the scaling factors of the position/velocity and the force, the the position/velocity command to the slave and the force command to the master are modified such that

$$x_s = k_p x_{md} \tag{7}$$
$$f_h = k_f f_{ed} \tag{8}$$

where k_p and k_f are the position and force scaling factors, respectively, the values of which are to be selected appropriately depending on the characteristics of given tasks.

3.2 Control of the Master

With the impedance control, the desired characteristics between the human force and the external force can be selected appropriately. Suppose that the desired impedance for the master is specified by

$$M\ddot{x}_m(t) + B\dot{x}_m(t) + Kx_m(t) = f_h(t) - k_f f_{ed}(t) \tag{9}$$

where M, B and K are the desired inertia, damping coefficient, and stiffness, respectively.

Combining Eqs. (9) and (1) and removing acceleration $\ddot{x}_m$ result in the control input to the master:

$$u_m(t) = \left(B_m - \frac{M_m B}{M}\right)\dot{x}_m(t) + \left(\frac{M_m}{M} - 1\right) f_h(t) - \frac{M_m}{M}\{k_f f_{ed}(t) + Kx_m(t)\}. \tag{10}$$

3.3 Control of the Slave

The main function of the sliding-mode controller for the slave is to track the trajectory of the master. Here, the regular slding-mode controller and the modified sliding-mode controller in [1] are summarized with more details of the latter.

3.3.1 Regular Sliding-Mode Controller

Let $\tilde{x}_d(t) = x_s(t) - k_p x_{md}(t)$ be the tracking error between the master position and the slave position. Suppose also that a sliding surface, $s_d(t)$ is defined as

$$s_d(t) = \dot{\tilde{x}}_d(t) + \lambda\tilde{x}_d(t) \tag{11}$$

where λ is a strictly positive constant. Based on the equivalent control [7], which is obtained by the condition of $\dot{s}_d = s_d = 0$, substituting Eqs. (3), (4) and (9) into Eq. (2), and considering the uncertainty in the estimate of the external force from the slave, the control law of the sliding-mode control is obtained:

$$u_s(t) = B_s\dot{x}_s(t) + f_e(t) - \frac{k_p M_s}{M}\{B\dot{x}_{md}(t) - f_{hd}(t) + k_f f_e(t) + Kx_{md}(t)\} - M_s\lambda\dot{\tilde{x}}_d(t) - K_{gain}\cdot \text{sat}\left(\frac{s_d(t)}{\Phi}\right) \tag{12}$$

where K_{gain} is the nonlinear gain, sat$(\cdot)$ is a saturation function, and Φ is the thickness of the boundary layer to reduce the chattering in the control input.

To satisfy the sliding condition of $\dot{s}_d s_d \leq -\eta|s_d|$, nonlinear gain, K_{gain}, should be selected such that

$$K_{gain} \geq M_s\eta + k_p k_f \frac{M_s}{M}\cdot |f_e(t) - f_e\left(t - T_1(t) - T_2(t - T_1(t))\right)| \tag{13}$$

If a set of task requirements forces that gain product $k_p k_f$ should not be smaller than a certain level, the nonlinear control gain in Eq. (13) could become very large, especially when the time delay, T_1 or T_2, is large and the external force, $f_e(t)$, is high, thus causing a high level of chatterings.

3.3.2 Modified Sliding-Mode Controllers

To keep the system performance independent of the variation in the time delay and to suppress the chattering level, the modified sliding-mode controller is proposed based on a slightly different system structure as shown in Fig. 2, which has one more additional channel of a force signal from the master to the slave.

The resulting control law differs from Eq. (12) only in the term related with the external force, $f_e(t)$. The control of the modified sliding-mode controller is:

$$u_s(t) = B_s\dot{x}_s(t) + f_e(t) - \frac{k_p M_s}{M}\{B\dot{x}_{md}(t) - f_{hd}(t) + k_f f_e\left(t - T_1(t) - T_2(t - T_1(t))\right) + Kx_{md}(t)\} - M_s\lambda\dot{\tilde{x}}_d(t) - K_{gain}\cdot \text{sat}\left(\frac{s_d(t)}{\Phi}\right) \tag{14}$$

Note that $T_2(t - T_1(t))$ is used instead of $T_2(t)$ in Eq. (14). The delayed external force signal can be obtained easily by just sending it to and receiving it from the master (refer to Fig. 3). There is no need to measure the time delay in each direction and store the external force data.

Next, the property of the proposed controller is investigated in the following analysis. If the master is appropriately controlled by the impedance controller,

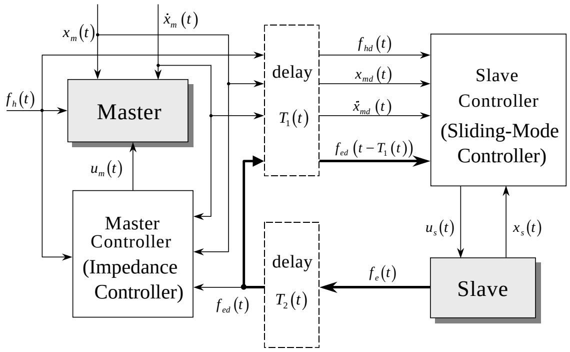

Figure 2: The overall system block diagram.

Eq. (10), the controlled master will behavior according to the desired impedance model, Eq. (9). And the controlled slave dynamics can be found as follows:

$$\begin{aligned} &M\ddot{x}_s(t) + k_p\{B\dot{x}_{md}(t) - f_{hd}(t) \\ &+k_f f_e(t - T_1(t) - T_2(t - T_1(t))) + Kx_{md}(t)\} \\ &+\frac{M}{M_s}K_{gain}\cdot \text{sat}\left(\frac{s_d(t)}{\Phi}\right) + M\lambda\dot{\tilde{x}}_d = 0. \qquad (15) \end{aligned}$$

Using the delayed impedance model by $T_1(t)$, the braced term in Eq. (15) can be substituted with $-M\ddot{x}_m$. Expressing Eq. (15) in terms of $s_d(t)$ gives:

$$\dot{s}_d(t) + \frac{K_{gain}}{M_s}\cdot \text{sat}\left(\frac{s_d(t)}{\Phi}\right) = 0 \qquad (16)$$

$$K_{gain} \geq M_s\eta. \qquad (17)$$

Since the boundary of K_{gain} to satisfy the sliding condition not the function of time delay, the time delay effect can be neglected when the nonlinear gain is selected.

3.4 Local Compliance to Reduce Impact Force

In the Internet-based communication, there exists communication time delay, which frequently becomes very large due to the network congestion. Under a large communication time-delay, the slave must depend on the delayed commands from the master. Such delayed commands would force the slave move toward a wall or an obstacle *as before* even though at that moment the master sends commands to stop the slave or to reduce the speed of the slave in an effort to avoid collisions. This would result in an impact of significant magnitude, which may damage the system and the environment.

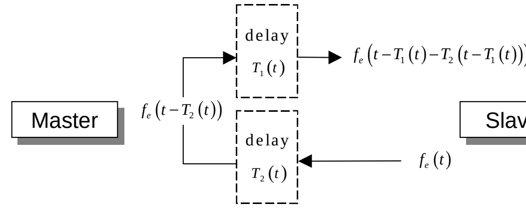

Figure 3: Delayed force signals for the modified sliding-mode controller.

In this paper, a local compliance control is introduced to reduce such an impact force, based on a linear impedance model:

$$M_c\ddot{x}_s(t) + B_c\dot{x}_s(t) + K_c\{x_s(t) - x_c\} = f_e(t) \qquad (18)$$

where M_c, B_c, and K_c are impedance parameters for a local compliance; x_c is a slave position when a contact occurs. Using this model, a control input, $u_c(t)$, for the slave during contact is:

$$\begin{aligned} u_c(t) \;=\; &\left(B_s - \frac{M_s}{M_c}B_c\right)\dot{x}_s(t) + \left(1 + \frac{M_s}{M_c}\right)f_e(t) \\ &-\frac{M_s}{M_c}K_c\{x_s(t) - x_c\} \qquad (19) \end{aligned}$$

4 Experiments

In this section, the performance of the regular and the modified sliding-mode controllers is compared in experiments with a 1-dof bilateral teleoperation system. The slave is driven by an AC motor as shown in Fig. 4. It can move straight back and forth with a ball-screw mechanism and a load-cell is installed at its tip to measure the contact force exerted by the environment. In the experiments, a wall with a compliance of about 31,000 [N/m] is used as the environment that the slave makes contacts with.

Since the human operator cannot generate an identical trajectory each time of experiments, a sinusoidal trajectory with respect to the time is applied at the master in order to be able to compare two controllers under the identical conditions. Then, human forces, f_h, are calculated from the desired impedance model, Eq. (9), with the master trajectory and the external forces. These master position, velocity, and human force data are sent to the slave under the TCP/IP.

In order to investigate the performance of the controllers under a large time delay, the communication

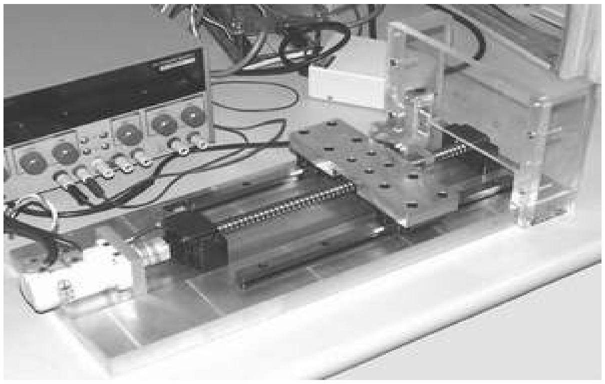

Figure 4: The slave system used in this experiment.

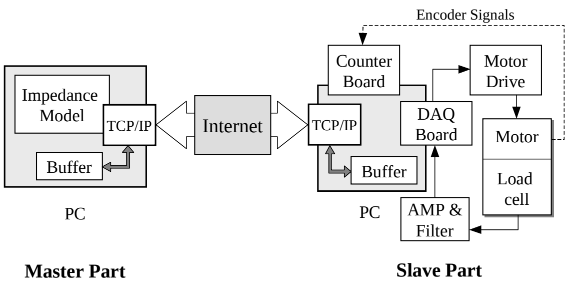

Figure 5: A detailed description of the master/slave system.

unit that introduces bilateral time delays is simulated with a memory buffer, in addition to the physical communication line. Data to be exchanged between the master and the slave is written to the buffer. It is sent to its intended destination only at the moment when the buffer is full. Thus, the time delay at the buffer depends on the size of the buffer. In the experiments, the buffer size is fixed at a constant value in each experiment. Another source of the time delay is the physical communication line. Thus, the average of the overall time delay or the RTT depends only on the size of the buffer, and its deviation is exactly that of the actual communication line. The detailed diagram of the entire system is given in Fig. 5.

In the experiments, the slave is controlled by the sliding-mode controller in free space and by Eq. (19) for a local compliance, during a contact motion. In a word, control inputs for the slave is switched according to the contact force and the sign of control input for the slave as Fig. 6. In Fig. 6, u_{slid} denotes the sliding mode controller, Eq. (12) or (14), and u_{imp} denotes the impedance controller in Eq. (19). And it is assumed that the minus sign of u_{slid} would generate backward motions of the slave.

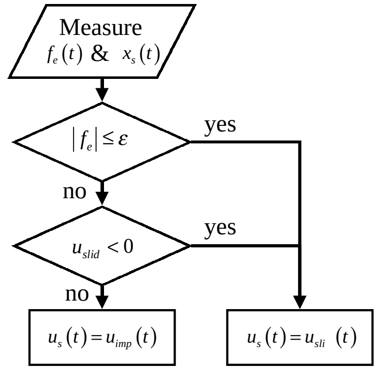

Figure 6: Flow chart for the control input selection.

Table 1: The parameters for the experiments

k_p	50 [mm/rad]	k_f	1.0
Φ	0.5	K_{gain}	85.0
λ	0.5	ε	0.05 [N]

In the experiments, the buffer size is selected such that the RTT varies slightly at around 1.5 s. The sinusoidal trajectory of the master and the human force are sent to the slave, and the slave follows the reference trajectories with the sliding-mode controller. The parameters for the experiment are summarized in Table 1. With the regular sliding-mode controller, the slave makes unstable contacts with the environment and shows poor tracking performance, as can be seen in Fig. 7. In this case, the nonlinear gain of the slave, K_{gain}, is set too low to satisfy its sliding condition.

On the other hand, the slave with the modified sliding-mode controller of the same nonlinear gain as in the regular sliding-mode controller shows stable contacts with the wall as well as good tracking performance in the free space, as can be seen in Fig. 8.

The proposed controller also performs the task well even when the force scaling factor and time delay (RTT) are further increased up to 10 and $\approx$ 4 s, respectively (refer to Fig. 9).

5 Conclusions

The modified sliding-mode controller, whose nonlinear gain is independent of the variation in the communication time delay, is derived. In experiments, with the modified sliding-mode controller, the sliding surface, $s(t)$, converges to the bounded small area effectively in spite of large time delay and increasing

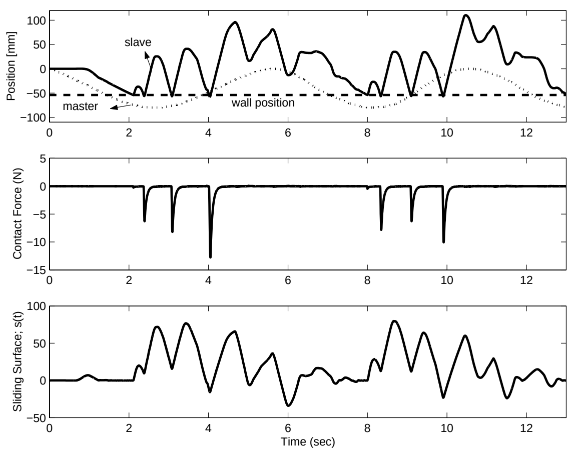

Figure 7: Position, external force, and sliding surface with the regular SMC (RTT≈1.5 s).

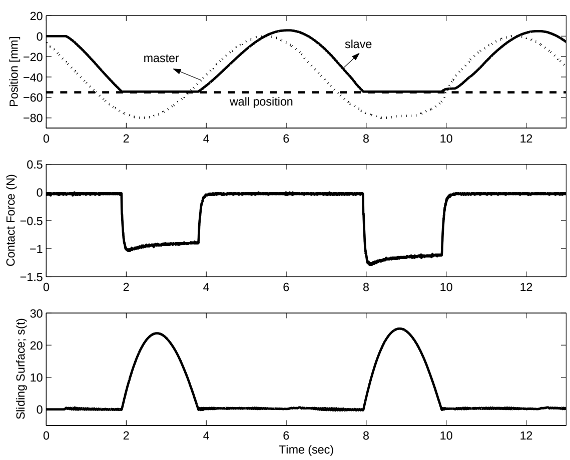

Figure 8: Position, external force, and sliding surface with the modified SMC (RTT≈1.5 s).

force scaling factor, $k_p k_f$. On the other hand, the regular sliding mode controller shows unstable behaviors with large $k_p k_f$ and varying time delay. In conclusion, the sliding-mode controller using delayed force signals has a capability to cope with large time-varying delays and scaling factor product, making itself a suitable candidate for Internet-based bilateral teleoperation systems. As any other position-based control scheme, it needs a kind of local compliance control to reduce impact at the collision between the slave and the environment.

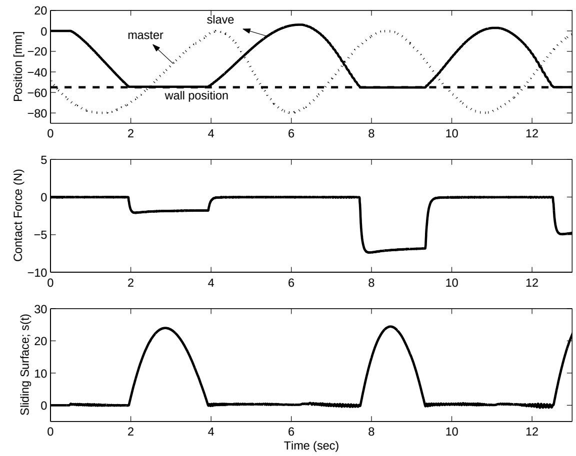

Figure 9: Position, external force, and sliding surface with the modified SMC (RTT≈4.0 s).

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