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# Robustly stable bilateral teleoperation under time-varying delays and data losses: an energy-bounding approach †

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**Abstract**

This paper presents an energy-bounding approach for robustly stable bilateral teleoperation over a communication channel with severe variable time delays and packet drops. We extend the energy-bounding algorithm (EBA) for haptic interaction with virtual environments to bilateral teleoperation with remote environments by using an analogy between haptic interaction and teleoperation controls. Robust stability is achieved by both restricting the extra energy that is generated by the sample-and-hold to within the consumable energy in the master device or slave robot and passifying the communication network. Theoretical analyses of transparency are performed for both position and force tracking aspects. Comprehensive test results for various free and contact motions subsequently show that the proposed bilateral EBA can ensure robust stability against fairy large constant/variable round trip time delays (tested for up to 5 sec for free motion and 600 msec for contact motion within the device workspace) as well as for packet losses of up to 90 % during data transmission.

*Keywords*: Bilateral teleoperation; Data loss; Stability; Variable time delay

## 1. Introduction

In teleoperation, a human operator controls a master manipulator during interaction with a remote environment via a slave robot. Teleoperation systems then allow remote robots to conduct difficult and hazardous tasks in undersea environments, outer space, nuclear plants, micro/nano worlds, or in the medical arena. There are a number of publications related to teleoperation. For a detailed review, Refs. [1, 2] provide well-organized overviews and outline major challenges in teleoperation control.

In bilateral teleoperation systems, there are two main requirements: stability and transparency. Transparency is needed to provide a realistic feeling—as if the user is working directly at the remote site. It is also essential to ensure robust stability of the whole system regardless of human operator, sampling operation, communication channel (delay, jitter, loss), or remote environment. In these systems, the operators and remote environments are typically considered to be passive. Thus, the sampling operation and communication channel are considered as the primary sources of instability because of the inevitable time delays and data losses incurred during data transmission.

Various control strategies [2] have been proposed to deal with the time delay and data loss problems. Among them, passivity-based approaches have provided a systematic framework for analyzing complex teleoperation systems and establishing control laws. A passivity theorem is based on the input-output point of view and deals with the stability problem in both linear and nonlinear systems. Passive systems cannot generate energy, which therefore guarantees a stable behavior of those systems. Moreover, passivity can ensure stability without requiring the exact knowledge of operator and environmental models. For this reason, it has been used extensively for the analysis of coupled stability problems in robotics [3, 4], haptic [5-8] and teleoperation systems [9-24].

Anderson and Spong [9] proposed a scattering theory to maintain stability in a force-reflecting bilateral teleoperator in the presence of a constant time delay. Neimeyer and Slotine [10] (see Ref. [11] for a recent survey in wave-based teleoperation) then proposed a wave variable formulation for a constant time delay extended from the scattering theory. They defined wave variables (U and V) and transmitted these variables instead of the position/velocity or force to make the communication channel passive. However, a steady-state error was observed due to the variable time delay between the master and the slave, referred to as position drift. To cope with this problem, additional control methods such as virtual time delay,

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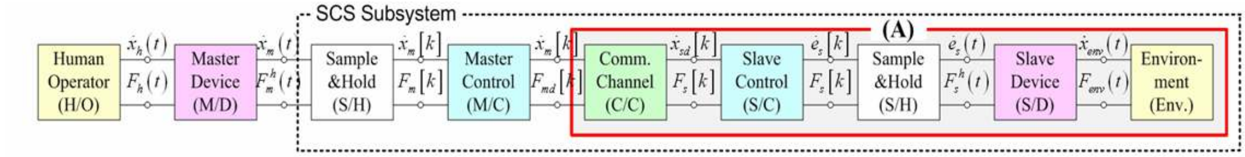
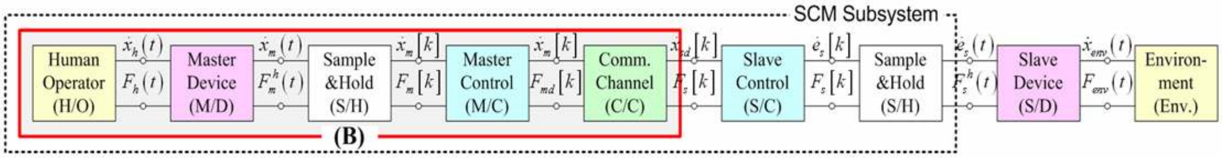



(a) Regarding the slave site as a virtual environment in haptic simulation




(b) Regarding the master site as a virtual environment in haptic simulation

Fig. 1. Network representation for bilateral teleoperation.

drift compensation, wave prediction, and explicit position data transmission through additional paths have been proposed [12-16]. A time domain passivity algorithm, initially proposed for stable haptic interactions [7] and was later extended to telepresence systems with constant time delays by Artigas et al. [17-19], ensures stability based on a passivity observer and a passivity controller. This algorithm was further extended to variable time delays by Ryu and Preusche [20]. Meanwhile, Lee and Spong [21] proposed a passive bilateral teleoperation control framework using a PD controller and a dissipative term for nonlinear robotic teleoperators with large constant time delays, which prevents position drift. Later, Nuno et al. [22] confirmed the global stability of the PD-like schemes of Lee and Spong [21].

This paper proposes an energy-bounding approach (EBA) for bilateral teleoperation systems having severe variations in time delays and data losses. The proposal is an extension of the EBA for stable haptic interactions in virtual environments [7] to bilateral teleoperation systems, since a teleoperation system can be viewed as a combination of two haptic interaction systems. The main objective of this paper is to robustly stabilize the bilateral teleoperation system with time delays by applying the EBA bilaterally. *Robust stability* means that the EBA can ensure stability of the bilateral teleoperation system regardless of the time delay magnitude and its variation, as well as packet dropouts. The basic concept and feasibility tests of the proposed bilateral EBA were presented in Refs. [23, 24] without any theoretical explanation. This paper, therefore, presents theoretical development of the control laws based on the passivity theory for the proposed bilateral EBA. Moreover, it presents theoretical analyses of transparency for both position and force tracking aspects. Finally, the paper presents comprehensive experimental results for both free and contact motions to show its effectiveness.

The remainder of this paper is organized as follows: Section 2 presents theoretical extension of the haptic EBA to bilateral teleoperation. Section 3 analyzes both position and force tracking performance. Comprehensive experimental results for teleoperation systems with significant variable time delays and data losses are then shown in Section 4. Next, Section 5 discusses a qualitative comparison with other existing research results and the performance of the proposed bilateral EBA. Finally, conclusions and future works are presented in Section 6.

## 2. EBA for bilateral teleoperation

This section presents a theoretical framework for the proposed bilateral EBA highlighting how the haptic EBA [7] can be extended to the bilateral teleoperation system for robustly stable operation. A teleoperation system is composed of a human operator, a master device, a communication block, a slave device, and a remote environment. A bilateral teleoperation system can be viewed as two separate haptic interaction systems, as shown in Fig. 1, where $x_m$, $x_s$, $F_m$, and $F_s$ are the positions and forces of the master and slave devices, respectively; $e_s$ denotes relative position between the delayed master position $x_{sd}$ and the slave position $x_s$. $F_h$ and $F_{env}$ denote the forces of a human operator and a remote environment. $F_m^h$ and $F_s^h$ are held master and slave forces passed through zero-order holder (ZOH). Looking from the master site (Fig. 1(a)), the configuration of the teleoperation system may be considered as that of a haptic interaction system [7] because the subsystem [dotted box (A)] from the communication channel to a remote environment can be regarded as a time-delayed virtual environment. In the figure, the master position $x_m$ is delivered to the slave site, and $F_{md}$ is the delayed slave force transmitted to the master. Similarly, looking from the slave site (Fig. 1(b)), on the other hand, the subsystem [dotted box (B)] may be regarded as a time-delayed virtual environment. In the figure, the slave force $F_s$ is transmitted to the master site and $x_{sd}$ is the delayed master position transmitted to the slave. Note that dotted boxes (A) and (B) are similar with the backward and forward networks in Ref. [17]. The following subsections explain the theoretical details of the two proposed EBAs.

### *2.1 Slave EBA (sEBA)*

In the case of a haptic interaction system, a human operator touches a virtual object using a haptic device. The contact force $F_{ve}$ is then determined by the penetration depth ($x_d - x_o$) in the virtual object as

$$F_{ve} = K_o\left(x_d - x_o\right) \tag{1}$$

where $K_o$, $x_d$, $x_o$ are the stiffness of a virtual object, the haptic device probe position and the virtual object position, respectively. When a fixed virtual object is touched, this penetration depth is governed only by the absolute motion of the haptic device ($x_d$) due to fixed virtual object position ($x_o$). On the other hand, when a moving virtual object is touched, the penetration depth is influenced by movements of both $x_d$ and $x_o$. In the proposed bilateral teleoperation, the master device can be considered as a virtual object that is moving relative to a slave device when viewed from the slave site. Therefore, the slave ($x_s$) and delayed master ($x_{sd}$) positions can be respectively corresponded to the positions of the haptic device and the moving virtual object in the aforementioned haptic interaction system.

Fig. 1(b) shows the typical force-position architecture (admittance display) of the haptic interaction system with a virtual environment. In this architecture, the slave force $F_s$ is transmitted to the virtual environment (dotted box B) while the delayed master position $x_{sd}$ is displayed back to the slave.

Since the admittance display requires an expensive force/torque sensor, another impedance display is used for the slave site in the proposed bilateral teleoperation. In the proposed impedance display mode, the relative position of the commanded master with respect to the actual slave position is given to a virtual environment (dotted box B) while the output force $F_s$ from a slave position controller is fed back to the slave. In this architecture, the force $F_s$ commanded to the slave site is then computed by the relative position between $x_s$ and $x_{sd}$. Note that in order to define a passivity condition, a power ($P = F \cdot v$) that is a multiplication of an effort variable (force) and a flow variable (velocity) is needed. Then, $\dot{e}_s$ ($= \dot{x}_s - \dot{x}_{sd}$) becomes a flow variable and $F_s$ becomes an effort variable in the network representation in Fig. 1(b).

Similar to the haptic EBA derivation in Ref. [7], assuming a passive remote environment, the passivity condition can then be written in terms of its relative position $e_s$ from the network representation of the bilateral teleoperation system that is composed of SCM (Sample-and-hold + master control + Communication channel + Master sites) subsystem, slave device, and remote environment in Fig. 1(b) as

$$E_{SD}\left[n\right] + \sum_{k=0}^{n-1} F_s\left[k\right]\Delta e_s\left[k+1\right] + \varepsilon_{S,0} \geq 0 \tag{2}$$

where $\varepsilon_{S,0}$ is the initially stored energy at $t = 0$ in the system and $e_s = x_s - x_{sd}$. { $e_s\left[k+1\right] - e_s\left[k\right]$ } is represented by $\Delta e_s\left[k+1\right]$ for simplicity. Note that the first term $E_{SD}\left[n\right]$ is the energy flow into the slave device over $0 \leq t < nT$ and is derived as

$$E_{SD}\left[n\right] = \int_0^{nT} \left\{F_{env}\left(t\right)\dot{x}_{env}\left(t\right) - F_s^h\left(t\right)\dot{e}_s\left(t\right)\right\}dt. \tag{3}$$

The second term in Eq. (2) is the energy flow into the one-port SCM subsystem in Fig. 1(b) over $0 \leq t < nT$ and is derived as

$$\begin{aligned} E_{SCM}\left[n\right] &= \int_0^{nT} F_s^h\left(t\right)\dot{e}_s\left(t\right)dt \\ &= \sum_{k=0}^{n-1}\left\{\int_{kT}^{(k+1)T} F_s^h\left(t\right)\dot{e}_s\left(t\right)dt\right\} \\ &= \sum_{k=0}^{n-1}\left\{F_s\left[k\right]\int_{kT}^{(k+1)T} \dot{e}_s\left(t\right)dt\right\} \\ &= \sum_{k=0}^{n-1} F_s\left[k\right]\left\{e_s\left[k+1\right] - e_s\left[k\right]\right\}. \end{aligned} \tag{4}$$

Note that $F_s\left[k\right]$ can be put outside of the integral because it is held to be a constant value over ZOH.

Both the time delays in the communication channel and the sample-and-hold operator are energy-generation factors because of their nonzero phase lag, which is the major source of energy generation in the sampled-data system. From Eq. (2), a passivity control law may be devised such that the energy dissipation capability in the slave device (i.e., in $E_{SD}$) may be utilized to consume the excessive energy that may be generated from ZOH and the communication channel. One control method is to restrict the generated energy to within the energy limit that is consumable by the slave device in order to satisfy the passivity condition in Eq. (2). Therefore, similarly to the haptic interaction control [7], the slave EBA (sEBA) has the following control and bounding laws:

**Control Law:**

$$F_s\left[k\right] = F_s\left[k-1\right] + \beta_s\left[k\right]\Delta e_s\left[k\right] \tag{5}$$

where

$$\beta_s\left[k\right] = \frac{F_{s\_desired}\left[k\right] - F_s\left[k-1\right]}{\Delta e_s\left[k\right]} \text{ for } \Delta e_s\left[k\right] \neq 0 \tag{6}$$

and $F_{s\_desired}\left[k\right]$ is an originally commanded slave force $F_s$ before applying the EBA as shown in Fig. 2.

**Bounding Laws:**

$$\text{if } \beta_s\left[k\right] > \beta_{s,\max}\left[k\right] \text{ then } \beta_s\left[k\right] = \beta_{s,\max}\left[k\right], \tag{7}$$

$$\text{if } \beta_s\left[k\right] < \beta_{s,\min}\left[k\right] \text{ then } \beta_s\left[k\right] = \beta_{s,\min}\left[k\right] \tag{8}$$

where $\beta_{s,\max}\left[k\right] = \min\left(c_{1s},\ \gamma_{s,\max}\left[k\right]\right)$ and

$\beta_{s,\min}[k]=\gamma_{s,\min}[k]$,

$$\gamma_{s,\max}[k]=c_{2s}-\frac{F_s[k-1]}{\Delta e_s[k]}+\sqrt{c_{2s}^2+\left(\frac{F_s[k-1]}{\Delta e_s[k]}\right)^2}, \quad (9)$$

$$\gamma_{s,\min}[k]=c_{2s}-\frac{F_s[k-1]}{\Delta e_s[k]}-\sqrt{c_{2s}^2+\left(\frac{F_s[k-1]}{\Delta e_s[k]}\right)^2}, \quad (10)$$

and where $c_{1s}$ and $c_{2s}$ are positive constants, details of which are in Ref. [7] and omitted in this paper.

Note that the multiplication of sampling time $T$ with $c_{1s}$ is an equivalent physical damping parameter of the slave device, as it represents the energy dissipative capability of the slave device ( $E_{SD}$ ).

### *2.2 Master EBA (mEBA)*

Fig. 1(a) shows the typical position-force architecture (impedance display) of the haptic interaction system with a virtual environment. In this architecture, the master position $x_m$ is transmitted to the virtual environment (dotted box A) while the delayed slave force $F_{md}$ is displayed back to the master. Therefore, master EBA (mEBA) in the proposed bilateral teleoperation system is exactly the same as that in a haptic simulation system. By assuming a passive human operator [25], the passivity condition can then be derived as in Ref. [7].

$$E_{MD}[n]+\sum_{k=0}^{n-1}F_m[k]\Delta x_m[k+1]+\varepsilon_{M,0}\geq 0 \quad (11)$$

where $\varepsilon_{M,0}$ is the initially stored energy at $t=0$ in the system and $\Delta x_m[k]=x_m[k+1]-x_m[k]$ . $E_{MD}[n]$ is the energy flow into the master device over $0\leq t<nT$ and is derived as

$$E_{MD}[n]=\int_0^{nT}\left\{F_h(t)\dot{x}_h(t)-F_m^h(t)\dot{x}_m(t)\right\}dt. \quad (12)$$

Similarly, the second term in Eq. (11) is the energy flow into the one-port SCS (Sample-and-hold + slave control + Communication channel + Slave sites) subsystem over $0\leq t<nT$ and is derived as

$$\begin{aligned}E_{SCS}[n]&=\int_0^{nT}F_m^h(t)\dot{x}_m(t)dt\\&=\sum_{k=0}^{n-1}\left\{\int_{kT}^{(k+1)T}F_m^h(t)\dot{x}_m(t)dt\right\}\\&=\sum_{k=0}^{n-1}\left\{F_m[k]\int_{kT}^{(k+1)T}\dot{x}_m(t)dt\right\}\\&=\sum_{k=0}^{n-1}F_m[k]\{x_m[k+1]-x_m[k]\}.\end{aligned} \quad (13)$$

Then, similar to the slave control, mEBA has the following control law:

**Control Law:**

$$F_m[k]=F_m[k-1]+\beta_m[k]\Delta x_m[k] \quad (14)$$

where

$$\beta_m[k]=\frac{F_{md}[k]-F_m[k-1]}{\Delta x_m[k]}\text{ for }\Delta x_m[k]\neq 0. \quad (15)$$

Bounding laws are similar to those in Eqs. (7)-(10) should then be applied to the master control law.

### *2.3 Comments*

Note that mEBA is exactly the same as the haptic interaction EBA in Ref. [7], and sEBA is almost the same, with only a slight modification to replace $\Delta x[k]$ with $\Delta e[k]$ . The controllers in Eqs. (5) and (6) satisfy the passivity condition of Eq. (2); likewise, the controllers in Eqs. (14) and (15) satisfy the passivity condition of Eq. (11). The detailed proofs are shown in the Appendix.

The main differences of the proposed EBAs from the existing bilateral teleoperation control algorithms are that the proposed EBAs neither feed additional damping to the system as in Ref. [21] nor monitor the energy behavior as in Refs. [17-20]. Moreover, the proposed EBAs do not transform any variables, as in Refs. [9-16]. It only restricts the excessive energy to the energy limit that can be consumed by the energy dissipation capability in the system. Moreover, it can be applied to multi degrees-of-freedom systems by implementing the EBA to each axis with the same control and bounding laws as had been discussed for haptic interaction in Ref. [8].

One important advantage of the proposed bilateral EBA is that it is robust against nonlinear communication channel characteristics because it is not dependent on the magnitude and variability of time delays or packet losses, as shown in the above equations. Thus, the proposed EBA does not need to adjust $c_1$ , $c_2$ parameters according to time delays unlike other algorithms—e.g., characteristic impedance $b$ in wave variable approach [10-16] and dissipation gain $K_d$ in Lee and Spong's framework [21]. This advantage is demonstrated in Section 4 through a series of experiments with severe time-varying delays and packet losses.

## 3. Transparency analysis of the proposed EBA

The proposed bilateral EBA always guarantees stable interaction but compromises on transparency. This is a typical and unavoidable tradeoff between stability and transparency for any control system. This section then analyzes the transparency of the proposed bilateral EBA in terms of position and force tracking responses. Transparency can be said to be per-

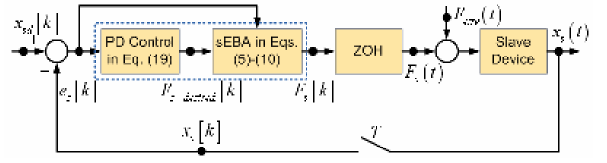



Fig. 2. Block diagram for the slave control.

fect if the impedance that is displayed to the operator side is the same as the environment impedance [26] or if both the position responses $x_m$ and $x_s$, and the force responses $f_m$ and $f_s$ are respectively identical [27].

### 3.1 Position tracking responses

Transparency in terms of the position tracking response in the slave site can be analyzed by Fig. 2.

If $\beta_s[k]$ of Eq. (6) is not bounded, then $F_s[k] = F_{s\_desired}[k]$ holds from Eqs. (5) and (6), which means that the position tracking performance is entirely governed by the PD controller. If $\beta_s[k]$ is assumed to be upper-bounded by $\beta_{s,\max}$, then from Eqs. (5) and (6),

$$F_s[k] - F_s[k-1] = \beta_{s,\max}\left\{e_s[k] - e_s[k-1]\right\}. \tag{16}$$

Then by using the z-transform,

$$\frac{F_s(z)(1-z^{-1})}{e_s(z)(1-z^{-1})} = \frac{F_s(z)}{e_s(z)} = \beta_{s,\max}. \tag{17}$$

This implies that the combination of a PD controller with sEBA creates a proportional controller (with a gain of $\beta_{s,\max}$), which may degrade the position tracking performance. In other words, the slave robot may not perfectly follow the master command in order to satisfy the passivity condition in Eq. (2).

### 3.2 Force tracking responses

Transparency in terms of the force tracking response in the master site can be analyzed as follows. If $\beta_m[k]$ of Eq. (15) is not bounded by the bounding laws, i.e., if $\beta_{m,\min} \le \beta_m \le \beta_{m,\max}$, then $F_m[k] = F_{md}[k]$ holds from Eqs. (14) and (15). This means that the force transmitted from the slave site can be transparently displayed to the human operator without any magnitude reduction by mEBA. If bounded, however, the magnitude of $F_{md}[k]$ cannot be fully displayed but is reduced to the bounded force $F_m[k]$. In this case, the amount of transparency degradation can be computed in terms of displayable impedance as

$$Z_{m,\,lost} = T\left(\beta_{m,\text{unbounded}} - \beta_{m,\max}\right) \tag{18}$$

where $Z_{m,\,lost}$ is the amount of impedance degradation when $\beta_m$ is bounded to $\beta_{m,\max}$ by mEBA, $T$ is the sampling time, $\beta_{m,\text{unbounded}}$ is the calculated $\beta_m$ from Eq. (15) before applying the bounding laws, and $\beta_{m,\max}$ is the upper bounding value of $\beta_m$.

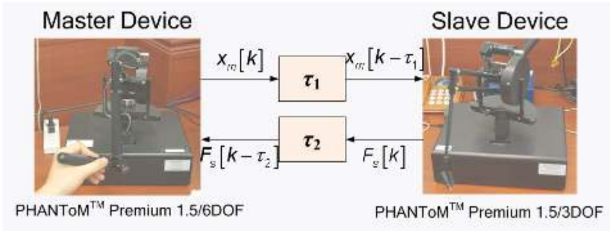



Fig. 3. Experimental setup.

Note that master site transparency may also be defined in the time-domain in terms of transient response matching. For example, the human operator may want to feel contact transients when contacting or grasping a remote object. In this case, a force magnitude reduction by the proposed mEBA might not be a significant problem as long as the reduced force magnitude can be felt by the human operator.

## 4. Experiments

In order to show the effectiveness and robustness of the proposed EBA for bilateral teleoperation having significant time delays and data losses, comprehensive experiments were conducted for motion tracking scenarios such as sinusoidal and abrupt motions in free space, as well as for rigid wall contact operation. Generally, free and contact motion tests in bilateral teleoperation are performed as benchmark tests to show performance. Ideally, in free space motion, the slave should follow the master without error, while an operator must not feel any force in free space. In contact tasks, however, the operator should feel contact forces when contacting a remote object. Several communication channels were tested for short, very long constant, and variable time delays, as well as cases of severe data loss.

The experimental setup is shown in Fig. 3. Two similar PHANToM™ devices [28] (SensAble Technologies, Inc.) were used: a PHANToM™ Premium 1.5/6DOF as a master and a PHANToM™ Premium 1.5/3DOF as a slave. In the slave site, a PD controller was used for position tracking such that

$$F_s = K_p e_s + K_d \dot{e}_s \tag{19}$$

where $K_p$ (0.05 *N/mm*) and $K_d$ (0.0001 *Ns/mm*) are the proportional and derivative gains, respectively, used in the experiments.

The same value of $c_1$ ($c_1 = 1$) was used for both $c_{1m}$ and $c_{1s}$ because the two PHANToMs were very similar; if different devices are used, different $c_{1m}$ and $c_{1s}$ values may be used. The parameter product $Tc_1$, which has the meaning of physical damping of the haptic device, $c_1$ could easily be determined through the passivity criterion $b > KT/2$ [5], where $b$ is the physical damping of the haptic device, and $K$ and $T$ are the stiffness of a virtual wall and sample period, respectively. Through the virtual wall tests, it was observed that the PHANToM device could stably simulate virtual wall stiffnesses up to 2 *N/mm* at a 1 *kHz* control rate. Therefore, the value of $c_1$ was selected to be 1 *N/mm*. Both $c_{2m}$ and $c_{2s}$ values are selected as the same value of the proportional gain ( $K_p$ ) of the PD controller in the experiments.

We then implemented the proposed bilateral EBA using Microsoft Visual C++ 6.0 in Windows XP to control the teleoperation system and simulate the time delays. Note that even when using a Windows operating system with no real-time control, the proposed EBA could robustly guarantee passivity regardless of the time delay magnitude and its variation (jitter), since time delay is not explicitly included in the control and bounding laws, nor in the proofs.

For data communication, the UDP protocol was selected and a buffer was used to simulate various time delays, which emulated possible communication scenarios. Note that in the variable delay simulation, we treated out-of-sequence (late arriving) packets as lost packets due to jitter; therefore, no packet disorder occurred. To deal with this data loss, however, data from the previous position was held until a new packet was successfully transmitted. In this paper, only representative results for severe cases are presented; for other experimental results, see previous studies [24].

### 4.1 Tracking in free motion

In the free motion tracking tests, we changed the time delays from 100 msec to 2500 msec (round trip time: 200-5000 msec), and no loss of data was considered in these experiments. The sinusoidal position histories in Fig. 4 show that the system tended to be unstable without the EBA, even for a small 100 msec constant time delay. The corresponding force histories in Fig. 4 show that the master force is saturated since the maximum force of the PHANToM is *8.5* N. Meanwhile, the EBA system in Fig. 5 displayed a stable behavior even for a larger 2500 msec variable delay. Fig. 5 also shows a distorted sine curve in the slave motion due to lost data that is lately arrived by jitter. Consequently, the slave motion is not smooth; this distortion can potentially deteriorate the operator's experience. However, stability is still sufficient, as shown in the figures.

For the free abrupt motion change responses (not shown in this paper) for variable time delays using the proposed bilateral EBA, the slave position also stably follows the master position despite the abrupt changes [24]. These results clearly show that the proposed EBA can ensure robust stability of bilateral teleoperation against significant constant or variable time delays as well as for various motion commands in free motion. In fact, the system may be stable without EBA for lower P-gain values, though it may incur bad position tracking performance. When we increase the P-gain value for better position tracking performance, the system becomes unstable unless the EBA is applied; then, stable behavior with better position tracking performance can be achieved, which has been investigated in Ref. [23].

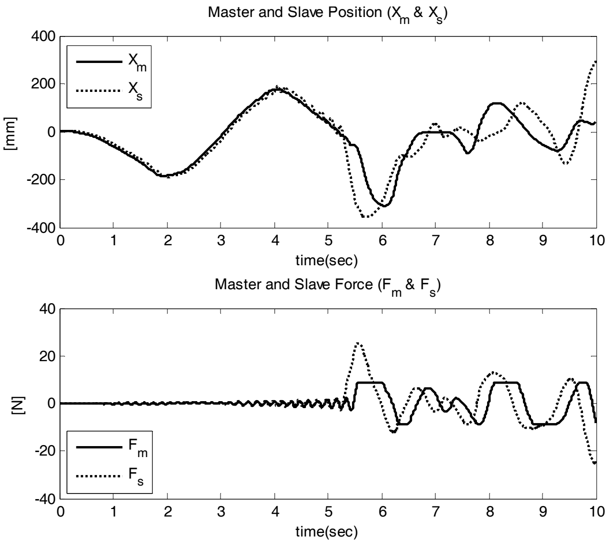



Fig. 4. Free sinusoidal motion responses for short constant time delay ( $\tau_1 = \tau_2 = 100$ *msec*) without EBA.

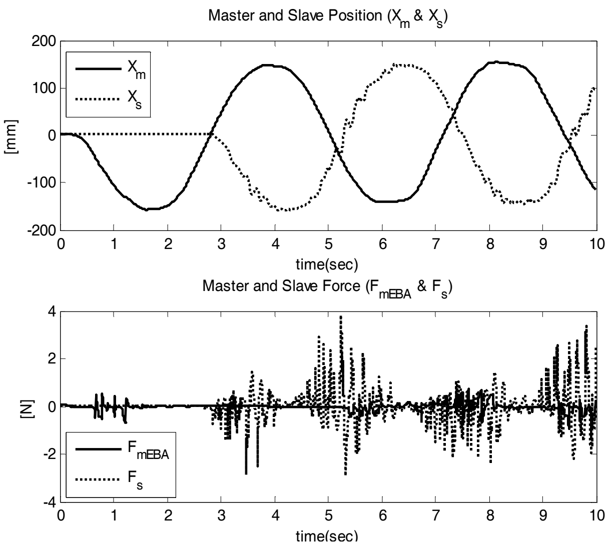



Fig. 5. Free sinusoidal motion responses for *variable(30%)* time delay ( $\tau_1 = \tau_2 = 2500$ *msec*) *with* EBA.

### 4.2 Tracking in contact motion

Experiments also investigated wall contact motions with time delays, using a steel plate (about 200 N/mm) as the wall. For a single wall contact motion without EBA, Fig. 6 shows the unstable behavior for a constant 100 msec one-way time delay. For repeated contact motions with the proposed bilateral EBA, Fig. 7 shows stable behavior even for variable 300 msec one-way time delays. Note that for time delays greater than 300 msec (round-trip of 600 msec), the operator could

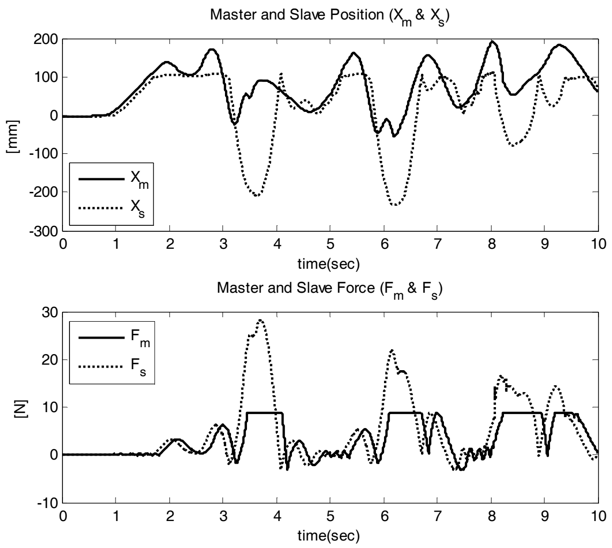



Fig. 6. Single contact motion responses *without* EBA, $\tau_1 = \tau_2 = 100$ *msec* (*constant*).

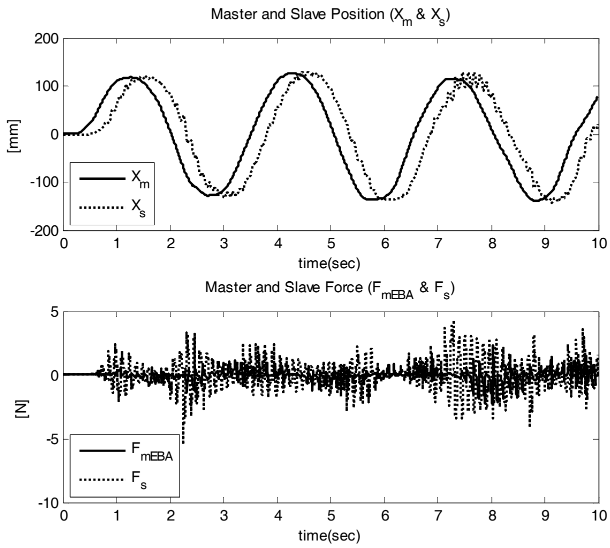



Fig. 8. Free sinusoidal motion responses for *variable* (10%) time delay ( $\tau_1 = \tau_2 = 300$ *msec*) and data loss (90%) with EBA.

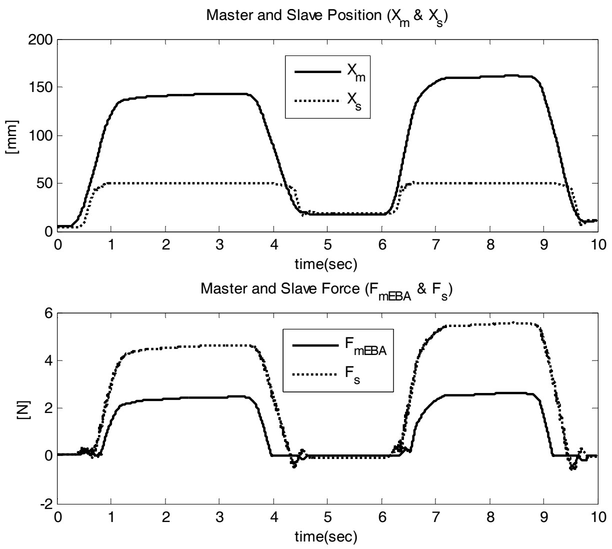



Fig. 7. Multiple contact motion responses *with* EBA $\tau_1 = \tau_2 = 300$ *msec* (*variable, 10%*).

not feel the contacted wall if he/she moved the master device relatively quickly during the time delay because the master device reached the end of the limited workspace before contact information arrived to the master. For large delays, therefore, the operator needs to manipulate slowly because contact information arrive late.

### *4.3 Data loss*

During teleoperation over some networks, some packets may occasionally be lost during data transmission [29]. To handle this loss, the strategy of holding previous data was used; if a packet was lost, the previous packet was used until new position data was delivered. In fact, a packet loss is equivalent to an increment on the sampling time. Fig. 8 shows the results for a loss rate of 90%; this rate indicates that 90% of the data was dropped, i.e., that on average, only 100 out of every 1000 packets were received at each second. However, even in a case of such severe data loss, the slave followed the master, although the transparency was somewhat lost, as was seen in more oscillations. These results show that the proposed bilateral EBA can robustly stabilize the system, even for severe data loss. For the contact cases, data losses were not considered problematic under previous data holding strategies because the position and force maintained constant values during the contact.

## 5. Discussions

### *5.1 Qualitative comparison*

A direct and quantitative comparison with other approaches is not easy because other algorithms cannot be exactly implemented within the same experimental setup. A qualitative comparison, however, may be conducted for similar kind of task scenarios. The wave variable approach generates a position drift problem in the time-varying delay cases as shown in Fig. 6(a) in Ref. [13]. In the time domain passivity algorithms, high frequency oscillation occurs in position and force histories as shown in Fig. 13 in Ref. [17] and Fig. 11 in Ref. [20] due to the activation/deactivation nature of the passivity controllers. In Lee and Spong’s framework [21], unwanted force peaks as shown in Figs. 2-4, 6 and 7 are observed before and after contact with a wall due to the added dissipation term. In order to take into account those problems, additional approaches such as a wave predictor [14, 15], drift compensation [15], or reference energy following [18], have been proposed. The experimental results of the EBA, however, show none of the aforementioned drawbacks of other approaches. Therefore, the proposed bilateral EBA does not need any additional control algorithm. However, the proposed EBA may show degradation of the position tracking performance because the slave EBA may limit the position gain as discussed in Section 3.1. Optimal gain tuning for best possible performance may be needed in future research.

### *5.2 Transparency*

As shown in the experiments, transparency may be degraded due, in part, to both the time delay and data loss. Fig. 7 shows that the magnitude of the reflected force $F_{mEBA}$ for the contact scenarios is smaller than that of the slave force $F_s$ due to the proposed energy-bounding action—a typical and unavoidable tradeoff between stability and performance. The magnitude reduction of the reflected force, however, may not be a critical factor in detecting a contact situation as long as a magnitude of about 2 N is perceivable by the human operator.

Moreover, degradation such as position trembling due to data loss can be partially overcome by using intelligent network-based transmission methods, including forward error correction (FEC) for packet loss recovery, packet reordering, and buffering for jitter. In other words, degradation can be overcome by increasing the reliability of the transmission and improving the quality of service (QoS) [29]. These efforts, however, have the effect of increasing the time delay in the viewpoint of the control because it takes time to process these additional services.

To improve transparency, the proposed bilateral EBA needs accurate information of the physical damping parameters ($c_{1m}$ and $c_{1s}$) for both the master and the slave devices. Different physical damping values may be used for dynamically dissimilar master and slave devices as well as at different poses. In any case, the larger the physical damping parameter, the better the performance in terms of stably displayable impedance range. One simple way of improving transparency is to adjust the physical damping of the master and slave systems as suggested by Refs. [30, 31].

### *5.3 Robust stability*

Other than the transparency degradation as discussed in the previous subsection, the main importance of the proposed bilateral EBA may lie in the fact that the proposed algorithm is very robust against the amount and variability of time delay and the amount of data losses in the transmitted data over the network because the proposed bilateral EBA is not dependent on those parameters. Moreover, the passivity framework guarantees passivity regardless of the human operators and types of remote environments (linear, nonlinear, time-varying etc.) as long as the remote environments are passive, because the second conditions in the master and slave EBA passify them. Therefore, the proposed bilateral EBA may be applied to many classes of remote environments.

## 6. Conclusions and future works

This paper extended the haptic EBA to bilateral teleoperation, and then confirmed its effectiveness in the sense of robust stability through a series of comprehensive experimental trials. The transparency analyses of the slave control showed that the slave might not perfectly follow the master commanded position due to the energy-bounding action. On the other hand, the transparency analyses for the master control showed that only magnitude reduction occurred when the mEBA was applied to the master force reflection. The proposed EBA ensured, however, robustly stable bilateral teleoperation for a large amount of constant/variable time delays and packet drops as well as for any passive operators and environments. Meanwhile, the proposed EBA may be conservative in terms of the stably displayable impedance range compared to other approaches. However, the transparency may be good enough to track the commanded position and feel the environments in terms of contact detection etc. as was verified by the real experimental setup. Although the proposed bilateral EBA achieved robust stability of the bilateral teleoperation system, more studies remain such as i) further improvement of transparency, ii) practical applications to stiffness discrimination or contact surface identification, and iii) scaled teleoperation.

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## Appendix

### *A.1 Proof of the master EBA for the bilateral teleoperation*

The proof of the proposed bilateral EBA for the master system is exactly the same as that of the EBA for the stable haptic interaction 0.

For the master EBA, the passivity condition in Eq. (11) can be divided into Conditions 1 and 2 as follows:

**Condition 1**:

$$E_{MD}[n]+\sum_{k=0}^{n-1}F_m[k]\Delta x_m[k+1] - \sum_{k=0}^{n-1}F_m[k+1]\Delta x_m[k+1]+\varepsilon_{MD,0}\geq 0. \tag{A.1}$$

**Condition 2**:

$$\sum_{k=0}^{n-1} F_m[k+1]\Delta x_m[k+1] + \varepsilon_{CS,0} \ge 0 \quad \text{(A.2)}$$

where $\varepsilon_{MD,0}$ is the initial energy stored in the master device and $\varepsilon_{CS,0}$ $(= F_m[0]\Delta x_m[0])$ is initial stored energy at $t=0$ in the CS (communication channel plus slave site) subsystem. $\varepsilon_{M,0} = \varepsilon_{MD,0} + \varepsilon_{CS,0}$ .

**<Proof of Condition 1>**

**Lemma I**: The inequality condition in Eq. (A.1) with the control law given by Eq. (14) can be satisfied if there exists a positive constant $c_{1m}$ such that $\beta_m[k]$ is upper bounded as $\beta_m[k] \le c_{1m}$ .

**Proof**:

By applying the control law in Eq. (14), the left-hand side of Eq. (A.1) can be rewritten as

$$\begin{aligned} & E_{MD}[n] + \sum_{k=0}^{n-1}\left(F_m[k] - F_m[k+1]\right)\Delta x_m[k+1] + \varepsilon_{MD,0} \\ & = E_{MD}[n] - \sum_{k=0}^{n-1}\beta_m[k+1]\Delta x_m^2[k+1] + \varepsilon_{MD,0}. \end{aligned} \quad \text{(A.3)}$$

If the computed $\beta_m[k]$ is chosen to be upper bounded by a positive constant parameter $c_{1m}$ $\left(c_{1m} \ge \beta_m[k+1]\right)$ for all $k$ and $n$, Eq. (A.3) can be rewritten as

$$\begin{aligned} & E_{MD}[k] - \sum_{k=0}^{n-1}\beta_m[k+1]\Delta x_m^2[k+1] + \varepsilon_{MD,0} \\ & \ge E_{MD}[k] - c_{1m}\sum_{k=0}^{n-1}\Delta x_m^2[k+1] + \varepsilon_{MD,0}. \end{aligned} \quad \text{(A.4)}$$

Therefore, in order for the right-hand side in Eq. (A.4) to be positive, $c_{1m}$ should be chosen such that

$$c_{1m} \le \left(E_{MD}[n] + \varepsilon_{MD,0}\right) \Big/ \sum_{k=0}^{n-1}\Delta x_m^2[k+1] \quad \text{for all } n. \quad \text{(A.5)}$$

Since $\left(E_{MD}[n] + \varepsilon_{MD,0}\right)$ is positive and the denominator is also positive, we can always find at least a positive constant value of $c_{1m}$ parameter for all $n$ in Eq. (A.5). ■

**<Proof of Condition 2>**

**Lemma II**: Condition 2 in Eq. (A.2) can be satisfied if the following inequality holds true:

$$F_m[k]\Delta x_m[k] \ge \frac{1}{2c_{2m}}\left\{F_m{}^2[k] - F_m{}^2[k-1]\right\} \quad \text{(A.6)}$$

where $c_{2m}$ is positive.

**Proof**:

$$\begin{aligned} & \sum_{k=0}^{n-1} F_m[k+1]\Delta x_m[k+1] + \varepsilon_{CS,0} \\ & = \sum_{k=0}^{n-1} F_m[k+1]\Delta x_m[k+1] + F_m[0]\Delta x_m[0] \\ & \ge \frac{1}{2c_{2m}}\sum_{k=0}^{n-1}\left(F_m^2[k+1] - F_m^2[k]\right) + \frac{1}{2c_{2m}}F_m^2[0] \\ & = \frac{1}{2c_{2m}}\left(F_m^2[n] - F_m^2[0]\right) + \frac{1}{2c_{2m}}F_m^2[0] \\ & = \frac{1}{2c_{2m}}F_m^2[n] \ge 0. \end{aligned} \quad \text{(A.7)}$$

■

**Lemma III**: The inequality condition in Eq. (A.6) with the control law given by Eq. (14) can be satisfied if $\beta_m[k]$ is bounded as:

$$\gamma_{m,\min}[k] \le \beta_m[k] \le \gamma_{m,\max}[k]. \quad \text{(A.8)}$$

**Proof**:

Inserting the control law in Eq. (14) into Eq. (A.6) gives

$$\begin{aligned} & \left\{F_m[k-1] + \beta_m[k]\Delta x_m[k]\right\}\Delta x_m[k] \\ & \ge \frac{1}{2c_{2m}}\left\{2F_m[k-1] + \beta_m[k]\Delta x_m[k]\right\}\beta_m[k]\Delta x_m[k]. \end{aligned} \quad \text{(A.9)}$$

Rearranging Eq. (A.9) gives the following equation:

$$\begin{aligned} & \Delta x_m^2[k]\beta_m^2[k] \\ & +2\left\{F_m[k-1]\Delta x_m[k] - c_{2m}\Delta x_m^2[k]\right\}\beta_m[k] \\ & -2c_{2m}F_m[k-1]\Delta x_m[k] \le 0. \end{aligned} \quad \text{(A.10)}$$

This can be rewritten as

$$\begin{aligned} & \beta_m^2[k] + 2\left\{\frac{F_m[k-1]}{\Delta x_m[k]} - c_{2m}\right\}\beta_m[k] \\ & \qquad - 2c_{2m}\frac{F_m[k-1]}{\Delta x_m[k]} \le 0. \end{aligned} \quad \text{(A.11)}$$

Note that $\Delta x_m[k] = 0$ , meaning no motion, makes the equality condition.

In order for Eq. (A.11) to yield real solutions for $\beta_m[k]$, the following inequality condition should be satisfied:

$$\left(\beta_m[k] - \gamma_{m,\max}[k]\right)\left(\beta_m[k] - \gamma_{m,\min}[k]\right) \le 0 \quad \text{(A.12)}$$

where

$$\gamma_{m,\max}[k] = c_{2m} - \frac{F_m[k-1]}{\Delta x_m[k]} + \sqrt{c_{2m}^2 + \left(\frac{F_m[k-1]}{\Delta x_m[k]}\right)^2}, \quad (A.13)$$

$$\gamma_{m,\min}[k] = c_{2m} - \frac{F_m[k-1]}{\Delta x_m[k]} - \sqrt{c_{2m}^2 + \left(\frac{F_m[k-1]}{\Delta x_m[k]}\right)^2}. \quad (A.14)$$

■

Both Condition 1 and Condition 2 are, therefore, satisfied if

$$\beta_{m,\min}[k] \le \beta_m[k] \le \beta_{m,\max}[k] \quad (A.15)$$

where

$$\begin{aligned}\beta_{m,\max}[k] &= \min\left(c_{1m},\ \gamma_{m,\max}[k]\right),\\ \beta_{m,\min}[k] &= \gamma_{m,\min}[k].\end{aligned} \quad (A.16)$$

### *A.2 Proof of the slave EBA for the bilateral teleoperation*

Similarly, for the slave EBA, Conditions 1 and 2 are obtained from Eq. (2) as follows:

**Condition 1**:

$$\begin{aligned}E_{SD}[k] &+ \sum_{k=0}^{n-1} F_s[k]\Delta e_s[k+1]\\ &- \sum_{k=0}^{n-1} F_s[k+1]\Delta e_s[k+1] + \varepsilon_{SD,0} \ge 0.\end{aligned} \quad (A.17)$$

**Condition 2**:

$$\sum_{k=0}^{n-1} F_s[k+1]\Delta e_s[k+1] + \varepsilon_{CM,0} \ge 0 \quad (A.18)$$

where

$$\begin{aligned}e_s[k] &= x_s[k] - x_{sd}[k],\\ \Delta e_s[k] &= e_s[k] - e_s[k-1]\end{aligned} \quad (A.19)$$

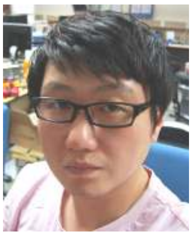
$\varepsilon_{SD,0}$ is the initial energy stored in the slave device and $\varepsilon_{CM,0}$ ($= F_s[0]\Delta e_s[0]$) is initial stored energy at $t = 0$ in the CM (communication channel plus master site) subsystem. $\varepsilon_{S,0} = \varepsilon_{SD,0} + \varepsilon_{CM,0}$.

The proof procedure is exactly the same as in the master EBA except that $F_s$ and $\Delta e_s$ are used instead of $F_m$ and $\Delta x_m$, respectively.

In summary, a positive constant parameter $c_{1s}$ can be selected as follows:

$$\left(P_{SD}[n] + \varepsilon_{SD,0}\right) \Big/ \sum_{k=0}^{n-1} \Delta e_s^2[k+1] \ge c_{1s}. \quad (A.20)$$

■



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