Passive-based Bilateral Controller Design under Varying Time Delay

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Abstract - Bilateral teleoperation systems, connected to computer networks such as Internet have to deal with the time delay varying depending on factors such as congestion, bandwidth or distance. And the entire system is easy to become unstable due to irregular time delay. Passivity concept has been using as a framework to solve the stability problem in bilateral control of teleoperation. Acontrol scheme for teleoperation systems with varying time delay is proposed based on a passivity concept is proposed in this paper. One approach makinguse of the characteristic impedances is proposed to achieve a passive control. Since passive control does not mean that the system performance will be acceptable, another transmission scheme which focuses on both the passive feature and the acceptable performance is configured for varying time delay in this paper. The tracking performance has been proved through the computer simulation for varying time delay bilateral teleoperation system using Matlab Simulink.

Key Words : teleoperation, passivity, time delay, passive control

1. Introduction

Nowadays, a passivity based bilateral tele-operation, a promising control law which addresses the issue of energetic interaction between the manipulator and the environment, is currently under active development. Several prominent results for passivity control include Anderson and Spong in 1989 [1], Neimeyer and Slotine [2] employing the passivity, scattering theory and wave-based teleoperation control method to overcome the instability caused by time delays. However, this method can not ensure a passivity of the system when the delay is time varying. Later, Lozano and Spong extended their previous approach for a varying time delay system by adding a smaller gain into the system to compensate the energy flowing [3]. Singha Leeraphan etc [4] proposed a method for a varying time delay using a time varying gain parameter b.

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 channel. Based on the original scheme, we propose a method which makes use of the characteristic impedances b to satisfy the passivity condition. Another parameter adaptive optimal control scheme is presented, in which extra variables, the master position and the integrating of slave force or slave impulse, are also transmitted together with the force and velocity.

The structure of this paper is: section 2 gives a brief introduction of passivity. Section 3 discusses how the varying time delay disturb the teleoperation system. The first proposed approach to passivity based control will be presented in section 4, and simulation results will be given. Conclusions of the study are presented in section 5.

2. Basic of teleoperation system

The passivity formalism is motivated by Lyapunov theory and provides a powerful tool for system stability analysis and control law design. It represents a mathematical description of the intuitive physical concepts of power and energy. Define the "power" P entering a system as the scalar product between the input vector x and the output vector y of the system. A system is said tobe passive, if and only if it obeys:

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

where E is a lower-bounded "energy storage" function and P_{diss} is a non-negative "power dissipation" function. We can see from equation (1), the power is either stored or dissipated. This implies that the total energy supplied by the system up to time tis limited to the initial stored energy E(0):

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

Using the stored energy as a Lyapunov-like function, one can quickly analyze stability and show that, without external input, a passive system is stable.

3. Passive control scheme based on characteristic impedance

In case of varying time delay, instead of using the same b at 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 1:

From this scheme, the variables relation becomes:

$$\dot{x}_s(t) = \dot{x}_m(t - T_1(t)), F_m(t) = F_s(t - T_2(t)) \qquad (3)$$

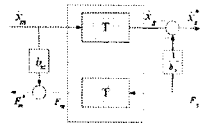

Figure 1. Communication scheme with different characteristic impedances

It is easily to compute the power inflow into the communication block

$$E = \int_0^t (\dot{x}_m F_m + b_m \dot{x}_m^2 - \dot{x}_s F_s + \frac{1}{b_s} F_s^2) d\tau = \int_0^t \frac{1}{2b_m}(F_m^2 + 2b_m \dot{x}_m F_m + b_m^2 \dot{x}_m^2) d\tau$$
$$+ \int_0^t \frac{b_s}{2}(\frac{1}{b_s^2} F_s^2 - 2\frac{1}{b_s}\dot{x}_s F_s + \dot{x}_s^2) d\tau + \int_0^t (\frac{b_m}{2}\dot{x}_m^2 - \frac{b_s}{2}\dot{x}_s^2) d\tau + \int_0^t (\frac{1}{2b_s} F_s^2 - \frac{1}{2b_m} F_m^2) d\tau$$
$$= \int_0^t \frac{1}{2b_m} F_m^{*2} d\tau + \int_0^t \frac{b_s}{2} \dot{x}_s^{*2} d\tau + \frac{b_m}{2}\int_0^t (\dot{x}_m^2 - \frac{b_s}{b_m}\dot{x}_s^2) d\tau + \frac{1}{2b_s}\int_0^t (F_s^2 - \frac{b_s}{b_m} F_m^2) d\tau \qquad (4)$$

Now, if we can ensure that $\int_0^t (\dot{x}_m^2 - \frac{b_s}{b_m}\dot{x}_s^2) d\tau$ and $\int_0^t (F_s^2 - \frac{b_s}{b_m} F_m^2) d\tau$ are positive, then E will be positive, and the system will be passive. Due to (2) we have

$$\int_0^t (\dot{x}_m^2 - \frac{b_s}{b_m}\dot{x}_s^2) d\tau = \int_0^t \dot{x}_m^2(\tau) d\tau - \frac{b_s}{b_m}\int_0^t \dot{x}_m^2(\tau - T_1(\tau)) d\tau \qquad (5)$$

Rewrite the above equation by denoting $t - T_1(t) = \alpha$ and $t - T_2(t) = \beta$ as follows

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

where $T_i'(\alpha) = \dot{T}_i(g_i(\alpha)), g_i(\alpha) - T_i(g_i(\alpha)) \equiv \alpha, i = 1, 2.$

If $\frac{b_s}{(1-T_1')b_m}$ is less than 1 or $\frac{b_s}{b_m} < 1 - T_1'$, 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 or $\frac{b_s}{b_m} < 1 - T_2'$, 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. Proposed adaptive scheme

In this section, we will detail our approach to get acceptable performance for varying time delay case. From above equations, it is evident that whether the system is passive is determined by the differential of time delay, T_1' and T_2' in forward and backward communication network. Therefore, if the values of T_1' and T_2' are obtained in real time, the system can be operated with passivity condition by harnessing the values of T_1' and T_2'.

4.1 The architecture of proposed scheme

The possible way to obtain the differential of time delay is to make use of differentiator and integrator in the transmission channels. The block diagram of the proposed system is depicted in Figure 2, in which additional data should be transmitted.

The additional transmission equations can be given by,

$$\dot{X}(t) = \frac{d(\int_0^{t-T_1(t)} \dot{x}_m(\gamma) d\gamma)}{dt}$$
$$F(t) = \frac{d(\int_0^{t-T_2(t)} F_s(\gamma) d\gamma)}{dt} \qquad (7)$$

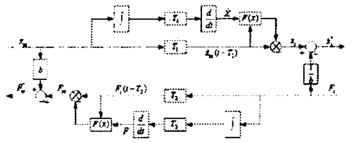

Figure 2. Overall scheme of proposed system

Perform mathematical change as follows,

$$\dot{X}(t) = \frac{d(\int_0^{t-T_1(t)} \dot{x}_m(\gamma) d\gamma)}{dt} = \frac{d(\int_0^{t-T_1(t)} \dot{x}_m(\gamma) d\gamma)}{d(t - T_1(t))}\frac{d(t - T_1(t))}{dt} = \dot{x}_m(t - T_1(t))(1 - T_1'(t)) \qquad (8)$$

From the equation (8), the $\dot{x}_m(t - T_1(t))(1 - T_1'(t))$ can be obtained. Now, it is possible to obtain $1 - T_1'(t)$ from the values of $\dot{x}_m(t - T_1(t))(1 - T_1'(t))$ and $\dot{x}_m(t - T_1(t))$. And it is possible to obtain the value of $(1 - T_1'(t))^{1/2}$ and $\dot{x}_m(t - T_1(t))(1 - T_1'(t))^{1/2}$. Let,

$$\dot{x}_s(t) = \dot{x}_m(t - T_1(t))(1 - T_1'(t))^{1/2} \qquad (9)$$

Similarly, we have

$$F_m(t) = F_s(t - T_2(t))(1 - T_2'(t))^{1/2} \qquad (10)$$

As showed in this figure, the relationships are listed as follows:

$$\dot{x}_s^* = (1 - T_1')^{1/2}\dot{x}_s - \frac{1}{b}F_s, F_m^* = (1 - T_2')^{1/2}F_m + b\dot{x}_m \qquad (11)$$

Substituting these Equations (11) into equation (5) and the initial energy is assumed to be zero, the stored energy in the system is computed as, the power flow of the system would be determined by

$$E=\int_0^t \frac{1}{2b}((1-T_2')F_m^2+2b(1-T_2')^{1/2}\dot{x}_m F_m+b^2\dot{x}_m^2)d\tau$$
$$+\int_0^t \frac{b}{2}(\frac{1}{b^2}F_s^2-2\frac{1}{b}(1-T_1')^{1/2}\dot{x}_s F_s+(1-T_1')\dot{x}_s^2)d\tau$$
$$+\int_0^t (\frac{b}{2}\dot{x}_m^2-\frac{b}{2}(1-T_1')\dot{x}_s^2)d\tau+\int_0^t (\frac{1}{2b}F_s^2-\frac{1}{2b}(1-T_2')F_m^2)d\tau$$
$$=\int_0^t \frac{1}{2b}F_m^{*2}d\tau+\int_0^t \frac{b}{2}\dot{x}_s^{*2}d\tau+\frac{b}{2}\int_0^t (\dot{x}_m^2-(1-T_1')\dot{x}_s^2)d\tau$$
$$+\frac{1}{2b}\int_0^t (F_s^2-(1-T_2')F_m^2)d\tau \tag{12}$$

Let $\beta=\tau-T_1(\tau)$, perform this change, we have

$$\int_0^t (\dot{x}_m^2-(1-T_1')\dot{x}_m^2(\tau-T_1(\tau)))d\tau=\int_0^t \dot{x}_m^2(\tau)d\tau-\int_0^t \dot{x}_m^2(\tau-T_1(\tau))d(\tau-T_1(\tau))$$
$$=\int_0^t \dot{x}_m^2(\tau)d\tau-\int_0^{t-T_1(t)} \dot{x}_m^2(\beta)d(\beta)=\int_{t-T_1(t)}^t \dot{x}_m^2(\tau)d\tau \tag{13}$$

Similarly, the equation (12) can be rewritten as

$$E=\frac{1}{2b}\int_0^t F_m^{*2}d\tau+\frac{b}{2}\int_0^t \dot{x}_s^{*2}d\tau+\frac{b}{2}\int_{t-T_1(t)}^t \dot{x}_m^2 d\tau+\frac{1}{2b}\int_{t-T_2(t)}^t F_s^2 d\tau \tag{14}$$

In the above equation, the negative integrators are eliminated, thus, the system is passivity even if the time delay is increasing. In this case, the output variables will decrease automatically to keep the passivity.

In addition this configure will also adapt to constant delay and varying time delay with the decreasing slope which is evident from the Equation (14) which is independent of the slope of time delay. When time delay is constant, equation (14) will be the same as equation (5), and the suggested additional part will not influence to the original system shown in Figure 1. When the time delay is decreasing or T_1' and T_2' are negative, the suggested scheme will increase the output power variablesappeared in equations (11). The energy stored in the original scheme expressed in equation (4) will be larger than that of the proposed approach expressed in equation (14). The proposed approach transmits the power with a higher rate compared to the original scheme as well keep the passivity. This result will compensate for a time delay decrease, thusmaking it possible to track the performance accurately between master and slave.

4.2 Simulation results

We perform the simulation for our proposed scheme with $b=10$. The varying time delay is as described in Figure 3. The time delay is varying with both negative and positive slope. During the time 0-10s, 20-30s time delay is increasing, while time delay is decreasing during the time 10-20s and 30-40s.The simulation result is shown in Figure 4.When the time delay is decreasing during the time 10-20s and 30-40s, the slave tracking performance is better. Fig.5 is the value of $1-T_1'(t)$ and $1-T_2'(t)$ which are calculated by the system itself.

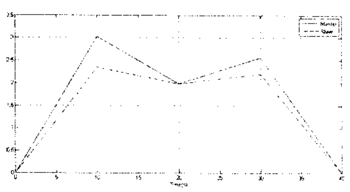

Figure 3. The varying time delay

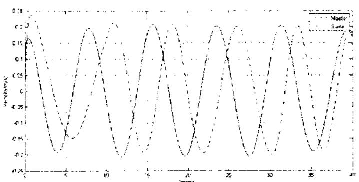

Figure 4. Tracking performance in the proposed scheme

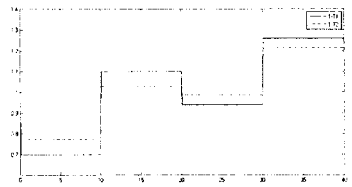

Figure 5. The value of $1-T_1'(t)$ and $1-T_2'(t)$

5. Conclusions

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. And we build a new scheme for velocity-force system with the parameters b_m, b_s, which are separately the character impedance parameters of mater/slave and can directly affect the system behavior.

Aimed at a passive control and acceptable tracking performance, another new adaptive approach based on parameter estimation in real time has been suggested. An additional transmission path has been inserted in both the forward and backward transmission, which will be used for estimating the time delay differentials in real time. The proposed scheme can adjust the output adaptively and achieve a stable acceptable tracking performance. The simulation results offered in the paper prove that our approach will ensure stability in the system and can improve the tracking performance.

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