Multilateral Teleoperation over Communication Time Delay using the Time-domain Passivity Approach

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***Abstract*—A general framework to stabilize multilateral teleoperation system over a communication time delay based on the well-known time-domain passivity approach (TDPA) is proposed. The uniqueness of this framework is that it's independent of the amount of communication time delay, the multilateral control architecture, and the number of masters and slaves. The multilateral system was first decoupled into subsystems with respect to each terminal by identifying the input signals' contributions to the output terminals, which was not straightforward due to the coupled nature of the multilateral teleoperation system. The decoupled subsystems were then converted into an electrical circuit using a mechanical-electrical analogy. Time-delay power network (TDPN) was introduced to clarify active energy sources from the time delay and Passivity Observer - Passivity Controller (PO-PC) was utilized to dissipate those active energies. A less conservative method, compare with prior work, was proposed to guarantee the stability. Experiments with a trilateral teleoperation system and with a multilateral teleoperation system with a dual master and dual slave were conducted to validate the proposed framework.**

I. Introduction

Researchers have recently shown increased interest in cooperative teleoperation because of its advantages over single teleoperation, such as increased dexterity, improved manipulation ability, higher loading capacity, and improved human collaboration. Despite the high potential of cooperative teleoperation, there has thus far been little discussion about stable multilateral teleoperation. Sirouspour [1] used μ-synthesis to design a multilateral control architecture for a system with multiple slaves holding a common tool for manipulating a common environment, and in [2], he expanded on his idea by accommodating nonlinearity and parameter uncertainty in the system dynamics using an adaptive nonlinear controller. Khademian and H-Zaad introduced four-channel [3] and six-channel [4] multilateral shared controllers for dual-user teleoperation systems by introducing a dominance factor that allows adjustable interaction between each user and the slave as well as the other user. However, the time-delay issue has not been considered in any of the above works. Setoodeh and Sirouspour [5] studied a method for more general architectures. They proposed an LQG controller for stable transparent multilateral teleoperation under a communication time delay. However, this controller requires a given dynamic model of masters and slaves and is limited to a known constant communication time delay.

Passivity has been a major criterion for designing a stable bilateral teleoperation system due to its numerous advantages, e.g., it only uses input/output information independent of system parameters, it is a sufficient condition for stability, and it is generally applicable to linear and nonlinear systems. Inspired by the passivity theorem, Kanno and Yokokohji [6] used the wave-variable method to overcome the time-delay problem in multilateral teleoperation systems, and in [7], they extended their approach to include a method to adjust the priority of each operator by relieving their force equilibrium constraint. However, this method was restricted to the position-position and the position-computed force bilateral control architecture, and not valid for position-measured force bilateral control architecture [8] due to the noncausal energy representation when position and measured force power conjugate pair is wave transformed. This noncausality comes from the fact that the wave variable approach considers master device directly receives the interaction force, sensed at the slave side, ignoring the physical medium between the master and environment [8]. Therefore, the ignorance of this medium in energy transformation does not allow a causal transfer of energy [8]. Moreover, due to the use of a conservative form of the passivity, the wave-variable approach provides significantly less performance and transparency compared with other energy-based approaches in the bilateral teleoperation applications [9, 10]. To the best of our knowledge, *stable multilateral control over the unknown varying time-delay, the arbitrary multilateral control architecture, and the arbitrary number of masters/slaves with unknown dynamic model has not been established yet.*

There has been a considerable amount of research regarding stable bilateral teleoperation based on the time-domain passivity approach (TDPA) [11–13] as the main energy-based approach. TDPA-based teleoperation may have several advantages over other control methods, such as it guarantees passivity against an unknown varying length of time delay [12], it does not require any knowledge about the dynamics of the connected master and slave [11], and it works for any bilateral control architecture [13]. However, it was not clear how the conventional representation of the multilateral teleoperation system can be converted to a network representation for the

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implementation of this well-developed TDPA framework.

It is essential to have a network representation with clear energy flows for implementing the TDPA. However, this has not been straightforward when seeking to convert a multilateral teleoperation system in a conventional block diagram domain into an electric circuit in a network domain with energy flows. The primary difficulty has been the coupled nature of the multilateral teleoperation system.

The major contribution of this paper is a method to convert the conventional block diagram representation of the multilateral teleoperation system into a network representation with energy flows for the implementation of this well developed TDPA. We first decoupled the multilateral teleoperation system into several subsystems with respect to each terminal by identifying the input signals' contribution to the output terminals, then the decoupled terminal was converted into an electrical circuit by using mechanical-electrical analogy. The converted electrical circuit allowed us to introduce the TDPN (Time Delay Power Network) clarifying active energy sources from time-delay, and the PO/PC (Passivity Observer/Passivity Controller) dissipating those active energies. Then, a general framework based on the time-domain passivity approach (TDPA) is introduced to realize stable multilateral teleoperation, which is independent of the amount of time delay, the multilateral control architecture, and the numbers of masters and slaves. The framework also allows us to easily modify the existing multilateral architecture without redesigning the controller whenever additional masters or slaves are introduced. This paper is a more comprehensive version of our previous work [14] with complete expansion of the theory and overall passivity proof. The less conservative passivation approach is introduced as well.

II. Network Representation of Multilateral Teleoperation Systems

Fig. 1 shows the concept of a multilateral teleoperation system with multiple masters/slaves where position/force signals are exchanged among three or more terminals. We defined the terminal as a master or slave that contains a local position/velocity controller and force controller. As illustrated in Fig. 1, in each terminal, velocity and force signals can travel into and out of the network. v_1 indicates the input velocity signal from the terminal 1 to the network, which contributes to compose the output velocity of other terminals after a certain process. v_{d3} denotes the output velocity signal from the network to the terminal 3, which is used as the reference velocity of the local position/velocity controller of the terminal 3. Similarly, f_1 and f_{d3} indicates the input force signal from the terminal 1 to the network and the output force signal from the network to the terminal 3, respectively. In general, input signals are measurable states of the terminals, whereas output signals are computed reference signals to the local controller.

Note that in each terminal, outgoing signals have no direct effect on itself, but indirectly affect the incoming signals at the other terminals, which is already considered. Therefore, it is sufficient to take into account only the contribution of the incoming signals for the network representation of the

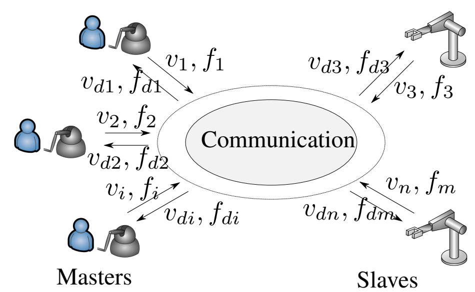


Fig. 1: Conceptual figure of the cooperative teleoperation system with multiple masters and multiple slaves.

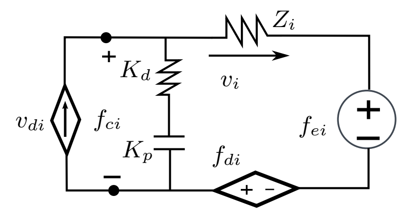


Fig. 2: Network representation of an *i*-th terminal with multiple force and velocity sources.

decoupled subsystem. Using a mechanical-electrical analogy, mapping velocity to current and force to voltage, the decoupled subsystems with respect to each terminal can be converted to an electrical circuit as in shown Fig. 2. The conversion allows us to have clear conjugate power pairs and energy flows. The output velocity (v_{di}) and force signal (f_{di}), which are the desired velocity and feedback force respectively, are represented as dependent current and effort sources. In turn, v_i is the resulting velocity, Z_i is the impedance of the device at terminal i, K_p and K_d are the proportional and derivative position controller gains, f_{ci} is the resulting position controller force, and f_{ei} is the external force applied to the *i*-th terminal. Henceforth, we will use i-th notation without differentiating master and slave to reduce the length of the equations. The desired velocity for a terminal i is the sum of the velocities' contribution, which can generally be considered as a function of velocity, from the network, as:

$$v_{di} = h_1(\tilde{v}_1) + h_2(\tilde{v}_2) + \cdots + h_n(\tilde{v}_n) = \sum_{p=1}^{n}(h_p(\tilde{v}_p)), \quad (1)$$

where $h_p(v_p)$ is a function of input velocity signal v_p from terminal p, for example, scaled velocity signal: $\gamma_p v_p$. Note that there is no constraint on $h_p(v_p)$, as well as γ_p, because the function affects both the input energy and the output energy of the multilateral teleoperation system in the same way. $\tilde{v}_p$ is a delayed signal of v_p after the communication network. Similarly, the feedback force is defined as:

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

in which $g_q(\tilde{f}_q)$ is a function of delayed input force signal $\tilde{f}_q$ from terminal q. To explicitly extract the delayed communication block, we first separate the network representation (Fig. 2) into two networks with respect to the type of dependent source. Fig. 3 shows a network with only dependent force sources. Each delayed force source is connected in series since we assumed that delayed force sources in series at the terminal as in Eq. 2.

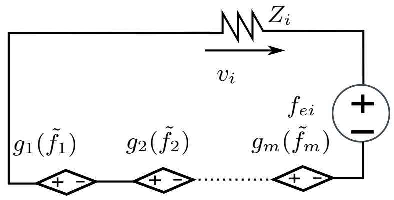


Fig. 3: Network representation of the *i*-th terminal with only considering multiple effort sources.

It is well known that serially connected electrical branches share a common current. Therefore, the conjugate power pair of each delayed effort source is determined as:

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

where D_q is the amount of time delay from the source terminal q to terminal i for discrete instants of time k.

Consequently, the power conjugate pair for each delayed effort source is identified. However, it is still not possible to discriminate the active energy from the communication time delay. In [13], Artigas et al. proposed a method to clarify active energy components due to time delay by shifting the source to its undelayed location and adding a transport network: so-called time-delay power network (TDPN). Thanks to the TDPN, the original source of energy and active energy due to time delay were separated, and it became possible to estimate the amount of active energy due to time delay by simply comparing the amount of energy at undelayed and delayed locations. By applying the concept of TDPN to every delayed effort source, the network circuit in Fig. 3 is equivalently converted to Fig. 4.

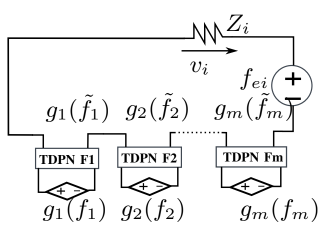


Fig. 4: Augmented network representation of the *i*-th terminal with multiple effort sources.

Fig. 5 shows a network representation in which only velocity sources are considered from Fig. 2. The sum of flow sources (Eq. 1) can be represented as a parallel circuit. It is also well known that the voltage across all branches of a parallel circuit are the same; therefore, the conjugate power pair for each delayed flow source is as follows:

$$\begin{cases} \text{Effort:} \quad f_{ci} \\ \text{Flow:} \quad h_p(\tilde{v}_p) = h_p(v_p(k - D_p)), p \in \{1, 2, ..., n\} \end{cases}$$

where f_{ci} is the computed output control force of the velocity controller at the *i*-th terminal and D_p is the amount of time delay from terminal p to terminal i.

Similarly, TDPNs allow us to equivalently converted the electrical representation in Fig. 5 to network representation as in Fig. 6. Finally, a general network representation of

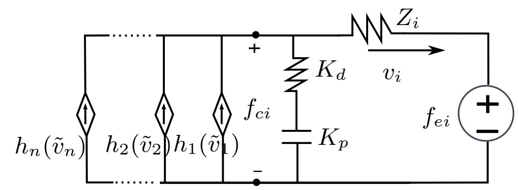


Fig. 5: Network representation of the *i*-th terminal with only considering multiple velocity sources.

the decoupled subsystem with respect to the i-th terminal is obtained as in Fig. 7 by augmenting Fig. 4 and Fig. 6. We now have a clear network representation, which allows us to estimate input and output energies at each network port including time delay.

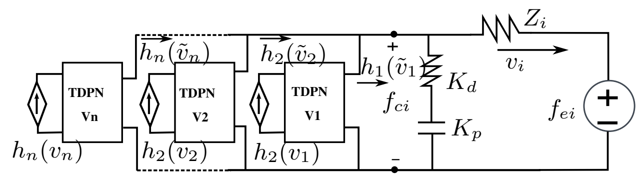


Fig. 6: Augmented network representation of the *i*-th terminal with multiple velocity sources. TDPN discriminates active energy components due to time delay.

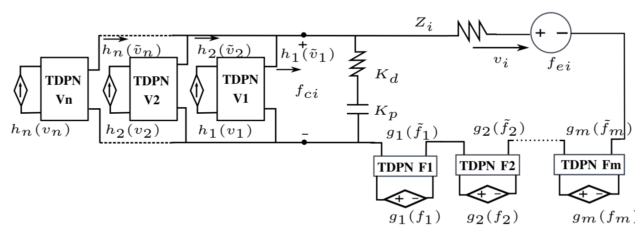


Fig. 7: Final augmented network representation of the decoupled multilateral teleoperation system with respect to a terminal.

III. Passivation Method of the Converted Network using the TDPA

This section presents a method to passivate the converted network of the i-th terminal of the multilateral teleoperation system using the TDPA. Based on the basic property of passivity [15], the overall network system can be passive and stable if every component in the network is passive. Fig. 7 shows the merged overall network representation of the decoupled multilateral teleoperation system with respect to a terminal. Most of the components in Fig. 7 are passive, such as device (Z_i) and the velocity controller (K_p and K_d), as long as it is designed to be locally stable. It is shown that in a linear electrical circuit with an ideal voltage or current source, the ideal voltage or current source only produce dissipatable amount of energy by the linear passive component [13]. Therefore, as long as the rest of system is passive, the ideal dependent sources $(h_n(v_n), g_m(f_m))$ do not affect the system passivity because they only produce big enough amount of energy, which can be dissipated by the rest of the passive components. Only TDPNs can produce active energy and may affect the passivity of the system.

The total stored energy in all TDPNs in the *i*-th terminal is:

$$E_i^N(k) = E_i^v(k) + E_i^f(k),$$

where E_i^v and E_i^f are the sum of the stored energy in all velocity and all force TDPNs, as follows:

$$E_i^v(k) = \sum_{p=1}^{n} E^{v_p}(k), \quad E_i^f(k) = \sum_{q=1}^{m} E^{f_q}(k). \tag{3}$$

Moreover, according to [12], the stored energy in each TDPN is estimated by subtracting the output energy from the input energy. Therefore, Eq. 3 can be rewritten as:

$$E_i^v(k) = \sum_{p=1}^{n} E^{v_p}(k) = \sum_{p=1}^{n} (E_{in}^{v_p}(k) - E_{out}^{v_p}(k)),$$
$$E_i^f(k) = \sum_{q=1}^{m} E^{f_q}(k) = \sum_{q=1}^{m} (E_{in}^{f_q}(k) - E_{out}^{f_q}(k)).$$

Each TDPN has two energy flows from one port to the other, and both of them might produce active energy. However, since the dependent source can absorb an infinite amount of energy, the energy flow toward the source does not affect the passivity of the TDPN. Therefore, taking only the energy flows from the source to the terminal into account was sufficient to guarantee the passivity of TDPN [12]. The network representation with the TDPN in Fig. 7 allows us to obtain the input and output energies at each TDPN with respect to each type of source as:

$$E_{in}^{v_p}(k) = \Delta T \sum_{j=0}^{k} \tilde{f}_{ci}(j) h_p(v_p(j)),$$
$$E_{out}^{v_p}(k) = \Delta T \sum_{j=0}^{k} f_{ci}(j) h_p(\tilde{v}_p(j)),$$

for velocity source and

$$E_{in}^{f_q}(k) = \Delta T \sum_{j=0}^{k} \tilde{v}_i(j) g_q(f_q(j)),$$
$$E_{out}^{f_q}(k) = \Delta T \sum_{j=0}^{k} v_i(j) g_q(\tilde{f}_q(j)),$$

for force source. A TDPN is passive if and only if the stored energy at the TDPN remains positive all the time [13]. Therefore, the passivity condition of the *i*-th terminal is:

$$\begin{aligned} E_i^N(k) = &\sum_{p=1}^{n} (E_{in}^{v_p}(k) - E_{out}^{v_p}(k)) \\ &+ \sum_{q=1}^{m} (E_{in}^{f_q}(k) - E_{out}^{f_q}(k)) \geq 0. \end{aligned} \tag{4}$$

Although all the output energies in Eq. 4 are observable in real time at the terminal, the input energies are not observable at the same sampling time since they come with a network delay. According to Ryu et al. in [12], it is sufficient to satisfy the passivity condition by comparing the delayed input energy with the current output energy. As the result, the passivity condition in Eq. 4 is satisfied if the total output energy in this port never exceeds the total delayed input energies from all the sources as in the following equation:

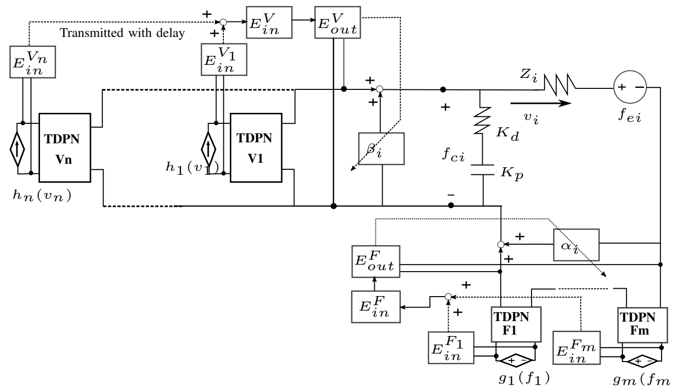


Fig. 8: Passivated architecture of the i-th terminal of the multilateral teleoperation system with the TDPA.

$$\begin{aligned} E_i^N(k) = &\sum_{p=1}^{n} E_{in}^{v_p}(k - D_p) - \sum_{p=1}^{n} E_{out}^{v_p}(k) \\ &+ \sum_{q=1}^{m} E_{in}^{f_q}(k - D_q) - \sum_{q=1}^{m} E_{out}^{f_q}(k) \geq 0, \end{aligned} \tag{5}$$

where D_p and D_q are the time delays in the communication channel from the *p*-th and *q*-th terminals to the *i*-th terminal.

To satisfy Eq. 5, a PC can be introduced to dissipate active energy flows at each TDPN [14]. However, passivating every TDPN independently may become too conservative because there may be some level of energy allowance that can be used in other channels. To minimize the amount of dissipated energy and make the framework less conservative, single PCs for each type of source can be sufficient to dissipate active energy flows at the output terminal rather than introducing PCs at each TDPN.

- For the terminals with flow sources, single admittance type PC is sufficient to passivate this channel as follows:

$$\beta_i = \begin{cases} -\frac{E_i^v(k)}{f_{ci}^2 \Delta T} & \text{if } E_i^v(k) < 0 \text{ and } f_{ci} \neq 0 \\ 0 & \text{else} \end{cases},$$

  where the sum of the energy of each TDPN with flow source is given as:

$$E_i^v(k) = \sum_{p=1}^{n} E_{in}^{v_p}(k - D_p) - \Delta T \sum_{j=0}^{k} f_{ci}(j) v_{di}(j).$$

- For the terminals with effort sources, a single impedance-type PC is sufficient to passivate this channel as follows:

$$\alpha_i = \begin{cases} -\frac{E_i^f(k)}{v_i^2 \Delta T} & \text{if } E_i^f(k) < 0 \text{ and } v_i \neq 0 \\ 0 & \text{else,} \end{cases}$$

  where the sum of the energy of each TDPN with effort source is given as:

$$E_i^f(k) = \sum_{q=1}^{m} E_{in}^{f_q}(k - T_D) - \Delta T \sum_{j=0}^{k} f_{di}(j) v_i(j).$$

Consequently, the passivated i-th terminal with the TDPA is designed as shown in Fig. 8. The calculated input energies at the undelayed location are transferred to the terminal with delay. Transferred energies with the same type of source are added and represented as one delayed input energy. For example, transferred energies from all flow sources are added and represented as a single delayed input energy. The output energy is also separately calculated at the terminal with respect to the type of source. Finally, two PCs are introduced to regulate each output energy under the delayed input energy.

IV. Implementations and Experimental Evaluations

To demonstrate the feasibility of the proposed approach, this section applies the proposed framework to a trilateral teleoperation system. In addition, the designed trilateral teleoperation system is extended to a multilateral teleoperation system to demonstrate the ease of extension of the previously designed architecture. In general, the design procedure of the proposed framework can be summarized as: (a) Express output signals at a terminal as a combination of input signals' contribution from the other side of the network. (b) Convert each terminal to a network circuit with the output signals as dependent effort or flow sources. (c) Connect delayed effort sources in series and delayed flow sources in parallel. (d) Introduce TDPN by shifting each delayed effort or flow source to an undelayed location. (e) Introduce POs/PCs at each TDPN to passivate it or introduce a single PO/PC for TDPNs with the same type of source.

A. Trilateral Teleoperation

Fig. 9 shows the trilateral teleoperation system with two Phantom OMNIs as master 1 and master 2 and a Phantom Premium as a slave. Trainer/trainee and cooperative teleoperation scenarios were considered, which allow dual operators to simultaneously teleoperate the single slave with different amounts of authority based on their levels of experience or control ability. The interaction force of the slave was fed back to both operators to transmit the sense of touch. Operators were coupled with each other by sharing the velocity signal from master 1 to master 2 and the control force signal from master 2 to master 1. Z_c and Z_{sc} are the local position controllers of master 2 and the slave. Note that each terminal, master 1 and slave, contains a local position controller. A total of 100 msec of fixed communication time delay was introduced at channels T_1, T_2 and T_5, and 150 msec of fixed communication time delay was also introduced at channels T_3, T_4 and T_6. Note that the proposed framework can also cover time-varying delay.

To make the trilateral teleoperation system passive, we first identified the input signals' contribution to each terminal. For the slave terminal, there was only incoming velocity signal from the network which consisted of the input velocities' contribution from both masters as:

$$v_{out}^{S} = \gamma v_{in}^{M_1} + (1-\gamma) v_{in}^{M_2},$$

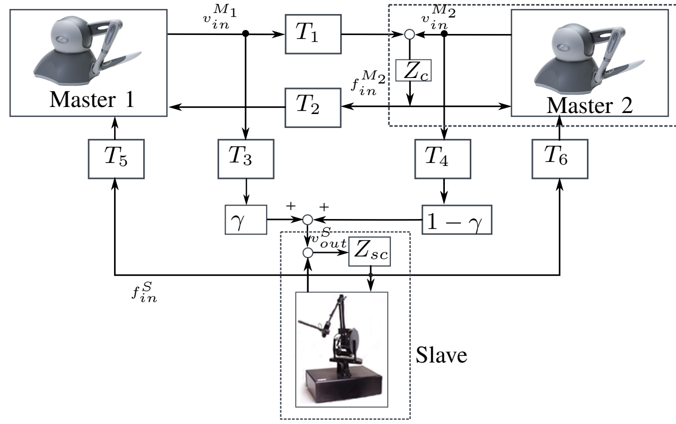


Fig. 9: Trilateral teleoperation system with two Phantom OMNIs as master 1 and master 2 and a Phantom Premium as a slave.

where γ is the authority factor that decides which master has a greater effect on the slave. Note that as mentioned in Section II, there is no constraint on the authority factor, and in this experiment, for the sake of simplicity, we set the value as 0.5.

Conversely, for master 1, there was only incoming force signal from the network which is calculated as:

$$f_{out}^{M_1} = f_{in}^{M_2} + f_{in}^{S},$$

where $f_{in}^{M_2}$ was the computed force of master 2's position controller for kinesthetically coupling both masters, and f_{in}^{S} was the position controller's force of the slave to track the desired velocity command from both masters.

For master 2, there were both force and velocity incoming signals, respectively defined as:

$$f_{out}^{M_2} = f_{in}^{S}, v_{out}^{M_2} = v_{in}^{M_1},$$

where f_{in}^{S} was the position controller's computed output force of the slave and $v_{in}^{M_1}$ was the velocity of master 1.

Since we explicitly represented the incoming force and velocity signals of each end terminal with input signals from the other side of the network, it was possible to transform the block diagram representation of the trilateral teleoperation system into a decoupled three network representation as in Fig. 10 for each end terminal. Each representation includes TDPNs to clarify active energy components due to time delay and POs/PCs to guarantee the passivity.

Fig. 11 and Fig. 12 show the experimental results without the proposed method. When both operators started to move each master to teleoperate the single slave, as with the given authority factor, both the masters and slave started to oscillate, even in a free space, and the system eventually diverged as in Fig. 11. As we expected, the output energy became greater than the input energy at all the TDPNs as in Fig. 12. However, with the proposed method as designed, both masters and the slave showed stable position tracking and force feedback performance as in Fig. 13, even when the operators made the slave collide with the environment to produce inferior operating conditions. The output energy was also bounded by the input energy at all the TDPNs as in Fig.14. Please note that the main objective of the proposed approach is stabilizing the system under communication time-delay. Since

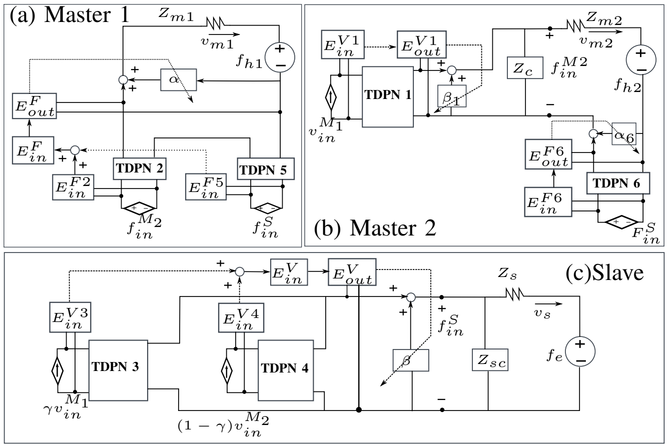
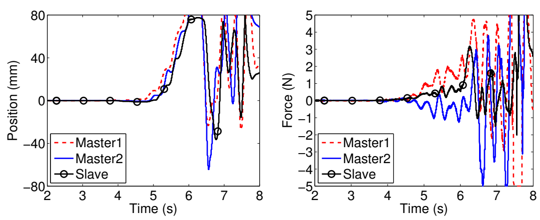


Fig. 10: Decoupled three network representation of the trilateral teleoperation system as in Fig. 9 with TDPNs and POs/PCs.



(a) Position (b) Force

Fig. 11: Unstable position/force response without the proposed multilateral controller.

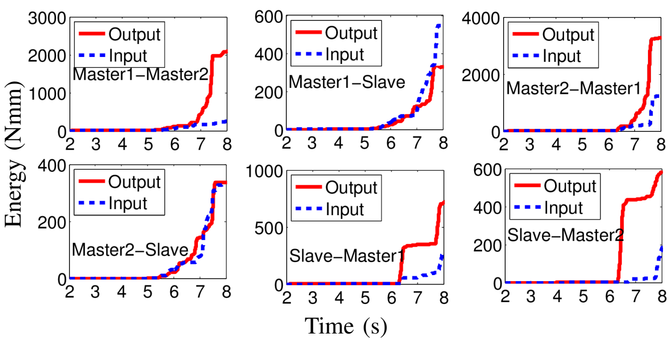
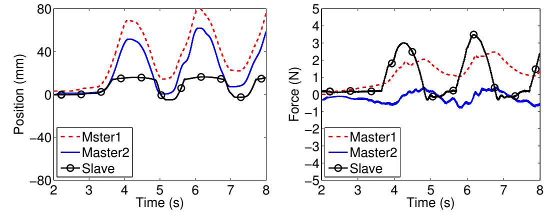


Fig. 12: Comparison of input and output energies at each TDPN without the proposed multilateral controller.

the authority factor was chosen arbitrarily without considering the performance, it is hard to discuss tracking performance. However, the position and force tracking performance can be optimized by tunning the authority factor and gains under the stable teleoperation condition.

B. Introducing an Additional Slave for a Coordinated Lifting

As mentioned in the introduction, one of the proposed framework's advantages is that it allows easy modification of the existing multilateral architecture without redesigning the controller. Introducing additional masters or slaves only require designing new channels based on the framework. To demonstrate the ease of modification, an extended multilateral



(a) Position (b) Force

Fig. 13: Stable position/force contact response with the proposed less-conservative multilateral controller.

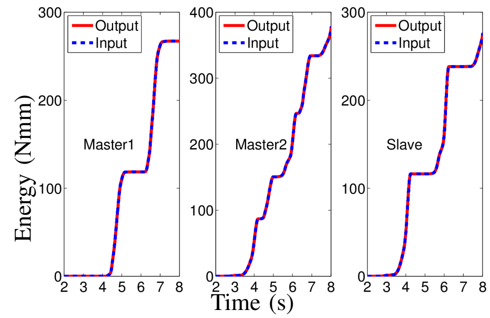


Fig. 14: Comparison of input and output energies at the output terminal with the proposed approach.

teleoperation system from the trilateral teleoperation system (Fig. 9) with an additional slave for a coordinated lifting is designed. Fig. 15 illustrates the extended multilateral teleoperation system with the additional slave(Phantom Premium 1.5A), co-lifting a beam together with the existed slave. Additional networks, indicated by the red dashed lines, were added for the coordinated lifting and enhancing the coupling between both masters. The velocity of slave 1 was used as a reference velocity in slave 2 to induce the coordinated motion while the control force of slave 2 was used as a feedback force in slave 1 for compensating the coordinated motion error. The control force of slave 2 is also sent to master 2 for transmitting the interaction force. In addition, the velocity of master 2 is sent to master 1 for a stronger kinesthetic coupling between the two masters. Z_{sc_2} is the local position controller of slave 2. In this scenario, a time-varying communication delay was introduced. For the former existing channels, triangular shaped time-delay disturbances (50 msec peak-to-peak, 0.2 Hz) were added to make it vary as in [12]. For the newly introduced channels, 100 $msec$ average communication time delays with the same amount of variation were introduced at channel T_{10}, and 150 $msec$ average communication time delays with the same amount of variation were introduced at channels T_7 and T_9. Real experiment setup is shown in Fig. 18. A rigid white beam, connected between the two slaves, was co-lifted by the dual-master, dual-slave multilateral teleoperation.

As the proposed framework allows the global passivity with the passivity of each network channel, it was sufficient to introduce the TDPN and PO/PC for the new channels without affecting existed channels. Fig. 16 illustrates the extended network representation with additional TDPNs and POs/PCs inside of the gray boxes. For master 1, one additional TDPN with the velocity source $(V_{in}^{M_2})$ and PO/PC were designed.

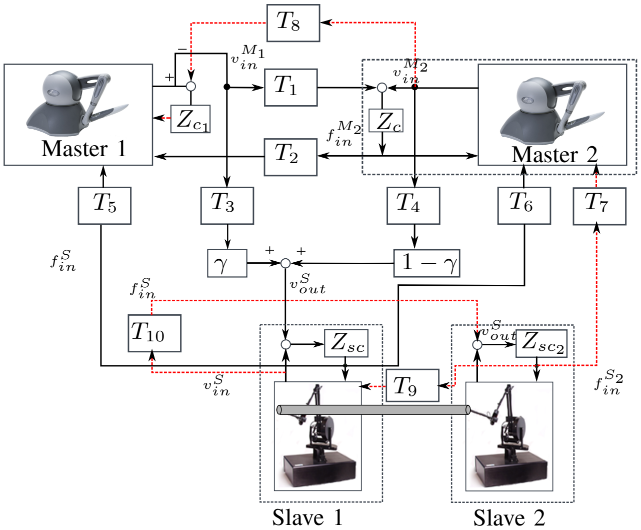


Fig. 15: Extended multilateral teleoperation system from the trilateral teleoperation system (Fig. 9) with the additional slave for a coordinated lifting.

For master 2 and slave 1, a respected TDPN with PO/PC was added at each new channel of force source from the slave 2. Regarding slave 2, a new network with a velocity source from slave 1 was designed. Note that *adding an additional passive network on the previously designed passive network is sufficient to guarantee the passivity and the stability of the overall system.*

Fig. 17 shows the comparison of the input and output energies at each TDPN of the extended multilateral teleoperation system with the proposed approach. In this experiment, most of the end terminals, except slave 2, have both velocity and force sources, whereas the previous trilateral teleoperation mostly has a single type of energy source. The output energy was bounded by the input energy at all the TDPN channels, and it is interesting to observe a large amount of energy margin at some channels. One channel (either force or velocity) was active while the other channel remained passive. In particular, for master 2, the velocity channel was active while the force channel was passive. For slave 1, the behavior was the opposite. It will be interesting to further study how different types of energy sources affect each other's energy channel when they exist in the same network.

Fig. 19 illustrates the position and force responses of the coordinated lifting experiment. Even under a time-varying communication delay, the proposed multilateral controller achieved stable position and force responses for the extended multilateral teleoperation. Coordinated slaves followed the position command from the dual master with delay, and the two masters were kinesthetically coupled with each other.

V. Conclusion

This paper proposed a TDPA-based general framework for stable multilateral teleoperation. The key aspect of this framework was how the conventional block diagram representation of the multilateral teleoperation system can be converted to the network representation with clear energy flows for implementing the TDPA. The conversion was developed without using any system-dependent specific parameters, controller gains, amount of time-delay and so forth. Therefore, the greatest advantage of the proposed framework was that this framework can be implemented on any multilateral teleoperation system regardless of the amount of time delay, multilateral control architecture, and numbers of masters/slaves. In addition, this framework enables easy modification of the existing multilateral architecture without redesigning the controller from the beginning. Therefore, designing an additional channel based on the framework allows introducing additional masters or slaves. The proposed concept was tested with the trilateral teleoperation system and extended to the multilateral teleoperation system by introducing an additional slave for coordinated lifting. Stability was guaranteed under an arbitrary amount of fixed and time-varying communication delays, and the ease of extension from the previously designed architecture was demonstrated.

Note that this framework can be applied regardless of the nonlinear dynamics of the master and slave robots since it only deals with the network channel. Multi-DOF extension is also possible by simply implementing the method on each Cartesian coordinate independently. Current approach haven't considered performance in the controller design. Therefore, further study is required for improving or optimizing the performance.

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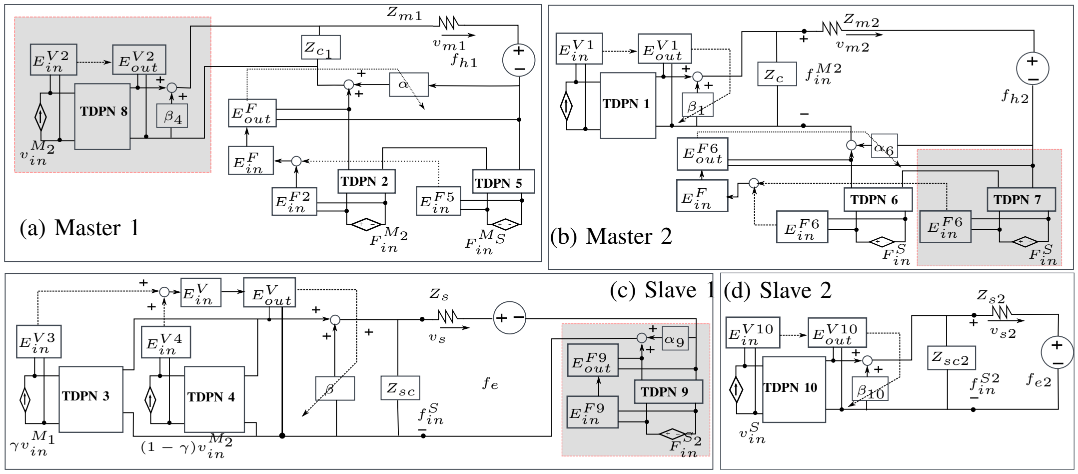


Fig. 16: Decoupled four network representation of the multilateral teleoperation system as in Fig. 15 with TDPNs and POs/PCs.

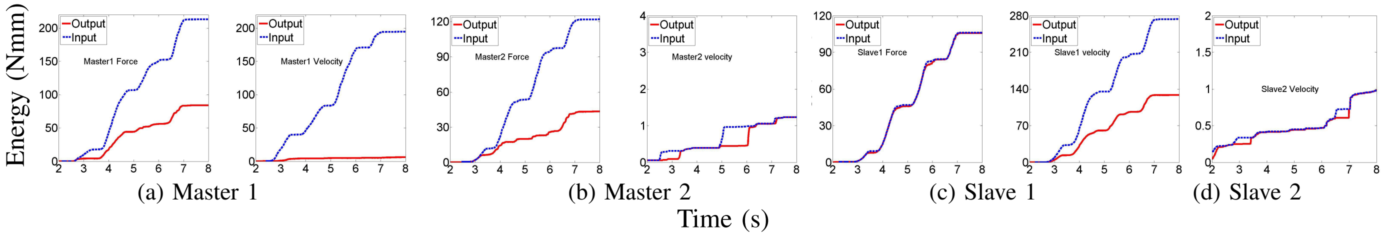
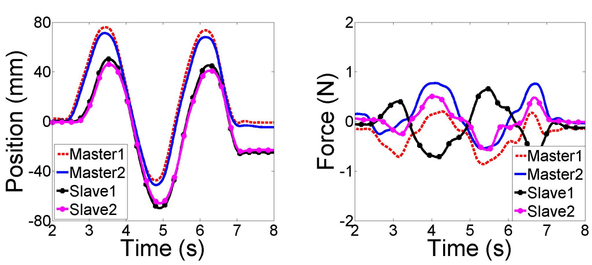


Fig. 17: Comparison of input and output energies at each TDPN of the extended multilateral teleoperation system with the proposed approach.

(a) Dual Master (b) Dual Slave

Fig. 18: Dual-master, dual-slave multilateral teleoperation system for a coordinated lifting.



(a) Position (b) Force

Fig. 19: Stable position/force response of the extended multilateral teleoperation system with the proposed multilateral controller.

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