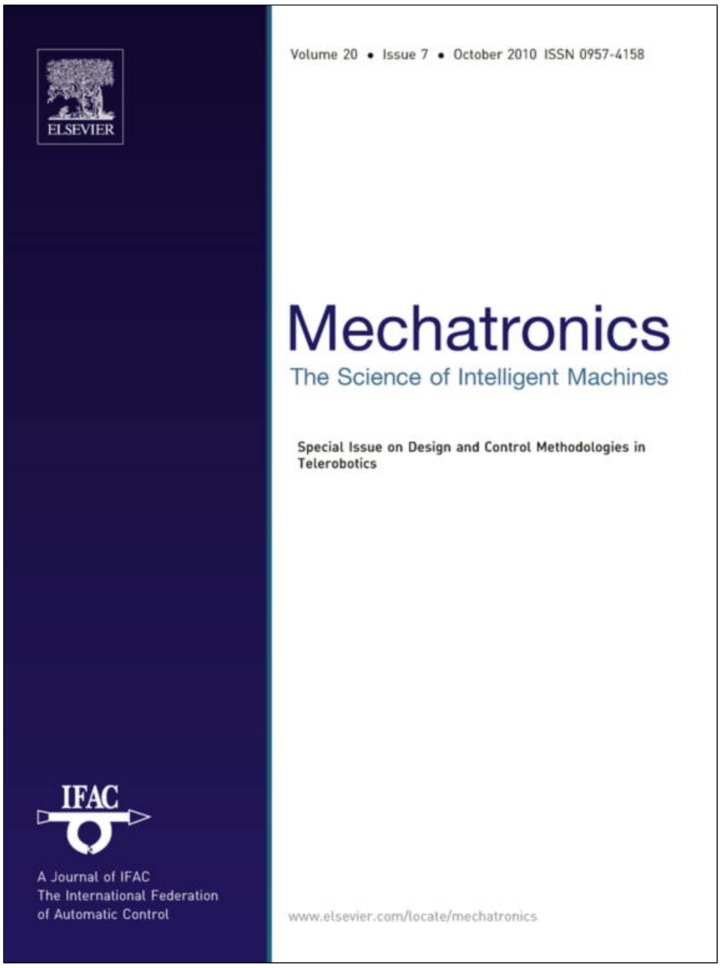
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A passive bilateral control scheme for a teleoperator with time-varying communication delay

Jee-Hwan Ryu [a,*], Jordi Artigas [b], Carsten Preusche [b]

[a] School of Mechanical Engineering, Korea University of Technology and Education, Cheoan-city 330-708, Republic of Korea
[b] Institute of Robotics and Mechatronics, German Aerospace Center, 82234 Wessling, Germany

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ABSTRACT

In this paper, a passive bilateral control scheme is proposed for a teleoperator with time-varying communication delay. Recently proposed two-port time-domain passivity approach (TDPA), which composed of Passivity Observer (PO) and Passivity Controller (PC), is extended. A set of sufficient conditions is derived, which satisfies the passivity of the two-port delayed network system, by separating the input and output energy at each port. This condition satisfies the passivity of the network system independent of the amount of delay, its variation and lost packet. Two PCs are designed at each port based on its causality to guarantee the passivity condition. In order to filter out the sudden force change of the PC, a passive virtual dynamic system, composed of virtual mass and spring, is inserted between the master and the PC. Even under a large time-delay with variation and communication blackout, the proposed approach can guarantee passive bilateral teleoperation.

1. Introduction

The field of teleoperation is getting considerable attention again [8] because of its potential applications, including tele-surgery and tele-maintenance and welfare. When a robot is operated remotely, force feedback can improve an operator's ability to perform complex tasks by kinesthetically coupling the operator to the environment. However, any data communication over the computer network has an intrinsical time-delay. In the presence of communication time-delay, even though it is small, force feedback has a strong destabilizing effect [28].

There have been numerous studies that have tried to solve the time-delay problem in the bilateral control of a teleoperator. Based on the scattering theory, Anderson and Spong [1] proposed a bilateral control law that maintains stability under the communication time-delay. Niemeyer and Slotine [17] extended this idea and introduced the notion of "wave variable". Even though the wave variable method was successful, it assumed constant time-delay. Several approaches extended the original wave variable method to case where there was time-varying communication delay [6,7,12,16,18,31].

There were also several approaches based on the robust control theory. Leung [15] proposed a bilateral controller for time-delay based on the H_∞ optimal controller and the μ-synthesis frameworks. Oboe and Fiorini [19] and Lee [14] dealt with the time-delay problem over the Internet by using a simple PD-type controller. Santo [27] proposed a gain-scheduled H_∞ controller by using measured time-delay. Haddadi and Hashtrudi-Zaad [9] introduced a design method for delay-robust transparent bilateral controller.

In [10], a new concept of the energy-based approach, also known as the time-domain passivity approach (TDPA), was proposed for guaranteeing the passivity of haptic interfaces. In TDPA, a "Passivity Observer" (PO) that could monitor energy in real-time and a "Passivity Controller" (PC) that could dissipate the required amount of energy based on PO were developed. Afterwards, TDPA was extended to teleoperation systems that had no communication time-delay [21]. Even though TDPA has been recognized as a simple and effective control method for haptic interfaces and teleoperation systems, there were some difficulties in extending this idea to include time-delay.

There have been several trials thus far that have extended TDPA to consider time-delay. In [11], the bilateral controller, slave and environment were considered as a big one-port network system, and the PO/PC was attached at the gate of a big one-port network. The whole one-port network could behave passively thanks to the PO/PC. However, it was found that the internal energy of the one-port network, like the states of the slave manipulator, cannot be regulated. Moreover, if the environment were active, this active energy would not be transmitted to the operator. Artigas et al. [3] approached the time-delay issue with two one-port networks. The bilateral controller, slave, and environment were considered to

* Corresponding author.
E-mail addresses: jhryu@kut.ac.kr (J.-H. Ryu), Jordi.Artigas@dlr.de (J. Artigas), Carsten.Preusche@dlr.de (C. Preusche).

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be one one-port, while the human operator, master, and the bilateral controller were considered to be the other one-port. The PO/PC was located at each gate of the two one-ports. Each PO/PC could make the respective one-port network passive. However, the second PO/PC, which regulated the energy from the master side, cut all the active energy flow from the human operator, which made the slave manipulator dose not move. Recently, Artigas [4] proposed a bilateral energy transfer idea, and extended this further in [5]. Although a stable interaction was shown, the passivity of the overall system was not guaranteed. Kim and Ryu [13] also tackled this problem with a similar two one-port network approach with their energy bounding algorithm, but the passivity of the overall system could not be guaranteed either. In [26], the author also extended the previously proposed two-port time-domain passivity approach by considering the time-varying communication delay. However, only feasibility was tested without rigorous passivity proof.

In this paper, based on the TDPA, a complete framework of passive bilateral control scheme is proposed for a teleoperator with time-varying communication delay, which upgrades the previous conference's paper [26]. In this paper, a more rigorous passivity analysis and general framework are added with details. A method to remove the sudden force change of the PC is proposed as well. In addition, the idea was implemented to different bilateral control architecture, which is also known as position-force bilateral control architecture. The experimental results in more severe conditions, such as a longer time-delay up to 2000 ms with variation and communication blackout, are presented as well.

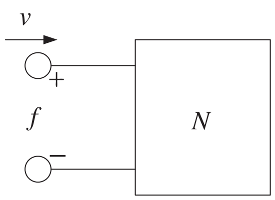


Fig. 1. One-port network system.

2. Review of the time-domain passivity approach (TDPA)

2.1. Time-domain Passivity Observer and Controller

The following widely known definition of passivity is used.

Definition 1. The one-port network (Fig. 1), N, with initial energy storage $E(0) = 0$ is *passive* if and only if,

$$\int_0^t f(\tau)v(\tau)d\tau \geqslant 0, \quad \forall t \geqslant 0 \tag{1}$$

holds for admissible forces (f) and velocities (v), where their product is defined to be positive when power enters the system port. Eq. (1) states that the energy supplied to a passive network must be positive for all time [29,30].

The conjugate variables that define power flow in such a network system are discrete-time values, and the analysis is confined to systems that have a sampling rate that is substantially faster than the dynamics of the system. Thus, we could easily "instrument" one or more blocks in the system with the following "Passivity Observer" (PO) for a one-port network in order to check the time-domain passivity (1).

$$E_{obsv}(t_k) = \Delta T \sum_{j=0}^{k} f(t_j)v(t_j) \tag{2}$$

where ΔT is the sampling period, and $t_j = j \times \Delta T$. If $E_{obsv}(t_k) \geqslant 0$ for every $k \geqslant 0$, this means the system does not generate energy. If there is an instance when $E_{obsv}(t_k) < 0$, this means the system generates energy and the amount of generated energy is $-E_{obsv}(t_k)$.

Consider a one-port system that may be active. Depending on the operating conditions and the specifics of the one-port element's dynamics, the PO may or may not be negative at a particular time. However, if it is negative at any time, we know that the one-port may then be contributing to instability. Moreover, since we know the exact amount of the generated energy, we can design a time-varying damping element to dissipate only the required amount of energy. We call this element a "Passivity Controller"

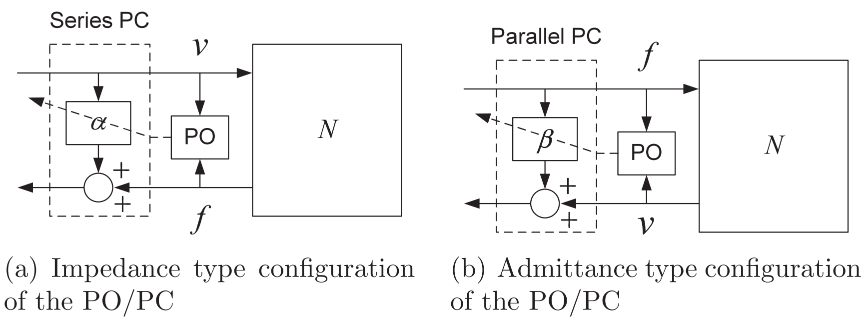


Fig. 2. Impedance and admittance type configuration of the Passivity Controller for a one-port network system.

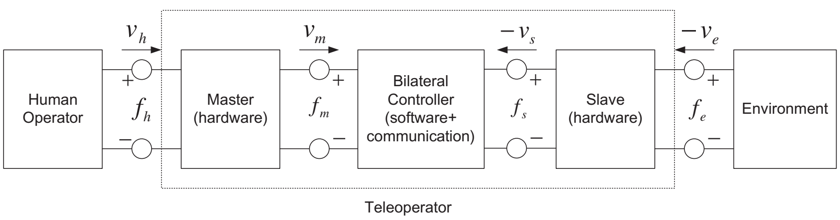


Fig. 3. Block diagram of a complete teleoperation system.

(PC). The PC takes the form of a dissipative element in an impedance or admittance type configuration depending on the input causality [10]. Fig. 2 shows the impedance and admittance type configuration of the PO/PC for a one-port network system. α and β is an adjustable damping elements at each port. The choice of configuration depends on the input/output causality of model underlying each port.

2.2. TDPA for a passive bilateral teleoperation without time-delay

Fig. 3 shows a network model of a teleoperation system, where v_h and v_e denote the velocities at the interacting points of the human/master and environment/slave, respectively, and f_h and f_e represents the force that the operator applies to the master manipulator and the slave manipulator applies to the environment, respectively.

It is a well-known fact that the passivity of the teleoperator two-port guarantees the stable interaction of the teleoperation system [2,32]. In previous work [21], the following two-port PO was designed to check the time-domain passivity and monitor the energy flow of the bilateral controller,

$$E_{obsv}(t_k) = \Delta T \sum_{j=0}^{k} (f_m(t_j)v_m(t_j) + f_s(t_j)v_s(t_j)) \quad (3)$$

and two series PCs were attached at each port of the bilateral controller (Fig. 4) to dissipate the active energy flow at each port by adjusting the damping elements α_1 and α_2. Please see [10,21,22,24,25] for more details about the TDPA.

When there was no time-delay, the previous two-port TDPA showed a satisfying performance that guarantees the passivity [21]. However, once the time-delay was introduced, the passivity condition could not be satisfied anymore with the previous approach. The main reason was the fact that the PO could not integrate the power flow at each port of the bilateral controller at the same sampling instant.

3. Two-port TDPA that considers time-varying communication delay

In this section, a modified two-port TDPA that considers time-varying communication delay is introduced and the two-port passivity is proved.

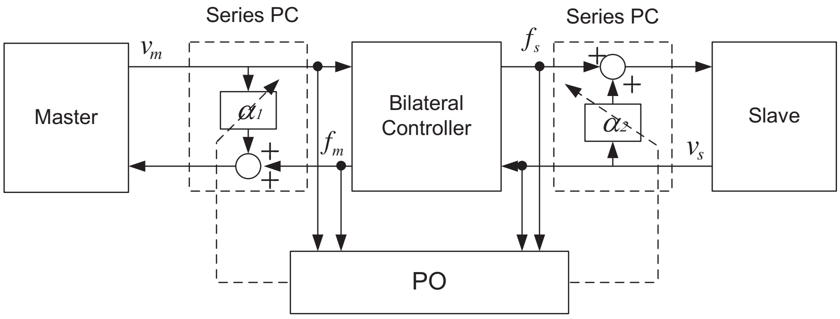


Fig. 4. Block diagram of a teleoperator with PC. Two series PCs are attached at each port of the bilateral controller.

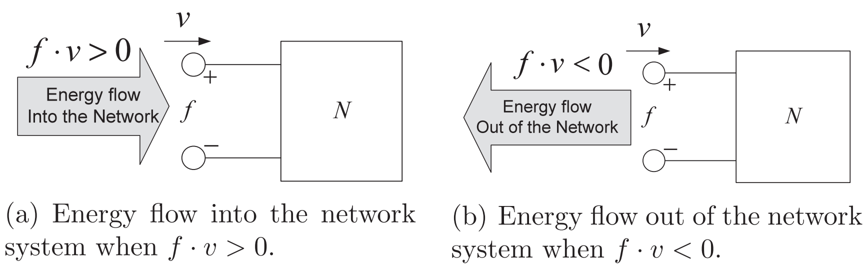


Fig. 5. Based on the sign of the power at a port, it is possible to differentiate whether energy is flowing into the network system or flowing out of the network system.

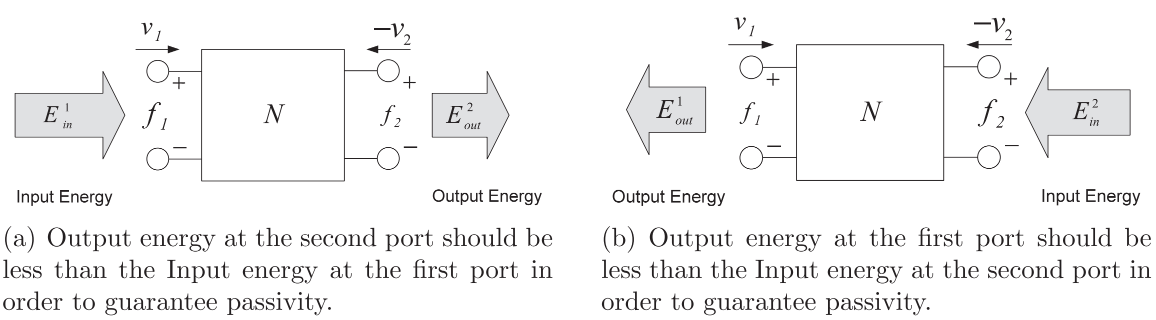


Fig. 6. In two-port network systems, the main source of the output energy at one-port is the input energy at the other port, and the output energy should be less than the input energy.

Energy at a port can be separated into input and output energy, as follows:

$$E_{obsv}(k) = E_{in}(k) - E_{out}(k) \quad (4)$$

Note that k means the kth step sampling instant (t_k). If the sign of the power flow ($f \cdot v$) at a port is positive, energy is defined to be flowing into the network system. If the sign is negative, energy is defined to be flowing out of the network system (Fig. 5). The input and the output energy of the network system can be calculated by integrating the power flow of each case.

$$E_{in}(k) = \begin{cases} E_{in}(k-1) + \Delta T \cdot P(k) & \text{if } P(k) > 0 \\ E_{in}(k-1) & \text{if } P(k) \leqslant 0 \end{cases} \quad (5)$$

$$E_{out}(k) = \begin{cases} E_{out}(k-1) - \Delta T \cdot P(k) & \text{if } P(k) < 0 \\ E_{out}(k-1) & \text{if } P(k) \geqslant 0 \end{cases} \quad (6)$$

where ΔT is the sampling time, and $P(k) = f(k) \cdot v(k)$, the power flow at the port.

With the above notation, the time-domain passivity condition for an one-port network $\Delta T \sum_{j=0}^{k} f(t_j)v(t_j) \geqslant 0$ can be rewritten as follows:

$$E_{in}(k) \geqslant E_{out}(k), \quad \forall k \geqslant 0 \quad (7)$$

For the two-port network system (Fig. 6), the input and output energy at each port can be calculated in a similar way as (5) and (6).

$$E^1_{in}(k) = \begin{cases} E^1_{in}(k-1) + \Delta T \cdot P_1(k) & \text{if } P_1(k) > 0 \\ E^1_{in}(k-1) & \text{if } P_1(k) \leqslant 0 \end{cases} \quad (8)$$

$$E^1_{out}(k) = \begin{cases} E^1_{out}(k-1) - \Delta T \cdot P_1(k) & \text{if } P_1(k) < 0 \\ E^1_{out}(k-1) & \text{if } P_1(k) \geqslant 0 \end{cases} \quad (9)$$

$$E^2_{in}(k) = \begin{cases} E^2_{in}(k-1) + \Delta T \cdot P_2(k) & \text{if } P_2(k) > 0 \\ E^2_{in}(k-1) & \text{if } P_2(k) \leqslant 0 \end{cases} \quad (10)$$

$$E^2_{out}(k) = \begin{cases} E^2_{out}(k-1) - \Delta T \cdot P_2(k) & \text{if } P_2(k) < 0 \\ E^2_{out}(k-1) & \text{if } P_2(k) \geqslant 0 \end{cases} \quad (11)$$

where E^1_{in} is the input energy at the first port, and E^2_{out} is the output energy at the second port. The other two cases follow the same notation. $P_1(k)(=f_1(k) \cdot v_1(k))$ and $P_2(k)(=f_2(k) \cdot v_2(k))$ is the power flow at the first port and the second port, respectively.

With the above notation, the time-domain passivity condition of the two-port network $\Delta T \sum_{j=0}^{k}(f_1(t_j)v_1(t_j) + f_2(t_j)v_2(t_j)) \geqslant 0$ can be rewritten as follows:

$$E^1_{in}(k) + E^2_{in}(k) \geqslant E^1_{out}(k) + E^2_{out}(k), \quad \forall k \geqslant 0 \quad (12)$$

In the previous approach [21], $E^1_{out}(k)$ and $E^2_{out}(k)$ were adjusted to satisfy the above single condition (12) by adding adaptive dissipation elements. However, if there was time-delay, the above condition (12) could not be satisfied in real-time anymore since it was impossible to compare $E^1_{in}(k)$ and $E^1_{out}(k)$ with $E^2_{in}(k)$ and $E^2_{out}(k)$ at the same sampling instant. To overcome this problem, a new TDPA for a delayed two-port network is proposed in this paper. Please note that the condition, $\forall k \geqslant 0$, will be skipped afterward since it will be repeated.

By separating the time-domain passivity condition of the two-port network system (12), the following set of sufficient conditions can be derived, which means, to satisfy (12), it is sufficient that the output energy at the second port is less than the input energy at the first port and the output energy at the first port is less than the input energy at the second port.

$$\begin{aligned} E^1_{in}(k) &\geqslant E^2_{out}(k) \\ E^2_{in}(k) &\geqslant E^1_{out}(k) \end{aligned} \quad (13)$$

Actually, it is still impossible to compare $E^2_{out}(k)$ with $E^1_{in}(k)$ (and $E^1_{out}(k)$ with $E^2_{in}(k)$) at the same sampling instant. However, physically it is meaningful that the main source of the output energy at one-port is the input energy at the other port, and the output energy should be less than the input energy. It is interesting to note that the similar condition was used in [18,31], which were based on the wave variable approach.

Even though it is impossible to compare $E^2_{out}(k)$ with $E^1_{in}(k)$ at the same sampling instant, $E^2_{out}(k)$ can be compared with delayed input

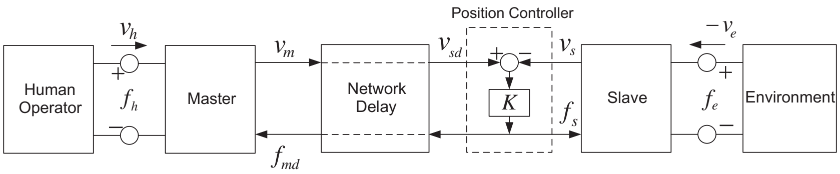


Fig. 7. A time-delayed teleoperation system with position-force bilateral control architecture.

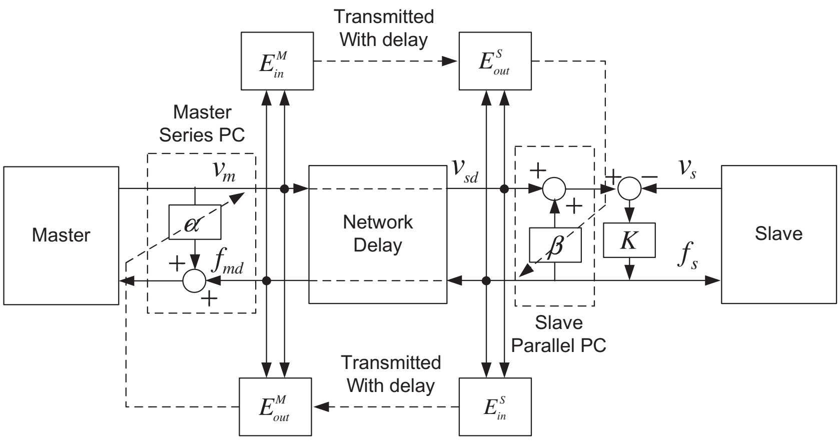
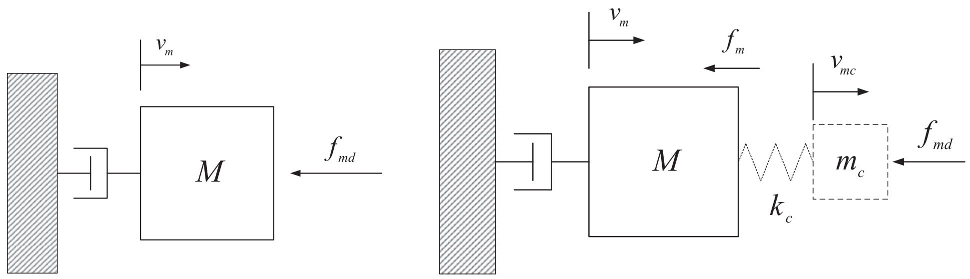


Fig. 8. A time-delayed teleoperator with the proposed two-port PO/PC.



(a) One-DOF master with feedback force (f_{md}). (b) One-DOF master with virtual mass and spring after the feedback force (f_{md}).

Fig. 9. Comparison of one-DOF master with and without virtual mass and spring.

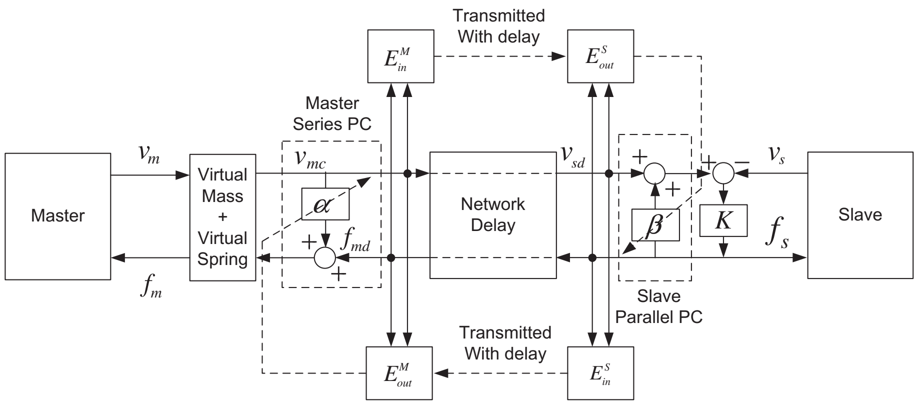


Fig. 10. A time-delayed teleoperator with the proposed two-port TDPA and the virtual mass with spring.

energy ($E^1_{in}(k - D^{12}(k))$) at the second port if we transmit $E^1_{in}(k)$ to the second port through the network channel. $D^{12}(k)$ is the number of delayed sampling step, which take until the input energy from the first port arrives at the second port. Please note that it is positive and varying when there is time-varying communication delay. For the other case, $E^1_{out}(k)$ can be compared with delayed input energy ($E^2_{in}(k - D^{21}(k))$) at the first port if we transmit $E^2_{in}(k)$ to the first port through the network channel. $D^{21}(k)$ is the number of delayed sampling step, which take until the input energy from the second port arrives at the first port. Where $E^1_{in}(n) = E^2_{in}(n) = 0$ when $n < 0$ since there is no energy input before the system start.

By simply adding and subtracting the delayed input energy, (13) can be rewritten as follows:

$$\begin{aligned} E^1_{in}(k - D^{12}(k)) - E^1_{in}(k - D^{12}(k)) + E^1_{in}(k) &\geqslant E^2_{out}(k) \\ E^2_{in}(k - D^{21}(k)) - E^2_{in}(k - D^{21}(k)) + E^2_{in}(k) &\geqslant E^1_{out}(k) \end{aligned} \tag{14}$$

Thanks to the monotonicity of the input energy (please see (8) and (10)), it is sufficient to satisfy followings in order to satisfy (14):

$$\begin{aligned} E^1_{in}(k - D^{12}(k)) &\geqslant E^2_{out}(k) \\ E^2_{in}(k - D^{21}(k)) &\geqslant E^1_{out}(k) \end{aligned} \tag{15}$$

Please note that each input energy are defined to be monotonically increasing as time goes, which means that the input energy at time step k is always greater than or equal to the input energy at the previous time step, no matter how much delayed sampling step there is.

$$\begin{aligned} E^1_{in}(k) - E^1_{in}(k - D^{12}(k)) &\geqslant 0 \\ E^2_{in}(k) - E^2_{in}(k - D^{21}(k)) &\geqslant 0 \end{aligned} \tag{16}$$

Therefore (15) is sufficient to satisfy (12), which is the time-domain passivity condition of two-port network systems with time-varying communication delay. By modifying each output energy, $E^2_{out}(k)$ and $E^1_{out}(k)$, with the PC at each port (15) can be satisfied. More detail about the PC will be introduced in next Section.

If data packets are lost during the communication, Recently arrived packet is usually used until new packet arrives. So, the arrived input energies for the comparison in (15) are changed as follows:

$$\begin{aligned} E^1_{in}(k - D^{12}(k) - L^{12}(k)) &\geqslant E^2_{out}(k) \\ E^2_{in}(k - D^{21}(k) - L^{21}(k)) &\geqslant E^1_{out}(k) \end{aligned} \tag{17}$$

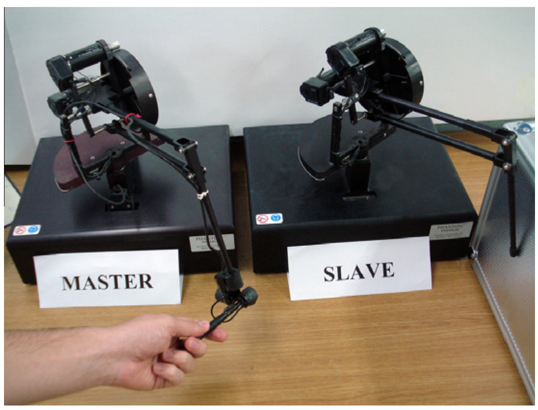


Fig. 11. Dual PHANToM for the teleoperation with time-delay.

where $L^{12}(k)$ and $L^{21}(k)$ means the number of lost sample step for each direction. Even though the compared reference energies on the left side are changed (17) is still sufficient to satisfy (12) due to the monotonicity of the input energy as follows:

$$\begin{aligned} E^1_{in}(k - D^{12}(k)) &\geqslant E^1_{in}(k - D^{12}(k) - L^{12}(k)) \geqslant E^2_{out}(k) \\ E^2_{in}(k - D^{21}(k)) &\geqslant E^2_{in}(k - D^{21}(k) - L^{21}(k)) \geqslant E^1_{out}(k) \end{aligned} \tag{18}$$

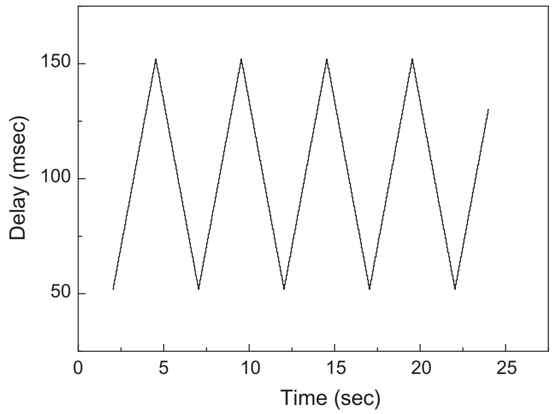


Fig. 12. Amount of time-varying delay during the experiment. An average round trip delay was 100 ms and varied between 150 ms and 50 ms.

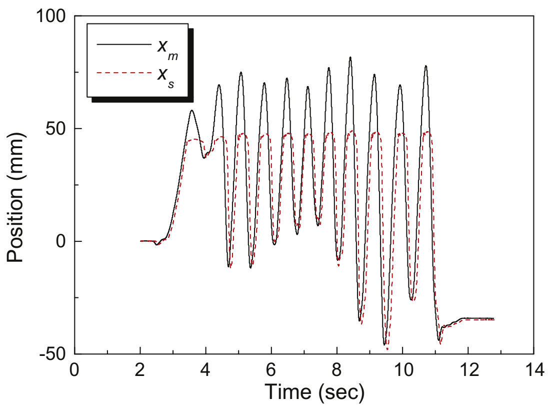
Communication blackout can be considered as an extreme case of packet loss. In case of no information exchange, output energy is limited by the input energy which arrived before blackout. So the lost data would not do anything to break passivity.

Theoretically there is no limitation to the amount of the delay and its variation. However, out-of-order packet cannot be covered directly with this scheme, but we can solve this issue by putting a time stamp into a data packet, and disregard the out-of-ordered packet. Then, the problem becomes packet loss problem, which the proposed controller can cover.

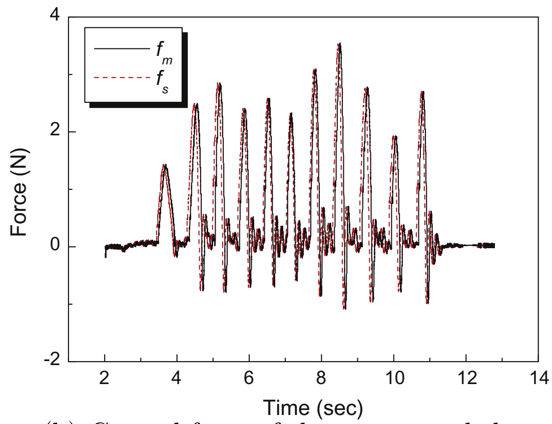
4. Implementing the two-port TDPA to a teleoperation system

This section addresses how to implement the developed two-port TDPA to a teleoperation system with position-force bilateral control architecture (Fig. 7). v_{sd} is the desired velocity of the slave, which is the master velocity (v_m) with delay. f_{md} is the control force of the master, which is the control force of the slave (f_s) with delay. K is the position controller of the slave.

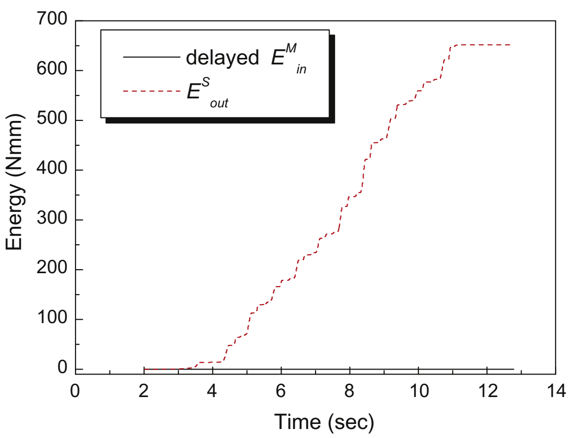
Based on the idea of passivity, it is a well-known fact that the passivity of the teleoperator two-port, from the master to the slave, is the sufficient condition for the passivity of the teleoperation system. Since the master and the slave without a controller are intrinsically passive, and the position controller of the slave can also be designed passive, the only active part is the network channel with time-delay.



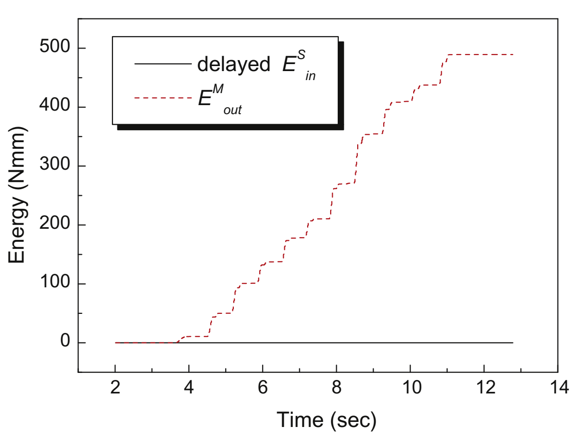
(a) Position response of the master and slave



(b) Control force of the master and slave



(c) Output energy at the slave and input energy from the master with delay.



(d) Output energy at the master and input energy from the slave with delay.

Fig. 13. Hard contact with time-varying communication delay (average round trip delay: 100 ms) and without the proposed TDPA. Due to the delay, this resulted in an oscillation that was observed to be force and position pulses. Note that E^M_{in} and E^S_{in} looked like zero due to the large magnitude difference, but actually had some value.

Therefore, the proposed TDPA can be implemented to the two-port network channel. Two POs are attached to each port of the network channel in order to monitor the input and output energy separately. Based on causality, the impedance type PC is placed between the master and the network channel, and the admittance type PC is attached between the network channel and the position controller of the slave (Fig. 8).

The input energy at the master side (E^M_{in}) is monitored and transmitted to the slave side, while the damping element β is adjusted to satisfy (15), which bound the output energy of the slave ($E^S_{out}(k)$) below the delayed input energy from the master ($E^M_{in}(k-D^{MS}(k))$) according to

$$\beta(k)=\begin{cases}\frac{E^S_{out}(k)-E^M_{in}(k-D^{MS}(k))}{\Delta T f^2_s(k)} & \text{if } E^S_{out}(k)>E^M_{in}(k-D^{MS}(k)) \text{ and } f_s(k)\neq 0\\ 0 & \text{if } E^S_{out}(k)\leqslant E^M_{in}(k-D^{MS}(k))\end{cases} \tag{19}$$

As a result, the desired velocity of the slave (v_{sd}) is modified, where $D^{MS}(k)$ represents the amount of delayed sampling step from the master to the slave.

The input energy from the slave side (E^S_{in}) is monitored and transmitted to the master side, and the damping element α is implemented to satisfy (15), which bound the output energy of the master ($E^M_{out}(k)$) below the delayed input energy from the slave ($E^S_{in}(k-D^{SM}(k))$) according to

$$\alpha(k)=\begin{cases}\frac{E^M_{out}(k)-E^S_{in}(k-D^{SM}(k))}{\Delta T v^2_m(k)} & \text{if } E^M_{out}(k)>E^S_{in}(k-D^{SM}(k)) \text{ and } v_m(k)\neq 0\\ 0 & \text{if } E^M_{out}(k)\leqslant E^S_{in}(k-D^{SM}(k))\end{cases} \tag{20}$$

As a result, the feedback force to the master (f_{md}) is modified, where $D^{SM}(k)$ represents the amount of delayed sampling step from the slave to the master.

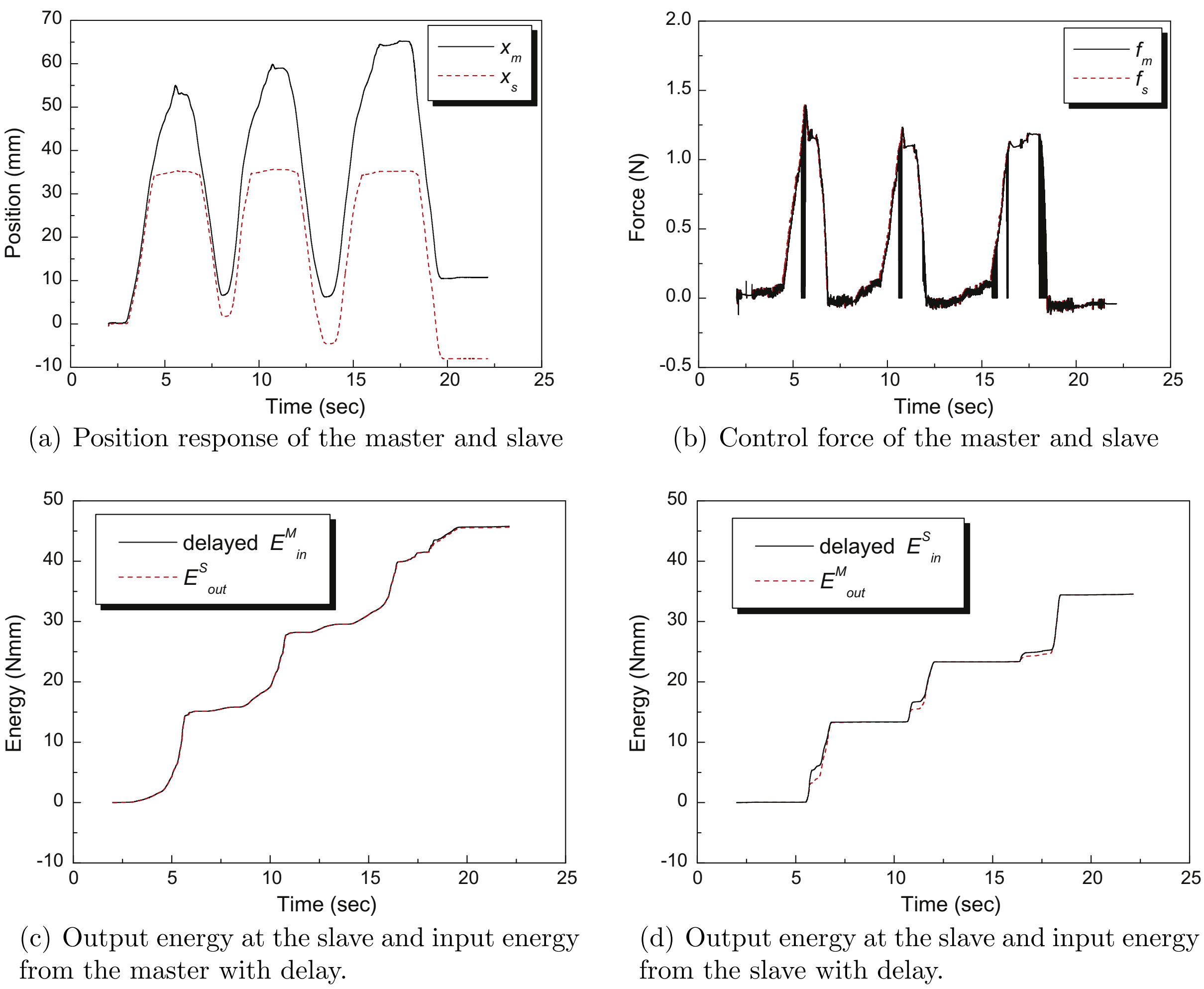
We can easily demonstrate that the set of sufficient conditions for the passivity of the two-port network, (15), can be satisfied with the additional damping α and β, which is computed by (19) and (20). Please see [10] for a more detailed passivity proof.

Please note that the sampling time is assumed to be the same on both the master and the slave side in order to simplify the derivation, and the proposed approach can be easily extended to the case when the sampling time is different.

5. A method to remove sudden force change

One of the problems of the TDPA, especially in impedance type PC, is the sudden force change. In order to solve this issue, we put a passive virtual system, composed of mass (m_c) and spring (k_c), between the master and the impedance type PC.

Fig. 9a shows one-DOF master with force feedback (f_{md}). Since the feedback force (f_{md}) is directly applied to the master, the



(a) Position response of the master and slave (b) Control force of the master and slave (c) Output energy at the slave and input energy from the master with delay. (d) Output energy at the slave and input energy from the slave with delay.

Fig. 14. Hard contact with time-varying communication delay (average round trip delay: 100 ms) and with the proposed TDPA. The position response of the master and slave manipulator showed stable behavior, but there was a series of sudden changes on the force to the master in the middle of contact.

operator may be able to feel a sudden force change if the feedback force is suddenly modified, which actually happened due to the PC action. When we put the virtual mass and spring in-between the master and feedback force, the sudden force from the PC escaped thanks to the inertia effect (Fig. 9b). However, there may be some force and velocity distortion. The applied force to the master changed to f_m, and the velocity signal from the master to slave changed to v_{mc} (Fig. 10). The following two relationships are used to calculate f_m and v_{mc} in real-time.

$$f_m = k_c(x_m - x_{mc}) \tag{21}$$

$$m_c \dot{v}_{mc} = f_m - f_{md} \tag{22}$$

It is interesting to note that the virtual mass with a spring is a kind of low pass filter of the force and velocity in both directions. If one directional filter, like the force filter or the velocity filter, is added, it would make the system active, but the bi-directional filter maintains the system's passivity. The passivity of the inserted virtual system can be checked as follows:

$$\begin{aligned}
&\int_0^t (f_m(\tau)v_m(\tau) - f_{md}(\tau)v_{mc}(\tau))d\tau \\
&= \int_0^t (f_m(\tau)v_m(\tau) - f_{md}(\tau)v_{mc}(\tau) + f_m(\tau)v_{mc}(\tau) - f_m(\tau)v_{mc}(\tau))d\tau \\
&= \int_0^t (f_m(\tau)(v_m(\tau) - v_{mc}(\tau)) + (f_m(\tau) - f_{md}(\tau))v_{mc}(\tau))d\tau \\
&= \int_0^t (k_c e\dot{e} + m_c v_{mc}\dot{v}_{mc})d\tau \\
&= \frac{1}{2}k_c e^2 + \frac{1}{2}m_c v_{mc}^2 \geqslant 0
\end{aligned}$$

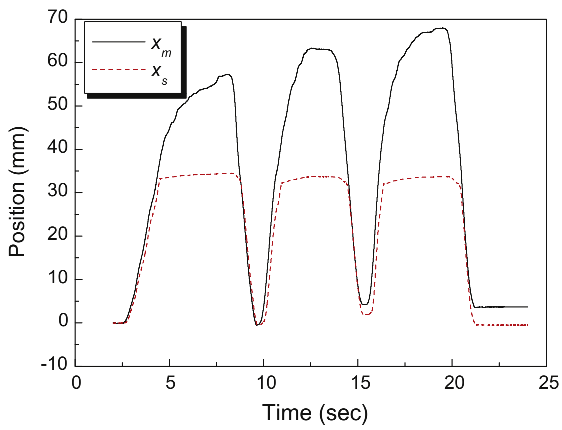
where $e = x_m - x_{mc}$.

Eq. (23) is the transfer functions of the low pass force filter, and Eq. (24) is the transfer functions of the low pass velocity filter. If the cutoff frequency of the force filter is lower than the frequency of the PC noise from the sudden force change, the PC noise can be filtered out, and only low frequency force component would be transmitted to the operator.

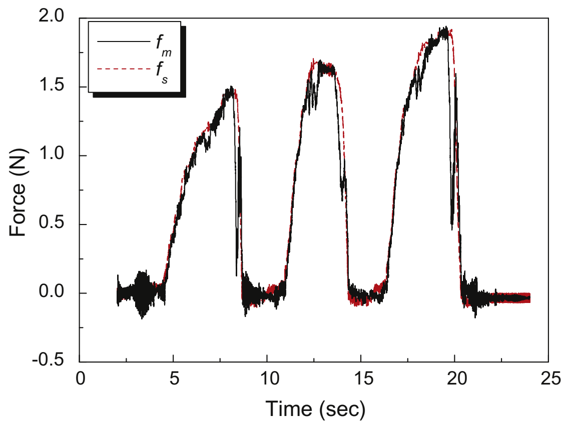
$$\frac{F_m(s)}{F_{md}(s)} = \frac{k_c}{m_c s^2 + k_c} \tag{23}$$

$$\frac{V_{mc}(s)}{V_m(s)} = \frac{k_c}{m_c s^2 + k_c} \tag{24}$$

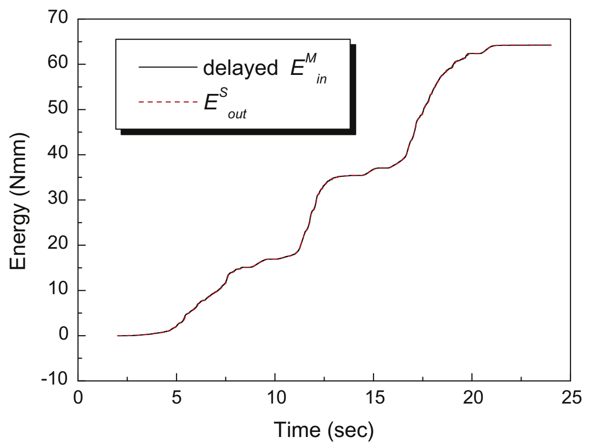
Please note that the distorted force can be ignorable, if we increase the stiffness (k_c) to be as high as possible, and reduce the mass (m_c) to be as low as possible as long as the cutoff frequency of the force filter is lower than the frequency of the PC noise.



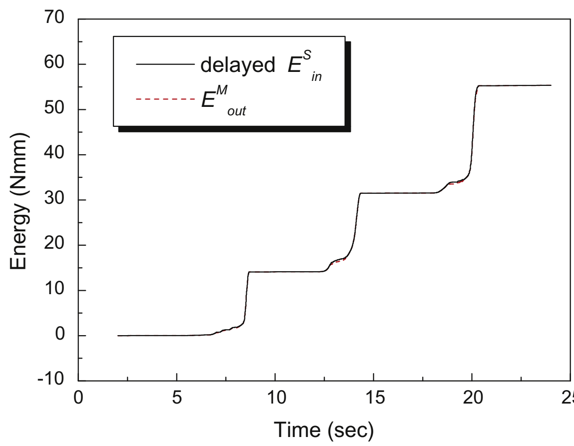
(a) Position response of the master and slave



(b) Control force of the master and slave



(c) Output energy at the slave and input energy from the master with delay.



(d) Output energy at the master and input energy from the slave with delay.

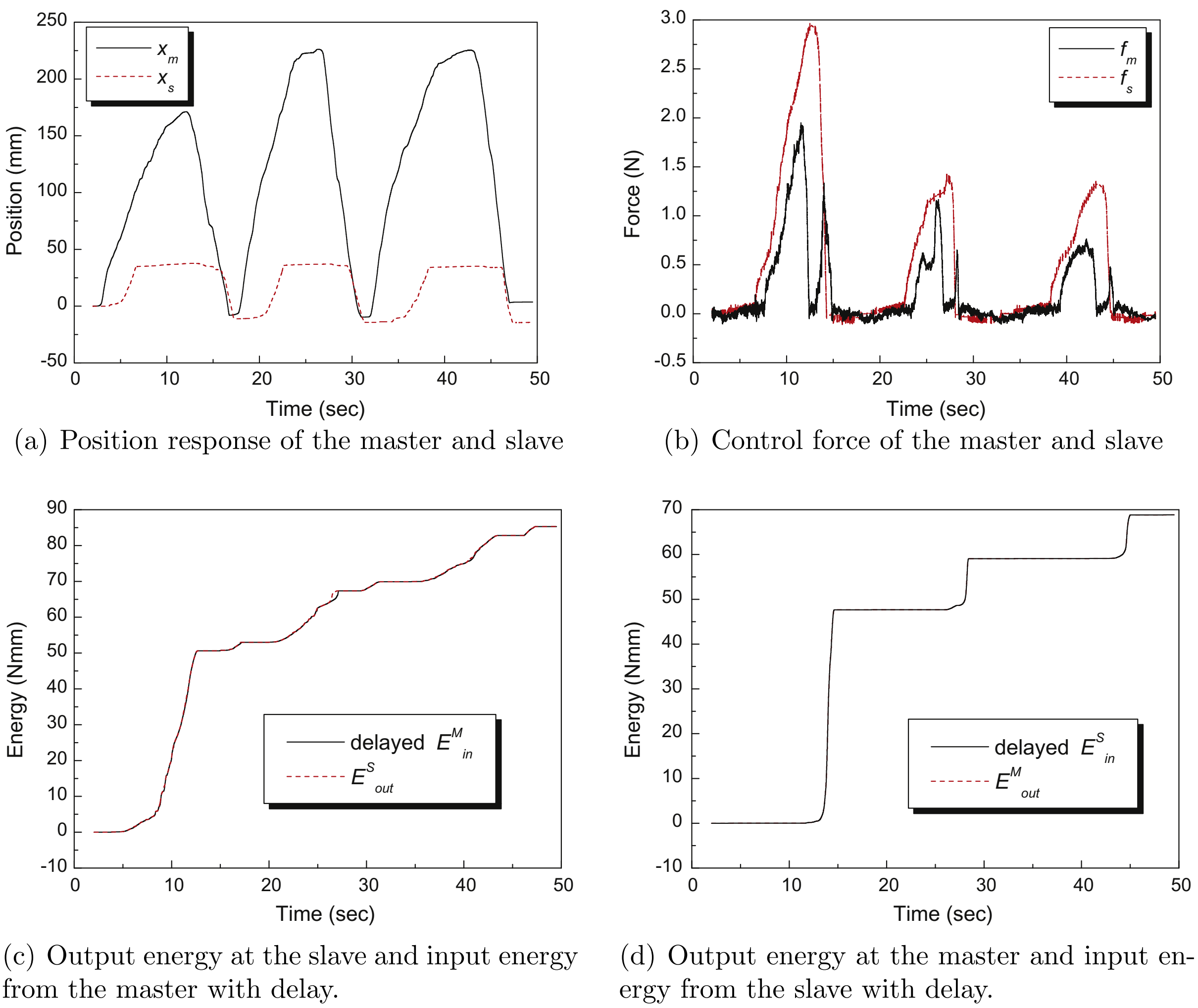
Fig. 15. Hard contact with time-varying communication delay (average round trip delay: 100 ms) and with the proposed TDPA and the virtual mass with spring. Position response of the master and slave manipulator was stable, and thanks to the virtual mass and spring, the high frequency noisy control force after the PC was filtered out and only a low frequency component of the interaction force could be transmitted.

6. Experimental evaluations

Fig. 11 shows the dual PHANToM configuration for the teleoperation experiment with time-delay. A single computer was used as a controller for the master and slave teleoperator at 1 kHz sampling rate, and the time-varying delay was simulated inside the computer. Fig. 12 shows the amount of time-varying communication delay during the experiment. The communication had about 100 ms average round trip delay and was oscillating between 150 ms and 50 ms. The position-force bilateral control architecture was used. The delayed slave control force was used as a feedback control force to the master while the position PD controller was used to make the slave follow the position command from the master.

In the first experiment, without the TDPA, the operator maneuvered the master to make the slave contact the hard wall (over 150 kN/m). Due to the delay, this resulted in an oscillation that was observed to be a force as well as position pulses (Fig. 13a and b). Please note that this was not a voluntary motion. The operator was not able to maintain the contact due to the delayed big force. During the contact, the output energy of the master and slave became greater than the input energy from the slave and master (Fig. 13c and d), which broke the passivity condition (15). Only the X-directional signals are plotted since the main interaction occurs on the X-axis. Note that E^M_{in} and E^S_{in} looked like zero due to the large magnitude difference, but it actually had some value.

The same experiment shown in Fig. 13 was performed with the proposed TDPA. The operator maneuvered the master to make the slave contact the hard wall three times. Please note that this contact of three times was a voluntary motion. The operator moved to the next contact after achieving stable contact. The position response of the master and slave manipulator showed stable interaction (Fig. 14a). The PC made the bilateral controller passive by making the output energy at the master port stay below the input energy from the slave port (Fig. 14d), and the output energy at the slave port stay below the input energy from the master port (Fig. 14c). When the output energy at the master port was about to be greater than the input energy from the slave port in Fig. 14d, the PC was activated and the control force of the master was modified (Fig. 14b). Due to this PC action, there was a series of sudden changes on the force on the master in the middle of the contact. The reason could be found in the low velocity during the contact, especially the sudden sign change and zero value of the velocity. In our previous work [23], this noisy sudden force change of the PC, due to the low velocity, was studied. Even though it was not serious in this case, this behavior obviously degraded the operator's perception. In order to make the output energy at the



(a) Position response of the master and slave

(b) Control force of the master and slave

(c) Output energy at the slave and input energy from the master with delay.

(d) Output energy at the master and input energy from the slave with delay.

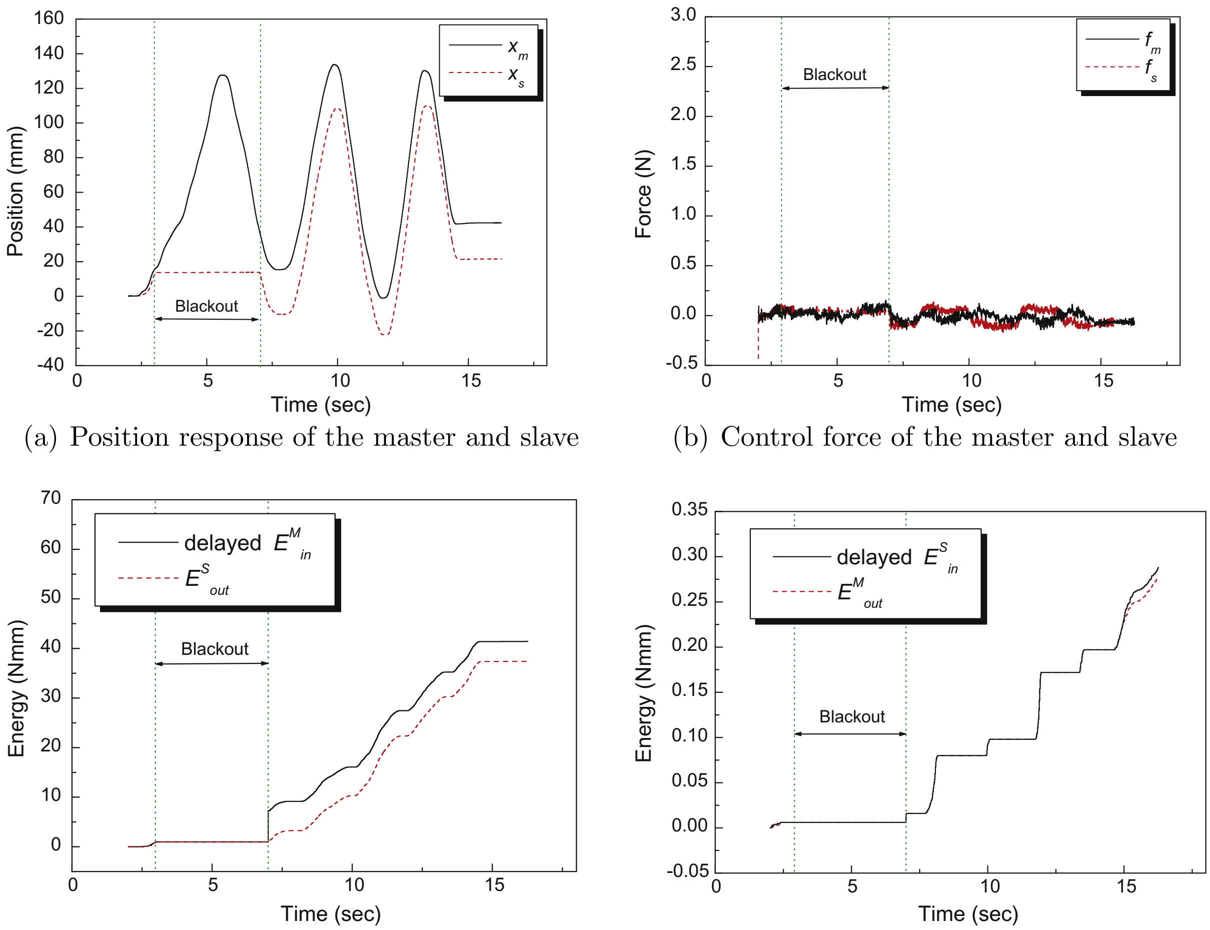
Fig. 16. Hard contact with time-varying communication delay (average round trip delay: 2000 ms) and with the proposed TDPA and the virtual mass with spring. As the delay increased, the more the position drift and the more the force modification were the results of the expense of the stable interaction.

slave port stay below the input energy from the master port, the PC at the slave port modified the reference velocity from the master. As a result, it caused a position drift at the end of the contact.

We made a hard contact again with the proposed method in order to remove the noisy sudden force change together with the TDPA. The stiffness of the virtual spring and the inertia of the virtual mass were set to be 1000 (N/m) and 0.0001 (kg), respectively. The cutoff frequency of the virtual mass/spring system with 1 ms sampling time was around 320 (HZ), which is lower than the frequency of the PC noise (around 500 Hz). As a result, the noise component of the PC was filtered out. The position response of the master and slave manipulator was stable (Fig. 15a), and the control force of the master became much smoother than the one in previous experiment (Fig. 15b). During the contact, the control force of the master followed the force from the slave, and thanks to the virtual mass and spring, the high frequency noisy control force after the PC was filtered out and only a low frequency interaction force could be transmitted. Please note that even though the virtual systems cut off the high frequency force component, the modified force was following the original force from the slave quite well (Fig. 15b), and was minimally modified only when necessary.

In order to show the feasibility of the proposed method in a more severe communication condition, a longer time-delay was tested as well. The proposed method could achieve a stable hard contact, even 2000 ms (Fig. 16) average round trip delay with variation. The delay was varied in the same way as Fig. 12. Since the amount of delay was increased, the more position drift and the more force modification resulted in the expense of the stable interaction. However it is interesting to note that the force profile at the beginning of the contact was similar with the original one, which is very important to give contact discrimination to the operator. It is also worth to mention that the proposed method could guarantee a passive bilateral teleoperation, independent of the amount of time-delay.

Communication blackout situation was also tested. Communication was in breakdown from 3 s to 7 s in free motion (Fig. 17). During the blackout, the slave stopped the motion (Fig. 17a) since the PC at the slave port limited the output energy below the input energy from the master, which has arrived before the blackout and remained constant during the blackout (Fig. 17c). After communication back, the position of the slave started to follow the position of the master again without any unstable behavior. In hard contact, communication was in breakdown from 5 s to 10 s (Fig. 18). During the contact, the slave was not moving, like in Fig. 17, and the control force of the master was controlled only to dissipate energy (Fig. 18b) since the PC at the master port limited the output energy below the input energy from the slave before the blackout, which remained constant during the blackout (Fig. 18d). After communication was recovered, the control force of the master stared to follow the force from the slave again without any unstable oscillation. Even in communication blackout, the proposed method showed passive teleoperation in free and constrained motion.



(a) Position response of the master and slave

(b) Control force of the master and slave

(c) Output energy at the slave and input energy from the master with delay.

(d) Output energy at the master and input energy from the slave with delay.

Fig. 17. Free motion with time-varying communication delay (average round trip delay: 100 ms) and communication blackout (from 3 s to 7 s) with the proposed TDPA and the virtual mass with spring. During the blackout, the slave stopped the motion since the PC at the slave port limited the output energy below the input energy from the master.

7. Discussion

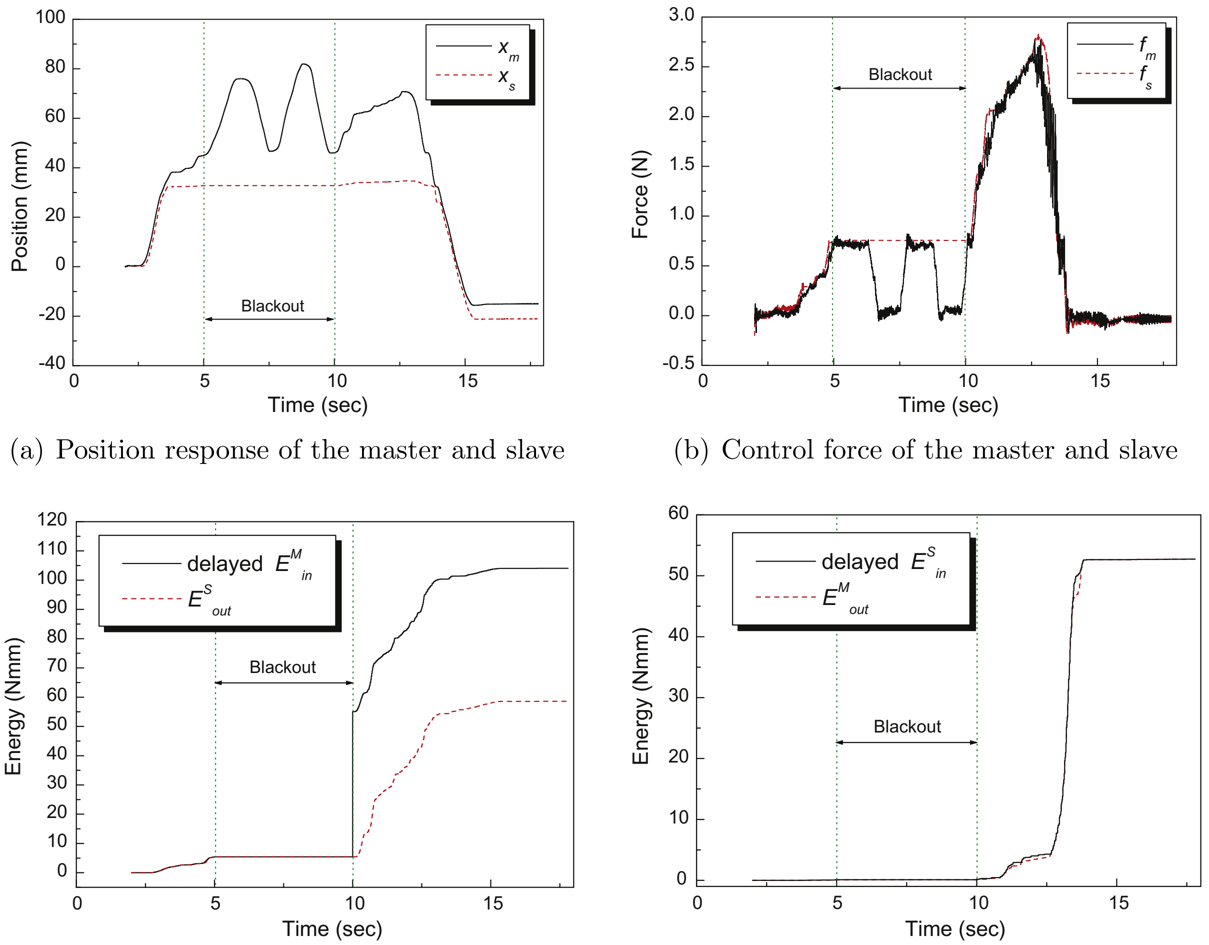
Nevertheless, the method has several issues which we need to study further.

First, it resulted position drift on the slave side. In Figs. 14–18, it showed position difference at the end of the motion. Since it was impossible to observe the real exact amount of energy flow in the network channel, both PCs at the master and the slave side were forced to dissipate more energy than strictly needed. The error between the channel energy and observed energy has been proved to be a passive "leak". This is actually how passivity was proved by sufficiency. The energy dissipated in excess could results in different transparency losses depending on the causality of the PC. In the admittance case, which was the one of the slave side, the dissipation was produced by modulating the damping parameter which acted upon velocity. In the case of activity the controller slowed down the slave. Since there was no position link toward the master device, position drift occurred. In [5], some preliminary idea was addressed, and currently we are working on how to improve and integrate this with the proposed method while maintaining the passivity.

In addition, the virtual mass and spring system may cause unwanted force distortion in free motion. When the operator pushed the master, the virtual spring would be deformed to move the virtual mass. Even though there was no force feedback from the slave side, the force from the deformation of the spring would be applied to the operator. In Fig. 17b, we can see this behavior rather clearly comparing other figures. However, the amount of the force distortion was very small. Therefore the operator was rarely bothered by this distortion.

Another interesting issue would be comparing the proposed approach with other conventional approaches and carefully analyze the advantages and disadvantages of each method. One thing we can carefully expect is that our approach will gives more transparency than others since our approach modifies feedback force less than others, especially when it is compared with the methods based on wave variable. But, this kind of claim should come along with clear data and fair comparison study.

One possible thing we can discuss further is the energy coupling issue when we extend this idea to multi-dimensional case. Although we only illustrated one dimensional result for easy explanation, it can be easily extended to multi-dimensional case by implementing the proposed scheme to each axis independently. Alternatively, all axis can be considered together by properly distributing damping among each axis for less conservatism. A related work has been done for haptic displays in [20], but we need more study to implement this idea to teleoperation systems.



(a) Position response of the master and slave

(b) Control force of the master and slave

(c) Output energy at the slave and input energy from the master with delay.

(d) Output energy at the master and input energy from the slave with delay.

Fig. 18. Hard contact with time-varying communication delay (average round trip delay: 100 ms) and communication blackout (from 5 s to 10 s) with the proposed TDPA and the virtual mass with spring. During the contact, the slave did not move, and the master force was controlled only to dissipate energy since the PC at the master port limited the output energy below the input energy from the slave before the blackout.

8. Conclusions

In this paper, a time-domain passivity based bilateral controller was proposed for a passive teleoperation under time-varying communication delay. The proposed controller can guarantee the passive bilateral teleoperation with high stiffness remote environments independent of the amount of time-delay, its variation and lost packet. By introducing a passive virtual system, which is composed of mass and spring, the high frequency noisy force after the PC was filtered out and only a low frequency interaction force could be transmitted to the operator while maintaining the passivity of the overall system. The feasibility of the proposed approach was proved with a real experiment that used the dual PHANToM teleoperation system. It showed a stable interaction under a large time-delay of average up to 2000 ms with variation, and even several seconds of communication blackout.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.mechatronics.2010.07.006.

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