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STABILIZATION OF DELAYED TELEOPERATION USING PREDICTIVE TIME-DOMAIN PASSIVITY CONTROL

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ABSTRACT
Stability is an important issue in bilateral teleoperation due to different factors like varying operating conditions, existence of time-delays, etc. Recently, time-domain passivity control (see [1]) has been proposed to stabilize unstable telerobotic systems and has shown good performance in situations where one or more components of the system behave actively. However, this scheme requires the computation and updating of passivity controllers in real-time in order to dissipate the surplus energy thus making it difficult to be used in many telerobotic scenarios where time-delays are inevitable. In this contribution, we present a unique approach to solve this problem by using a Kalman filter based energy predictor which allows us to design master and slave passivity controllers even in the presence of time-delays in forward and backward channels. In order to accurately predict the slave-side energy levels, the predictor makes use of a recursively updated model of the remote system. Provision of slave or environment models is not required because an adaptive mechanism constructs them from the command velocity and delayed force information. Simulation results are provided showing the validity of proposed approach.

KEY WORDS
Tele-robotics, Time-Delay, Time-Domain Passivity Control, Stabilization, Kalman Estimator

1 Introduction

It was stated as early as 1966 [2] that force feedback from remote site greatly enhances the teleoperation performance. However there are several issues attached to the provision of force-feedback in teleoperation. First of all, it turns the unilateral control scheme into a bilateral one. In addition, introduction of time delay in such a configuration seriously affects the stability. The problem of delay is essential to address because in certain situations, its presence is unavoidable like deep space, on internet, or in acoustic signals used in sonar, etc.

The problem of stability in the bilateral teleoperation with time delay was first reported by Ferrell[2]. Since its identification, different solutions have been proposed to solve it. Anderson and Spong[3] published the first solid result on the stabilization of bilateral control of teleoperators with time delay by passivation of the system using scattering theory. In almost all teleoperation literature, the system is described as a network consisting of *n*-ports where master, communication block, and slave are represented by two-ports and the operator and environment by one-ports as shown in Fig. 1. Niemeyer and Slotine[4] used wave variables based approach for the passivation of telerobotic systems. A lot of work in recent years has focussed on using wave variables for stabilization in the presence of constant or time-varying delays, see for example [5, 6, 7] and the references therein.

Time domain passivity control, a new approach for stabilization of teleoperation systems involving haptic interfaces, was introduced by Hannaford and Ryu et. al. [8]. This approach does not require for the power variables to be transformed into wave-variables. Rather a very clear notion of energy is used to define passivity of the system. The proposed framework has been used in several applications to stabilize teleoperation systems showing very good results, see, for example, [1, 9]. Time domain passivity control is based on two components, (i) passivity observer, and (ii) passivity controller. Passivity observers monitor energies that go into the system and come out of it. Passivity controllers are then used to dissipate any surplus energy if passivity observers indicate any violation of passivity by recording a negative energy flow.

If the communication network is taken as a component that is to be stabilized, then time domain passivity control approach can be applied to it, provided there are no delays involved. This requirement is vital because the function of passivity controller is based on accurate measurement of *net energy* by passivity observer. In the presence of time delays, it becomes impossible (i) to compute, and (ii) to convey the energy information, in a timely fashion, from both sides across the communication channel to passivity controller which, in our case, is located on master side.

In this contribution, we attempt to solve this problem using a novel energy prediction approach for passivity controller design. A Kalman filter is used to estimate the

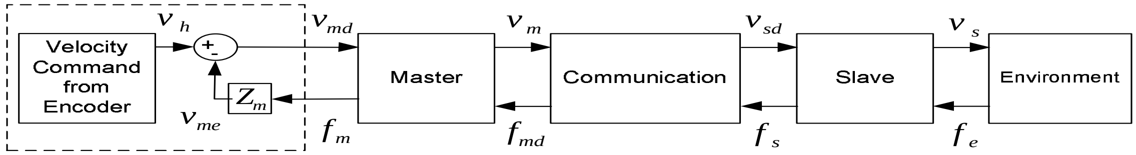


Figure 1. Telerobotic network

transfer function from the slave velocity to the environment force. This model is updated recursively on every sampling instant based on the most current data available. The available model is then used for $k-$step ahead prediction of slave-side energy. In this way, we can achieve a network block that is passive and such that Time Domain Passivity Control functions properly resulting in a stable teleoperation even in the presence of time delays in forward and backward communication channels.

Section 2 provides background information about stability and passivity concepts, including time domain passivity control. Predictive time domain passivity control is presented in section 3. Simulation results and discussion follow in section 4. We conclude in section 5.

2 Background

Passivity is necessary and sufficient condition for the stability of a two-port coupled to an arbitrary network [10]. In haptic literature, human operator is often taken as a passive element on frequencies of interest. Environment is also considered to be passive. Master, and slave, even if not, can be made passive by proper control schemes. The communication channel, however, if containing delay, can be a difficult task to be shown passive. Different approaches have been suggested to passivate it, like scattering theory[3], wave-variables[4], impedance-matching[11], etc.

In what follows, a very brief overview of passivity theory and time domain passivity control is given that is of relevance to our work.

2.1 Passivity Theory

Passivity is concerned with energies of a system. Let E_i denote the initial energy of a system. Then this system will be called passive if:

$$E(t) = \int_0^t P d\tau + E_i \geq 0 \tag{1}$$

where $E(t)$ is the total energy of the system at time t. P denotes the net power at input and output ports. Assuming initial system energy to be zero, we get a well-known expression for energy of the system:

$$E(t) = \int_0^t P d\tau = \int_0^t \boldsymbol{u}^T \boldsymbol{y}\, d\tau \geq 0 \tag{2}$$

$\boldsymbol{u}$ and $\boldsymbol{y}$ represent system input and output vectors respectively. In the case of a telerobotic system, they are usually the causal pair $\boldsymbol{f}$ and $\boldsymbol{v}$. As an *n*-port is characterized by the causal relationship between effort f(force, voltage), and flow v(velocity, current). So for a network 2-port, as shown in Fig. 2, the equation changes to:

$$E(t) = \int_0^t P d\tau = \int_0^t (f_1(\tau)v_1(\tau) - f_2(\tau)v_2(\tau))d\tau \geq 0 \tag{3}$$

Signs should be carefully selected in this expression. Here we are considering f_1, v_1 to be input- whereas f_2, v_2 to be output-variables. Equation 3 means that a passive system

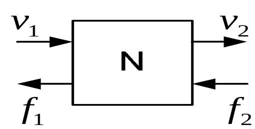


Figure 2. A telerobotic 2-port

must not generate energy by itself. It can only dissipate the input energy or in ideal conditions can function as lossless channel in which case $E(t) = 0$. For a network of p connected elements, the condition of passivity (see [12]) can be written as:

$$E_{total}(t) = \sum_{j=1}^{p} E_j(t) \geq 0 \tag{4}$$

2.2 Time Domain Passivity Control

As described in the section 1, passivity can be guaranteed using different control techniques to manipulate the ports of an active system. Time domain passivity control[8] uses the direct notions of energy and power variables. For a discrete case, on a network 2-port, as given in Fig. 2, a passivity observer can be designed as:

$$E_{obs}(n) = \Delta T \sum_{k=0}^{n} (f_1(k)v_1(k) - f_2(k)v_2(k)) \tag{5}$$

or

$$E_{obs}(n) = \Delta T\, W(n) \tag{6}$$

With sufficiently small ΔT, $E_{obs}(n)$ closely matches the system energy at instant n. In normal passive operation, $E_{obs}(n)$ should always be positive. In cases when

$E_{obs}(n) < 0$, passivity observer indicates that the system is generating energy and has gone active. Sometimes, control action may not be required, for example, when this is due to some noise, or for a very brief value, etc.

But generally, once the system is regarded as an active port, a passivity controller must be engaged to dissipate the excess energy. Placement and configuration of a passivity controller depends on the causality of the port. It should be noted that while designing a passivity controller at any port, care must be taken not to change the input variable as that would essentially result in command signal errors. Rather, the output variables of the port should be modified in real-time. In our case, as given in Fig. 3, two passivity controllers are placed on both sides of the network port to be stabilized. These ports have different causalities, the master side being an impedance causality whereas the slave side is an admittance causality.

Computation of passivity controllers α_1 and α_2 depends on the observed power value $W(n)$ given as(see Ryu et. al. [1]):

$$\begin{aligned} W(n) &= W(n-1) + f_1(n)v_1(n) - f_2(n)v_2(n) \\ &\quad + \alpha_1(n-1)v_1(n-1)^2 \\ &\quad + \alpha_2(n-1)f_2(n-1)^2 \end{aligned} \tag{7}$$

Here the previous value $W(n-1)$ is to integrate over time, where as the last two terms are to deduct energy contributions by passivity controllers, as computed in equations 8-11. As we formulate in section 3, the effect of time-delay is cancelled in the calculation of passivity controllers, so their values are computed as below [1]:

$$\alpha_1 = -W(n)/v_1(n)^2, \quad \text{if port 1 is active} \tag{8}$$
$$\alpha_2 = -W(n)/f_2(n)^2, \quad \text{if port 2 is active} \tag{9}$$

where α_1 dissipates energy on an impedance causality (master side) and α_2 on an admittance causality (slave side). When both master and slave ports become negative, the previous energy value $W(n-1)$ is also used as given in [1] to make, in our case, the slave side additionally conservative. So in such a case passivity controllers (α_1 and α_2) are computed as:

$$\alpha_1 = -(f_1(n)v_1(n))/v_1(n)^2 \tag{10}$$
$$\alpha_2 = -(W(n-1) + f_2v_2)/v_2(n)^2 \tag{11}$$

$W(n)$ is evaluated at each step based on the previous sampling interval and if found negative, a corrective action is taken.

3 Adaptive Energy Estimation for Predictive Time Domain Passivity

This section describes the main contribution of this work. In order to make use of the Time Domain Passivity Control framework, given in section 2.2, to stabilize a delayed telerobotic system, one needs to compute master and slave energies, in real-time without delay. However, if the controller design is carried out on master side, the real-time value of slave energy is unknown because of the delay. To overcome this issue, a novel estimation based approach is presented here.

In order to measure energy on slave side, see Fig. 3, we need to measure v_{sd} and f_s. Out of these two, $v_{sd}(t)$ can be determined given knowledge of the forward time-delay and of the forward gains, if any. However $f_s(t)$ requires the actual response of the combined transfer function from $v_{sd}(t)$ to $f_s(t)$ or $\mathscr{L}[f_s(t)/v_{sd}(t)]$.

As the environment and slave conditions may change over time, so an offline identified model is not a promising solution. In this case, we can design an adaptive model of slave-side system which includes both slave and the environment. This model will be an online estimator, the parameters of which would be computed recursively using optimal Kalman filtering. The predictor can then, using this estimated model, predict $\hat{f}_s(t)$ using $v_m(t)$ and the delay information. Once estimated, $\hat{f}_s(t)$ can be used for computation of α_2, the passivity controller, as if no delay existed in the forward channel.

If $\hat{\theta}(t)$ denotes the parameters of online estimator, the recursive parameter update equation can be written as:

$$\hat{\theta}(t) = \hat{\theta}(t-1) + K(t)[f_s(t) - \hat{f}_s(t)] \tag{12}$$

where

$$\theta(t) = [a_1 \;\; a_2 \;\; b_1 \;\; b_2] \tag{13}$$

for the following 2nd-order model:

$$a_2\ddot{f}_s(t) + a_1\dot{f}_s(t) + f_s(t) = b_2\dot{v}_{sd}(t) + b_1 v_{sd}(t) \tag{14}$$

where $a_i,\ b_j\ (i,j \in \{1,2\})$ are parameters of the recursive model.

Using Kalman estimator from [13], the Kalman gain $K(t)$ can be computed as:

$$K(t) = F(t)\phi(t) \tag{15}$$
$$F(t) = \frac{P(t-1)}{\phi^T P(t-1)\phi(t) + R} \tag{16}$$
$$\begin{aligned} P(t) &= P(t-1) \\ &\quad - \frac{P(t-1)\phi(t)\phi(t)^T P(t-1)}{R + \phi(t)^T P(t-1)\phi(t)} \end{aligned} \tag{17}$$

where $P(t)$ and R are output error- , and measurement error- covariances, respectively. $\phi(t)$ is the vector containing input and output values at time t.

Because the output of network f_s is delayed output of remote system, so we must synchronize the input and out pair that is fed to Kalman filter. So at any time instant t, the input to Kalman filter is given by:

$$\phi(t-\tau_b) = [\hat{v}_{sd}(t-T_b) \quad f_s(t-T_b)] \tag{18}$$

where

$$\hat{v}_{sd}(t-T_b) = v_m(t-T_f-T_b) \tag{19}$$

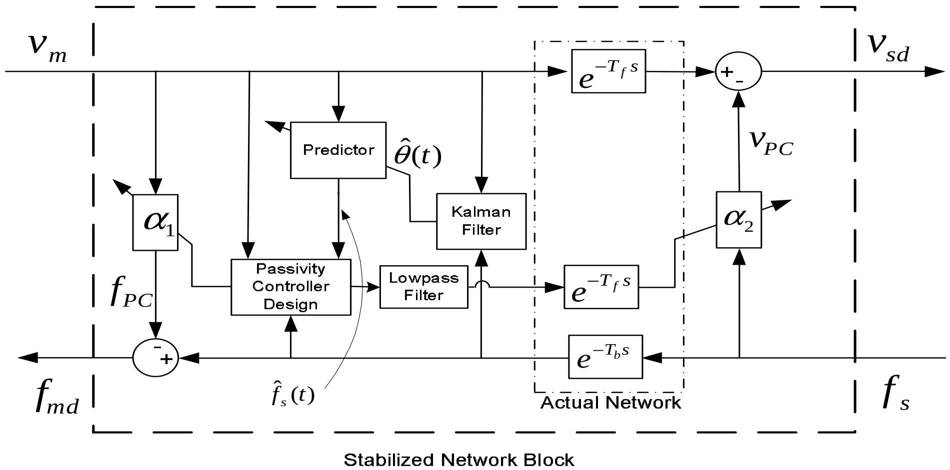


Figure 3. Passive network 2-port

which is obtained by backward time-shifting v_m because both the forward and backward time-delays are known. The complete stabilization scheme using online estimation and $k-$step ahead energy prediction is shown in Fig. 3.

After Kalman filter provides recursively updated estimate of parameters $\hat{\theta}(t)$, the remaining $(T_b + T_f)/\Delta T$ inputs can be used in $k - step$ ahead predictor. The k-th output corresponds to current time t and is given as $\hat{f}_s(t)$ which is the predictive estimate of environment force. Corresponding to equation (7), this information can be used as following to estimate the energy:

$$\begin{aligned} W(n) \quad = \quad & W(n-1) \\ & + f_m(n)v_m(n) - \hat{f}_s(n)\hat{v}_{sd}(n) \\ & + \alpha_1(n-1)v_m(n-1)^2 \\ & + \alpha_2(n-1)\hat{f}_s(n-1)^2 \end{aligned} \tag{20}$$

where

$$\hat{v}_{sd}(n) = v_m(n-\zeta) \tag{21}$$

and

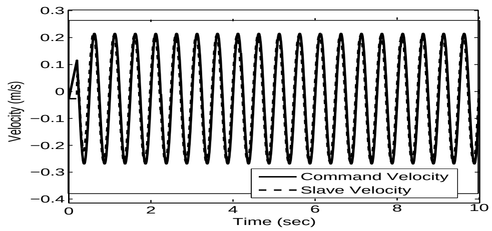
$$\zeta = \lfloor T_f/\Delta T \rfloor \tag{22}$$

After $W(n)$ is computed, controllers α_1 and α_2 are calculated as stated in section 2.2. But as the calculation of α_2 is based on estimated force information, which may contain noise, so the system response becomes quite noisy if α_2 is used directly. To counter this problem, we suggest a low-pass filter for α_2 which is designed to pass only those frequencies that are closer to the expected correction rate. The concept of filters in teleoperation is not new. Spong et. al.[14] report that a digital implementation of a continuous time passive system may no longer remain passive/stable and would require the introduction of strictly causal and stable linear filters to ensure stability of sampled-data master/slave systems. In addition, simple low-pass filters can also serve to help limit the bandwidth utilization [5].

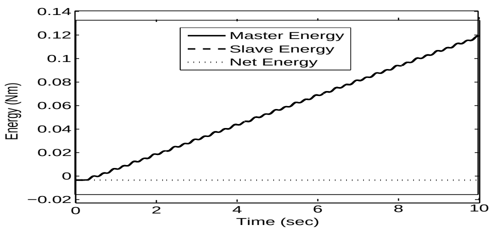
4 Simulation Results and Discussion

The proposed approach is simulated using one degree of freedom master and slave arms. Environment model uses a stiffness constant $K = 5N/m$. The damping constant is $0.5Ns/m$. Master arm uses a force control loop to output the reflected force from the environment while slave arm uses velocity control to follow the operator commands. Velocity command is set to a sine wave with an amplitude of $0.24m/s$ and a frequency of $3Hz$. Sampling time is set at $10ms$.

First of all, the system is simulated without any delay in the forward and backward channels, and because it consists of inherently stable components, the response is stable, as shown in Fig. 4(a). A plot showing the energies of the system is given in Fig. 4(b). As can been seen clearly, the net energy is zero thus marking it a passive system. Next, time delays of $0.3s$ and $0.2s$ are introduced in forward and backward channels respectively. As expected, the delays cause the system to become unstable. In this case, the command and slave velocities are shown in Fig. 5(a) and slave velocity is clearly growing unstable. A look at energies on both sides of communication port, see Fig. 5(b), reveals a negatively growing net energy thus destabilizing the whole system. Now, the proposed scheme is employed including Kalman filter and energy predictor to estimate the slave side energy. First we start without any filter on the value of α_2, thus allowing any noise-effects to pass to passivity control. The velocity tracking results are shown in Fig. 6(a) while the energies are plotted in Fig. 6(b). In this case, we see that the system has become stable but there is very little transparency as the slave response is very noisy. However, the drop in negative energy level from $-25Nm$, in Fig. 5(b) to just $-0.5Nm$ in Fig. 6(b) can be easily discerned. The choice of proper filter for α_2 is very important because excessive filtering can leave the

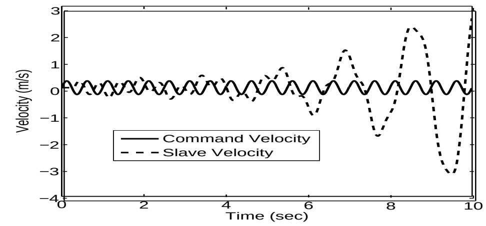


(a)

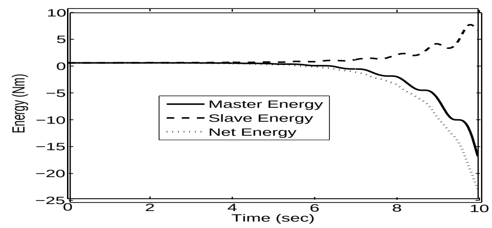


(b)

Figure 4. Without delay, (a) command and slave velocities, and (b) energies



(a)



(b)

Figure 5. Delays $T_f = 0.3s$, $T_b = 0.2s$, without passivity control. (a) command and slave velocities, and (b) energies

whole scheme very conservative while too less or no filtering can lead to noisy outputs. Results with filtering at cutoff frequency of about $20Hz$ are shown in Figs. 7(a), and 7(b). Net energy can be seen to be almost zero. The very small negative value can be attributed to small variations in predicted and actual energy levels as well as the differences between continuous and discrete energies. A divergence of the slave velocity in the beginning in Fig. 7(a) is because of the error between actual and estimated environment force as shown in Fig. 7(c). This is due to initialization of recursive joint model of remote manipulator and environment. Making sampling interval smaller can also improve the performance by providing better energy estimates. Passivity controller corrections are shown in Figs. 7(d) and 7(e).

5 Conclusion

Predictive time domain passivity control has been suggested for stabilization of teleoperation systems in presence of time-delays. The scheme is based on the use of an online energy estimator to predict the slave energy. This energy is then used to design stabilizing passivity controllers for both master and slave sides of the unstable (active) network block. Recursive estimation of remote-side transfer function obviates the need for slave or environment models. The proposed system has shown good performance in teleoperation simulations of a one degree of freedom robot over a delayed communication channel. Further work will address issues like transparency and time-varying delays.

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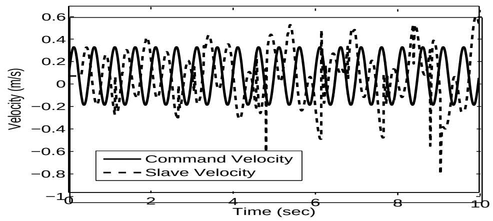
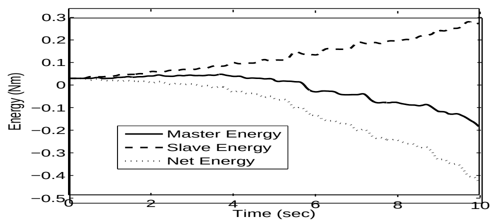


(a)



(b)

Figure 6. Delays $T_f = 0.3s$, $T_b = 0.2s$, α_2 not filtered. (a) Command and slave velocities, and (b) energies

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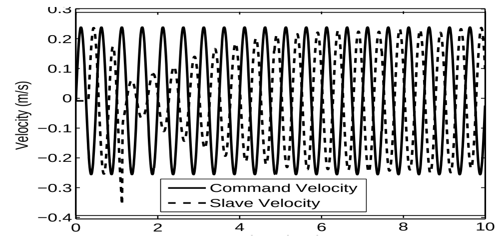

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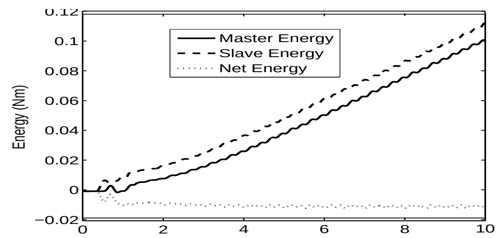

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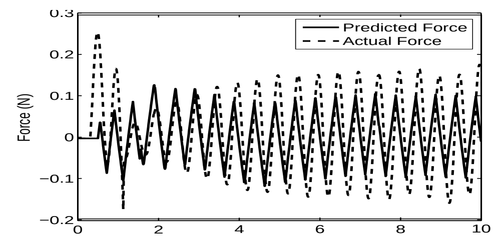

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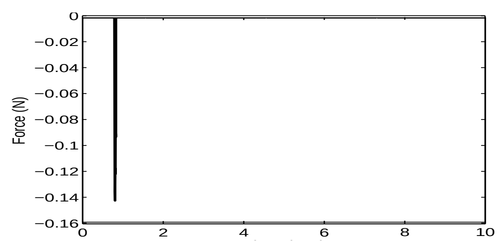

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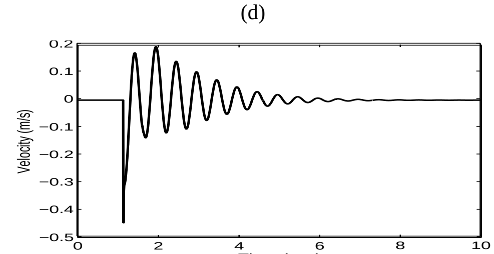

(e)

Figure 7. Delays $T_f = 0.3s$, $T_b = 0.2s$ and α_2 filtered at $20Hz$ (a) Command and slave velocities, (b) energies, (c) estimated and real environment force, (d) force corrections (f_{PC}) from passivity controller α_1, and (e) velocity corrections (v_{PC}) from passivity controller α_2.