Predictive Time Domain Passivity Control For Delayed Teleoperation Using Energy Derivatives

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***Abstract*— Time Domain Passivity Control deals with the stabilization of haptic interfaces in teleoperation using the notion of passivity directly in the continuous time variables like force and velocity. In a previous work, authors have already shown that this concept can be utilized to stabilize the time-delayed teleoperation by considering the communication channel as an active component and to design passivity controllers for it on master side using a Kalman filter based recursive prediction of slave side energy. However, such a scheme is prone to large corrective impulses generated by passivity controllers as the scheme only comes into action when the net energy goes negative, while on other time instants it stays out of the control loop providing a completely transparent teleoperation. These impulses degrade the performance of teleoperator. It is thus proposed, that the derivative of net energy should also be computed in real-time, and as soon as this term becomes negative, indicating a decline in the net energy, the passivity controllers should immediately compensate this active behavior. Simulation results of the proposed scheme showing very good stability and transparency are presented.**

***Keywords*—Time Domain Passivity Control, Stabilization, Teleoperation, Time Delay**

I. Introduction

Stability is a fundamental issue in networked control systems. In many of the present day teleoperation systems, a computer network serves as the basis of communication. Force feedback in such a system turns the unilateral control scheme to a bilateral one and seriously raises the question of the stability[1]. Anderson and Spong[2] published the first solid result by passivation of the system using scattering theory. Niemeyer and Slotine introduced wave variables based approach for the passivation of telerobotic systems in the presence of constant or time-varying delays[3]. Despite the benefits offered by wave-variables, they still lack a direct physical meaning when compared to their counterparts like force and velocity[4]. The absence of physical manifestation can pose challenges when designing controllers and it can be difficult to make use of intuitive insight in this process.

Time Domain Passivity Control(TDPC) was introduced by Hannaford and Ryu et. al. [5]. This approach does not require for the power variables to be transformed into wave-variables. Rather a straight-forward 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 [6] and references therein. A brief review of TDPC is given in Section II. If the communication network in a port-based teleoperation system, as given in Fig. 1, is taken as a component that is to be stabilized, then TDPC approach can be applied to it provided there are no delays involved. However, in the presence of time delays, it becomes hard (i) to compute, and (ii) to convey the energy information, in a timely fashion, from both sides across the communication channel.

Here we attempt to solve this problem using i) an energy prediction approach for passivity controller design, and ii) the derivatives of net energy that are obtained using the aforesaid energy prediction. A Kalman filter is used to recursively estimate the parameters of transfer function from the slave velocity to the environment force. The available model is then used for $k-$step ahead prediction of slave-side energy. Using this information and the derivatives of net energy, we can achieve a network block that is passive and such that TDPC functions properly resulting in a stable teleoperation even in the presence of time delays.

II. Time Domain Passivity Control

A. *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:

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

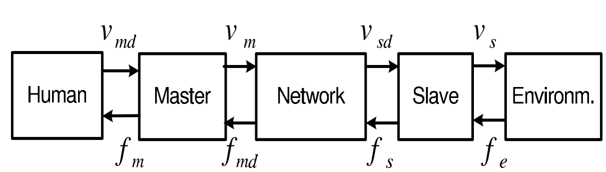

Fig. 1. A Telerobotic Network

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. 1, the equation changes to:

$$E(t) = \int_0^t P d\tau$$
$$= \int_0^t (f_{md}(\tau) v_m(\tau) - f_s(\tau) v_{sd}(\tau)) d\tau \geq 0 \tag{3}$$

Signs should be carefully selected in this expression. Here we are considering f_{md}, v_m to be input- whereas f_s, v_{sd} to be output-variables.

Equation 3 means that a passive system 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 $E(t) = 0$.

B. Time Domain Passivity Control

Using TDPC[5] on a network 2-port, as given in Fig. 1, a passivity observer can be designed as:

$$E_{obs}(n) = \Delta T \sum_{k=0}^{n} (f_{md}(k) v_m(k) - f_s(k) v_{sd}(k)) \tag{4}$$

or

$$E_{obs}(n) = \Delta T \; W(n) \tag{5}$$

With sufficiently small ΔT, $E_{obs}(n)$ closely matches the system energy at instant t_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, e.g., when this is due to some noise, or has occurred for a very brief time instant and is of a negligible magnitude, etc.

But generally, once the system is regarded as an active port, a passivity controller, depending on the causality of the port, must be engaged to dissipate the excess energy. 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. 2, two passivity controllers are placed on both sides of the network port to be stabilized.

Passivity controller α_m dissipates energy on an impedance causality (master side) and α_s on an admittance causality (slave side), see Fig. 2. Computation of these controllers depends on the observed power value $W(n)$ and the results of Ryu. et. al.[5] are used as a basis for extension of TDPC concept to delayed teleoperation given in this work. Calculation of these controllers is improved for better tracking of velocity signal using energy derivatives as will be described in Section III-B.

III. Extending Time Domain Passivity to Delayed Teleoperation

In order to make use of the TDPC framework, given in Section II-B, to stabilize a delayed telerobotic system, one needs to compute master and slave energies, in real-time without delay. In order to measure energy on slave side, we need to measure v_{sd} and f_s, see Fig. 2. 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 a recursive model of remote system which includes both slave and the environment. This model will be estimated online, the parameters of which would be computed recursively using non-linear Kalman filtering as given in Section III-A. Then the predictor can, with the help of 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_s, the passivity controller, as if no delay existed in the forward channel. In addition, energy derivatives can be used to recognize a decrease in the net energy of the system. This information is then used, as described in Section III-B, to design passivity controllers that offer excellent velocity tracking.

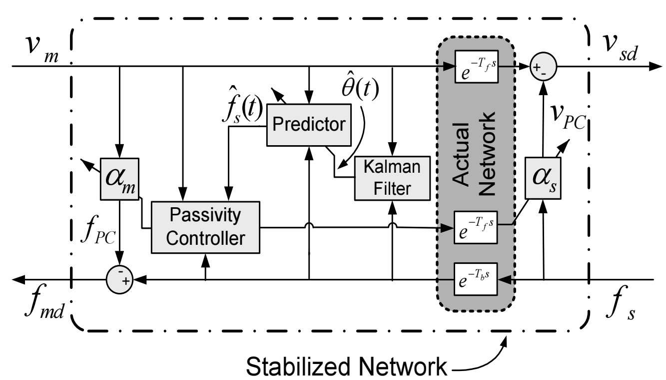

Fig. 2. Passive Network 2-Port using Predictive Time Domain Passivity

A. Non-linear Recursive Estimation of Slave Energy

To estimate the slave energy in real-time requires a non-linear recursive estimator of the parameters of slave robot as well as of environment because these parameters can change over time. There can be different solutions to this problem like:

1) Assigning exponential weights to the measurements, thus discounting the weight of previous measurements as the new ones become available, or

2) To use a linear estimator, like Kalman filter, and then to postulate that the true parameter vector is not constant but rather varies like a random walk, etc.

We select the second approach in our work. In this case, if $\hat{\theta}(t)$ denotes the parameters of online predictor, the recursive parameter update equation can be written as:

$$\hat{\theta}(t) = \hat{\theta}(t-1) + L(t)\left[f_s(t) - \hat{f}_s(t)\right] \tag{6}$$

or

$$\hat{\theta}(t) = \hat{\theta}(t-1) + L(t)\left[f_s(t) - \psi^T(t)\hat{\theta}(t-1)\right] \tag{7}$$

where

$$\theta(t) = [\beta_1 \dots \beta_3 \quad \gamma_1 \dots \gamma_3] \tag{8}$$

for the following 3^{rd} order model for prediction of $f_s(t)$:

$$\hat{f}_s(t) = -\sum_{i=1}^{3}[\beta_i(t) f_s(t-i)] + \sum_{i=1}^{3}[\gamma_i(t) v_{sd}(t-i)] + e(t) \tag{9}$$

The parameter estimation model can be described as:

$$\theta(t+1) = F(t)\theta(t) + w(t) \tag{10}$$

$$\hat{f}_s(t) = H(t)\theta(t) + e(t) \tag{11}$$

where in our case, $F(t) = I$, and $H(t) = \psi^T(t)$. $\theta(t)$ is the parameter vector at time t, and $\psi(t)$ is the regressor vector. w is white Gaussian noise and serves to help drift the parameter vector in the manner of a random walk. v is white noise. The above equations can be rewritten as:

$$\theta(t+1) = \theta(t) + w(t) \tag{12}$$

$$\hat{f}_s(t) = \psi^T(t)\theta(t) + e(t) \tag{13}$$

where

$$Ew(t)w^T(t) = R_1(t) \tag{14}$$

$$Ee^2 = R_2(t) \tag{15}$$

In such a case, equation (6) can be computed as[7]:

$$L(t) = \frac{P(t-1)\psi(t)}{R_2(t) + \psi^T(t)P(t-1)\psi(t)} \tag{16}$$

$$P(t) = P(t-1) - \frac{P(t-1)\psi(t)\psi^T(t)P(t-1)}{R_2(t) + \psi^T(t)P(t-1)\psi(t)} + R_1(t) \tag{17}$$

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.

Using the above mentioned method, the non-linear joint model of the slave and environment can be estimated recursively. As a first attempt, a 2^{nd}-order ARX model was used. However simulations suggested that a 3^{rd}-order model best describes the dynamics of the system as well as smoothens the predicted energies considerably.

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

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

where

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

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. 2. There, however, can be instances when an external unpredicted force is exerted by the environment which might drive the system to instability before the predictor could compensate for the abrupt change. This situation can be countered by restricting the f_s to a certain bound which if reached, would saturate it. This way any potential instabilities can be avoided.

B. Design of Passivity Controllers based on Energy Derivatives

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.

Clearly this information can be used as following to recursively calculate the energy:

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

where

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

and

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

Here the previous value $W(n-1)$ is to integrate over time, whereas the last two terms in equation 20 are to deduct energy contributions by passivity controllers. As we formulate in Section III, the effect of time-delay is canceled in the calculation of passivity controllers, so their values are computed as given in Table I.

The contributions of passivity controllers are converted into power variables as either f_{PC} or v_{PC} using the relationships:

$$f_{PC}(n) = \alpha_m(n)v_m(n) \tag{23}$$

$$v_{PC}(n) = \alpha_s(n)f_s(n) \tag{24}$$

When both master and slave ports become negative, the previous energy value $W(n-1)$ is also used, as given in [5], to make, in our case, the slave side additionally conservative which belongs to Case 3 in table I. It is to be noted that $W(n)$ and $\left.\frac{dW}{dt}\right|_{t=n}$ are evaluated at each step based on the previous

TABLE I

CALCULATION OF PASSIVITY CONTROLLERS

Case	Energy Variables' Conditions						Designed Controllers	
	$W(n)$	$\frac{dW}{dt}\Big\vert_{t=n}$	$P_m(n)$	$P_s(n)$	$W(n-1)+P_m(n)$	$W(n-1)+P_s(n)$	$\alpha_m(n)$	$\alpha_s(n)$
1	< 0	n/a	< 0	≥ 0	n/a	n/a	$-\frac{W(n)}{v_m(n)^2}$	0
2	< 0	n/a	≥ 0	< 0	n/a	n/a	0	$-\frac{W(n)}{\hat{f_s(n)}^2}$
3	< 0	n/a	< 0	< 0	< 0	< 0	$-\frac{P_m(n)}{v_m(n)^2}$	$-\frac{W(n-1)+P_s(n)}{\hat{f_s(n)}^2}$
4	< 0	n/a	< 0	< 0	≥ 0	< 0	0	$-\frac{W(n-1)+(P_s(n)-P_m(n))}{\hat{f}_s(n)^2}$
5	< 0	n/a	< 0	< 0	< 0	≥ 0	$-\frac{W(n-1)+(P_m(n)-P_s(n))}{v_m(n)^2}$	0
6	≥ 0	< 0	≥ 0	≥ 0	n/a	n/a	0	$-\frac{[W(n)-W(n-1)]}{\hat{f_s(n)}^2}$

sampling interval and if found negative, respective corrective action is taken based on the cases given in Table I. Here $P_m(n)$ and $P_s(n)$ represent the power at the master and slave ports and are given as:

$$P_m(n) = f_{md}(n)v_m(n) \quad (25)$$

$$P_s(n) = \hat{f}_s(n)\hat{v}_{sd}(n) \quad (26)$$

The calculation of α_s is based on estimated force information, which may contain noise, so the system response becomes quite noisy if α_s is used directly. To counter this problem, we suggest a low-pass filter for α_s 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.[8] reported 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 [9].

Cases 4 and 5 have been designed to dissipate the additional energy symmetrically on both master and slave ports. In the work of Ryu et. al.[5], these two cases are made to dissipate either $-\frac{W(n-1)+P_s(n)}{f_s(n)^2}$ or $-\frac{W(n-1)+P_m(n)}{v_m(n)^2}$, respectively, while in our case, these terms are modified as $-\frac{W(n-1)+(P_s(n)-P_m(n))}{f_s(n)^2}$ and $-\frac{W(n-1)+(P_m(n)-P_s(n))}{v_m(n)^2}$, respectively to make the transmission as lossless as possible. Case 6, on the other hand, tries to dissipate energy even when the network port is passive, based on the real-time derivative of net energy. This step ensures that the system will always dissipate energy. The effect of this term will be further elaborated using the simulations results in Section IV.

IV. 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 $0.5N.s/m$. 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 $2Hz$. Sampling time is set at $10ms$.

First 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. 3(a). Continuous and discrete energies of the system are given in Fig. 3(b)-3(c). It is clear that net continuous energy is zero while a small positive value in the discrete case in Fig. 3(c) is due to numerical errors in discrete integration. However, these figures are important as they represent the ideal response of a passive system in the absence of time-delay.

Figs. 4(a)-4(b) show the same teleoperation system when simulated with delays of $0.2s$ in the forward- and $0.3s$ in the backward-path respectively. The net energy in the system is rapidly growing negative and is making it unstable.

The proposed scheme using only the prediction of slave-side energy as described in Section III and without energy derivatives is now engaged into the simulation of the given teleoperation system in the presence of time-delays. It clearly stabilizes the system as can be seen from the velocity tracking in Fig. 5(a). Passivity controllers are computed using Cases 1-5 from Table I. Fig. 5(b) shows an apparent *decrease* in negative energy as it drops from $-25Nm$ for an unstable system in Fig. 4(b) to just about $-0.2Nm$ in Fig. 5(b).

The performance of the teleoperated system is directly linked to discrete energies given in Fig. 5(c) as the algorithm that computes passivity controllers makes use of only the discrete energy values. Looking closely at Figs. 5(a) and 5(c)

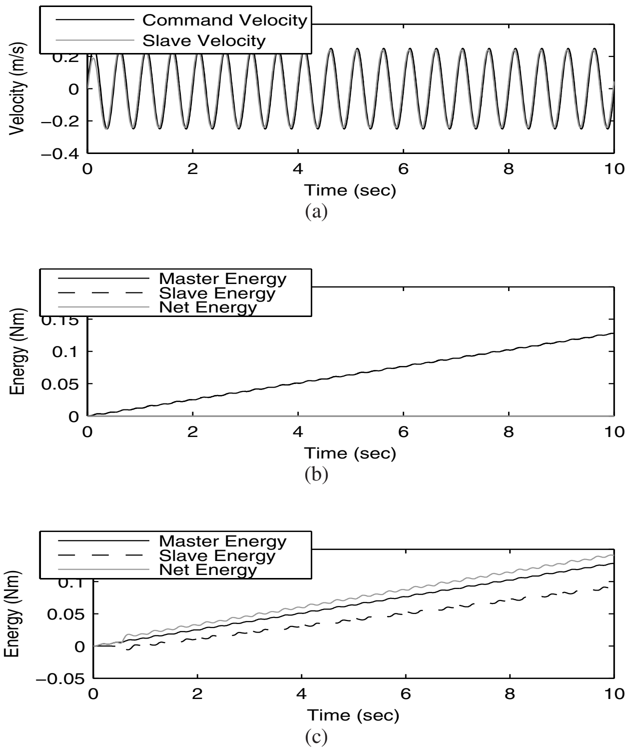

Fig. 3. Teleoperation without any time-delay (a) Command and slave velocities, (b) continuous-time energies at master- and slave-side ports of the network, (c) discrete energies

reveals that the slave velocity gets noisy after 8 sec. which is directly related to the decrease in the net energy at the same time instant in Fig. 5(c). The passivity controller will, however, not fire till the net energy will become negative. It becomes then obvious that a compensation of the decrease in net energy would certainly improve the system performance as it will force the system to always stay passive. To implement this feature, we keep track of the net energy $W(n)$ and its derivative $\left.\frac{dW}{dt}\right|_{t=n}$. Once *the derivative* gets negative, we do not wait for *net energy* to become negative. Rather this decrease in net energy is compensated immediately using Case 6 given in Table I. This approach gives another meaning to the *Reference Energy Following* approach described in [6].

Simulation results using this energy derivative based TDPC are given in Figs. 6(a)-6(f). Excellent velocity tracking is observed in Fig. 6(a). A striking resemblance between the discrete and continuous energies of a delay-free system shown in Fig. 3 and of a delayed system under energy derivative based TDPC in Fig. 6 can be easily seen. Fig. 6(e) shows the activations of passivity controller α_s in terms of the velocity compensation v_{PC} (refer to Fig. 2) to compensate the active behavior of the network 2-port. Fig. 6(f) shows how the Kalman filter based non-linear estimation of joint model of slave dynamics and environment provides the real-time prediction of environment force.

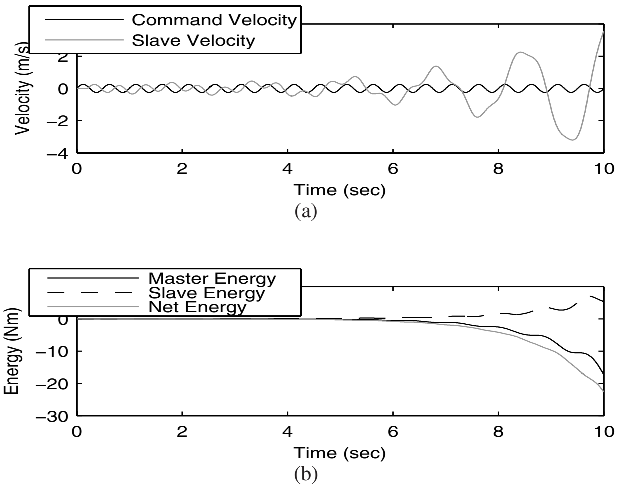

Fig. 4. Delays $T_f = 0.3s$, $T_b = 0.2s$, without passivity controllers (a) Command and slave velocities, (b) energies in continuous time

It should be noted that although the results presented here are based on constant time delay, the approach is equally valid for time-varying time delays provided a good estimate of the current value of time-delay is given. Our future work will further explore this direction.

V. Conclusion

This contribution extends the time domain passivity theory for teleoperated systems in the presence of constant time delays. The proposed approach, in addition to online non-linear estimation of joint model of slave dynamics and the environment, makes use of energy derivatives to compensate for an active behavior of the network 2-port. Passivity controllers to this effect are designed and their stabilizing action is demonstrated through the simulation of a one-degree-of-freedom teleoperation system.

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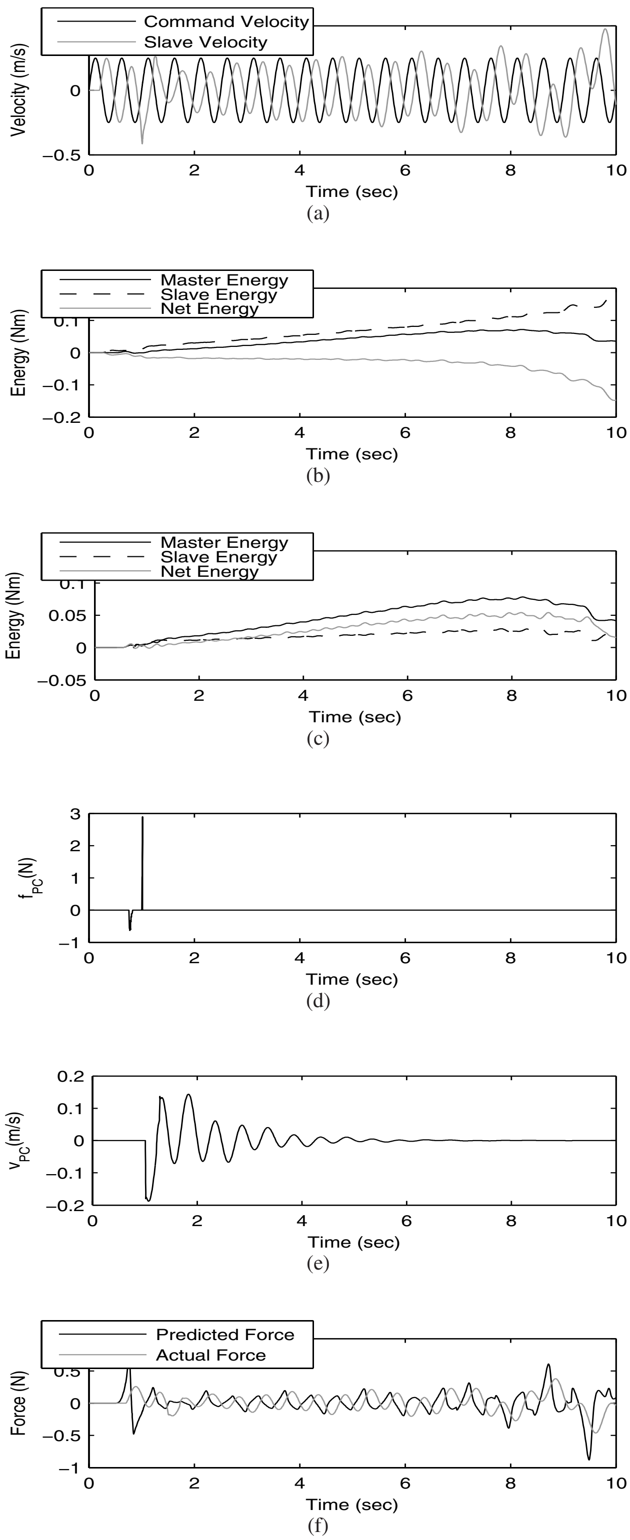

Fig. 5. **Without energy derivatives**, Delays $T_f = 0.3s$, $T_b = 0.2s$ (a) Command and slave velocities, (b) continuous energies, (c) discrete energies , (d) f_{PC}, (e) v_{PC}, (f) predicted and actual environment force

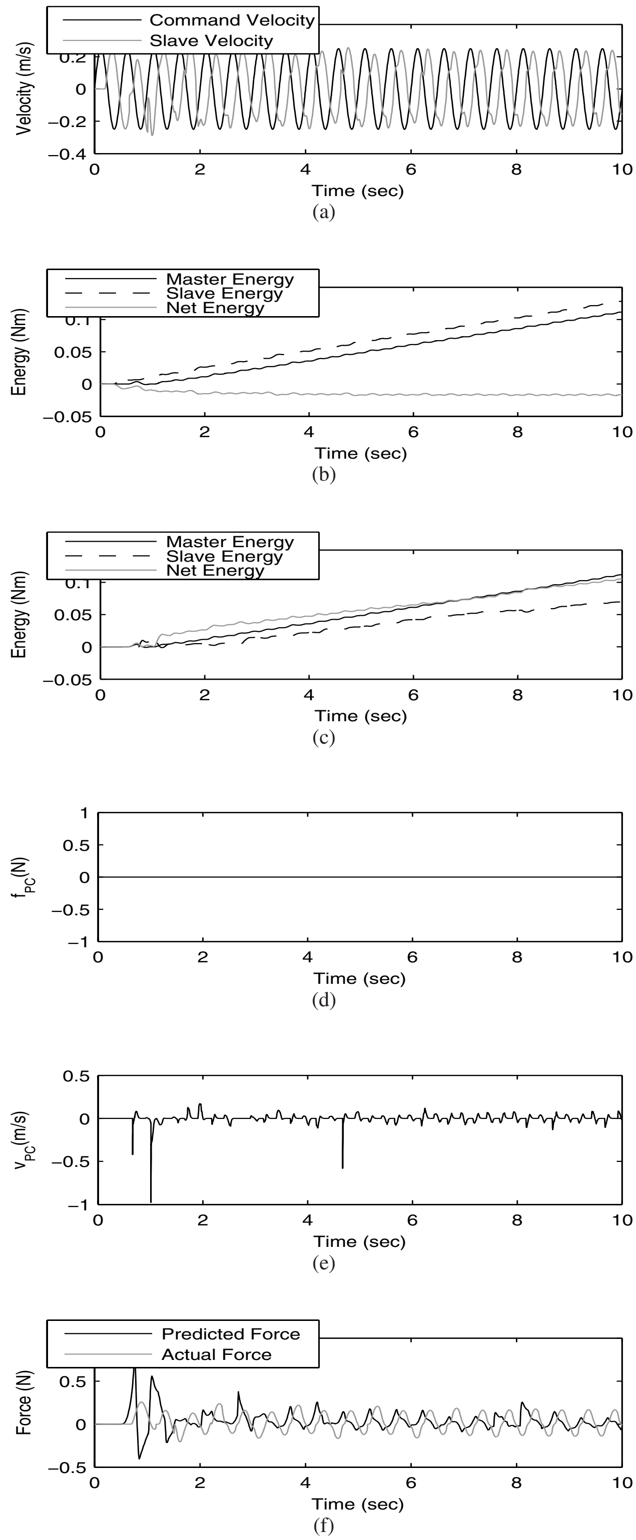

Fig. 6. **With energy derivatives**, Delays $T_f = 0.3s$, $T_b = 0.2s$ and α_s filtered at $1KHz$ (a) Command and slave velocities, (b) energies in continuous time, (c) discrete energies, (d) f_{PC}, (e) v_{PC}, (f) predicted and actual environment forces