가변 시간 지연에 대해 안정한 쌍방향 텔레오퍼레이션

A new approach to passive bilateral teleoperation with varying time delay

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Abstract-This paper is devoted to the passivity based control in bilateral teleoperation for varying time delay. Toimprove the stability and task performance, master and slave in bilateral teleoperation must be coupled via the network through which the force and velocity are communicated. However, time delay existing in the transmission channel is a long standing impediment to bilateral control and can destabilize the system, even if the system is stable without time delay. In this paper, we investigate how the varying time delay affects the advanced teleoperation stability and results in an out-of-control status. A new approach based on passivity control has been bilaterally designed for both the master and slave sites and the simulation result will verify that our approach is better and effective for passive bilateral teleoperation.

Key word : Teleoperation, passivity, varying time delay, stability, force feedback

1. Introduction

Master-slave teleoperation, which ridges human control and purely autonomous machines, has been developed rapidly in the recent and is expected to be a merging point of modem developments in robotics, control theory, cognitive science, machine design, and computer science. When a teleoperator operates a robot remotely, it is desirable that communicate contact force information is transferred from the slave to the master, in order to kinesthetically couple the operator to the environment.

In communication channel, time delay is incurred along with the network congestion, bandwidth and distant, which can degrade the performance or even result in the system unstable. In literature, several noticeable results concerning both stability analysis and control system design for bilateral teleoperation with force reflecting have been presented for time delay. Nowadays, passivity based bilateral teleoperation, a promising control law which addresses the issue of energetic interaction between the manipulator and the environment, has been physically realized and is the currently under active development [1,2,3,4,5]. The most famous effort for time varying delay case is from Neimeyer and Slotine [1,2]. They proposed a new idea by using the wave variables in teteoperation to consider the 2-port system. But their approach preserves passivity in general only for const time dalay and can not ensure a passivity control with varying time delay case. There always exists a controller/manipulator setup which can cause a negative dissipation and make the system nonpassive and unstable[2].Anderson and Spong, in 1989 [3], proposed a scattering scheme to erase the unstable status caused by constant delay. Later, they derived a similar result with varying time delay with velocity control input [4]. Singha Leeraphan etc [5] proposed a method with adding a varying gain parameter b, which is equal to adding a constant gain at both sides of $\dot{x}_s$ and F_m But, this approach can not be sufficient to passivity control.

This paper concentrates on the analysis of passivity based bilateral control, in particular, addresses the stability and tracking performance with varying time delay arising in the communication network. And we build a new scheme for velocity-force system with the different parameters b_m b_s which are separately the character impedance parameters of mater/slave and can directly affect the system behavior.

This paper has been organized as follows: in chapter 2, we will review the preliminary knowledge about passivity based bilateral control with the varying time delay. Chapter 3 will detail our proposed approach to passive control. the simulation will be presented in Chapter 4. On the last chapter, we will draw a conclusion.

2. Time delay

Teleoperation is the extension of a person's sensing to a remote environment. The standard communication system has been depicted in Figure 1 with one port connecting to the master and the other to the remote system. Passivity based bilateral control focuses on the energetic interaction in the system, which provides a simple and robust tool to analyze the stability. The passivity formalism represents a mathematical description of the intuitive physical concepts of power and energy.

Denote that P is the power entering the system and x is the input vector, y output vector.

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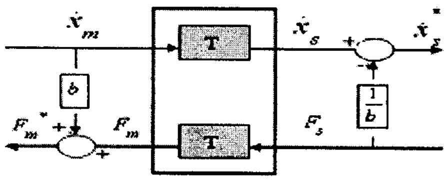

Figure 1. Standard communication with force reflection

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

The energy E define a lower bounded "energy storage" in the system and P_{diss} means a non-negative "power dissipation". This implies the total energy supplied by the system up to time t is limited to the initial stored energy. If a system is passive, we say that it follows

$$\int_0^t P d\tau = \int_0^t x^T y d\tau = E(t) - E(0) + \int_0^t P_{diss} d\tau \geq -E(0) = CONSTANT \tag{2}$$

As long as the power dissipation is zero or positive all time, the system is strictly positive[4]. From Figure 1, the relationship will be described as follows,

$$F_m^* = F_m + b\dot{x}_m$$

$$\dot{x}_s^* = \dot{x}_s - \frac{1}{b} F_s$$

we get,

$$E = \int_0^t (\dot{x}_m F_m^* - \dot{x}_s^* F_s) d\tau = \int_0^t [\dot{x}_m (F_m + b\dot{x}_m) - (\dot{x}_s - \frac{1}{b} F_s) F_s] d\tau$$

$$= \int_0^t (\dot{x}_m F_m + b\dot{x}_m^2 - \dot{x}_s F_s + \frac{1}{b} F_s^2) d\tau \tag{3}$$

Where $\dot{x}_m/\dot{x}_s$ are velocity of master/slave, F_m/F_s are force applied on the master/salve. According to Lyapunov-like function, a passive system is stable without external input. Otherwise, the system will inject the energy which will make an unstable status.

In case of the constant communication delay where T is constant, the equation is given by,

$$\dot{x}_s(t) = \dot{x}_m(t - T)$$

$$F_m(t) = F_s(t - T)$$

thus,

$$E = \int_0^t (\dot{x}_m F_m + b\dot{x}_m^2 - \dot{x}_s F_s + \frac{1}{b} F_s^2) d\tau$$

$$= \int_0^t [(\frac{1}{2b} F_m^2 + \dot{x}_m F_m + \frac{b}{2}\dot{x}_m^2) + (\frac{1}{2b} F_s^2 - \dot{x}_s F_s + \frac{b}{2}\dot{x}_s^2)] d\tau$$

$$+ \int_0^t [(\frac{b}{2}\dot{x}_m^2 - \frac{b}{2}\dot{x}_s^2) + (\frac{1}{2b} F_s^2 - \frac{1}{2b} F_m^2)] d\tau$$

$$= \int_0^t (\frac{1}{2b} F_m^{*2} + \frac{b}{2}\dot{x}_s^{*2}) d\tau + \int_{t-T}^t (\frac{1}{2b} F_s^2 + \frac{b}{2}\dot{x}_m^2) d\tau \tag{4}$$

We can find that the system is passive independent of the magnitude of constant delay T if and only if b is positive. However, the above result can not hold when time delay is varying. In varying time delay case, the relations become:

$$\dot{x}_s(t) = \dot{x}_m(t - T_1(t))$$

$$F_m(t) = F_s(t - T_2(t))$$

The total energy stored in the communications during the signal transmission between master and slave at any time is given by

$$E = \int_0^t (\dot{x}_m F_m + b\dot{x}_m^2 - \dot{x}_s F_s + \frac{1}{b} F_s^2) d\tau$$

$$= \int_0^t (\frac{1}{2b} F_m^{*2} + \frac{b}{2}\dot{x}_s^{*2}) d\tau + \int_0^t (\frac{b}{2}\dot{x}_m^2 + \frac{1}{2b} F_s^2) d\tau$$

$$- \int_0^t (\frac{b}{2}\dot{x}_m^2 (t - T_1(t)) + \frac{1}{2b} F_s^2 (t - T_2(t))) d\tau \tag{5}$$

Now, we can not always ensure E>0, that means there always exists a controller/manipulator setup which can cause a negative dissipation and make the system nonpassive and unstable.

3 Our proposed passive control

To solve this, instead of using the uniform b in both sides of master and slave, we choose to adopt different characteristic impedances, b_m and b_s.The new scheme is as follows in Figure 2:

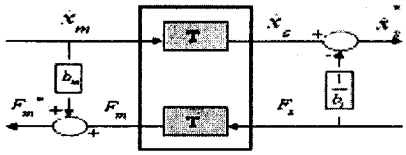

Figure 2 our proposed communication scheme

From this scheme, the relation becomes:

$$F_m^* = F_m + b_m \dot{x}_m$$

$$\dot{x}_s^* = \dot{x}_s - \frac{1}{b_s} F_s$$

It is easily to compute the power inflow into the communication block between master and slave during the signal transmission.

$$E = \int_0^t [\dot{x}_m (F_m + b_m \dot{x}_m) - (\dot{x}_s - \frac{1}{b_s} F_s) F_s] d\tau$$

$$= \int_0^t (\dot{x}_m F_m + b_m \dot{x}_m^2 - \dot{x}_s F_s + \frac{1}{b_s} F_s^2) d\tau$$

$$= \int_0^t \frac{1}{2b_m} (F_m^2 + 2b_m \dot{x}_m F_m + b_m^2 \dot{x}_m^2) d\tau + \int_0^t \frac{b_s}{2} (\frac{1}{b_s^2} F_s^2 - 2\frac{1}{b_s} \dot{x}_s F_s + \dot{x}_s^2) d\tau$$

$$+ \int_0^t (\frac{b_m}{2}\dot{x}_m^2 - \frac{b_s}{2}\dot{x}_s^2) d\tau + \int_0^t (\frac{1}{2b_s} F_s^2 - \frac{1}{2b_m} F_m^2) d\tau$$

$$= \int_0^t \frac{1}{2b_m} F_m^{*2} d\tau + \int_0^t \frac{b_s}{2} \dot{x}_s^{*2} d\tau$$

$$+ \frac{b_m}{2} \int_0^t (\dot{x}_m^2 - \frac{b_s}{b_m} \dot{x}_s^2) d\tau + \frac{1}{2b_s} \int_0^t (F_s^2 - \frac{b_s}{b_m} F_m^2) d\tau$$

Let $\beta = \tau - T_1(\tau)$, then $d\beta = (1 - T_1'(\tau)) d\tau$, perform this change,

$$\int_0^t (\dot{x}_m^2 - \frac{b_s}{b_m}\dot{x}_s^2)d\tau = \int_0^t \dot{x}_m^2(\tau)d\tau - \frac{b_s}{b_m}\int_0^t \dot{x}_m^2(\tau - T_1(\tau))d\tau$$
$$= \int_0^t \dot{x}_m^2(\tau)d\tau - \frac{b_s}{b_m}\int_0^{t-T_1(t)} \frac{\dot{x}_m^2(\beta)}{1-T_1'}d\beta$$
$$= \int_{t-T_1(t)}^t \dot{x}_m^2(\tau)d\tau + \int_0^{t-T_1(t)} (1 - \frac{b_s}{(1-T_1')b_m})\dot{x}_m^2(\beta)d\beta \qquad (6)$$

If $\frac{b_s}{(1-T_1')b_m}$ is less than 1, then $\int_0^t (\dot{x}_m^2 - \frac{b_s}{b_m}\dot{x}_s^2)d\tau$ will be positive (Assume $1-T_1'$ is positive). Also, if $\frac{1}{(1-T_2')}\frac{b_s}{b_m}$ is less than 1, the $\int_0^t (F_s^2 - \frac{b_s}{b_m}F_m^2)d\tau$ will be positive. Consequently, we can get a passive system.

4 Simulation

To prove our approach, we perform the simulation with different cases and track the master and the slave positions. To easily control the system, we denote the dynamics relation:

$$M_m\ddot{x}_m + B_m\dot{x}_m = F_h - F_m^*$$
$$M_s\ddot{x}_s^* + B_s\dot{x}_s^* = F_s - F_e \qquad (7)$$

In which, F_h is the torque from human and F_e is the torque from environment, M_m and M_s are the respective inertias. The system input is under the control of F_h which is applied by human simulating with a cos function, which is easier to control by human with hand than velocity control. Choosing M_m with 1kg, B_m with 0.2 Ns/m, M_s with 0.25kg and B_s with 0.1 Ns/m, we perform lots of simulations for the master/slave force and position tracking with varying time delay. Figure 3 shows the simulation result with varying time delay in the original scheme $T_1 = 0.03t + 0.01, T_2 = 0.05t$, $b = b_m = b_s = 1.25$, and Figure 4 is the simulation result in our proposed scheme with $b_m = 0.5, b_s = 5$, which does not satisfy the function requirement. Obviously, in Figure 3 and Figure 4, both master and slave will move freely in the space.

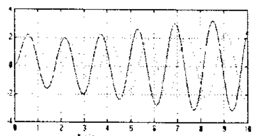

Figure 3 simulation in the original scheme with $b = b_m = b_s = 1.25$

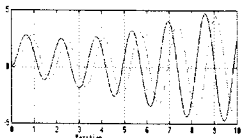

Figure 4 simulation in proposed method with $b_m = 0.5, b_s = 5$

Figure 5 is the simulation result by our proposed scheme under the same situation with $b_m = 2.5, b_s = 1.1$, which satisfies the function requirement. With our approach applying, the result is better and tends to be stable more quickly as respected.

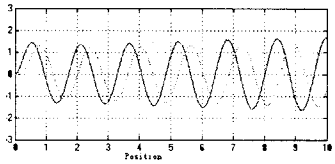

Figure 5 simulation in proposed method with satisfied $b_m = 2.5, b_s = 1.1$

Another simulation has been done with random network time delay with T=0.6s and 0.02 variance showed in Figure 6.

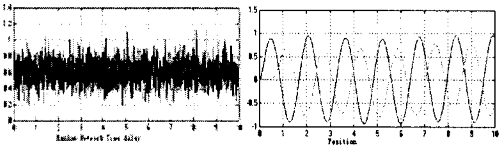

Figure 6 simulation with random network time delay $b_m = 1.5, b_s = 1.25$

We can find the positions of the master and slave is matching with our proposed scheme.

4. Conclusion and the future work

In this paper, we discuss the varying time delay influence in bilateral teleoperation with force reflecting, aiming at a passive control and acceptable tracking performance. A new approach has been proposed and simulation results offered in the paper prove our approach will make the system stable and improve the tracking performance. Our future work will discuss the discrete time delay in the teleoperation, which is important for Internet-based teleoperation.

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