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Stable Multilateral Teleoperation with Time Domain Passivity Approach

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Abstract— **In this paper, we propose a generalized method to represent multilateral teleoperation system as an electrical network with dependent effort/flow sources which allows us to implement Time Domain Passivity Approach (TDPA) to passivate the system. Using the conventional mechanical-electrical analogy, the multilateral teleoperation system with mechanical nature is modelled as an electrical circuit. Power correlated signal are then identfied to extract the augmented network representation in which time-delay is taken into account. The passivity of multilateral teleoperation system are also analyzed and the method of using TDPA to passivate the network is proposed. This framework is independent of control architecture and communication delay. Experiment on a trilateral teleoperation system has been done and showed good performance with proposed method.**

I. INTRODUCTION

Teleoperation system, one of the first domains in robotics, has become one of the most challenging issue in robotic field[1]. Although autonomous robots have been developed and logged many successes, many applications require robots to perform complex tasks at remote sites and human intervention can not be replaced. In teleoperation system, human operator conducts the tasks by using master and slave robots which communicate through a network. With the development of network technology, teleoperation technology gains more and more attention due to its promissing applications to tele-surgery, tele maintenance, etc... Moreover, in teleoperation systems, force feedback can considerably improve an operators ability to perform complex task by kinesthetically coupling the operator to the environment[2]. However, due to the distributed master-slave nature in teleoperation system, time-delay can not be avoided. Time-delay, even though it is small, causes unstable behavior when force feedback makes the system closed [3].

In many applications[4][5] that a number of operators cooperate to perform a complex task, a multilateral teleoperation system in which multiple operators control multiple slave robots is needed. The distributed nature of the multilateral teleoperation system makes the problem of communication time-delay become more critical. Several methods have been proposed to solve this issue such as adaptive control[6], PD control[7], wave variables[8]. The adaptive control approach requires system dynamic and range of parameters while the PD control method assumes that the maximum time delay is known, the wave variables method has many advantages but also has difficulty in system with ambiguous causalities. The well-developed framework TDPA proposed by Ryu et. al. [9] which can guarantee system stability under arbitrary communication time delay and data lost, compatible with any control architecture, has been recently extended using Time Delay Power Network (TDPN) to deal with bilateral teleoperation system with ambiguous causalities. Quang et. al. [11] has successfully utilized TDPA and TDPN to stabilize mobile robot teleoperation system in rate mode with various types of force feedback and the combination of these forces. In [10], Michael et. al. proposed a general method to stabilize trilateral teleoperation system with any control architecture and any communication delay using TDPA. Experiment results showed good results for roundtrip delays up to 200ms but this method was limited to trilateral control architecture with given control structure.

This paper proposes a generalized framework to design a stable multilateral teleoperation system independent of the number of masters/slaves, amount of time-delay, control and communication architecture. The major contribution of this paper is proposing a network representation method of a multilateral teleoperation system to have clear energy flows for the implementation of TDPA. It was unclear where to locate and what is conjugate energy pairs especially when a number of masters and slaves are exchanging signals with communication time-delay. This paper addresses how to tackle this issue and proved passivity with TDPA. The rest of this paper is organized as follows: network representation of multilateral teleoperation system is introduced in section II, passivity analysis and proposed framework are presented in section III, section IV shows experiment results for a trilateral teleoperation system with proposed framework.

II. NETWORK REPRESENTATION OF MULTILATERAL TELEOPRATION SYSTEM

Fig. 1 shows a multilateral teleoperation system in which m masters are used to operate n slaves through a network. In teleoperation system, generally velocity and/or force signals are exchanged to kinesthetically couple masters and slaves. It is well known that stabilizing such a complicated multilateral teleoperation system is difficult, and there haven't been many trials to tackle this issue.

In this research, we proposes a general framework to stabilize a multilateral teleoperation system with TDPA which successfully used as a controller for time-delayed teleoperation system. However, in order to used TDPA, it was essential to represent the system as a electrical network circuit with clear energy flows.

In order to convert the conventional representation of a multilateral teleoperation system with signal flows only into

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the network representation with energy flows, it is necessary to clearly identify the conjugate pair of power (force and velocity) in each network port. In multilateral teleoperation system, it is difficult to identify these pairs because a force applied on a device is often a combination of both force and velocity signals or one of them. It usually depends on control architecture. In this section, we propose a method to represent multilateral teleoperation system as a network with clear energy relation that allows us to implement well developed TDPA framework.

In each master or slave, a terminal from now on, there are incoming signals to the terminal and outgoing signals from the terminal. In general, outgoing signals from the port have no direct effect on this port, but it gives indirect effect through incoming signals which are affected by this outgoing signals at other ports. Therefore, it is enough to consider only incoming signals to model the port as long as the dependency of the signals is considered.

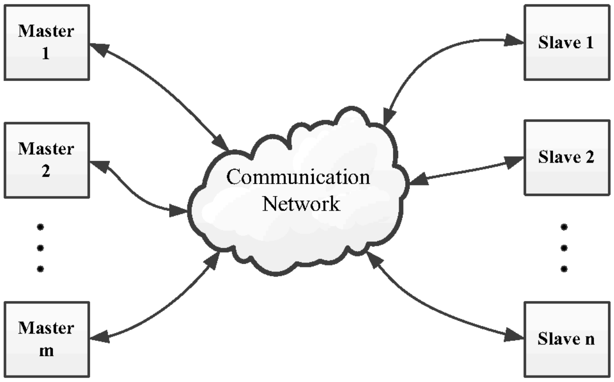


Fig. 1. Multilateral teleoperation system

By using the conventional mechanical-electrical analogy which maps velocity into current and force to voltage and only considering incoming signals to each terminal, we can generally represent each port as an electrical circuit as in Fig. 2. Note that desired velocity (v_{sdi}) and feedback force (f_{ci}) at terminal i are represented as dependent current and effort sources respectively. In turn, v_i is the resulting velocity and Z_i is impedance of device at terminal i, C is the slave controller, f_{ei} is the external force applied to the i-th terminal.

We assume that the combination of velocity signals at a terminal i follows

$$v_{sdi} = h_1(\tilde{v}_1) + h_n(\tilde{v}_2) + ... + h_n(\tilde{v}_n) = \sum_{p=1}^{n}(h_p(\tilde{v}_p)) \quad (1)$$

where $h_p(v_p)$ is a function of velocity signal v_p from terminal p. $\tilde{v}_p$ is a delayed signal of v_p after communication network.

Similarly, the commbination of feedback force signals is assumed to follow

$$f_{ci} = g_1(\tilde{f}_1) + g_2(\tilde{f}_2) + ... + g_m(\tilde{f}_m) = \sum_{q=1}^{m}(g_q(\tilde{f}_q)) \quad (2)$$

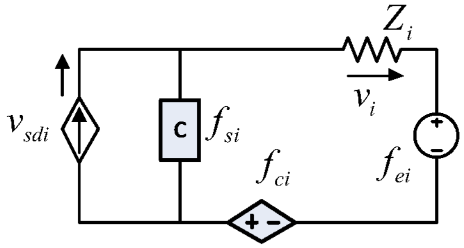


Fig. 2. Network representation of a i-th terminal with multiple force and velocity sources. v_i is the resulting velocity of the terminal and f_{ei} is the external force applied to i-th terminal

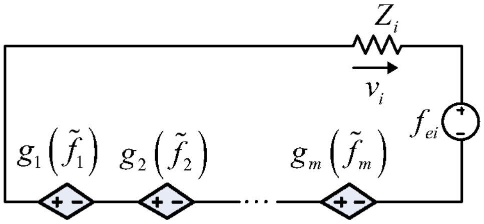


Fig. 3. Network representation of the i-th terminal with only considering multiple effort sources.

$g_q(\tilde{f}_q)$ is a function of delayed force command $\tilde{f}_q$ from terminal q. As shown in Fig. 2, there are two different types of augmented sources which also include all different values of time-delays. Therefore the system has high possibility to be active and unstable due to the produced active energy from delayed dependent sources. We know that TDPA can dissipate the active energy and make the system passive and stable, however, the network representation in fg. 2 is not ready to implement TDPA since it is not explicitly showing delayed communication block which mainly produce active energy. In order to explicitly extract delayed communication block, we first separate the network representation (Fig. 2) into two networks depend on dependent source. Fig. 3 shows a network with force sources only. Each delayed force source is connected in series since we assumed that delayed force sources are added like in Eq. 2. It is well known that serially connected electrical branches are sharing common current. So, the conjugate power pair of each delayed effort source are determined as:

$$\begin{cases} \text{Effort:} \quad g_q(\tilde{f}_q) = g_q(f_q(t - T_q)), q \in \{1, 2, ..., m\} \\ \text{Flow:} \quad v_i \end{cases} \quad (3)$$

As a result, it becomes possible to analyze the passivity of each communication channel independently since the power conjugate pair for each delayed effort source is identified. However, we can not discriminate the active energy only from the time-delay because the total energy of the delayed effort source is the sum of the energy of undelayed effort source and the produced energy by the time-delay. In [13], Artigas et. al. proposed a method to discriminate active energy component due to delay with the original effort or

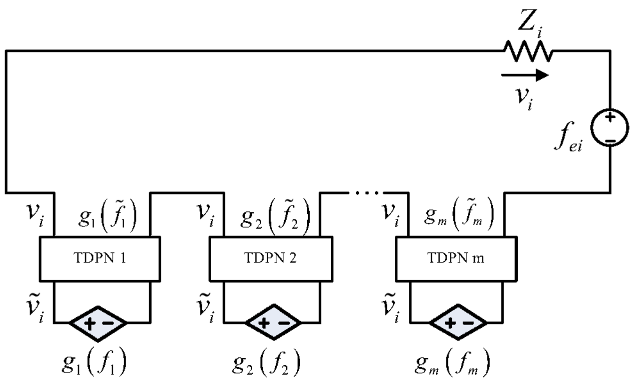


Fig. 4. Augmented network representation of the i-th termial with multiple effort sources.

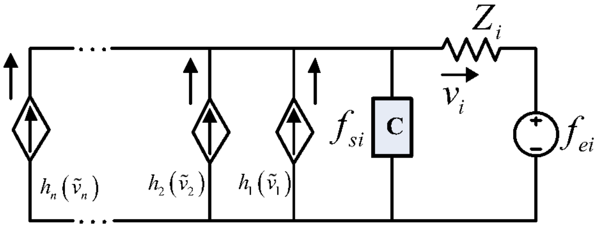


Fig. 5. Network representation of the i-th terminal with only considering multiple velocity sources.

flow sources by shifting the source to its undelayed location and putting a transport network so-called Time Delay Power Network (TDPN). Thanks to TDPN, original source of energy and active energy due to delay are seperated and it is possible to estimate active energy due to time-delay by simply comparing energy of undelayed and delayed source. Utilizing the idea of TDPN to every delayed sources, the network circuit in Fig. 3 are represented equivalently as in Fig. 4. Fig. 5 shows a network in which only velocity sources are considered. As the combination of velocity signals follows Eq. 1, delayed velocity sources are connected in parallel to each other. Since the voltage across all branches of a parallel circuit are the same, the conjugate power pair for each delayed flow source are:

$$\begin{cases} \text{Effort:} & f_{si} \\ \text{Flow:} & h_p(\tilde{v}_p) = h_p(v_p(t - T_p)), p \in \{1, 2, ..., n\} \end{cases} \tag{4}$$

Note that f_{si} is the output force of the velocity controller at i-th terminal.

Similarly, each delayed flow source in Fig. 5 is shifted to undelayed location and attached to a TDPN. The electrical scheme in Fig. 5 is then represented as equivalent to augmented network in Fig. 6.

As a result, a multilateral teleoperation system is separated into multiple terminals (each can be master or slave) considering only incoming signals, and a terminal with multiple incoming effort and flow sources is represented as in Fig. 7 with clear energy flows.

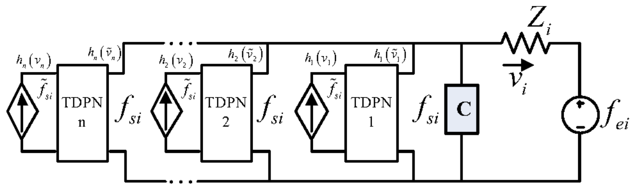


Fig. 6. Augmented network representation of the i-th termial with multiple velocity sources.

III. PASSIVITY ANALYSIS

In this research, TDPA is used as a tool to make each terminal with communication network under time-delay passive. TDPA has two elements: a Passivity Observer (PO) which monitors energy flows and estimates the amount of active energy produced by time-delay, and a Passivity Controller (PC) which passivate the system by dissipating active energy. In this section, the passivity analysis of multilateral teleoperation system is presented and the method of using TDPA to stabilize the system is introduced.

Based on the basic property of passive system, overall network system can be passive and stable if every component in the network system is passive. Most of the component in Fig. 7 are passive components, such as controller impedance (Z_i) and velocity controller (C), as long as it is properly designed. Ideal independent source (f_{ei}) and dependent sources (v_i,f_i) do not effect on the system passivity since all the produced energy can be dissipated as long as the system is passive. Only one component, TDPN, can be active and effect on system passivity.

The total stored energy in all TDPN at the i-th terminal is:

$$E_i^N(t) = E_v^N(t) + E_f^N(t) \tag{5}$$

where E_v^N and E_f^N are stored energies in velocity command and force feedback channels respectively.

Each TDPN have two energy flows from one port to the other and both of them might produce active energy. However, since the dependent source can absorb infinite amount of energy, the energy flow toward the source will not effect the passivity of the TDPN. Therefore, taking only the energy flow from the source into account is sufficient to guarantee the passivity of TDPN. Because the conjugate power pairs are identified, the energy at each port of TDPN are obtained easilly and stored energy in each TDPN in

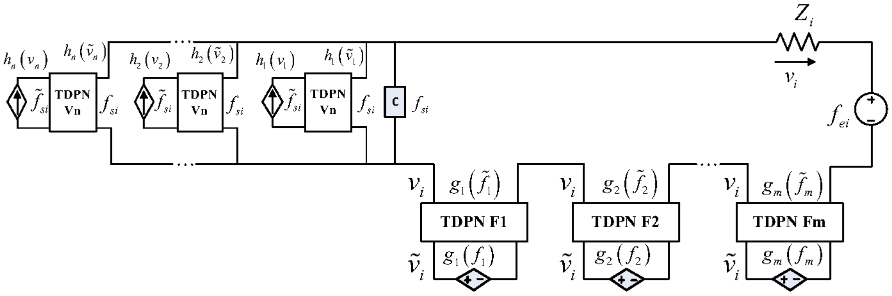


Fig. 7. Augmented electrical representation of a termial with multiple effort and velocity sources

sampling time k is estimated as follow:

$$
\begin{aligned}
E^{in}_{v_p}(k) &= \Delta T \sum_{j=0}^{k} \tilde{f}_{si}(j) h_p(v_p(j)) \\
E^{out}_{v_p}(k) &= \Delta T \sum_{j=0}^{k} f_{si}(j) h_p(\tilde{v}_p(j)) \\
E^{in}_{f_q}(k) &= \Delta T \sum_{j=0}^{k} \tilde{v}_i(j) g_q(f_q(j)) \\
E^{out}_{f_q}(k) &= \Delta T \sum_{j=0}^{k} v_i(j) g_q(\tilde{f}_q(j)) \\
E_{v_p}(k) &= E^{in}_{v_p}(k) - E^{out}_{v_p}(k) \\
E_{f_q}(k) &= E^{in}_{f_q}(k) - E^{out}_{f_q}(k)
\end{aligned}
\tag{6}
$$

Then, the total stored energy is estimated as follow:

$$
\begin{aligned}
E^N_v(k) &= \sum_{j=1}^{k} E_{v_p}(k) \\
E^N_f(k) &= \sum_{j=1}^{k} E_{f_q}(k)
\end{aligned}
\tag{7}
$$

In [12], a system is defined as passive if and only if the stored energy stays positive for all the time. Therefore, the passivity condition of communication system at the i-th terminal is:

$$
E^N_i(k) = \sum_{j=1}^{k} E_{v_p}(k) + \sum_{j=1}^{k} E_{f_q}(k) \geq 0, \forall j \geq 0 \tag{8}
$$

In Eq. 8, all output energies at sampling time k can be monitored at the terminal, but it is difficult to monitor each input energies at the same sampling time k at the terminal. Therefore, we split the stored energies respect to the source, and find a sufficient condition of Eq. 9 to satisfy the passivity of the network channel independently as follows:

$$
\begin{cases}
E_{v_p}(k) \geq 0, 0 \leq p \leq n, \forall k \geq 0 \\
E_{f_q}(k) \geq 0, 0 \leq q \leq m, \forall k \geq 0
\end{cases}
\tag{9}
$$

Eq. 9 is still difficult to satisfy in realtime due to time-delay. In [9], Ryu proposed an sufficient condition to satisfy passivity condition of the network by comparing the delayed input energy with current output energy as follows:

$$
\begin{cases}
E_{v_p}(k) \geq E^{obs}_{v_p} = E^{in}_{v_p}(k - T_p) - E^{out}_{v_p}(k) \geq 0, \\
\qquad 0 \leq p \leq n, \forall k \geq 0 \\
E_{f_q}(k) \geq E^{obs}_{f_q} = E^{in}_{f_q}(k - T_q) - E^{out}_{f_q}(k) \geq 0, \\
\qquad 0 \leq q \leq m, \forall k \geq 0
\end{cases}
\tag{10}
$$

Note that T_p and T_q is the time delay in communication channel from the p-th and q-th terminal to the i-th termianl. Being able to observe the active energy in each TDPN, a PC is assigned to dissipate this amount of energy. The damping factor is determined as:

$$
\alpha_q = \begin{cases}
-\frac{E^{obs}_{f_q}(k)}{v_i^2 \Delta T} & \textbf{if } E^{obs}_{f_q}(k) < 0 \ \& \ v_i \neq 0 \\
0 & \textbf{if } E^{obs}_{f_q}(k) \geq 0 \ \| \ v_i = 0
\end{cases}
\tag{11}
$$

in case of force commanding channel or:

$$
\beta_p = \begin{cases}
-\frac{E^{obs}_{v_p}(k)}{f_{si}^2 \Delta T} & \textbf{if } E^{obs}_{v_p}(k) < 0 \ \& \ f_{si} \neq 0 \\
0 & \textbf{if } E^{obs}_{v_p}(k) \geq 0 \ \| \ f_{si} = 0
\end{cases}
\tag{12}
$$

in case of velocity commanding channel.

In conclusion, the generalized framework as shown in Fig. 8 is propsed. Briefly, each communication channel is modelled as a two-port network and a PO/PC pair is dedicated to monitor the energy flow and passivate this channel by dissipating active energy.

IV. EXPERIMENT

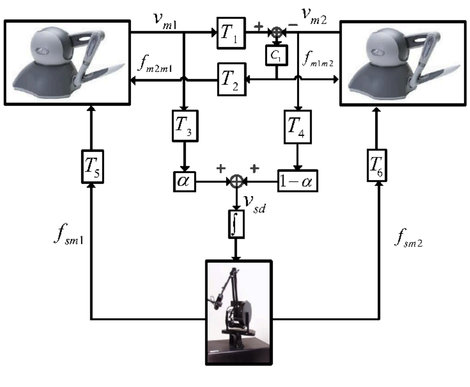


Fig. 9. Experiment setup: Trilateral teleoperation system

Fig. 9 shows a trilateral teleoperation system which can be used as a training and cooperating system. At first, the local

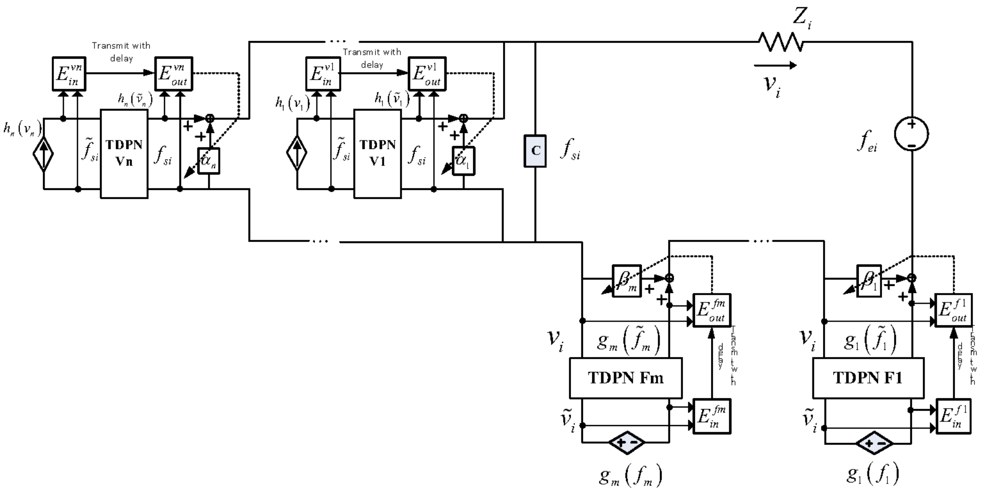


Fig. 8. Multilateral teleoperation system with TDPA

operator with less experience can temporary get supports from the mentor without influence the slave robot by setting the authority factor α close to 1. Corresponding to the increase of local operator's experience, α is decreased so that two operators can cooperate to control the slave robot. Since there are always time delayed between operators and slave robot, the system has potential of unstable behavior. In this section, the proposed framework is utilized to stabilize the system under time delay.

In this system, slave robot follows commands from both two master devices and the authority factor α will decide which master gives more effect on slave robot. Mathematically, the combination of master velocities in slave site is as follows:

$$v_{sd} = \alpha v_{m_1} + (1-\alpha) v_{m_2} \tag{13}$$

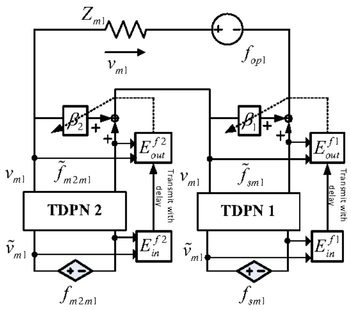
Two master devices are kinesthetically coupled by position-force architecture so that the local operator can observe and follow the action of the mentor. At the same time, force feedbacks from slave robot are sent to two operators so that they can feel the interacting force between slave robot and environment. So, the total forces displayed to operators by two master devices are as follows:

$$f_{m_1} = f_{m_2 m_1} + f_{s m_1} \tag{14}$$

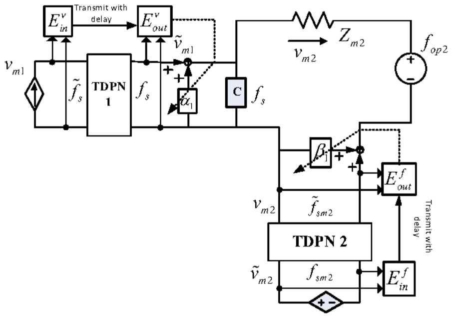
$$f_{m_2} = f_{m_1 m_2} + f_{s m_2} \tag{15}$$

Note that f_{m_1},f_{m_2} are force displayed to operators, $f_{m_1 m_2}$, $f_{m_2 m_1}$ are coupling force of the two masters, f_{sm_1} and f_{sm_2} are force feedback from slave to master 1 and 2 respectively.

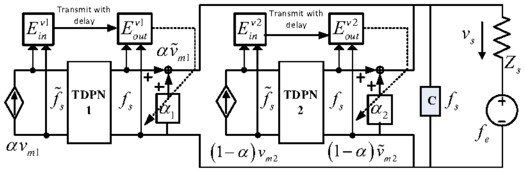
In order to show the performance of proposed framework, in addition to system delay, an artificial time delay of 200 ms/round trip is introduced in each communication channel. Based on the receiving signal at each terminal, by utilizing the proposed framework, Fig. 10 show the network representation and passivity configuration of these terminals. Experimental results in case of without proposed method



(a) Master 1



(b) Master 2



(c) Slave

Fig. 10. Passivity configuration of experiment system

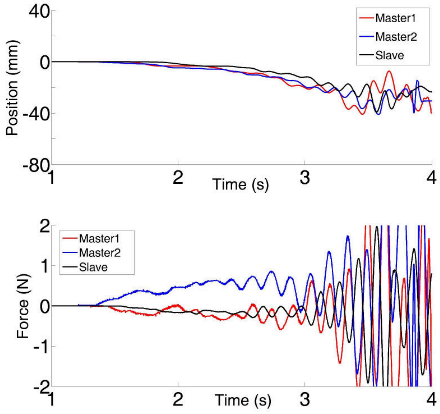


Fig. 11. Position/Force tracking without TDPA

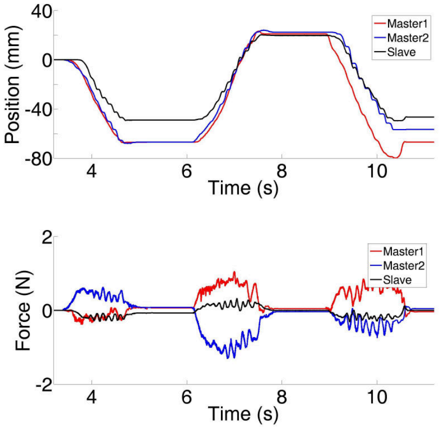


Fig. 12. Position/Force tracking with TDPA

are shown in Fig. 11. It is obvious that because of time-delay, it was very difficult for operators to control the system and the force feedback made the system unstable instead of supporting operator. On the other hand, Fig. 12 shows position and force tracking in case of with proposed framework. As can be seen from these figures, our proposed methods were successfully stabilize the system and the operators can control slave robot to interact with environment easily.

V. CONCLUSION

In this paper, a generalized framework to stabilize multilateral teleoperation system is proposed. The network representation of such system is introduced and TDPA is implemented to stabilize the network system. The proposed network representation method clarify energy flows in a multilateral teleoperation system with multiple masters and slaves for the implementation of TDPA. Passivity of the system is proved with TDPA. The biggest advantage of the proposed framework is that it can be generally implemented to any multilateral teleoperation system regardless of the amount of time-delay, the number of master/salve, control architecture and dynamic uncertainties. The proposed method is experimentally verified with tri-lateral teleoperation experiment.

In this research, the passivity of the communication channels at a terminal is guaranteed by satisfying the passivity of each channel independently as shown in Eq. 9. Since this is a sufficient condition, it might lead to over dissipating energy and possition drift. Although there was a research work to compensate position drift in bilateral teleoperation [14], we're working on satisfying Eq. 8 directly to make the system less conservative.

VI. ACKNOWLEDGMENT

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