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Improving Force Feedback Fidelity in Wave-Variable-Based Teleoperation

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***Abstract*— In wave-variable-based teleoperation systems, the perceived force at the master side is biased due to the nature of wave-variable-based communication. This paper proposes an augmented wave-variable-based approach that can partially cancel the bias portion and improve the fidelity of force feedback significantly. In this approach, the returning wave is augmented by the velocities of the both sides of the communication channel. The steady-state position tracking is not affected by the modification. Passivity of the new teleoperation scheme can be obtained by tuning the bandwidth of a low-pass filter. Hence stability is always achievable. Simulation results demonstrate the effectiveness of the scheme.**

I. INTRODUCTION

Teleoperation is to extend a person's sensing and manipulation capabilities and has led to applications ranging from space and undersea exploration, handling of hazardous materials, high-precision assembly, and tele-surgery [1]. A typical teleoperation system consists of a master (such as a robotic arm or a joystick), a slave manipulator, and a communication channel between them. The master is moved by the human operator, and the slave is commanded to follow the motion of the master. In bilateral teleoperators, forces from the slave side are fed back through the communication channel to the master to provide the operator with haptic information, thereby improve the operator's ability to perform complex tasks [2].

Force reflection in bilateral teleoperation systems often faces a key challenge: the force feedback forms a closed-loop in the presence of communication delay. The system is very sensitive to delays. Small amounts of time delays can drive a force feedback loop unstable and make force feedback impossible without compensation [3]. Several approaches have been proposed to deal with this problem, including scattering theory [4] or wave variable encoding [5], remote compliance control [6], controller passivity [7], and small-gain based approaches [8], [9], etc. Among them, the framework of wave variable has a clear description of power flow as well as signal flow [10]. Moreover, it is robust to delays of any magnitude. For small delays, the system is transparent; for zero delay, the system reverts to a classic teleoperator configuration [5].

But the wave-variable-based communication channel automatically brings in a transient bias term in the force reflection from slave to master. The bias term is determined by the difference between the velocities at the both sides of the communication channel. Moreover, it can be derived that the bias term contains only non-dc components and is transient. Hence it does not affect the force feedback at steady state. However, it is noted that humans are sensitive to forces over a very wide range of frequencies [11]. Therefore the transient bias term may affect the user's feeling significantly. In medical applications like tele-palpation, highly authentic force reflection is required. For the user to perceive a highly authentic force feedback, this bias term should be removed. This paper proposes a method to remove part of the bias term. The adjustment action is performed in the wave loop so that the inserted energy caused by the augmentation can be removed simply by low-pass filtering. Hence stability can be achieved. Meanwhile, zero tracking error at steady state is preserved.

Simulation is performed. The augmented wave communication channel transmits the slave controller force back to the master with high fidelity in both free motion case and hard contact case. The position tracking is unaffected by the augmentation.

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II. BACKGROUND

A. Wave Encoding and Passivity

The wave encoding mechanism defines a complementary pair of wave variables (u, v) in term of the standard power variables $(\dot{x}, F)$ as follows [5],

$$u = \frac{1}{\sqrt{2b}}(b\dot{x} + F) \qquad v = \frac{1}{\sqrt{2b}}(b\dot{x} - F) \tag{1}$$

where u is the forward wave traveling from master to slave, v is the returning wave traveling from slave to master, and b is the wave impedance. Through the wave transformation, the power flow

$$P = \dot{x}^{\mathrm{T}}F = \frac{1}{2}u^{\mathrm{T}}u - \frac{1}{2}v^{\mathrm{T}}v \tag{2}$$

is separated into independent forward and reverse power flows.

Supposing an element in the wave space whose input is u_{in} and output is u_{out}, the passivity is satisfied if

$$\int_0^t \frac{1}{2}u_{out}^{\mathrm{T}}u_{out}d\tau \leq \int_0^t \frac{1}{2}u_{in}^{\mathrm{T}}u_{in}d\tau + E_{store}(0) \quad \forall t \geq 0. \tag{3}$$

In other words, if the magnitude of the transfer function of the element is no more than unit, passivity is assured [5].

In teleoperation, the system is often viewed as a chain of passive two-port elements where passivity is preserved upon concatenation [10]. This passivity analysis approach often renders the system overly conservative [10]. Recent

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results allow active elements in the system. In [12], [13], the activeness is measured and compensated for to keep the overall system passive. Since the wave's control loop is insensitive to time delay or phase lag, active behavior can be easily compensated for by appropriate attenuation, using low-pass filters in the wave's control loop as an energy dissipation tool [10]. Since the magnitude of a simple first-order linear filter $G(s) = \frac{\lambda}{s+\lambda}$ is at or below unity for all frequencies, $G(s)$ is guaranteed to be passive and dissipates energy at frequencies above the cutoff frequency [10]. Hence first-order linear filters are often used to ensure stability in teleoperation.

B. Wave-Variable-Based Teleoperation

A standard waved-variable-based teleoperation system is depicted in Fig. 1. The low-pass filter $\frac{\lambda}{s+\lambda}$ is imposed on the

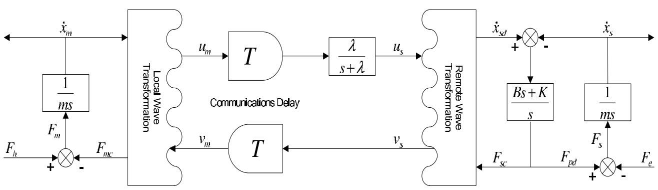


Fig. 1. A standard wave-variable-based teleoperator with a forward wave filter.

right-moving wave variable to reduce oscillations caused by the wave reflections [5]. Moreover, it can smooth out noise introduced during the transmission.

The wave variables are transmitted across the communication channel, as depicted in Fig. 1. In addition, the left-moving variable is low-pass filtered. The passivity of the communication channel is preserved as [14]

$$\int_0^t \frac{1}{2}u_s^{\mathrm{T}}u_s + \frac{1}{2}v_m^{\mathrm{T}}v_m d\tau \leq \int_0^t \frac{1}{2}u_m^{\mathrm{T}}u_m + \frac{1}{2}v_s^{\mathrm{T}}v_s d\tau + E_{store}(0) \quad \forall t \geq 0. \tag{4}$$

Hence stability can always be guaranteed, insensitive to communication delay.

The transmission is governed by

$$u_s(t) = L^{-1}(\frac{\lambda}{s+\lambda}) \otimes u_m(t-T) \tag{5}$$

$$v_m(t) = v_s(t-T), \tag{6}$$

where L^{-1} denotes the Inverse Laplace Transform and $\otimes$ denotes convolution. Using the wave encoding mechanism (1) in the wave transmission equations (5) and (6), the wave transmission equations can be written in the traditional power variables as [15]

$$\dot{x}_{sd}(t) = L^{-1}(\frac{\lambda}{s+\lambda}) \otimes \dot{x}_m(t-T) - \frac{1}{b}[F_{sc}(t) - L^{-1}(\frac{\lambda}{s+\lambda}) \otimes F_{mc}(t-T)] \tag{7}$$

$$F_{mc}(t) = F_{sc}(t-T) + b[\dot{x}_m(t) - \dot{x}_{sd}(t-T)]. \tag{8}$$

III. CANCELING TRANSIENT BIAS IN FORCE REFLECTION

The standard non-wave communication procedure is given by

$$\dot{x}_{sd}(t) = \dot{x}_m(t-T) \tag{9}$$

$$F_{mc}(t) = F_{sc}(t-T). \tag{10}$$

The force transmission (10) is ideal because it replicates the slave driving force exactly to the master side. While in (8), F_{mc} is the perceived force at the master side. Comparison of (10) and (8) indicates that the second term in the right hand side of (8), $b[\dot{x}_m(t) - \dot{x}_{sd}(t-T)]$, is a bias term. This bias term is transient, as at steady state, $\dot{x}_m(t) = \dot{x}_{sd}(t-T)$ can be derived by solving the steady state solution of (7) and (8). The effect of the bias term is two-sided. On the positive side, this term together with the second term in the right-hand-side of the velocity transmission equation (7) makes the communication channel passive. On the negative side, the bias term degrades the fidelity of force feedback. To improve the fidelity of force feedback, this bias term should be better removed.

To formalize the stability arguments, we proposed to cancel the bias in the wave variable loop. Our scheme can be depicted by Fig. 2. The configuration is similar to the

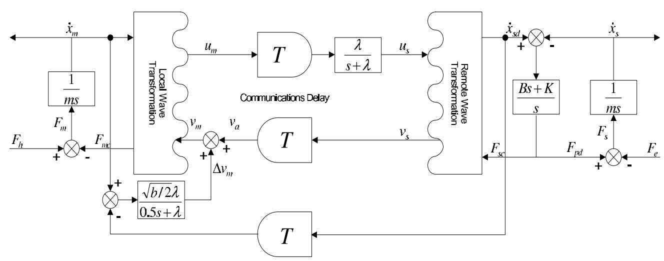


Fig. 2. An augmented wave-variable-based teleoperator with fore feedback bias partially canceled.

high-frequency force feedback in [10]. But the motivation is totally different. Actually these two approaches can be combined to further improve perception in time-delayed telerobotics. The additional path will inevitably insert energy, and may violate the passivity of the whole system, leading to possible instability. To limit the energy inserted, a low-pass filter $\frac{\lambda}{0.5s+\lambda}$ is added on the augmenting path. Note that the bandwidth of the canceling effort (2λ) is double of that of the left-moving wave variable. The bias term can now be partially canceled, i.e., the low frequency portion of the bias is removed, and the force transmission equation becomes,

$$F_{mc}(t) = F_{sc}(t-T) + bL^{-1}(\frac{s}{0.5s+\lambda}) \otimes [\dot{x}_m(t) - \dot{x}_{sd}(t-T)]. \tag{11}$$

Note that the high frequency portion of the bias is left untouched. While the velocity transmission equation (7) is not altered.

Remark A close examination of (8), (10), and (11) indicants that the augmented communication channel is essentially an in-between scheme of the standard communication channel and the wave-variable-based communication channel. The force feedback of the standard communication procedure is 100% authentic. But the standard communication is not passive. The wave-variable-based communication channel is passive; but its force feedback is biased. The proposed method cancel part of the bias term to improve the force feedback fidelity; while it maintains stability by utilizing the dissipative nature of low-pass filtering to dissipate the added energy.

A. Stability Analysis

The add-on term Δv_m is

$$\Delta v_m(t) = \sqrt{\frac{b}{2}}L^{-1}(\frac{\lambda}{0.5s+\lambda})\otimes[\dot{x}_m(t)-\dot{x}_{sd}(t-T)]. \quad (12)$$

Since

$$\dot{x}_m(t) = [u_m(t)+v_m(t)]/\sqrt{2b}, \quad (13)$$

and

$$\dot{x}_{sd}(t-T) = [u_s(t-T)+v_s(t-T)]/\sqrt{2b}, \quad (14)$$

(12) can be written as

$$\Delta v_m(t)=L^{-1}(\frac{\lambda}{s+2\lambda})\otimes[u_m(t)+v_m(t)-u_s(t-T)-v_s(t-T)]. \quad (15)$$

On the other hands, there exists the equation

$$, \quad (16)$$

where $v_a(t) = v_s(t-T)$. Substituting (15) into (16), one can have

$$v_m(t) = v_s(t-T)+L^{-1}(\frac{\lambda}{s+\lambda})\otimes[u_m(t)-u_s(t-T)]. \quad (17)$$

From (17) and (16), it is straightforward that

$$\Delta v_m(t) = L^{-1}(\frac{\lambda}{s+\lambda})\otimes[u_m(t)-u_s(t-T)], \quad (18)$$

which is another form of the add-on term Δv_m. Therefore, Fig. 2 can be drawn alternatively as Fig. 3.

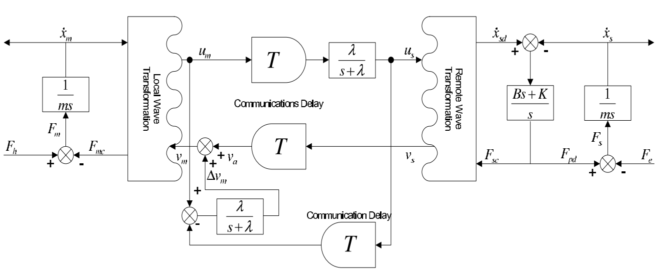


Fig. 3. Alternative configuration for partially canceling fore feedback bias.

Supposing the slave and the environment are both passive, the serial connection of the slave and environment is also passive. By examining the power flow at the port of (u_s, v_s), it can be concluded that the magnitude of the Laplace Transform of v_s/u_s is no more than 1, i.e.,

$$|V_s(s)/U_s(s)| \triangleq |\varepsilon| \leq 1. \quad (19)$$

By examining the power flow ratio at the port of (u_m, v_m),

$$|V_m(s)/U_m(s)| = |\frac{V_m(s)}{e^{sT}\frac{s+\lambda}{\lambda}U_s(s)}|. \quad (20)$$

From (17) and the definition of ε, (20) becomes

$$|V_m(s)/U_m(s)| = \left|\frac{\lambda}{s+\lambda}(\varepsilon-\frac{\lambda}{s+\lambda}+e^{2sT})\right|, \quad (21)$$

noting $|e^{sT}|$=1. Since the dc value of $|(\varepsilon-\frac{\lambda}{s+\lambda}+e^{2sT})|$ is $|\varepsilon|$ which is no more than 1 and the non-dc peak value is less than 3, one can always find a λ (low enough) to make $|V_m(s)/U_m(s)| \leq 1$. In other words, passivity can always be achieved by low-pass filtering for any ε and T. In turn, stability can always be guaranteed by tuning λ.

B. Steady State Tracking

The master position and the desired slave position can be computed as

$$x_m(t) = \frac{1}{\sqrt{2b}}\int_0^t u_m(\tau)+v_m(\tau)d\tau, \quad (22)$$

and

$$x_{sd}(t) = \frac{1}{\sqrt{2b}}\int_0^t u_s(\tau)+v_s(\tau)d\tau. \quad (23)$$

Similar to the derivation in [5], the position difference between the two sides of the communications can be obtained as,

$$\begin{aligned}
\Delta x(t) &= x_m(t)-x_{sd}(t)\\
&= \frac{1}{\sqrt{2b}}\int_0^t u_m(\tau)+v_m(\tau)-u_s(\tau)-v_s(\tau)d\tau\\
&= \frac{1}{\sqrt{2b}}\int_0^t u_m(\tau)+v_s(\tau-T)\\
&\quad +L^{-1}(\frac{\lambda}{s+\lambda})\otimes[u_m(\tau)-u_s(\tau-T)]\\
&\quad -L^{-1}(\frac{\lambda}{s+\lambda})\otimes u_m(\tau-T)-v_s(\tau)d\tau\\
&= \frac{1}{\sqrt{2b}}\int_{t-T}^t u_m(\tau)-v_s(\tau)d\tau+\frac{1}{\sqrt{2b}}\int_0^t\frac{1}{\lambda}\dot{u}_s(\tau)d\tau\\
&\quad +\frac{1}{\sqrt{2b}}\int_0^t L^{-1}(\frac{\lambda}{s+\lambda})\otimes[u_m(\tau)-u_m(\tau-2T)]d\tau\\
&\quad +\frac{1}{\sqrt{2b}}\int_0^t\frac{1}{\lambda}L^{-1}(\frac{\lambda}{s+\lambda})\otimes\dot{u}_s(\tau-T)d\tau. \quad (24)
\end{aligned}$$

Denoting

$$L^{-1}(\frac{\lambda}{s+\lambda})\otimes u_{m,s}(\tau) = u'_{m,s}(\tau), \quad (25)$$

(24) can be simplified as

$$\begin{aligned}
\Delta x(t) &= \frac{1}{\sqrt{2b}}\int_{t-T}^t u_m(\tau)-v_s(\tau)d\tau+\frac{1}{\sqrt{2b}\lambda}u_s(t)\\
&\quad +\frac{1}{\sqrt{2b}}\int_0^t[u'_m(\tau)-u'_m(\tau-2T)]d\tau\\
&\quad +\frac{1}{\sqrt{2b}\lambda}\int_0^t\dot{u}'_s(\tau-T)d\tau\\
&= \frac{1}{\sqrt{2b}}\int_{t-T}^t u_m(\tau)-v_s(\tau)d\tau+\frac{1}{\sqrt{2b}\lambda}u_s(t)\\
&\quad +\frac{1}{\sqrt{2b}}\int_{t-2T}^t u'_m(\tau)d\tau+\frac{1}{\sqrt{2b}\lambda}u'_s(t-T). \quad (26)
\end{aligned}$$

TABLE I
PARAMETERS AND GAINS USED IN SIMULATIONS.

	Value		Value		Value
T	100ms or 1s	λ	30rad/s	K_e	5000N/m
m	0.1kg	K	370N/m	B_e	5Ns/m
b	2.5Ns/m	B	2.5Ns/m		

In steady state, when the wave signals decay to zero without any velocity or force inputs ($u_m^{'}(t)$ and $u_s^{'}(t)$ also decay to zero), the position error is zero. Hence the modification of the communication channel does not alter the desired slave position which exactly equals the master location.

IV. SIMULATION

The simulation parameter are the same as those in [10] except that two one-way time delay T (0.1s and 1s) are tried. The model of the human operator in [7] is adopted where the human operator is modeled as a PD-type position tracking controller (i.e., spring and damper) with its spring and damper gains as 75N/m and 50Ns/m. The sampling rate is 1KHz. For clarity, the position signal at the master side and the force signal at the slave side have been shifted backward by the time delay so that the signals at both sides can be viewed synchronously. The conventional wave-variable-based approach and the augmented approach are tested and compared. In all the figures, the solid curves are for position and force signals at the master side and the dash curves are for position and force signals at the slave side.

A. Small Delay

The one-way communication delay T is 100ms.

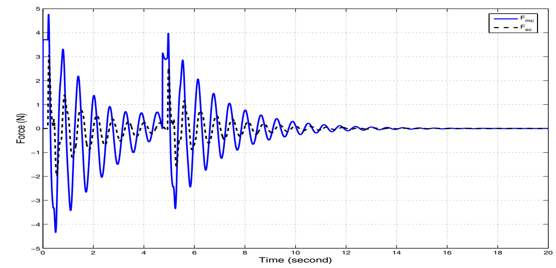
1) Free Space Motion: The master and slave both move in free space. The force perceived by the master F_{mc} and the slave driving force F_{sc} are illustrated in Fig. 4. It is seen from Fig. 4(a) that F_{sc} and F_{mc} have substantial differences under the conventional wave-variable-based teleoperation. Fig. 4(b) shows the performance under the augmented wave-variable-based communication configuration. Now the differences between F_{sc} and F_{mc} are minor which means the communication channel provides an authentic force feedback path.

2) Contact Performance: When $x_s = 1$, the slave makes contact with a hard surface represented by stiffness K_e and damping B_e in Table I. Under the conventional wave-variable-based communication configuration, the force perceived by the master F_{mc} and the slave driving force F_{sc} are illustrated in Fig. 5(a). Fig. 5(b) shows the performance under the augmented wave communication configuration. Now F_{sc} and F_{mc} have only sight high frequency (i.e. spikes) differences which means high fidelity of force transmission is achieved.

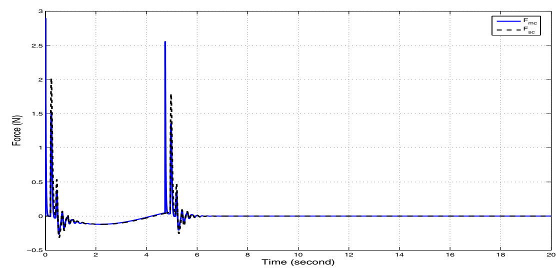
Fig. (6) shows the tracking ability of the augmented approach in both free space motion and hard contact cases. Steady state tracking ability is preserved.

B. Large Delay

The one-way communication delay T is 1s.

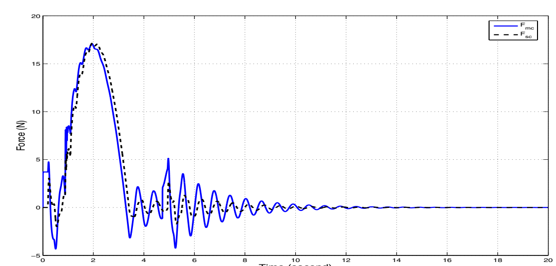


(a) Force reflection without augmentation.

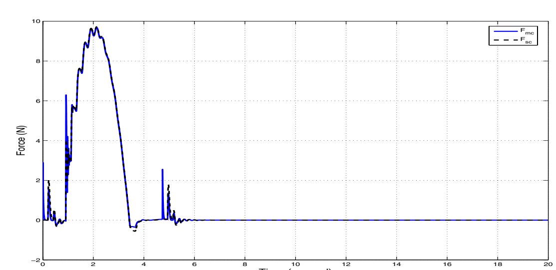


(b) Force reflection with augmentation.

Fig. 4. Comparison of force transmission fidelity (free space, small delay).

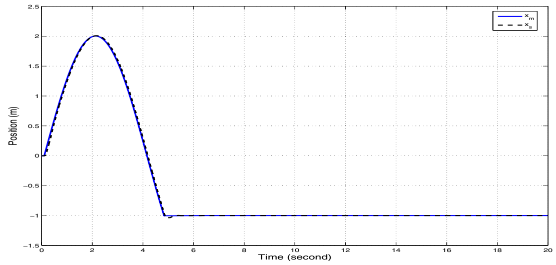


(a) Force reflection without augmentation.

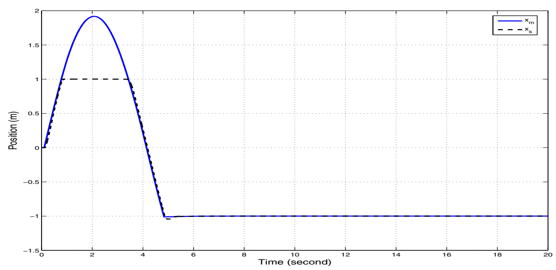


(b) Force reflection with augmentation.

Fig. 5. Comparison of force transmission fidelity (hard contact, small delay).

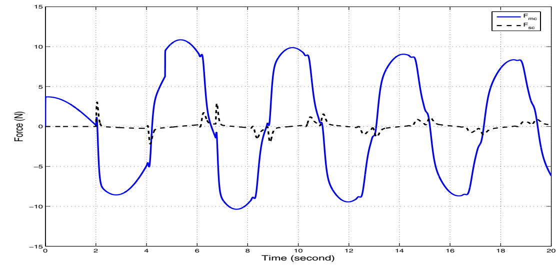


(a) Motion of master and slave (free space).

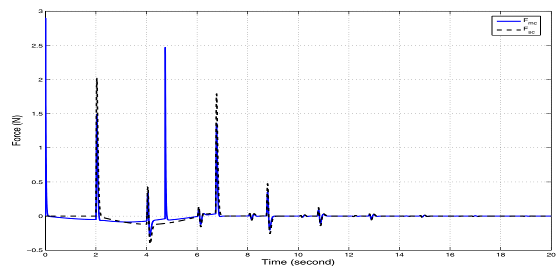


(b) Motion of master and slave (hard contact).

Fig. 6. Tracking ability of the augmented approach (small delay).

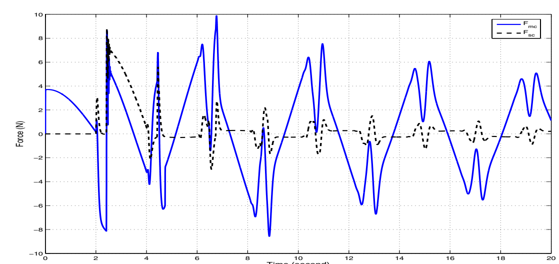


(a) Force reflection without augmentation.

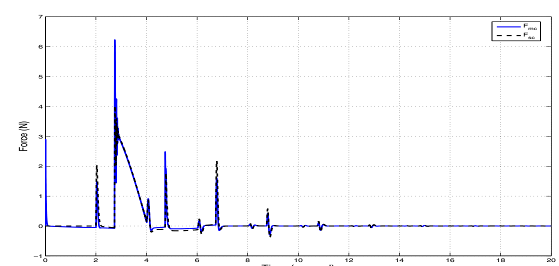


(b) Force reflection with augmentation.

Fig. 7. Comparison of force transmission fidelity (free space, large delay).



(a) Force reflection without augmentation.



(b) Force reflection with augmentation.

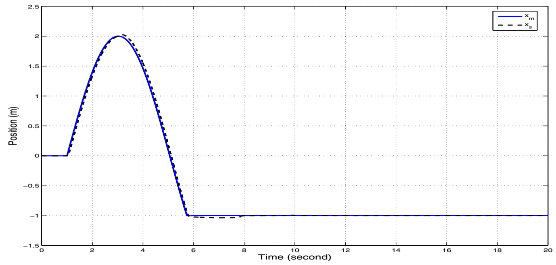
Fig. 8. Comparison of force transmission fidelity (hard contact, large delay).

Fig. 3 indicates that, if the delay is not trivial, intuitively $u_m(t) - u_s(t-T)$ may also be nontrivial. In turn, from (18), $\Delta v_m(t)$ may be significant. In other words, the effect of the augmentation may be prominent. The following simulations verify the estimation. The same tests (with the same motion/contact) are performed. Fig. 7 and Fig. 8 compare the fidelity of the force transmission with and without augmentation. In both free space case and hard contact case, the force feedback bias of the wave communication channel is much more severe than its counterpart with small delay. Actually the bias is so large that perceived force is totally distorted. Nevertheless the augmented wave communication channel effectively cancels most of the bias. Fig. (9) shows that steady state tracking is unaffected by the augmentation in both free space and hard contact cases.

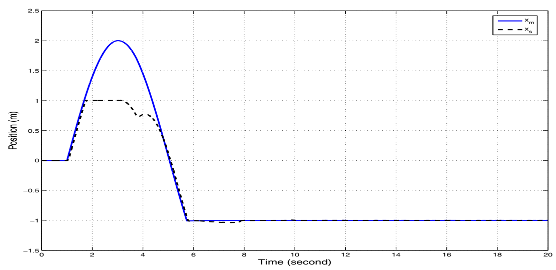
With both small delay and large delay, the teleoperation system runs stably with the augmented wave communication channel in both free space motion and hard contact cases.

V. CONCLUSION

In wave-variable-based teleoperation systems, the force feedback is biased by a transient term. For high fidelity force feedback, an augmented approach is proposed. The augmented communication channel is in essence a scheme in-between the standard communication channel and the wave-variable-based communication channel. After partially canceling the bias term, the force feedback fidelity is significantly improved. Stability is preserved by low-pass filtering.



(a) Motion of master and slave (free space).



(b) Motion of master and slave (hard contact).

Fig. 9. Tracking ability of the augmented approach (large delay).

Steady-state tracking is not affected. Simulation verifies the effectiveness of the scheme in both free space motion and hard contact cases.

VI. ACKNOWLEDGMENTS

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