PASSIVATION OF FORCE REFLECTING BILATERAL TELEOPERATORS WITH TIME VARYING DELAY*

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Abstract

This paper addresses the problem of time-varying communication delay in force reflecting bilateral teleoperation. The problem is motivated by the increasing use of the Internet as a communication medium where the time delay varies depending on factors such as congestion, bandwidth, or distance. The well-known scattering formalism introduced in (Anderson and Spong, 1989) preserves passivity of the communication channel for constant transmission delay. We demonstrate how passivity is lost in the case of time-varying transmission delay and show that a suitable time varying gain inserted in the transmission path can recover passivity provided a bound on the rate of change of the delay is known. Preservation of passivity by itself does not guarantee good transient performance and so we also investigate the use of saturation control to improve the tracking. Simulation results are presented showing the performance of the resulting control architecture.

1 Introduction

In this paper we investigate the control of force reflecting bilateral teleoperators with time varying delay. The problem is motivated by the use of the Internet as the communication medium connecting the master and slave manipulators where transmission delays vary over time. There has to date been relatively little research on this problem. Some preliminary results are contained in (Niemeyer and Slotine, 1998; Kosuge, Murayama and Takeo, 1996; Elhajj, Xi and Liu, 2000). The standard approaches to control of bilateral teleoperators with force feedback, based either on the

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scattering approach (Anderson and Spong, 1989) or the equivalent wave variable formulation (Niemeyer and Slotine, 1991), preserve passivity in general only for constant transmission delay. For teleoperation over the Internet the delay varies with such factors as congestion, bandwidth, or distance, and these varying delays may severely degrade performance or even result in an unstable system.

In this paper we present a simple modification to the scattering transformation of (Anderson and Spong, 1989) that inserts a time varying gain into the communication block which guarantees passivity for arbitrary time varying delays provided a bound on the rate of change of the time delay is known. Readily available network statistics can be used to estimate the delay variation needed to compute the gain compensation.

Guaranteeing passivity, however, is not sufficient to guarantee acceptable performance. We therefore investigate the use of additional control authority in the form of saturation in order to improve tracking performance. Simulation results are presented showing the performance of the overall compensation scheme.

2 Scattering Variables

The standard bilateral teleoperation system with the scattering transformation is shown in Figure 1. We denote by $\dot{x}_m(t)$ and $\dot{x}_s(t)$ the master and the slave velocities, respectively and we let F_m and F_e represent the force applied to the master and slave robots, respectively. The term F_s represents the so-called coordinating torque, which is transmitted to the master and is also sensitive to the environment contact force F_e, see (Anderson and Spong, 1989).

Instead of transmitting the velocities and forces directly, we utilize the scattering transformation of (Anderson and Spong, 1989), or, equivalently, the wave variable transformation of (Niemeyer and Slotine, 1991) and transmit the so-called *wave variables*. This transformation is given as

$$u_m = \frac{1}{\sqrt{2b}}(F_m + b\dot{x}_{md}) \qquad ; \quad v_m = \frac{1}{\sqrt{2b}}(F_m - b\dot{x}_{md}) \tag{1}$$

$$u_s = \frac{1}{\sqrt{2b}}(F_s + b\dot{x}_{sd}) \qquad ; \quad v_s = \frac{1}{\sqrt{2b}}(F_s - b\dot{x}_{sd}) \tag{2}$$

The constant b is referred to as the characteristic impedance and plays a critical role in determining the system response.

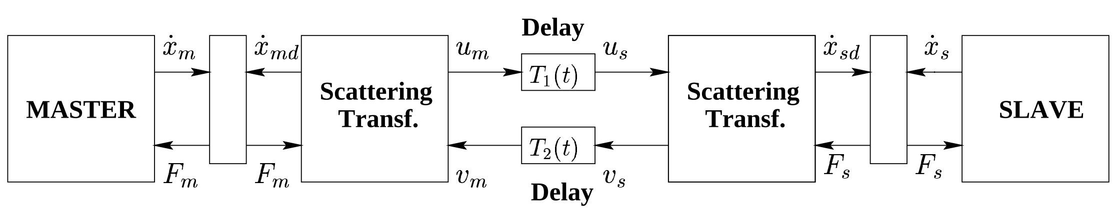

Figure 1: Scattering Transformation for Bilateral Teleoperation with Time Delay

3 Passivity

Let the power, P_{in}, entering a system be defined as the scalar product between the input vector x and the output vector y. Such a system is said to be passive if and only if

$$\int_0^t P_{in}(t) = \int_0^t x^T y d\tau \geq E_{store}(t) - E_{store}(0) \tag{3}$$

where $E(t)$ is the (nonnegative) energy stored at time t, and $E(0)$ is the initial stored energy. The power inflow into the communication block at any time is given by

$$P_{in}(t) \quad = \quad \dot{x}_{md}(t)F_m(t) - \dot{x}_{sd}(t)F_s(t) \tag{4}$$

In the case that the network delay is constant we have

$$\begin{aligned} u_s(t) &= u_m(t-T) \\ v_m(t) &= v_s(t-T) \end{aligned}$$

where T is constant. Substituting these equations into (4), and assuming that the initial energy is zero, it is easily computed that the total energy stored in the communications during the signal transmission between master and slave is given by

$$\begin{aligned} E &= \int_0^t P_{in}(\tau)d\tau = \int_0^t (\dot{x}_{md}(\tau)F_m(\tau) - \dot{x}_{sd}(\tau)F_s(\tau))d\tau \\ &= \frac{1}{2}\int_0^t u_m^T(\tau)u_m(\tau) - v_m^T(\tau)v_m(\tau) + v_s^T(\tau)v_s(\tau) - u_s^T(\tau)u_s(\tau)d\tau \\ &= \frac{1}{2}\int_{t-T}^t (u_m^T(\tau)u_m(\tau) + v_s^T(\tau)v_s(\tau))d\tau \geq 0 \end{aligned} \tag{5}$$

and, therefore, the system is passive independent of the magnitude of the delay T. The above result does not hold if $T = T(t)$, i.e., the delay is time-varying. In this case, the transmission equations become

$$\begin{aligned} u_s(t) &= u_m(t - T_1(t)) \\ v_m(t) &= v_s(t - T_2(t)) \end{aligned}$$

where, $T_1(t)$ is the delay in the forward path and $T_2(t)$ is the delay in the feedback path. Substituting these equations into (4), the energy stored in the communications is computed as

$$\begin{aligned} &\int_0^t P_{in}(\tau)d\tau = \frac{1}{2}\int_0^t u_m^T(\tau)u_m(\tau) - v_m^T(\tau)v_m(\tau) + v_s^T(\tau)v_s(\tau) - u_s^T(\tau)u_s(\tau)d\tau \\ &= \frac{1}{2}\{\int_{t-T_1(t)}^t u_m^T(\tau)u_m(\tau)d\tau + \int_{t-T_2(t)}^t v_s^T(\tau)v_s(\tau)d\tau \\ &+ \int_0^{t-T_1(t)} u_m^T(\tau)u_m(\tau)d\tau + \int_0^{t-T_2(t)} v_s^T(\tau)v_s(\tau)d\tau \\ &- \int_0^t u_m^T(\tau - T_1(\tau))u_m(\tau - T_1(\tau)) + v_s^T(\tau - T_2(\tau))v_s(\tau - T_2(\tau))\}d\tau \end{aligned} \tag{6}$$

We perform a change of variables $\sigma = \tau - T_i(\tau) := g_i(\tau)$ in the last term in the above equations. We assume that

$$g_i' = 1 - \frac{dT_i}{d\tau} \geq 0\,;\; i = 1, 2 \tag{7}$$

which is a statement that the change of variables is causal and (by the Implicit Function Theorem) invertible. Performing this change of variables it can be shown after some calculation that

$$\begin{aligned} &\int_0^t P_{in}(\tau)d\tau = \frac{1}{2}\{\int_{t-T_1(t)}^t u_m^T(\tau)u_m(\tau) + \int_{t-T_2(t)}^t v_s^T(\tau)v_s(\tau)d\tau \\ &- \int_0^{t-T_1(t)} \frac{T'_1(\sigma)}{1 - T'_1(\sigma)} u_m^T(\sigma)u_m(\sigma)d\sigma - \int_0^{t-T_2(t)} \frac{T'_2(\sigma)}{1 - T_2'(\sigma)} v_s^T(\sigma)v_s(\sigma)\} \end{aligned} \tag{8}$$

where

$$T_i'(\sigma) := \frac{dT_i}{d\tau}\Big|_{\tau = g^{-1}(\sigma)}$$

The first two integrals in the above equation represent the positive definite energy storage function that stores the energy of the waves during their transit. We note that the last two integrals are non-positive whenever the delay is increasing ($T_i' > 0$) and determine the energy produced by the communications due to the increasing delay. Therefore, the system is, in general, not passive due to the time varying delay. It is interesting to note that the system is passive during intervals of decreasing delay but not for increasing delay.

4 Passivation Scheme

In order to overcome the potential destabilizing effects of the time varying delay we propose the modified architecture shown in Figure 2 where a time varying gain f_i has been inserted after the time varying delay block. The new

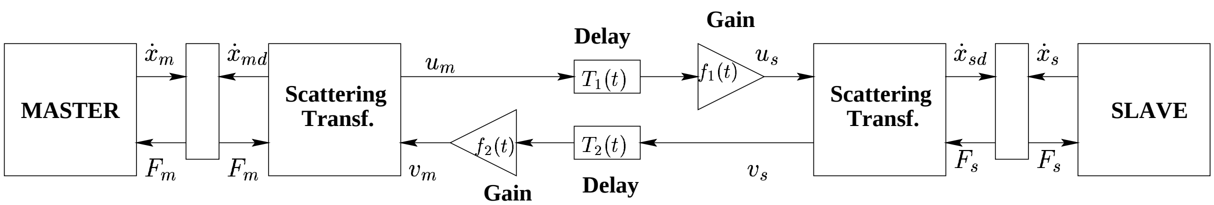

Figure 2: Time Varying Gain $f_i(t)$ inserted in the Communication Channel

transmission equations are given by

$$
\begin{aligned}
u_s(t) &= f_1(t)u_m(t - T_1(t)) \\
v_m(t) &= f_2(t)v_s(t - T_2(t))
\end{aligned}
$$

Computing the total energy as before yields

$$
\begin{aligned}
\int_0^t P_{in}(\tau)d\tau &= \frac{1}{2}\{\int_{t-T_1(t)}^t u_m^T(\tau)u_m(\tau) + \int_{t-T_2(t)}^t v_s^T(\tau)v_s(\tau)d\tau \\
+ &\int_0^{t-T_1(t)} (\frac{1-T'_1-f_1^2}{1-T'_1})u_m^T(\sigma)u_m(\sigma)d\sigma \\
+ &\int_0^{t-T_2(t)} (\frac{1-T'_2-f_2^2}{1-T'_2})v_s^T(\sigma)v_s(\sigma)d\sigma\}
\end{aligned}
\tag{9}
$$

Hence, if we choose $f_i^2 = 1 - T'_i$ in the above expressions, the second terms are eliminated and the system is passive. In fact, one can see that passivity is preserved provided the gains, f_i, are chosen to satisfy

$$
f_i^2 \leq 1 - \frac{dT_i}{dt} \;\; ; \; i = 1, 2 \tag{10}
$$

and hence exact cancellation is not necessary. In the case that the delay is constant, we may take $f_i = 1$ and recover the usual results. Note that the delay need not be the same in both directions and that any f_i satisfying the above inequality will preserve passivity. Although passivity is preserved, the performance of the system clearly depends on the choice of both the impedance parameter b and the gains f_i.

5 Simulations

To verify the efficacy of the proposed scheme, simulations were performed on a single-degree-of-freedom teleoperator. The master and slave were modelled as simple mass-damper systems. The dynamics of the simulated master and slave model were

$$\begin{aligned} M_m\ddot{x}_m + B_m\dot{x}_m &= F_h - F_m \\ M_s\ddot{x}_s + B_{s1}\dot{x}_s &= F_s - F_e \end{aligned}$$

where $\dot{x}_m$ and $\dot{x}_s$ are the respective velocities for the master and slave, M_m and M_s are the respective inertias, F_h is the operator torque, and F_e is the environment torque. The forces, F_s, and F_m are given as

$$\begin{aligned} F_m(t) &= K_m\int_0^t(\dot{x}_m - \dot{x}_{md})dt + B_{m2}(\dot{x}_m - \dot{x}_{md}) \\ F_s(t) &= K_s\int_0^t(\dot{x}_{sd} - \dot{x}_s)dt + B_{s2}(\dot{x}_{sd} - \dot{x}_s) \end{aligned}$$

In this kind of control architecture, both the master and the slave sites are put under velocity control. Such an architecture is helpful in avoiding wave reflections as pointed out in (Niemeyer and Slotine, 1991). The two inputs to the scattering transformations on both sides are now the input wave command from the communications and the local force command. For e.g, the commands that have to be generated on the master side are $\dot{x}_{md}$ and u_m. The inputs for calculating these commands are F_m and v_m. Therefore manipulating the above equations we get,

$$\begin{aligned} u_m &= \frac{1}{\sqrt{2b}}\{K_m\int_0^t(\dot{x}_m - \dot{x}_{md})dt + B_{m2}(\dot{x}_m - \dot{x}_{md}) + b\dot{x}_{md}\} \\ \dot{x}_{md} &= \frac{1}{b + B_{m2}}\{K_m\int_0^t(\dot{x}_m - \dot{x}_{md})dt + B_{m2}\dot{x}_m - \sqrt{2b}v_m\} \end{aligned}$$

To avoid reflections we choose, $B_{m2} = b$. The new equations are

$$\begin{aligned} u_m &= \frac{1}{\sqrt{2b}}(K_m\int_0^t(\dot{x}_m - \dot{x}_{md})dt + b\dot{x}_m) \\ \dot{x}_{md} &= \frac{1}{2b}(K_m\int_0^t(\dot{x}_m - \dot{x}_{md})dt + b\dot{x}_m - \sqrt{2b}v_m) \end{aligned}$$

Therefore the velocity information being communicated to the remote side, is still the master's velocity command and the force information is presented as a spring force. Similarly, the equations on the slave side are derived.

For illustration purposes, a simple delay model is constructed. The delay is increasing at a constant rate of $0.1 sec/sec$ on both the forward path on the feedback path. The system, ideally designed for a constant delay network, is unstable as can be seen from the Figure 3. In this experiment the slave does not contact the environment; the master and slave are moving freely in space.

To stabilize the system, the gains, f_i, were added after the communication block. From (10), these gains must satisfy

$$f_i^2 \le 1 - T' = 0.9 \tag{11}$$

Therefore, with $f_i = .8, i = 1, 2$ we see from Figure 4 that the system is now stable with the time varying delay.

The next two plots show the forces on the master and slave when the slave contacts a rigid wall. In each figure the dotted line represents the force at the master side and the solid line represents the force at the slave side. With no compensation both forces diverge as seen in Figure (5). With the introduction of the gain compensation the forces are bounded as shown in Figure (6).

6 Tracking Performance

We have seen how to maintain passivity and stability in the face of time varying delay by adding a (possibly time varying) gain into the communication path between master and slave. In this section we investigate ways to improve

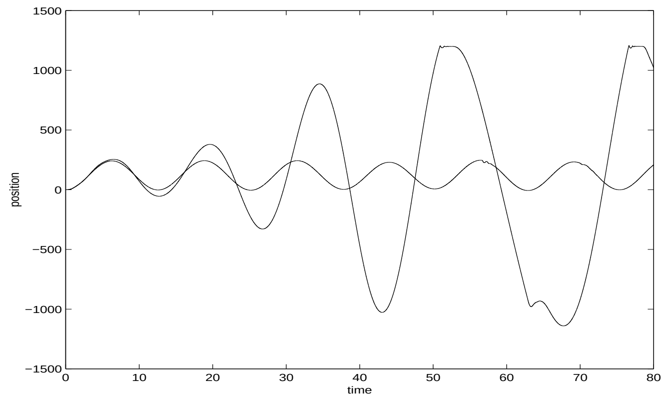

Figure 3: reference and slave position for system designed for constant delay. The slave velocity is unbounded as a result of the time varying delay.

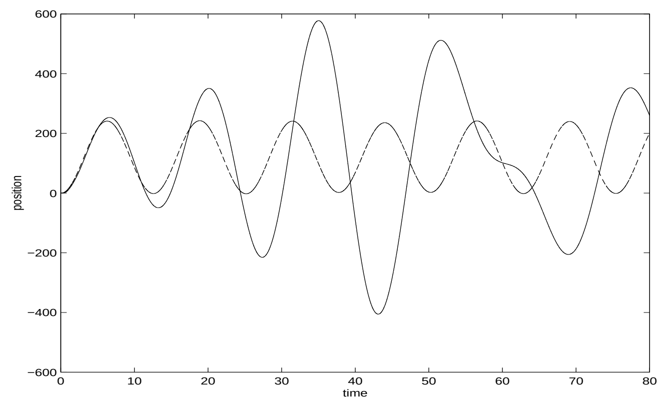

Figure 4: reference and slave position for system with the additional gains in the communication path, $f_i = 0.8$. The slave velocity remains bounded despite the time varying delay.

tracking performance further. Consider the system shown in Figure 7. The velocity command for the slave manipulator is saturated within the limits of the master velocity command. The information about the master's velocity limits can be easily incorporated on the slave side. The deviation of the slave velocity outside the masters velocity limits is a consequence of the time varying delay and thus saturating it within the master's velocity limit's would intutively help the slave in tracking the master effectively. With this saturation included in the system, the performance improves considerably as seen in the final two plots. Figure 8 shows the master and slave velocities in free space while Figure 9 shows the forces when the slave contacts the environment. The slave data have been shifted by the amount of the delay before plotting to better visualize the tracking performance.

7 Conclusions and Future Work

In this paper, a scheme was presented for maintaining passivity in a bilateral teleoperator operating over networks with time-varying-delays. Passivity is recovered by dissipating energy via two time-varying gains, inserted in the unit after the communication block, on both the master and the slave side. We also investigated the use of saturation of the

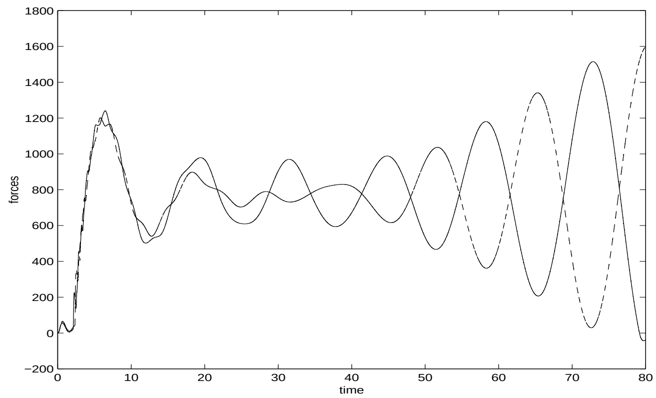

Figure 5: Force at the master and slave side - no compensation for varying delay

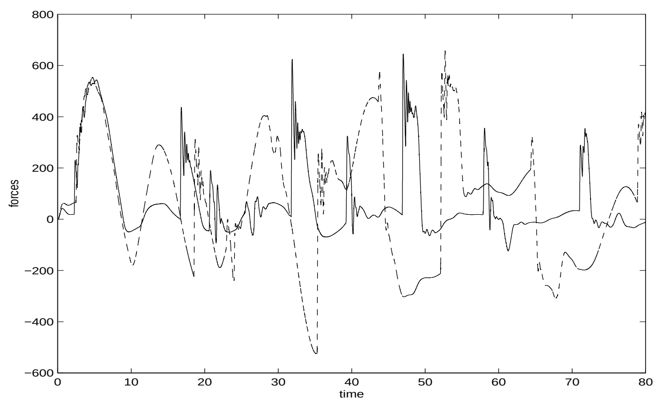

Figure 6: Force at the master and slave side - compensation for variable time delay

velocity command received at the slave side, within the limits of the master velocity, in order to improve the tracking performance.

This is only a preliminary study. Our future work will consist of developing realistic models of network delays and utilizing these models together with network statistics to develop switching control strategies for adjusting the communication gains on-line. Having a constant gain, f_i, to account for the worst-case rate of change of the delay leads to overly conservative performance. Varying the gain compensation according to the delay variation using switching control is a promising area for future investigation.

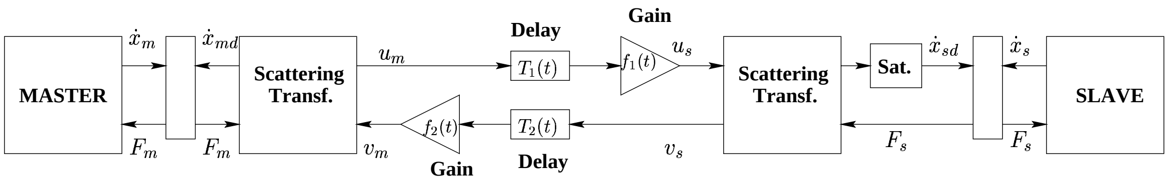

Figure 7: Control Architecture with Added Saturation

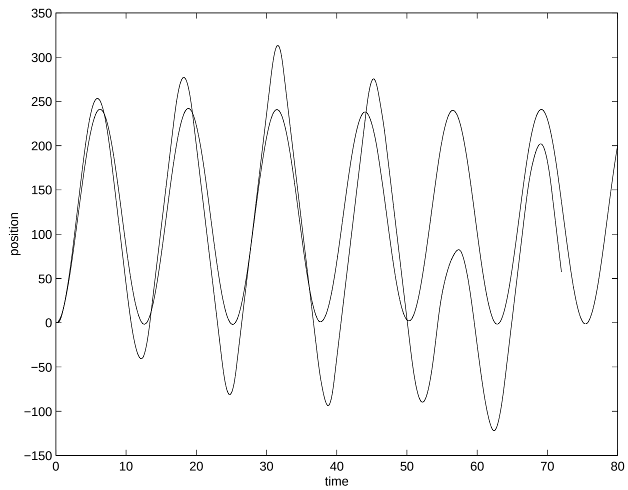

Figure 8: reference and slave position for system with the gains $f_i = 0.8$ and velocity saturation at slave side

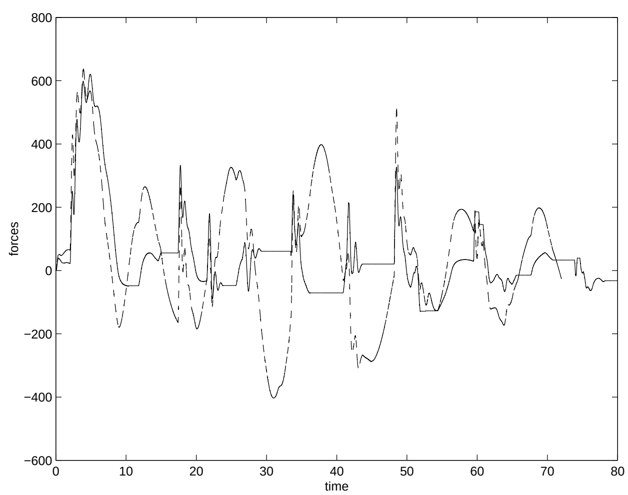

Figure 9: Force at the master and slave side - with the gains $f_i = 0.8$ and velocity saturation at slave side

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