

# Delay compensation in bilateral control using a sliding mode observer\*

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## Abstract

*In bilateral control applications, time delays in the communication channel have destabilizing effects and cause degradations in the performance of the system. In this paper, a sliding mode observer is used in conjunction with a disturbance observer to predict states of the slave system. Predicted states are then used in control formulation. Simulation and experimental results show that the proposed method avoids instability due to time delays in bilateral operation and provides satisfactory performance.*

**Key Words:** Bilateral control, teleoperation, sliding mode observer, disturbance observer, time delay

## 1. Introduction

There are many tasks which are difficult, if not impossible, for human operators to perform due to hostile work environments. Working in dangerous and unhealthy environments, exploring deep oceans and performing maintenance on the space station have become possible by bilateral teleoperation.

One of the major problems in bilateral teleoperation applications is the delay in the communication channel. The delay can be expressed as the latency of the shared signals between the master and slave sides. Due to the inevitable delay, which has a destabilizing effect on bilateral teleoperation, identical impedances at both sites (transparency) cannot be achieved. Delays can be constant or time variable depending on the communication medium. With the increasing use of Internet, it became necessary to consider time variable delays.

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In the literature there are many studies on the delay compensation problem including scattering variables, wave variables, observers, sliding mode and optimal control methods [1]-[12]. Scattering variables theory [1]-[4] is a passivity based approach which uses the transmission line theory. The data transmission between the systems is designed such that the transmission line becomes lossless and thus passivity is preserved. This method is first proposed for constant delays and then extended to the variable delays. Although stability of the system is guaranteed through passivity based on the scattering transformation, transparency of the system is not considered. Wave variables theory [5], [6] is developed as a reformulation of the scattering theory. While scattering variables are more electrical in nature, wave variables are defined using physical variables. In wave based method, damping is injected into the transmission line to render it passive. Some other methods in the literature consider the delay as a network disturbance and design an observer (communication disturbance observer) to compensate for this disturbance [7], [8]. Although these methods guarantee stability, their transparency analyses are not provided. Sliding mode based methods [9], [10], consider the delay as an uncertainty on the system. By using sliding mode controllers, robustness of the system against the delay is maintained. In the literature, there are also some approaches [11], [12] that seek an optimal solution to the delay problem by evaluating both stability and performance criteria.

Bilateral teleoperation can be designed in different ways in terms of the type of the signals that are shared between the master and the slave systems over the communication channel. In [1]-[6], velocity reference is sent from the master to the slave side. The control signal for the slave is generated by using this velocity reference. Environmental force information on the slave side is measured and sent to the master side via the communication channel. In observer based architectures ([7], [8]), the control signal of the slave is generated at the master side and sent over the communication channel while the position information of the slave is sent to the master side.

In this paper, a sliding mode observer is designed and used in conjunction with a disturbance observer to compensate for delays in bilateral teleoperation. Sliding mode observer is a predictor type observer which predicts states of the slave system. Predicted states are then used in the computation of the control signal for the slave system at the master side. Since the slave's states are predicted successfully, the overall system works as if delays do not exist in the system. The proposed method is easy to implement and produces satisfactory results both in simulations and experiments.

The rest of the paper is organized as follows: Time delay compensation using a sliding mode observer and a disturbance observer is detailed in Section 2. Simulation and experimental results are presented in Sections 3 and 4, respectively. Section 5 concludes the paper with some remarks and indicates possible future directions.

## 2. Delay compensation for a single degree of freedom system

A single degree of freedom slave system can be modeled by the following single link manipulator:

$$J\dot{\omega}(t) = -B\omega(t) + \tau(t) + d_o(t) \quad (1)$$

where  $\omega$  is the angular velocity of the link,  $\tau(t)$  is the control input to the actuator and  $d_o(t)$  is the external disturbance acting on the system.  $J$  and  $B$  are the inertia and the damping parameters associated with the link. In practice, only nominal values of these parameters are available.

In motion control applications, a disturbance observer is typically utilized to make the system robust to the external disturbances and plant parameter variations. Therefore, we will first introduce a disturbance observer and then design sliding mode observer for delay compensation.

### 2.1. Disturbance observer

Disturbance observer is a widely used method for estimating and rejecting the disturbances acting on motion control systems [13], [14]. The mismatch between the nominal and the actual parameters is considered as a disturbance. Therefore, not only external disturbances but also system parameter variations are compensated by a disturbance observer.

In light of Eqn. (1), denoting the nominal values with the subscript  $n$ , system parameters can be written as  $J = J_n + \tilde{J}$  and  $B = B_n + \tilde{B}$ . Substituting these expressions into Eqn. (1) implies

$$J_n \dot{\omega}(t) = -B_n \omega(t) + \tau(t) - \underbrace{\tilde{J} \dot{\omega}(t) - \tilde{B} \omega(t) + d_o(t)}_{d(t)} \tag{2}$$

where  $d(t)$  is the total disturbance to be estimated. To estimate the total disturbance, we solve Eqn. (2) for  $d(t)$  and take its Laplace transform, i.e.

$$D(s) = J_n s \Omega(s) + B_n \Omega(s) - \tau(s) \tag{3}$$

where  $D(s)$  and  $\Omega(s)$  are the Laplace transform of the total disturbance  $d(t)$  and the angular velocity  $\omega(t)$ , respectively. Due to the noncausal  $s\Omega(s)$  term,  $d(t)$  can not be estimated in practice. However, it can be estimated by utilizing a low-pass filter. To this end, both sides of Eqn. (3) is multiplied by the transfer function of a low-pass filter, ( $G(s) = \frac{g}{s+g}$ ), i.e.

$$\underbrace{\frac{g}{s+g} D(s)}_{\hat{D}(s)} = \frac{s}{s+g} J_n g \Omega(s) + \frac{g}{s+g} (B_n \Omega(s) - \tau(s)) \tag{4}$$

where  $\hat{D}(s)$  is an estimation of  $D(s)$ , i.e. low-pass filtered version of it, and it converges to  $D(s)$  at low frequencies. Replacing the term  $(\frac{s}{s+g})$  by  $(1 - \frac{g}{s+g})$  and rearranging the equation it follows that

$$\hat{D}(s) = J_n g \Omega(s) - \frac{g}{s+g} ((J_n g - B_n) \Omega(s) + \tau(s)) \tag{5}$$

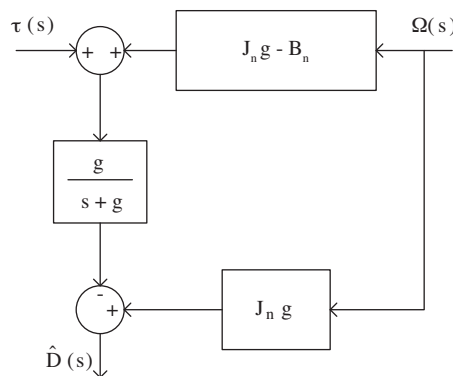


Figure 1. Estimation of total disturbance by disturbance observer.

A block diagram realization of the estimated disturbance is given in Figure 1. The total disturbance can be rejected by subtracting the estimated disturbance  $\hat{D}(s)$  from the input of the system. To this end, the modified control input,  $\tau(s) - \hat{D}(s)$ , is applied to the system defined by Eqn. (3)

$$D(s) = J_n s \Omega(s) + B_n \Omega(s) - \tau(s) + \frac{g}{s+g} D(s) \tag{6}$$

Rearranging Eqn. (6) implies

$$J_n s \Omega(s) + B_n \Omega(s) = \tau(s) + (1 - \frac{g}{s+g}) D(s) \tag{7}$$

If  $G(s) = \frac{g}{s+g} \approx 1$ , then the disturbance on the system is rejected and the system parameters are pushed to the nominal ones. Thus, the slave system becomes a nominal plant of the form

$$J_n \dot{\omega}(t) + B_n \omega(t) = \tau(t) \tag{8}$$

### 2.2. Sliding mode observer for delay compensation

In this section a sliding mode observer (SMO) will be designed for delay compensation. In light of Eqn. (8), nominal slave dynamics in state-space can be written as

$$\dot{p}_s(t) = \omega_s(t), \quad J_s \dot{\omega}(t) + B_s \omega(t) = u(t - T_1) \tag{9}$$

where  $T_1$  is the constant time delay from master to slave and  $u(t - T_1)$  is the control signal sent to the slave from the master side. On the other hand, the position of the slave  $p_s(t)$  will reach to the master side as  $p_d(t) = p_s(t - T_2)$  where  $T_2$  is the constant time delay from the slave to the master (see Figure 2). Since Eqn. (9) is defined for all  $t$ , we can replace  $t$  by  $t - T_2$  and substitute  $p_d = p_s(t - T_2)$  and  $\omega_d(t) = \omega_s(t - T_2)$ . As a result of these substitutions, we obtain the following differential equation in terms of delayed signals:

$$\dot{p}_d(t) = \omega_d(t), \quad J_s \dot{\omega}_d(t) + B_s \omega_d(t) = u(t - T) \tag{10}$$

where  $T = T_1 + T_2$  is the total round-trip delay.



Figure 2. Bilateral control system architecture.

In order to predict position (and/or velocity) of the slave system, we construct the following sliding mode observer (SMO):

$$\dot{\hat{p}}(t) = \hat{\omega}(t), \quad J_s \dot{\hat{\omega}}(t) = -B_s \omega_e(t) + u(t) + u_o(t), \quad \dot{p}_e(t) = \omega_e(t), \quad J_s \dot{\omega}_e(t) = J_s \dot{\omega}_d(t) - u_{o_{eq}}(t) \tag{11}$$

where  $\hat{p}(t)$  and  $\hat{\omega}(t)$  are observer's intermediate variables and  $p_e(t)$  and  $\omega_e(t)$  are estimated (or predicted) angular position and velocity of the slave. SMO input and its equivalent part are denoted as  $u_o(t)$  and  $u_{o_{eq}}(t)$ .

In order to design the observer input, an observer error is defined as  $e(t) = p_d(t) - \hat{p}(t)$ . Since the observer input will be designed in SMC (sliding mode control) framework, a sliding surface is defined in terms of observer error as

$$\sigma = \dot{e}(t) + C e(t) \quad (12)$$

where  $C > 0$  is the slope of the sliding surface. In sliding mode control (SMC) theory, the control that keeps the system on the sliding surface is called *equivalent control*. Since  $\sigma = 0$  when the system is on the sliding surface, equivalent control can be computed by setting  $\dot{\sigma}$  to zero, i.e.

$$\ddot{e}(t) + C \dot{e}(t) = 0 \quad (13)$$

The first and the second derivatives of the observer error are calculated as

$$\dot{e}(t) = \dot{p}_d(t) - \dot{\hat{p}}(t) = \omega_d(t) - \hat{\omega}(t), \quad \ddot{e}(t) = \dot{\omega}_d(t) - \dot{\hat{\omega}}(t) = \dot{\omega}_d(t) + \frac{B_s}{J_s} \omega_e(t) - \frac{1}{J_s} u(t) - \frac{1}{J_s} u_o(t) \quad (14)$$

Substituting  $\dot{e}(t)$  and  $\ddot{e}(t)$  into the equation Eqn. (13), we get the so-called equivalent control, i.e.

$$u_{oeq}(t) = J_s \dot{\omega}_d(t) + B_s \omega_e(t) - u(t) + J_s C \dot{e}(t) \quad (15)$$

Observer input can be written as the sum of the equivalent control  $u_{oeq}(t)$  and a discontinuous term,  $K \operatorname{sgn}(\sigma)$ , i.e.

$$u_o(t) = u_{oeq}(t) - K \operatorname{sgn}(\sigma) \quad (16)$$

where  $K > 0$  is a gain parameter and  $\operatorname{sgn}(\cdot)$  denotes the well-known signum function. Using a Lyapunov analysis, it is straightforward to show that the control law given in Eqn. (16) can bring the system onto the sliding manifold from arbitrary initial conditions and asymptotically stabilize there. Substituting the equivalent control given by Eqn. (15) into the last equation of Eqn. (11) implies

$$J_s \dot{\omega}_e(t) = -B_s \omega_e(t) + u(t) - J_s C \dot{e}(t) \quad (17)$$

Replacing  $t$  by  $t + T$  in the second equation of Eqn. (10) implies

$$J_s \dot{\omega}_d(t + T) + B_s \omega_d(t + T) = u(t + T - T) = u(t) \quad (18)$$

Subtracting Eqn. (18) from Eqn. (17) and defining  $\tilde{\omega}(t) = \omega_e(t) - \omega_d(t + T)$ , we obtain

$$J_s \dot{\tilde{\omega}} + b_s \tilde{\omega} = -J_s C \dot{e}(t) \quad (19)$$

At steady state, system trajectories are on the sliding surface ( $\sigma = 0$ ), and therefore both the observer error and its derivative converge to zero. Therefore, solution of Eqn. (19) as  $t \rightarrow \infty$  is given as  $\lim_{t \rightarrow \infty} \tilde{\omega}(t) = 0$ . As a result, it follows that  $\lim_{t \rightarrow \infty} \omega_e(t) = \omega_d(t + T)$ . Recall that  $\omega_d(t) = \omega_s(t - T_2)$ , and so  $\omega_d(t + T) = \omega_s(t + T - T_2) = \omega_s(t + T_1)$ . Thus, we reach the following important result

$$\lim_{t \rightarrow \infty} \omega_e(t) = \omega_d(t + T) = \omega_s(t + T_1) \quad (20)$$

Note that the sliding mode observer predicts future values of slave's velocity. Estimated velocity  $\omega_e(t) = \omega_s(t + T_1)$  and its integral  $p_e = p_s(t + T_1)$  can be used in controller design. Control signal  $u(t)$  for the slave can be designed as

$$u(t) = f(X_e(t)) = f(p_e(t), \omega_e(t)) \quad (21)$$

where  $f(\cdot)$  is a linear or nonlinear function. For instance,  $f(\cdot)$  could represent a linear control such as PID or a robust nonlinear control such as SMC (sliding mode control). Since the designed control input is delayed by  $T_1$  through the channel, slave control input  $\tau(t)$  can be written as

$$\tau(t) = u(t - T_1) = f(p_e(t - T_1), \omega_e(t - T_1)) = f(p_d(t + T_2), \omega_d(t + T_2)) = f(p_s(t), \omega_s(t)) \quad (22)$$

Equation (22) shows that the slave control input  $\tau(t)$  is designed in terms of non-delayed signals, and therefore the slave system is automatically stable.

### 3. Simulations

Performance of the proposed method is tested in Matlab/Simulink environment. Both constant and variable delays are considered. Figure 3(a) shows that the system becomes unstable even under small delays, i.e.  $\tau = 0.1$  sec, in the communication channel.

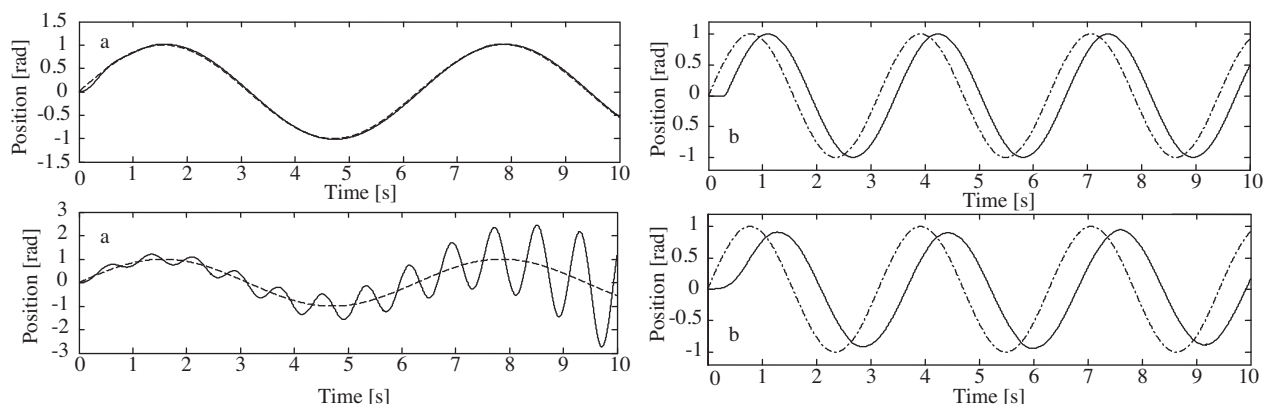


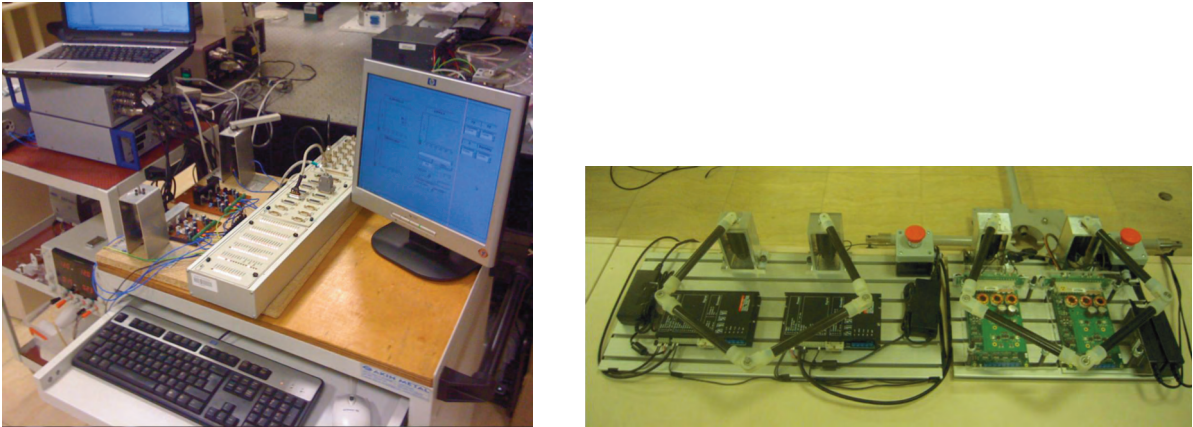
Figure 3. Delay compensation with SMO.

In the plots, dashed lines denote the reference positions whereas the solid lines denote the actual link position.

When the sliding mode observer is activated, result for a 0.3 sec constant delay in the communication channel is presented in the first plot of Figure 3(b). Second plot of Figure 3(b) presents the result of a simulation for a randomly varying delay which is characterized by a gaussian distribution of mean 0.8 and variance 0.04. Nominal parameters, which are taken to be  $\pm 15\%$  different from the actual parameters, are used in sliding mode observer. The parameter uncertainties are eliminated by the disturbance observer. These two simulation results show that the proposed method successfully compensates for the constant and randomly varying delays in the communication channel.

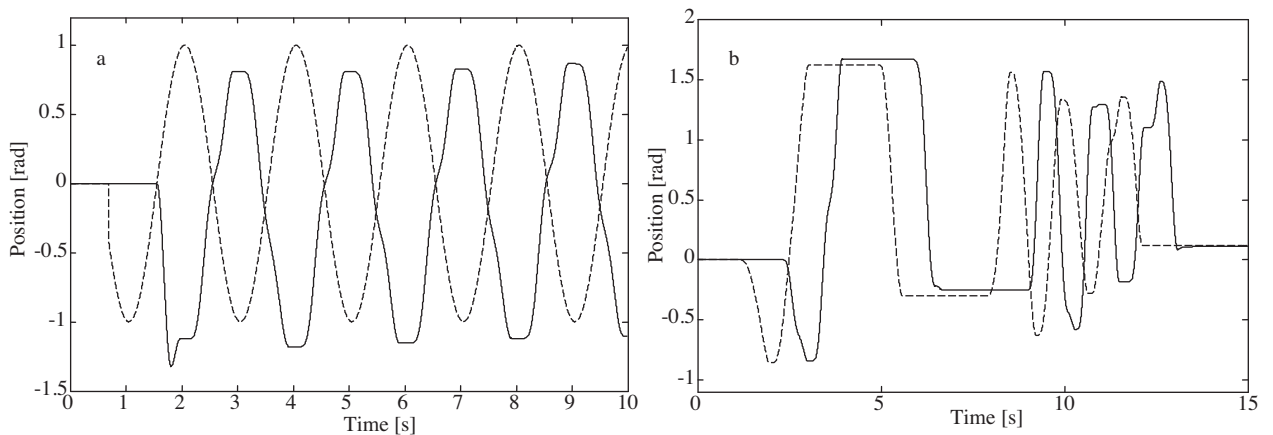
### 4. Experimental results

Experiments are carried out with a Maxon RE26 motor and a pair of pantograph robots to test the performance of the proposed method in both linear and nonlinear systems. Control algorithms are implemented using Dspace 1102 real-time controller board. Delay is generated by the Variable Time Delay block in Simulink. Experimental setups are shown in Figure 4. SMO based time delay compensation method is first implemented on a DC motor



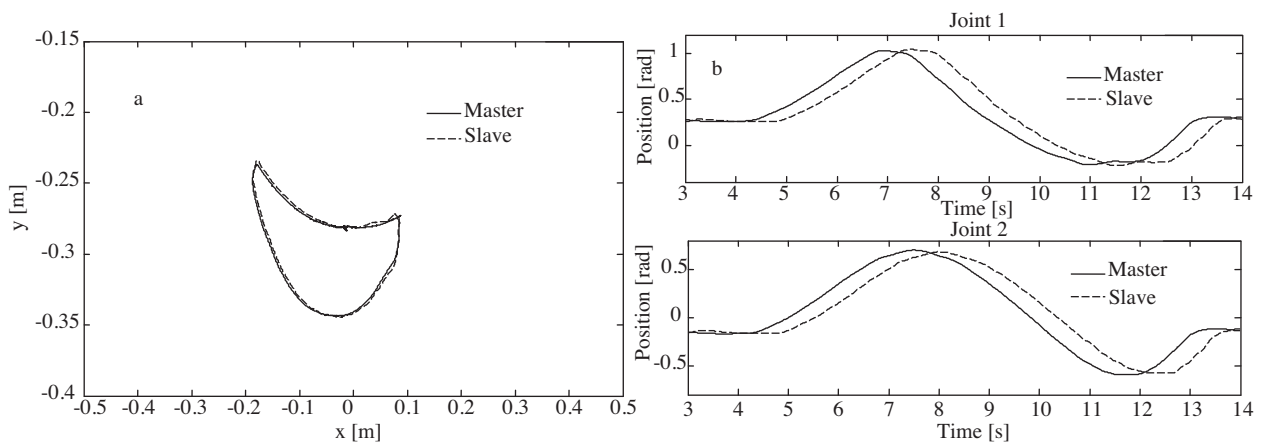
**Figure 4.** Experimental setups.

to see the effectiveness of our proposed approach. In Figure 5(a), response of the system to a sinusoidal reference is shown where a randomly varying delay of mean 1 sec and standard deviation 50 msec is used. Note that the response is stable and has little distortion. Experiments are also performed with random references generated by a human operator while there exists variable delay in the communication channel (Figure 5(b)).



**Figure 5.** Experiments with variable delay.

Second, delay compensation method is implemented on pantograph robots which have nonlinear dynamics. In the experiments, the end-effector positions of the pantographs in  $x - y$  plane and their joint angles versus time are examined. Pantographs are allowed to work in a bilateral teleoperation system by introducing a variable time delay characterized by a normally distributed random variable of mean 0.5 sec and standard deviation 0.025 sec. In the experiment, the human operator holding the end-effector of the master pantograph draws a free-form closed curve. As shown in Figure 6(a), the end-effector of the slave pantograph successfully tracks the trajectory drawn by the master pantograph. Angular joint positions of pantographs are depicted in Figure 6(b). Note that joint angles of the slave pantograph follow those of the master with a delay. This is inevitable since the future values of the reference generated by human operator can not be known in advance.



**Figure 6.** Bilateral teleoperation with pantograph robots.

## 5. Conclusions and future work

It has been shown that a sliding mode observer can be used in conjunction with a disturbance observer to predict states of the slave robot and control laws which utilize these predicted states imply a stable bilateral teleoperation system. Performance of the proposed method is quite satisfactory as verified with several simulations and experiments.

As a future work, the proposed approach will be extended to the force reflecting bilateral teleoperation.

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## References

- [1] R. J. Anderson , M. W. Spong, "Bilateral control of teleoperators with time delay", Proc. of International Conference on Systems, Man and Cybernetics, 1988.
- [2] R. Lozano, N. Chopra, M. W. Spong, "Passivation of Force Reflecting Bilateral Teleoperators with Time Delay", Proceedings of 8. Mechatronics Forum, 2002.
- [3] N. Chopra, M. W. Spong, "Bilateral Teleoperation Over the Internet: Time Varying Delay Problem", Proceedings of American Control Conference, 2003.
- [4] N. Chopra, P. Berestesky, M. W. Spong, "Bilateral Teleoperation Over Unreliable Communication Networks", IEEE Transactions on Control Systems Techology, 2008.
- [5] G. Niemeyer, J. E. Slotine, "Stable Adaptive Teleoperation", IEEE Journal of Oceanic Engineering, 1991.
- [6] G. Niemeyer, J. E. Slotine, "Towards Force Reflecting Teleoperation Over Internet", International Conference on Robotics and Automation, 1998.



- [7] K. Natori, T. Tsuji, K. Ohnishi, A. Hacı, K. Jezernik, "Robust Bilateral Control with Internet Communication", Conference of the IEEE Industrial Electronics Society, 2004.
- [8] K. Natori, K. Ohnishi, "Time Delay Compensation in Bilateral Teleoperation Systems", IEEE 3rd International Conference of Mechatronics, 2006.
- [9] L. G. Garcia-Valdovinos, V. Parra-Vega, M. A. Arteaga, "Observer-based Sliding-Mode Impedance Control of Bilateral Teleoperation under Constant Unknown Time Delay", International Journal of Robotics and Autonomous Systems, 2007.
- [10] J. H. Park, H. C. Cho, "Sliding-Mode Controller for Bilateral Teleoperation with Varying Time Delay", International Conference on Advanced Intelligent Mechatronics, 1999.
- [11] G. M. H. Leung, A. B. Francis, J. Apkarian, "Bilateral Controller for with Time Delay via Teleoperators  $\mu$ -Synthesis", IEEE Transactions on Robotics and Automation, 1995.
- [12] G. M. H. Leung, B. A. Francis, "Robust Nonlinear Control of Bilateral Teleoperators", Proceedings of the American Control Conference, 1994.
- [13] S. Komada, M. Ishida, K. Ohnishi, T. Hori "Disturbance Observer-Based Motion Control Of Direct Drive Motors", IEEE Transactions on Energy Conversion, Vol. 6, No. 3, September 1991.
- [14] K. Ohnishi, T. Murakami "Advanced Motion Control in Robotics", IEEE, IECON, vol. 2, pp.356- 359, 1989.