Stable Adaptive Bilateral Control of Transparent Teleoperation through Time-Varying Delay

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Abstract

Passivity concept has been using as a framework to solve the stability problem in bilateral control of telemanipulation. However, the conservative selection of dissipating element applied to maintain system stability in network communication leads the system to imperfect operation or losing transparency.

In this paper, we proposed a new control scheme to adapt characteristic impedance with time. The proposed method is not only presented in simple form, but also effectively make the operation transparent teleoperation. We verified the validity of our method by teleoperation simulations with constant and variable time delay.

1. Introduction

The first work solving time delay problem appeared in 1989. Anderson and Spong [1] proposed a new communication architecture based on the scattering theory to overcome instability caused by time delay. They used a constant time delay through their communication block and design their system to be linear time invariant. Their control algorithm cannot deal with varying characteristics of the system. Several works were devoted to compensate the effect of variable time delays: Sano, Fujimura and Tanaka [2] used a gain-scheduled method to compensate time delays in bilateral teleoperating system. However, they still used linearized dynamics to implement the system. There are some authors analyzed the system in term of discrete form. Wu and Hong [3] considered the time varying discrete linear and nonlinear system with state delay-independent. They have derived delay-independent exponential stability condition. At the end, the showed that their specified system is globally exponential stable but they still ignored the case of input delay in the system. Udwadia, Hosseini and Chen [4], aimed to design a robust system to handle uncertain parameters occurred in the system, i.e. time varying delays in control input, by bounding the uncertainties with known constants. They considered the varying system without non-stationary system parameter which is impractical for real world systems. Kosuge, Murayama and Takeo [5] proposed a new method to compensate variable time delay in the computer network communication. They used selected virtual time delay as a single delay, which is the maximum value of the sampled delay between the 5th percentile and the 95th percentile, to represent all of delays. However, this virtual delay is too conservative in the real world.

Neimeyer and Slotine [6] introduced the use of wave variables in teleoperation extended from scattering theory proposed by Anderson et al. [1]. They applied passivity concepts, wave variables and wave scattering to consider the 2-port communication time delays. Their method employed stationary characteristic impedance to achieve an acceptable response. However, this stationary impedance might not guarantee the negative dissipation of energy. Consequently, they posed the standard communications to make sure that the dissipation would be positive. And then, they further extended their own results from Neimeyer et al. [6] to integrated wave variables and the distortion of untreated variable time delays in Neimeyer and Slotine [7]. They preserved the stability of wave variables by sending wave integral and wave energy through time delay. Wave energy, which determined passivity, was then conserved and could eliminate position drift from sending wave variable directly. Yokokohji, Imaida, and Yoshikawa [8] proposed a new control scheme based on wave variables. In this control scheme, they developed a compensator located at both sites to compensate the distorted waveform caused by fluctuating delay. They proposed a proportional compensator to correct the waveform. They also modified their compensator by utilizing standard time delay to eliminate stretched signal. However the proposed compensator is still not practical due to the lack of perceiving the exact waveform of ideal signal.

In this paper, we first demonstrate the basic of bilateral control based of passivity concept in section 2. In this section we points out the conflict between maintaining stability and transparency. Next, we then proposed our new method to determine adaptive characteristic impedance in section 3. Section 4 will show results from simulations of utilization of adaptive b with constant and time-varying delay. The concluding remark is discussed at the end of this paper.

2. Bilateral Control Based Passivity Concept

2.1. Basic of Passivity Concept

Passivity theory is a method used to generalize the notion of energy in dynamic system, and to describe the combination of subsystems in a Lyapunov-like formalism. In this subsection, we will describe the basic of passivity concept briefly as the basic for our contribution.

As we mentioned above, the passivity formalism represents a mathematical description in power and energy format. The power "P" defines the power entering the system as a scalar product between the input vector x and the output vector y of the system. The energy E represents the energy storage in the system and P_{diss} defines the power dissipation, which should be positive to conserve the passive property.

$$P = x^T y = \frac{dE}{dt} + P_{diss} \tag{1}$$

In addition, the total energy supplied to the system to the time t is limited or bounded by the initial stored energy $E(0)$

$$\begin{aligned} \int_0^t P d\tau &= \int_0^t x^T y d\tau = E(t) - E(0) + \int_0^t P_{diss} d\tau \\ &\geq -E(0) = \text{constant} \end{aligned} \tag{2}$$

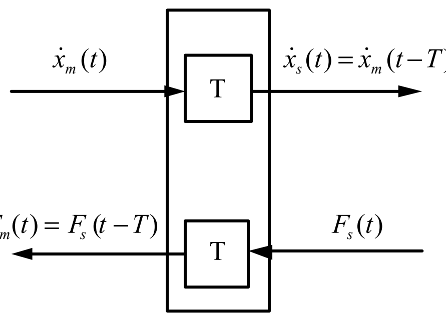

Figure 1: *A model of single delayed standard communication*

In general, a bilateral control system receives force feedback from the remote site. The local site sends position or velocity command to control the slave manipulator. Communication between two sites can be delayed from many reasons, e.g. properties of media transmission in undersea teleoperation, velocity of light in space teleoperation and traffics in network communication. Fig. 1 can represent a model of delayed communication in sending variables via a constant time-delayed communication.

Thus the power variables given by

$$\begin{aligned} \dot{x}_s(t) &= \dot{x}_m(t-T) \\ F_m(t) &= F_s(t-T) \end{aligned} \tag{3}$$

where T is time delay in the communication system, which is defined as a constant term.

For a system, if it behaves like a passive system, the power dissipation P_{diss} must always be positive. Conversely, if P_{diss} is negative, instead of dissipation energy from the system, it will inject energy to the system. That will make the system become unstable.

2.2. Stabilizing with Sufficient Power Dissipation

In this subsection, Neimeyer et al. [6] first described the stabilization of a time-delay system by making the system sufficiently well damped, in which the system was placed with a damping element next to the out port of the communication to make sure that system can guarantee the positive power dissipation definitely. Fig. 2 shows the standard communication with sufficient dissipation in which power variable is transmitting through time delay *T*.

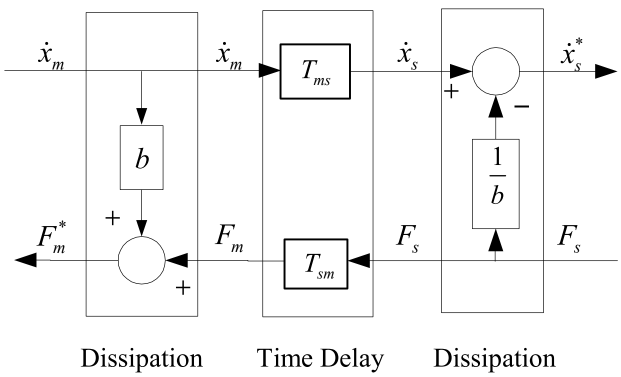

Figure 2: *The standard communication with sufficient dissipation*

The power flow of the system would be determined by

$$\begin{aligned} P &= \frac{dE}{dt} + P_{diss} = \dot{x}_m(t)F_m^*(t) - \dot{x}_s^*(t)F_s(t) \\ &= \left[\frac{1}{2b}F_m^2(t) + \dot{x}_m(t)F_m(t) + \frac{b}{2}\dot{x}_m^2(t)\right] + \left[\frac{1}{2b}F_s^2(t) - \dot{x}_s(t)F_s(t) + \frac{b}{2}\dot{x}_s^2(t)\right] \\ &\quad + \left[\frac{b}{2}\dot{x}_m^2(t) - \frac{b}{2}\dot{x}_s^2(t) + \frac{1}{2b}F_s^2(t) - \frac{1}{2b}F_m^2(t)\right] \\ &= \frac{1}{2b}F_m^{*2}(t) + \frac{b}{2}\dot{x}_s^{*2}(t) + \left[\frac{d}{dt}\int_{t-T_{ms}}^{t}\frac{b}{2}\dot{x}_m^2(\tau)d\tau + \frac{d}{dt}\int_{t-T_{sm}}^{t}\frac{1}{2b}F_s^2(\tau)d\tau\right] \end{aligned} \tag{4}$$

Similarly, we can define each term into the standard format as equation (1). The power dissipation P_{diss} and the stored energy E are defined as

$$P_{diss} = \frac{1}{2b} F_m^{*2}(t) + \frac{b}{2} \dot{x}_s^{*2}(t) \quad (5)$$

$$\frac{d}{dt}E = \frac{d}{dt}\int_{t-T_{ms}}^{t} \frac{b}{2}\dot{x}_m^2(\tau)d\tau + \frac{d}{dt}\int_{t-T_{sm}}^{t} \frac{1}{2b}F_s^2(\tau)d\tau \quad (6)$$

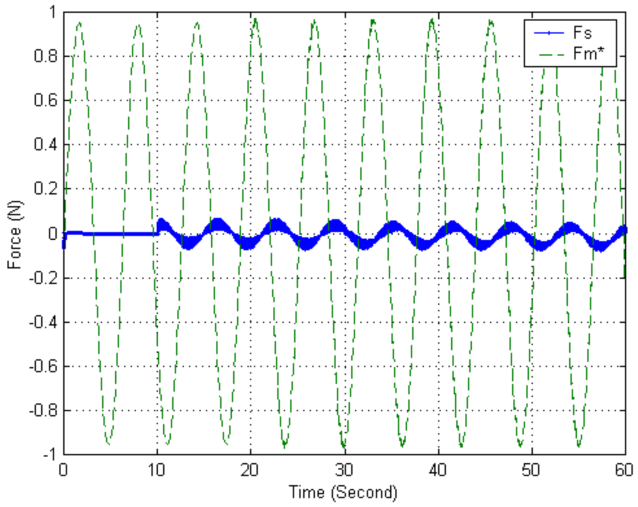

Figure 3: *Force Tracking between Master and Slave*

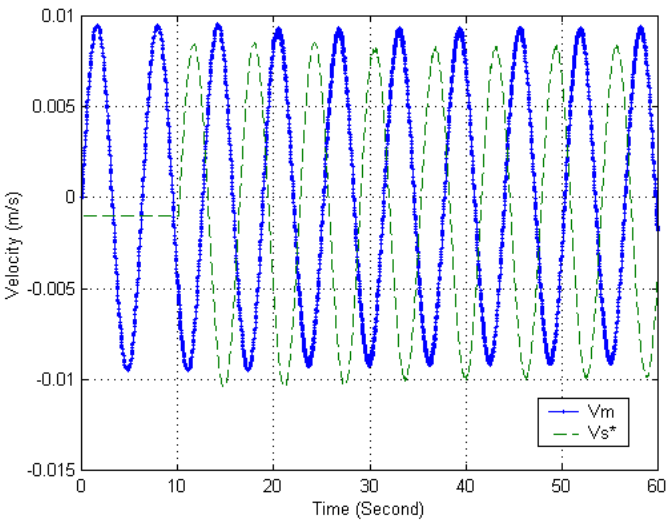

Figure 4: *Velocity Tracking between Master and Slave*

According to the relation of the passive communication in Fig. 2, the implemented power variables can be shown as follows.

$$F_m^* = F_m + b\dot{x}_m$$
$$\dot{x}_s^* = \dot{x}_s - \frac{1}{b}F_s \quad (7)$$

Equation (4) to (7) are not even to simply stabilize standard time-delay system, but also it would be use as a basic to make the system stable by using wave variables. However, the process of dissipation in (7) modifies power variable commands whenever the power variables are sent to the other site master and slave respectively. The equation (7) also tell us the system cannot track velocity and force by using a constant *b* at the same time. For instance, even though we can set *b* to a large number in order to make the system track command velocity precisely, implemented force cannot converge. Fig. 3 and 4 show a simulation of a system with constant *b* = 100 and *T* = 10 seconds.

In the next section, we will discuss about the proposed adaptive *b*, which is changed with time in order to gain the improved transparency.

3. Proposed Method in Transparently Adaptive Characteristic Impedance

3.1. Passivity Formalism with Time-Varying Delay

The condition of standard communication can be more general by described. Time delays during data transmission through the communication port are not necessary constant value, i.e. the delay time transmitted from master to slave site T_{ms} may not equal to the delay time transmitted from master to slave site T_{sm}. Similarly, characteristic impedance should be varied as denoted by b_m and b_s for master and slave characteristic impedance respectively. More general communication can be represented in figure 5 as follow.

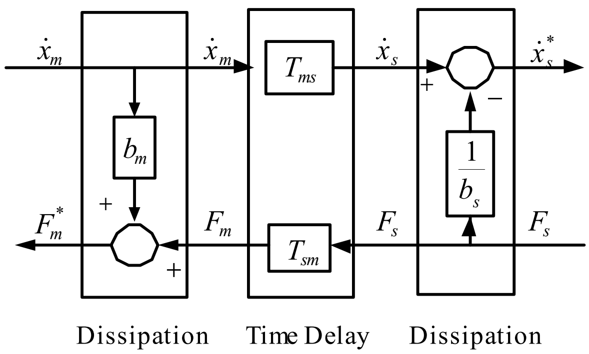

Figure 5: *Modified Standard Communication*

Similarly, we then obtain a similar power equation of the communication system as:

$$P = \frac{1}{2b_m(t)}F_m^{*2}(t) + \frac{b_s(t)}{2}\dot{x}_s^{*2}(t) + \left[\frac{d}{dt}\int_{t-T_{ms}}^{t}\frac{b_m(\tau)}{2}\dot{x}_m^2(\tau)d\tau + \frac{d}{dt}\int_{t-T_{sm}}^{t}\frac{1}{2b_s(\tau)}F_s^2(\tau)d\tau\right] \quad (8)$$

and

$$F_m^*(t) = F_m(t) + b_m(t)\dot{x}_m(t)$$
$$\dot{x}_s^*(t) = \dot{x}_s(t) - \frac{1}{b_s(t)}F_s(t) \quad (9)$$

3.2. Proposed Method in Transparently Adaptive Characteristic Impedance

The main idea to determine critical characteristic impedance $b_{i,c}(t)$, where $i = m,s$ for master and slave respectively, is derived from of the power equation, which we have just shown in the previous subsection. In equation (8), we have expanded from the consideration that Neimeyer et al. [6] proved in one-degree of freedom with single time delay T and constant characteristic impedance b. Based on such condition, it is not clear whether the power dissipation will dissipate only the excessive energy or not.

We want all excess power to be eliminated by the power dissipation term P_{diss} that $\frac{dE}{dt}$ should be equal to $-P_{diss}$. We got the positive power dissipation term and the rate of change of stored energy as the function of time delay occurrence while power variable is being transmitted from the master site to the slave site T_{ms} and in the converse direction from slave site to master site after the delayed time T_{sm}.

Therefore, if we can control P_{diss} to be equal to $\frac{dE}{dt}$, then we can eliminate just the excess energy of the communication system. Then we use this critical condition to evaluate the sufficient characteristic impedance b as the base in determination of $b_{i,c}(t)$ for each time delay. According to figure 5, we substitute $b_{m,c}(t)$ to $b_m(t)$ and $b_{s,c}(t)$ to $b_s(t)$, and from equation (8). The critical condition will be represented by (10).

$$P_{diss} = \left[\frac{1}{2b_{m,c}(t)}F_m^2(t) + \dot{x}_m(t)F_m(t) + \frac{b_{m,c}(t)}{2}\dot{x}_m^2(t)\right] + \left[\frac{1}{2b_{s,c}(t)}F_s^2(t) - \dot{x}_s(t)F_s(t) + \frac{b_{s,c}(t)}{2}\dot{x}_s^2(t)\right]$$
$$-\frac{d}{dt}E = \left[\frac{b_{s,c}(t)}{2}\dot{x}_s^2(t) - \frac{b_{m,c}(t)}{2}\dot{x}_m^2(t) + \frac{1}{2b_{m,c}(t)}F_m^2(t) - \frac{1}{2b_{s,c}(t)}F_s^2(t)\right] \quad (10)$$

Assume that the power dissipation term in each site can totally eliminate the derivative of stored energy in each site as:

$$\frac{F_m^2(t)}{2b_{m,c}(t)} + \dot{x}_m(t)F_m(t) + \frac{b_{m,c}(t)}{2}\dot{x}_m^2(t) = \frac{F_m^2(t)}{2b_{m,c}(t)} - \frac{b_{m,c}(t)}{2}\dot{x}_m^2(t)$$
$$\frac{F_s^2(t)}{2b_{s,c}(t)} - \dot{x}_s(t)F_s(t) + \frac{b_{s,c}(t)}{2}\dot{x}_s^2(t) = \frac{b_{s,c}(t)}{2}\dot{x}_s^2(t) - \frac{F_s^2(t)}{2b_{s,c}(t)} \quad (11)$$

, where $b_{m,c}(t)$ and $b_{s,c}(t)$ are not equal to zero.

Then we get $b_{m,c}(t)$ for characteristic impedance at master and slave site

$$b_{m,c}(t) = -\frac{F_m(t)}{\dot{x}_m(t)}, \quad (12)$$

$$b_{s,c}(t) = \frac{F_s^2(t)}{\dot{x}_s(t)F_s(t)} = \frac{F_s(t)}{\dot{x}_s(t)} \quad (13)$$

3.3. Selecting characteristic impedance *b* by transparency constraint

Let us bring up the relation of the new standard communication with sufficient power dissipation of Fig. 5.From the architecture, we got

$$F_m^*(t) = F_m(t) + b_m(t)\dot{x}_m(t)$$
$$\dot{x}_s^*(t) = \dot{x}_s(t) - \frac{1}{b_s(t)}F_s(t) \quad (14)$$

If we use $b_{m,c}(t)$ for $b_m(t)$ and $b_{s,c}(t)$ for $b_s(t)$, equation (14) will become

$$F_m^*(t) = F_m(t) + b_{m,c}(t)\dot{x}_m(t) = F_m(t) + \left(-\frac{F_m(t)}{\dot{x}_m(t)}\right)\dot{x}_m(t) = 0$$

and

$$\dot{x}_s^*(t) = \dot{x}_s(t) - \frac{1}{b_{s,c}(t)}F_s(t) = \dot{x}_s(t) - \left(\frac{\dot{x}_s(t)}{F_s(t)}\right)F_s(t) = 0$$

The above two equations can be interpreted that the critical condition of power dissipation is completely satisfied. Therefore there is no remained power left in the communication anymore.

Next, we then can choose how transparent of the desired power variables leaving off the communication. Given that J_i stands for degree of transparency of master and slave power variables when $i = m$ and s respectively, and

$$b_m = \frac{1}{J_m} \times b_{m,c} \text{ and } b_s = J_s \times b_{s,c} \quad (15)$$

Now we back to (10) with the new adaptive characteristic impedance at master and slave site. Consider power-entering *P*, the power dissipation

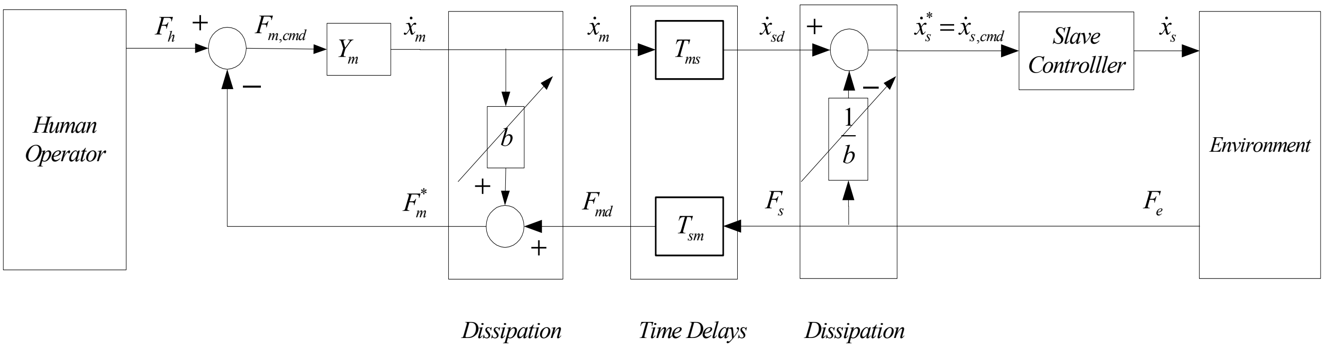

***Figure 6:** A single DOF system for simulation*

terms are spread from (8) so they can be guaranteed in case of positive b_i. Thus in this case, the system is definitely stable. Moreover, when the adaptive b_i are varying with the instant of power variables, P_{diss} and dE/dt are still held close to the critical condition by selecting $J = J_s = J_m$ more than one. The power entering to the system can be shown in (16).

$$P = (1 - 1/J)(\dot{x}_m F_m - \dot{x}_s F_s) \quad (16)$$

Equation (16) means that the power entering to the system is less than the power entering to the delayed communication by $100/J$ percents. The philosophy of this solution is compromised between lossless transmission and passive communication. If we transmit all exact received power variables through the delayed communication directly, the system will continually stored energy due to time delay in communication and then the system cannot maintain stability. Consequently, we use critical condition (10) to (13) and (15) to dissipate strict power $1/J$ times of exact power, which is enough to maintain stability, to make the system close to transparent teleoperation and to make the communication system remain passive. For instance, if $J_m = J_s = 1000$, the implemented power variables at master site will be

$$F_m^*(t) = F_m(t) + 0.001 \cdot b_{m,c}(t)\dot{x}_m(t)$$
$$= F_m(t) + \left(-0.001 \cdot \frac{F_m(t)}{\dot{x}_m(t)}\right)\dot{x}_m(t)$$
$$= 0.999 F_m(t)$$

The above equations mean that the implemented power variables will be deviated from the commanded power variables by 0.1 percent.

4. Simulations

We performed a simulation to illustrate the benefit of our method. Fig. 6 shows a single DOF system in which human operator exert force with sine function and slave manipulator is touching with the environment $m_e = 1.0$ *kg*, $b_e = 0.2$ *Ns/m* and $k_e = 0.4$ *N/m*. Time delay during the first simulation is constant 10 s. PD gains at slave are set to $K_p = 100$ *N/s* and $K_d = 20$ *Ns/m*. The delay T_{ms} has *mean* = *10 sec* and *variance* = *0*. The delay T_{sm} has *mean* = *9 sec* and *variance* =*0*. Fig.8 shows the result of using adaptive $b_m(t)$ and next Fig. 9 shows the result of using adaptive $b_s(t)$. For the second simulation, we keep the other parameter to be the same but changing with time-varying delay. The delay T_{ms} has *mean* = *10 sec* and *variance* = *0.01*. The delay T_{sm} has *mean* = *9 sec* and *variance* =*0.01*.

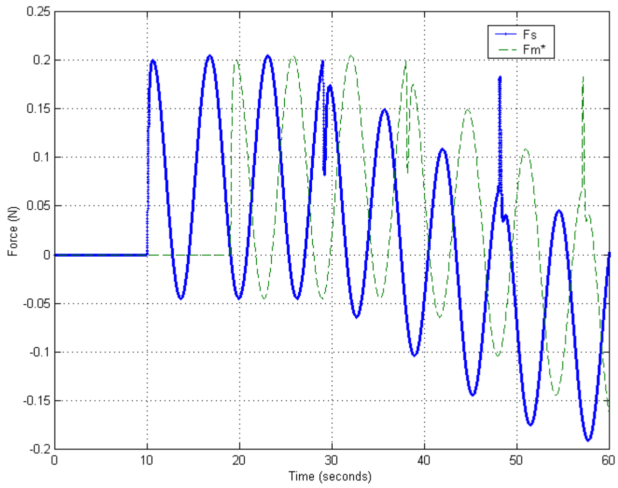

***Figure 7:** The result of adaptive $b_m(t)$ implementation with constant delay of 10 s.*

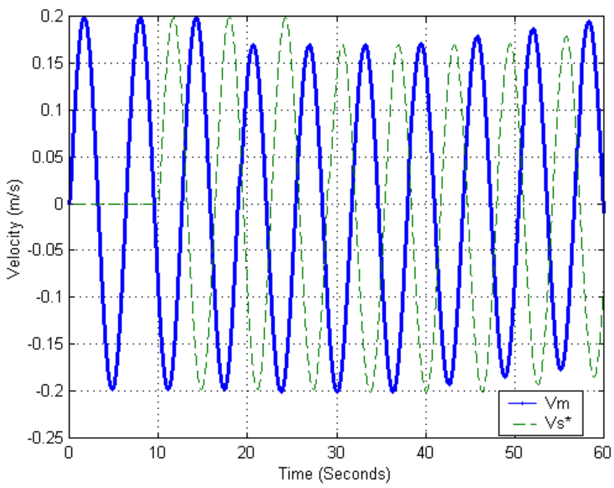

***Figure 8:** The result of adaptive $b_m(t)$ implementation with constant delay of 10 seconds*

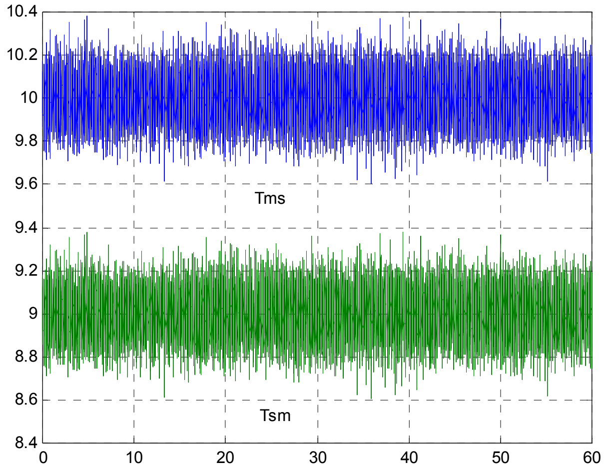

Figure 9: *Time-varying delay in network communication*

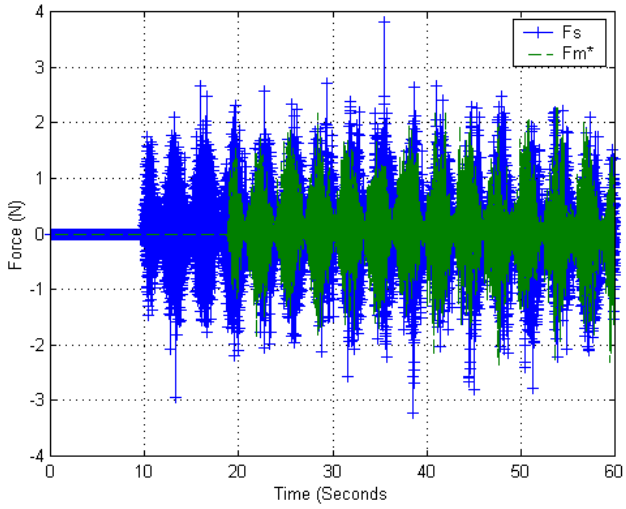

Figure 10: *Force Tracking with $b_m(t)$ under fluctuation of delay*

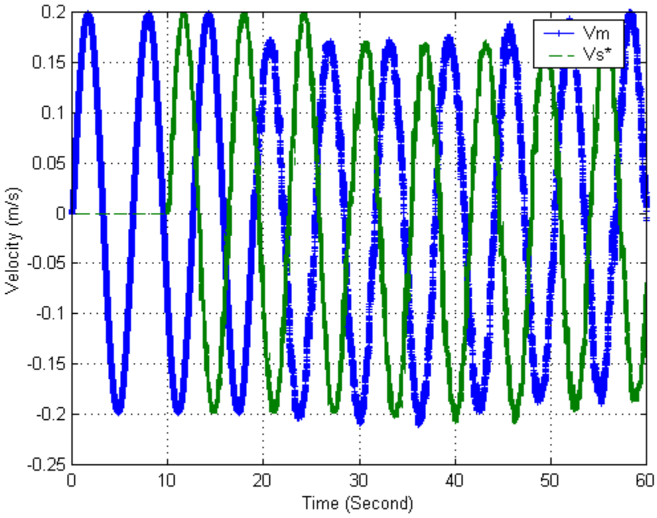

Figure 11: *Velocity Tracking with $b_s(t)$ under fluctuation of delay*

5. Concluding Remarks

In this paper, we proposed a method to solve the conflict between stability and transparency under constant and time-varying delay. The proposed adaptive characteristic impedance b is not only in a simple form but also easy to implement. Furthermore, time-delay knowledge does not require since the power entering equation is depended on received and sent power variables.

However, to apply adaptive characteristic impedance b_i, one should make sure that J_i must be satisfied with the derived equations, i.e. J_i must not less than one.

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References

[1] R. J. Anderson and M. W. Spong, 1989, "Bilateral Control of Teleoperators with Time Delay", IEEE Transactions on Automatic Control, vol.34, no. 5, pp. 494 – 501.

[2] A. Sano, H. Fujimura and M. Tanaka, 1998, "Gain-Scheduled Compensation for Time Delay of Bilateral Teleoperation Systems", Proceeding of the 1998 IEEE International Conference on Robotics and Automation, pp. 1916 – 1923.

[3] J. Wu and K-S. Hong, 1994, "Delay-Independent Exponential Criteria for Time-Varying Discrete Delay Systems", IEEE Transactions on Automatic Control, vol. 34, no. 4, pp. 811 – 814.

[4] F.E. Udwadia, M.A.M. Hosseini and Y.H. Chen, 1997, "Robust Control of Uncertain Systems with Time Varying Delays in Control Input", Proceeding of the American Conference, Albuquerque, New Mexico June, pp. 3641 – 3645.Takeo, 1996, "Bilateral Feedback Control of Telemanipulators via Computer Network.",

[5] K. Kosuge, H. Murayama and K. Proceeding of IROS, pp. 1380 – 1385.

[6] G. Niemeyer and J-J. E. Slotine, 1991, "Stable Adaptive Teleoperation", IEEE Journal of Oceanic Engineering", vol. 16, no. 1, pp. 152 – 162.

[7] G. Niemeyer and J-J. E. Slotine, 1998, "Towards Force-Reflecting Teleoperation Over the Internet", Proceeding of the 1998 IEEE International Conference on Robotics & Automation, pp. 1909 – 1915.

[8] Y. Yokokohji, T. Imaida, and T. Yoshikawa, 1999, "Bilateral Teleoperation under Time-varying Communication Delay", Proceedings of the 1999 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 1854 – 1859.