Robotica (2011) volume 29, pp. 863–871. © Cambridge University Press 2011
doi:10.1017/S0263574711000075

Trajectory tracking compensation for teleoperation with transmission delays

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(Received in Final Form: January 25, 2011. First published online: February 25, 2011)

SUMMARY

The proper transmission of wave variables rather than power variables in teleoperation with time delays ensures system passivity – rendering the entire system stable, but the introduction of wave variables leads to distortion between the velocities/positions of the master and slave, and the performance deteriorates significantly with the increase of time delays. This paper presents a new compensating scheme implemented at the slave side to remove or cancel partially the distortion. The system passivity can still be maintained by tuning a properly designed low-pass filter. Compared with previous work, the main contribution of this work exists in two points: first, it is the actual velocity/trajectory of the slave rather than the reference velocity/trajectory of the slave that tracks the master one, so the quality of tracking is better and converges faster; second, the proposed compensator does not require any additional signal from the master side, minimizing the amount of data transmitted over the channel, which is very important from the practical point of view. The simulation and experiment results show that the velocity (or trajectory) tracking is significantly improved under the condition of stability, and the force presented to the user is close to the environment one, meaning a high degree of system transparency is achieved.

KEYWORDS: Teleoperator; Time delay; Trajectory tracking; Wave variable.

1. Introduction

In a teleoperation system, a human operator (the user) interacts with the remote environment through a master–slave teleoperator. For a bilateral teleoperator, the operator commands the motion of a remote slave robot via a local master robot (or similar device), and the interaction force between the slave robot and the environment is fed back and presented to the user through the teleoperator system, giving the user a feeling of the remote interaction and improving his or her ability to perform complex tasks if the system is properly designed. Teleoperation has extensive applications ranging from space-based robotics to micro-telesurgery.[1–3]

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It is well recognized, however, that the existence of time delays in the communication channel causes the system unstable in the force-reflecting teleoperation systems. Anderson and Spong[4] put forward a well-known solution based on the scatter theory. They argued that the instability in bilateral teleoperation was due to a not-passive communication channel. The idea was further developed into the wave-variable-based approach by Niemeyer and Slotine.[5] Since then a few different solutions have been proposed, including the shared compliant control approach,[6] H^{∞} - optimal control and μ-synthesis techniques,[7] adaptive robust controller,[8] predictive control,[9] supervisory control,[10] and small-gain theory.[11,12]

Among all the above different ideas, the approaches based on wave communication attracts the widest attention for its simplicity and clear description of physical signal flows.[13–15] While system stability can be well guaranteed, an inherited problem for the wave-variable-based approaches is the departure between the master and slave trajectories because of a bias term introduced by the wave transmission. It is well proved that this distortion makes the system performance deteriorate significantly with the increase of time delays. While the low performance in trajectory tracking may not be a big problem for some applications, it is unacceptable for many new applications, such as remote telesurgery.[10] In order to improve trajectory tracking in wave-variable-based teleoperation, Ye and Liu[16] developed a new augmented scheme to remove the distortion because of the bias term introduced by the wave transmission by adding a correction term on the right moving wave path. Inspired mainly by the ideas presented in ref. [16], this paper proposes a new compensating method, which is implemented at the slave side to remove the bias term introduced by the wave communication because of time delays in order to improve trajectory tracking. Compared with the work[16] and previous similar work, the main contributions of this work exists in the following two facts: (1) The actual velocity/trajectory of the slave tracks the master velocity/trajectory directly in this work, while it is the reference velocity/trajectory of the slave that tracks the master one in ref. [16] and similar work. As a result, the tracking of trajectory/velocity in this paper converges faster and the quality of tracking is better; (2) the proposed compensating scheme does not require any additional signal from the master side, minimizing signal

https://doi.org/10.1017/S0263574711000075 Published online by Cambridge University Press

transmission over the channel and the effects because of transmission delays, which is very important from the point of view of real applications.

The rest of the paper is organized as follows. Section 2 gives a brief introduction to the main idea of wave-variable-based teleoperation and Section 3 defines the bias term. The developed compensating scheme is given in detail in Section 4. The simulation results and experiment results are discussed in Sections 5 and 6. Section 7 concludes the paper with some recommendations for future work.

2. Background on Wave-Variable-Based Teleoperation

Notation: For one variable, it is expressed using a low-case letter in the time t domain while the capitalized one means the counterpart in the complex frequency s domain.

2.1. Passivity theory

Define the power P entering a system as the scalar product between the input vector x and the output vector y of the system. The system is said to be passive, if it obeys

$$\int_0^t P d\tau = \int_0^t x^T y d\tau = \int_0^t \left(\frac{d}{d\tau}E + P_{diss}\right)d\tau = E(t) - E(0) + \int_0^t P_{diss} d\tau \geq -E(0) = \text{constant}, \tag{1}$$

where, E is a lower-bounded "energy storage function" and P_{diss} is a non-negative "power dissipation" function.

If the power dissipation is zero for all time, the system is passive, and it is also termed lossless. If the power dissipation is positive, the system is strictly passive.

A significant practical feature of passivity formulation is its closure property, which implies that the combination of two or more passive systems connected in either a feedback or parallel form is still passive.

2.2. Wave communication ensures system stability

It is well illustrated that the communication subsystem with time delays will generate energy rather than dissipate energy by specific choices of the input variables – the speed of the master manipulator $\dot{x}_m$ and the force reflection from the slave f_s. Hence, the communication subsystem is not passive and it would affect the stability of the whole system.

By introducing the wave transformation given by ref. [5], the input wave variable u and output wave variable v are related to the power variables (velocity $\dot{x}$ and force f) as follows:

$$u = \frac{b\dot{x} + f}{\sqrt{2b}}, \quad v = \frac{b\dot{x} - f}{\sqrt{2b}}.$$

The wave-variable communication is shown as Fig. 1,

$$u_s(t) = u_m(t - T), \quad v_m(t) = v_s(t - T), \tag{2}$$

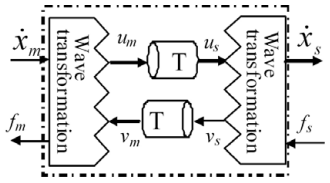


Fig. 1. Communication with wave variables.

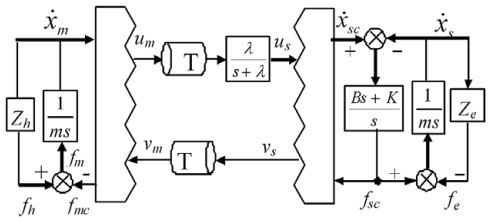


Fig. 2. Wave-variable teleoperator with a forward wave filter.

where, the subscripts s and m in Eq. (2) mean the master and the slave, respectively, and T is a constant one-way transmission delay through the communication channel.

The power flow into the communication channel expressed in terms of wave variables can be determined by

$$\begin{aligned} P &= \dot{x}_m(t) f_m(t) - \dot{x}_s(t) f_s(t) \\ &= \frac{1}{2}u_m(t)^2 - \frac{1}{2}v_s(t-T)^2 + \frac{1}{2}v_s(t)^2 - \frac{1}{2}u_m(t-T)^2 \\ &= \frac{d}{dt}\int_{t-T}^{t}\left[\frac{1}{2}u_m(\tau)^2 + \frac{1}{2}v_s(\tau)^2\right]d\tau. \end{aligned}$$

According to Eq. (1), if we define the stored energy E as

$$E = E(t) - E(0) = \int_{t-T}^{t}\left[\frac{1}{2}u_m(\tau)^2 + \frac{1}{2}v_s(\tau)^2\right],$$

then $P_{\text{diss}} = 0$. In other words, the communication channel under a constant time delay T is made passive if wave variables rather than power variables are communicated over the delayed channel. Accordingly, the entire system is passive, meaning the system is stable.[4,5] The simplicity and easy to maintain system passivity is the reason that the wave communication attracts the wide attention including us.

3. Trajectory Distortion in Wave-Variable-Based Teleoperator

Niemeyer[17] has demonstrated that the wave filter was necessary for the wave communication and the filter would not affect the system passivity. The model for the wave-variable-based teleoperator with a forward filter is shown as Fig. 2.

The human operator applies force f_h on the master, driving the master to move with the velocity $\dot{x}_m$. The wave transformation encodes a velocity command $\dot{x}_m$ into the forward moving wave u_m and generates a force feedback f_{mc} from the returning wave v_m. The forward moving wave u_m is transmitted by the communication channel and filtered by the low-pass filter. With the invertible wave transformation, the

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command (reference) velocity at the slave $\dot{x}_{sc}$ is generated and the feedback force of the slave f_{sc} is encoded into the backward wave v_s. The PD controller is applied at the slave side, which is expressed by

$$f_{sc}(t) = (\dot{x}_{sc}(t) - \dot{x}_s(t)) \otimes L^{-1}\left(\frac{Bs + K}{s}\right), \tag{3}$$

where s is the complex variable in the complex frequency domain, $\otimes$ is convolution operation, $\dot{x}_s$ is the actual slave velocity, K is the proportional parameter, and B is the differential parameter of the local PD control at the slave end.

The command (reference) velocity at the slave side is computed as:[5,16,18]

$$\dot{x}_{sc}(t) = L^{-1}\left(\frac{\lambda}{s+\lambda}\right) \otimes \dot{x}_m(t-T) - \frac{1}{b}\left[f_{sc}(t) - L^{-1}\left(\frac{\lambda}{s+\lambda}\right) \otimes f_{mc}(t-T)\right]. \tag{4}$$

From Eq. (4), we can see that the command (reference) velocity at the slave $\dot{x}_{sc}(t)$ drifts away from the delayed master velocity $\dot{x}_m(t-T)$. By the slave local PD controller, the actual velocity of the slave $\dot{x}_s$ is expected to track the command (reference) velocity $\dot{x}_{sc}$.

From Eq. (3), $\dot{x}_{sc}$ is computed as

$$\dot{x}_{sc}(t) = L^{-1}\left(\frac{s}{Bs + K}\right) \otimes f_{sc}(t) + \dot{x}_s(t). \tag{5}$$

Substituting Eq. (5) into Eq. (4), the actual slave velocity $\dot{x}_s$ is computed as

$$\dot{x}_s(t) = L^{-1}\left(\frac{\lambda}{s+\lambda}\right) \otimes \dot{x}_m(t-T) - \frac{1}{b} f_{sc}(t) + \frac{1}{b} L^{-1}\left(\frac{\lambda}{s+\lambda}\right) \otimes f_{mc}(t-T) - L^{-1}\left(\frac{s}{Bs+K}\right) \otimes f_{sc}(t). \tag{6}$$

From Eq. (6), it is clear that the actual slave velocity $\dot{x}_s$ drifts away from the master velocity $\dot{x}_m$ and the magnitude of difference is increased with the increase of transmission delay T.

4. The Proposed Teleoperator with Compensator

4.1. Design of the compensator

The ideal slave velocity $\dot{x}_s(t)^*$ is the delayed/filtered master velocity expressed by

$$\dot{x}_s(t)^* = L^{-1}\left(\frac{\lambda}{s+\lambda}\right) \otimes \dot{x}_m(t-T). \tag{7}$$

According to Eqs. (6) and (7), the slave velocity drifts from the ideal velocity with a distortion

$$-\frac{1}{b} f_{sc}(t) + \frac{1}{b} L^{-1}\left(\frac{\lambda}{s+\lambda}\right) \otimes f_{mc}(t-T) - L^{-1}\left(\frac{s}{Bs+K}\right) \otimes f_{sc}(t).$$

For perfect trajectory tracking, the distortion between the actual slave velocity $\dot{x}_s$ and the ideal slave velocity $\dot{x}_s{}^*$ should be canceled. Let us add a compensating term $\Delta U(s)$ in the forward moving wave path, which can be written as

$$U_s(s) = \frac{\lambda}{s+\lambda} U_m(s) e^{-sT} + \Delta U(s). \tag{8}$$

The backward wave communication is unchanged and remains the same as $V_m(s) = V_s(s)e^{-sT}$.

Let m donate the masses of the master and the slave. The impedance of the human arm and the environment are Z_h, and Z_e, respectively, which are defined as $Z_h \cong F_h/\dot{X}_m$, $Z_e \cong F_e/\dot{X}_s$, where F_h and F_e are the forces from human and environment, respectively.

The dynamics of the master is given by

$$F_h(s) - F_{mc}(s) = ms\dot{X}_m(s). \tag{9}$$

The wave transformation equation is given by

$$U_m(s) = \frac{b\dot{X}_m(s) + F_{mc}(s)}{\sqrt{2b}}, \tag{10}$$

$$V_m(s) = \frac{b\dot{X}_m(s) - F_{mc}(s)}{\sqrt{2b}}, \tag{11}$$

$$U_s(s) = \frac{b\dot{X}_{sc}(s) + F_{sc}(s)}{\sqrt{2b}}, \tag{12}$$

$$V_s(s) = \frac{b\dot{X}_{sc}(s) - F_{sc}(s)}{\sqrt{2b}}. \tag{13}$$

The dynamics of the slave is given by

$$ms\dot{X}_s(s) = F_{sc}(s) - Z_e(s)\dot{X}_s(s). \tag{14}$$

Substituting wave variables in Eq. (8) with power variables and according to Eqs. (10)–(13), we have

$$\sqrt{\frac{b}{2}}\dot{X}_{sc}(s) + \frac{1}{\sqrt{2b}} F_{sc}(s) = \frac{\lambda}{s+\lambda}\left(\sqrt{\frac{b}{2}}\dot{X}_m(s) + \frac{1}{\sqrt{2b}} F_{mc}(s)\right) e^{-sT} + \Delta U(s). \tag{15}$$

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Taking the Laplace transform of Eq. (5) and substituting it into Eq. (15), the actual velocity $\dot{X}_s(s)$ is computed as

$$\begin{aligned}&\sqrt{\frac{b}{2}}\dot{X}_s(s)\\&=\sqrt{\frac{b}{2}}\frac{\lambda}{s+\lambda}\dot{X}_m(s)e^{-sT}-\sqrt{\frac{b}{2}}F_{sc}(s)\frac{s}{Bs+K}\\&-\sqrt{\frac{1}{2b}}F_{sc}(s)+\sqrt{\frac{1}{2b}}\frac{\lambda}{s+\lambda}F_{mc}(s)e^{-sT}+\Delta U(s).\end{aligned}\tag{16}$$

If

$$\begin{aligned}\Delta U(s)=&\sqrt{\frac{1}{2b}}F_{sc}(s)-\sqrt{\frac{1}{2b}}\frac{\lambda}{s+\lambda}F_{mc}(s)e^{-sT}\\&+\sqrt{\frac{b}{2}}F_{sc}(s)\frac{s}{Bs+K},\end{aligned}\tag{17}$$

then the distortion between the actual slave velocity and the ideal slave velocity is eliminated, and the actual slave velocity is computed as $\dot{X}_s(s)=\frac{\lambda}{s+\lambda}\dot{X}_m(s)e^{-sT}$, which is exactly the ideal slave velocity according to Eq. (7).

In order to reduce the amount and type of data transmitted over the communication channel, the ideal compensator should be implemented at the slave side and does not require any additional information from the master side. In other words, $\Delta U(s)$ should be ideally constructed from the variables at the slave side only.

From Eqs. (10) to (13), the wave transformation can also be expressed as follows:

$$F_{mc}(s)=\sqrt{\frac{b}{2}}(U_m(s)-V_m(s)),\tag{18}$$

$$F_{sc}(s)=\sqrt{\frac{b}{2}}(U_s(s)-V_s(s)).\tag{19}$$

Substituting Eqs. (18) and (19) into the first two terms in Eq. (17), we can have $\Delta U(s)$ as follows:

$$\begin{aligned}\Delta U(s)=&\frac{1}{2}(U_s(s)-V_s(s))+\sqrt{\frac{b}{2}}F_{sc}(s)\frac{s}{Bs+K}\\&-\frac{1}{2}(U_m(s)-V_m(s))\frac{\lambda}{s+\lambda}e^{-sT}.\end{aligned}\tag{20}$$

Define $U_T(s)\cong\frac{\lambda}{s+\lambda}U_m(s)e^{-sT}$, the slave forward wave variable is expressed as

$$\begin{aligned}U_s(s)=&U_T(s)+\frac{1}{2}(U_s(s)-V_s(s))\\&-\frac{1}{2}(U_m(s)-V_m(s))\frac{\lambda}{s+\lambda}e^{-sT}+\sqrt{\frac{b}{2}}F_{sc}(s)\frac{s}{Bs+K}.\end{aligned}$$

That is to say,

$$\begin{aligned}U_s(s)=&U_T(s)-V_s(s)+V_s(s)\frac{\lambda}{s+\lambda}e^{-2sT}\\&+\sqrt{2b}F_{sc}(s)\frac{s}{Bs+K}.\end{aligned}\tag{21}$$

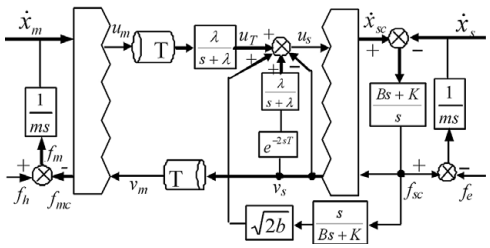


Fig. 3. Wave-variable teleoperator with the proposed compensator.

As a pictorial illustration, the wave-variable teleoperator with the proposed compensator is shown in Fig. 3.

From Fig. 3, we can see that the compensator is implemented at the slave side and it does not require any additional information from the master side when compared with ref. 16.

4.2. Stability of the teleoperator with compensator

For simplicity, we assume that the dynamics of both master and slave are dominated by masses, and the local controller is a PD controller, so both master and slave are passive. Since most environments are passive in nature,[19] the slave combined with the environment is also passive. Define the transfer function for the combined subsystem as $G_{se}(s)\cong V_s(s)/U_s(s)$.

The transfer function $V_s(s)/U_s(s)$ can be computed as[18]

$$G_{se}(s)=\frac{V_s(s)}{U_s(s)}=\frac{bG_{pd}(s)+(ms+G_{\text{env}}(s))(b-G_{pd}(s))}{bG_{pd}(s)+(ms+G_{\text{env}}(s))(b+G_{pd}(s))},$$

where, $G_{pd}(s)$ is the transfer function of the slave PD controller, and $G_{\text{env}}(s)$ is the transfer function of the environment. In addition, we have

$$|G_{se}(s)|_{s=jw}\le 1$$

for the subsystem to be passive.

The power flow ratio at the port of (u_m, v_m), which includes the communication, local slave control, and environment in Fig. 3, is

$$|V_m(s)/U_m(s)|=\left|\frac{e^{-sT}V_s(s)}{e^{sT}\frac{s+\lambda}{\lambda}U_T(s)}\right|.\tag{22}$$

According to Eq. (21), we have

$$\begin{aligned}U_T(s)=&U_s(s)+V_s(s)-V_s(s)e^{-2sT}\frac{\lambda}{s+\lambda}\\&-\sqrt{2b}F_{sc}(s)\frac{s}{Bs+K}\\=&\left[1-\frac{bs}{Bs+K}\right]U_s(s)-V_s(s)e^{-2sT}\frac{\lambda}{s+\lambda}\\&+b\frac{s}{Bs+K}V_s(s)+V_s(s).\end{aligned}\tag{23}$$

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Substitute Eq. (23) into Eq. (22), we have

$$|V_m(s)/U_m(s)| = \left|\frac{\lambda e^{-2sT}}{s+\lambda}\frac{V_s(s)}{U_T(s)}\right|$$
$$= \left|\frac{\lambda e^{-2sT}}{s+\lambda}\frac{1}{\left(1-\frac{bs}{Bs+K}\right)\frac{U_s(s)}{V_s(s)}-\frac{\lambda e^{-2sT}}{s+\lambda}+\frac{bs}{Bs+K}+1}\right|. \quad (24)$$

For $|e^{-2sT}| = 1$

$$|V_m(s)/U_m(s)|_{s=jw} = \left|\frac{\lambda}{s+\lambda}\frac{1}{\left(1-\frac{bs}{Bs+K}\right)\frac{1}{G_{se}(s)}-\frac{\lambda e^{-2sT}}{s+\lambda}+\frac{bs}{Bs+K}+1}\right|_{s=jw}. \quad (25)$$

Since the steady-state value of $|V_m(s)/U_m(s)|_{s=jw}$ is $|G_{se}(s)|_{dc}$, which is less than one, the system is convergent in the steady state. For the non-dc frequency, $|V_m(s)/U_m(s)|_{s=jw}$ is the function of λ and ω.

Transforming (24), we can have

$$|V_m(s)/U_m(s)| = \left|\frac{\lambda(Bs+K)}{(s+\lambda)(Bs-bs+K)\frac{1}{G_{se}(s)}+(s+\lambda-\lambda e^{-2sT})(Bs+K)+bs(s+\lambda)}\right|$$
$$= \left|\frac{(Bs+K)}{\left(\frac{s}{\lambda}+1\right)(Bs-bs+K)\frac{1}{G_{se}(s)}+\left(\frac{s}{\lambda}+1-e^{-2sT}\right)(Bs+K)+bs\left(\frac{s}{\lambda}+1\right)}\right|,$$

where, the magnitude of $|V_m(s)/U_m(s)|$ is reduced with the decrease of λ. Therefore, we can find a λ that is low enough to ensure the $|V_m(s)/U_m(s)| < 1$.

Next, we use an example to verify that $|V_m(s)/U_m(s)| < 1$ can be ensured by tuning λ. Consider a teleoperator with the following parameters: $B = 3.6\,\text{Ns/m}$, $b = 3.6\,\text{Ns/m}$, $K = 80\,\text{N/m}$, $m = 0.5\,\text{kg}$, $T = 0.5\,\text{s}$, and $Z_e = 5\,\text{Ns/m}$. The environment is considered as a damping element.

$$G_{\text{env}}(s) = \frac{F_e(s)}{\dot{X}_s(s)} = Z_e = 5.$$

This environment can be analogues as that the slave is moving through a fluid at a relatively slow speed, this configuration has been adopted by many previous researchers. $|G_{se}(s)|_{s=jw}$ can be numerically computed by using Matlab. The magnitude of $|G_{se}(s)|_{s=jw}$ is shown as Fig. 4, which is less than one as we inferred from the passivity of the combined system.

The value of $|V_m(s)/U_m(s)|_{s=jw}$ with different ω and λ is shown in Fig. 5(a). The maximum of $|V_m(s)/U_m(s)|_{s=jw}$ for a certain λ occurs when $\omega \in [20, 30]$. The maximum of $|V_m(s)/U_m(s)|_{s=jw}$ for a certain λ is computed by using Matlab, which is shown in Fig. 5(b). The maximum of $|V_m(s)/U_m(s)|_{s=jw}$ is increasing with the increase of λ. When $\lambda \geq 20$, $|V_m(s)/U_m(s)|_{s=jw} > 1$, which leads to the system's non-passivity. Therefore the subsystem, including the communication, local slave control, and environment, is passive as long as λ is in a certain range. In this example, if $\lambda \leq 19$, $|V_m(s)/U_m(s)|_{s=jw} < 1$. The communication with the proposed compensator does not affect the system's passivity. Accordingly the whole teleoperator system can be passive.

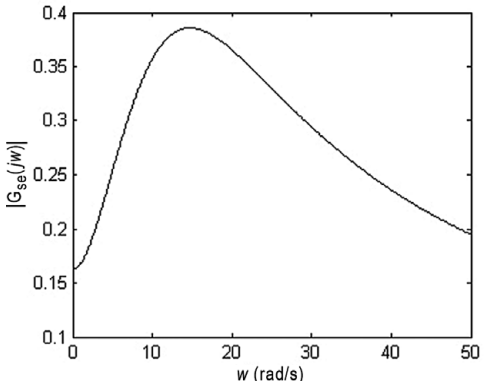


Fig. 4. The magnitude of $G_{se}(s)_{s=jw}$.

5. Simulation

In this section, we will simulate a teleoperation system under the condition of time delays. We simulate both the cases with and without the proposed compensator in order to verify the effectiveness and validity of the compensating scheme. The teleoperation task is that the velocity (displacement) of the slave robot tracks that of the master.

For the simplicity and fairness of comparison, a widely used wave-variable-based teleoperator (shown in Fig. 2) is used. The system parameters are same as ones in Section 4. The human operator is modeled as a system composed of spring and damper components with constants as 75 N/m and 50 Ns/m, respectively. The teleoperator with the designed compensator is illustrated in Fig. 3. The parameter for the low-pass filter should satisfy the range prescribed in Section 4. We choose the maximal allowable integer, i.e., $\lambda = 19$.

The human operator grasped the master manipulator and moved it forward (the direction is defined as positive). At the displacement of 0.27 m, the human operator paused for 2 s, then moved the master manipulator backward to the original position and continued to move backward (toward the negative direction). When the manipulator reached the position of -0.1 m, the movement stopped.

The displacement and velocity for the wave-variable-based teleoperator with/without the compensator are shown as Figs. 6 and 7, respectively. In order to visualize the accuracy

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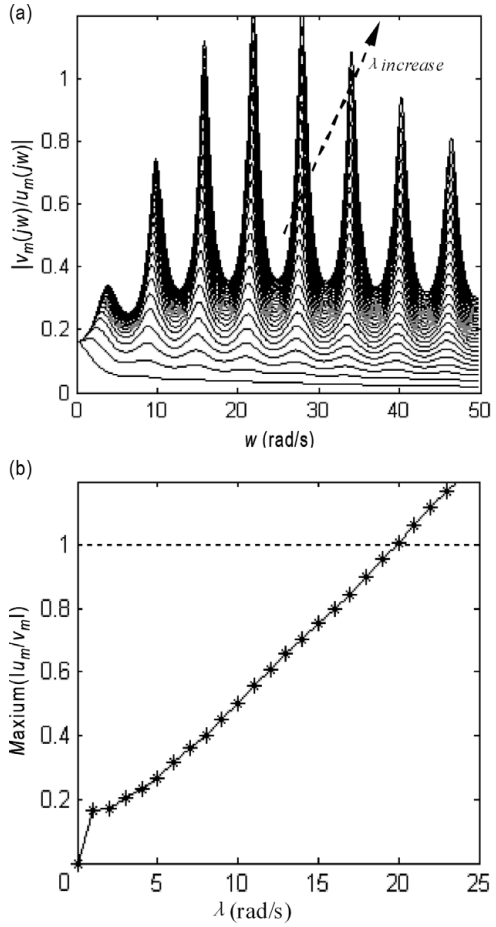


Fig. 5. The magnitude of $|V_m(s)/U_m(s)|_{s=jw}$. (a) $|V_m(s)/U_m(s)|_{s=jw}$. (b) Maximum of $|V_m(s)/U_m(s)|_{s=jw}$.

of tracking, both the velocity and displacement of the master were shifted back by time delay T, i.e., the displacement and velocity of the master appeared to be $x_m(t-T)$ and $\dot{x}_m(t-T)$, respectively, in these figures.

For the conventional wave-variable-based teleoperator without distortion compensation, the reference signal of the slave velocity is distorted as demonstrated in Section 3, which is shown in Fig. 6(b), so the actual slave velocity is distorted relative to the master velocity, which is consequentially shown as Fig. 6(a). The corresponding displacement distortion between the master and the slave is shown in Fig. 6(c).

With the developed compensator, the velocity distortion between the mater and the slave is well eliminated as shown in Fig. 7(a). Since now the slave velocity tracks the delayed master velocity directly and the bias term because of time delay is completely cancelled, perfect trajectory tracking is achieved as shown in Fig. 7(c).

Figures 8 and 9 showed the environment force and the force presented to the slave, and the environment force and the force presented to the master for teleoperator without/with compensator, respectively. For two teleoperators, the force presented to slave and master are both close to the environment force. The master can correctly feel interaction force between environment and slave robot. Therefore, the system with compensator can improve the trajectory tracking without sacrificing its telepresence or fidelity.

The system passivity can be always maintained if λ is equal or less than the maximal allowable integer, $\lambda = 19$. Since passivity is only the sufficient, but not the necessary condition for system stability, the actual system could still be

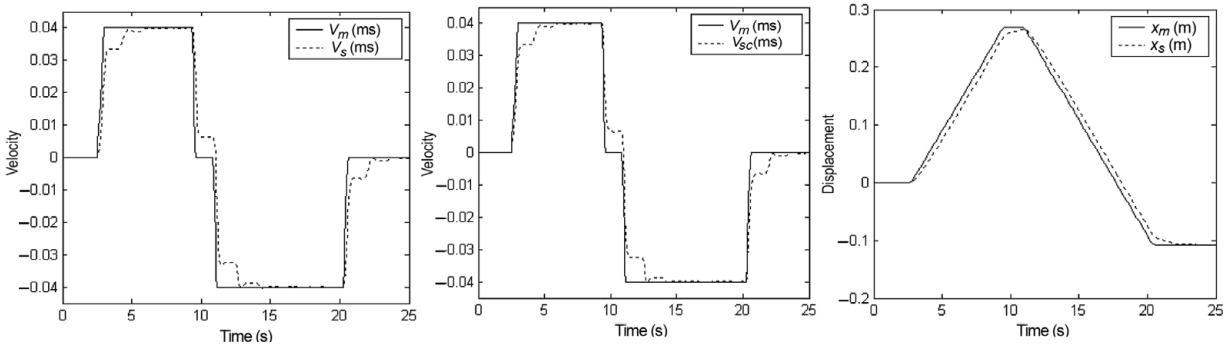


Fig. 6. Displacement and velocity for the wave-variable teleoperator without compensator. (a) The velocity of master & slave. (b) The velocity of master & slave command. (c) The displacement of master & slave.

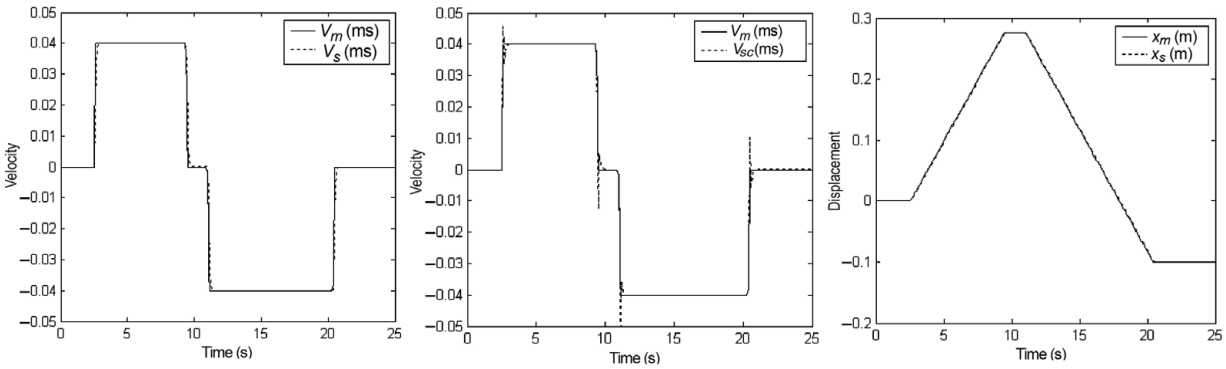


Fig. 7. Displacement and velocity for the wave-variable teleoperator with compensator. (a) The velocity of master & slave. (b) The velocity of master & slave command. (c) The displacement of master & slave.

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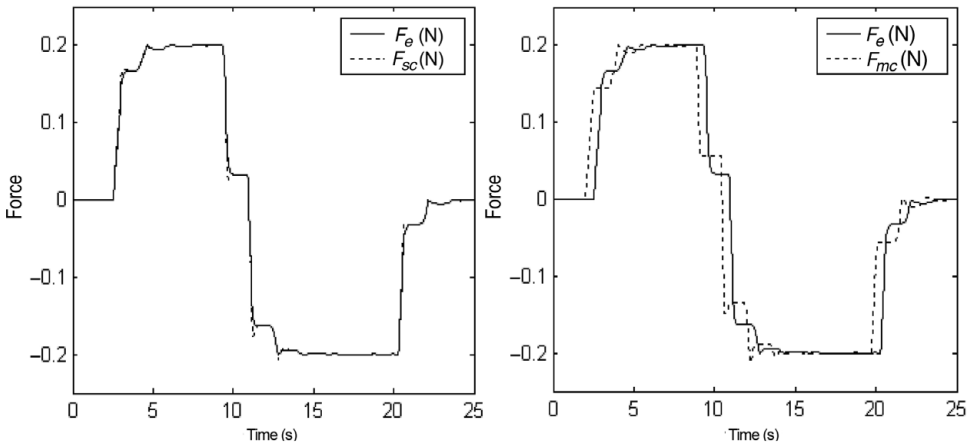


Fig. 8. Force of the teleoperator without compensator. (a) Environment force & force presented to slave. (b) Environment force & force presented to master.

stable even if λ goes beyond the range. In the experiments, for instance, it is shown that the system is still stable if $\lambda = 24$ and all other parameters are chosen to be the same as shown in Fig. 10. In this experiment we increased λ to 24, which made system's nonpassivity theoretically. But from the simulation result the system can be stable. The perfect trajectory tracking can also be achieved. It proved that passivity was the sufficient condition for stability. The range of λ can be enlarged by certain degrees.

6. Experiment

For experimental evaluation, we used the teleoperation platform consisting of two identical Phantom^{TM} Premium 1.5A robots. The configuration of the platform is shown in Fig. 11. The two robots are connected through the internal network and the communication time delays in-between are simulated. Each Phantom^{TM} robot has three joints and is equipped with standard gimbal end-effectors. Each joint is attached with encoder for joint position measurement.

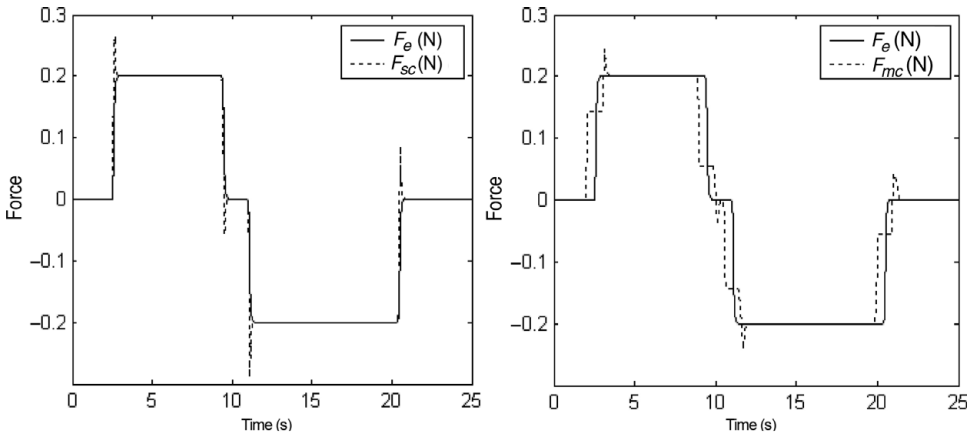


Fig. 9. Force of the teleoperator with compensator. (a) Environment force & force presented to slave. (b) Environment force & force presented to master.

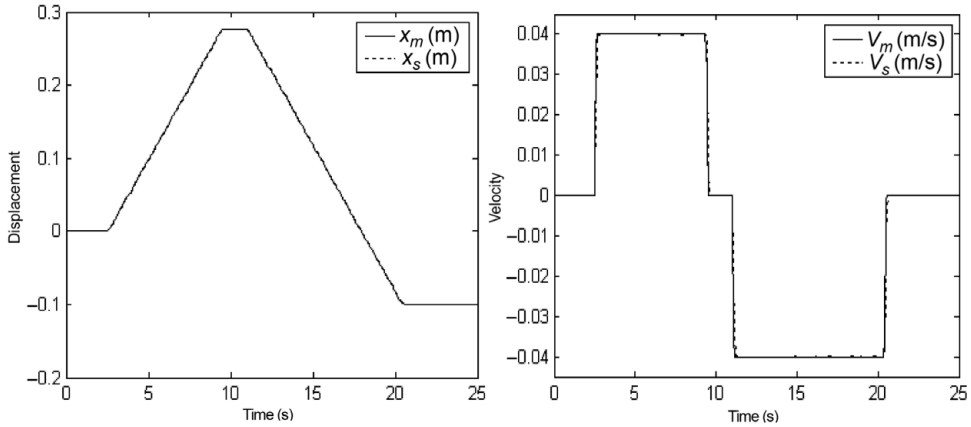


Fig. 10. Teleoperator with compensator for $\lambda = 24$. (a) Displacement of master & slave. (b) Velocity of master & slave.

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Fig. 11. The configuration of the experiment platform.

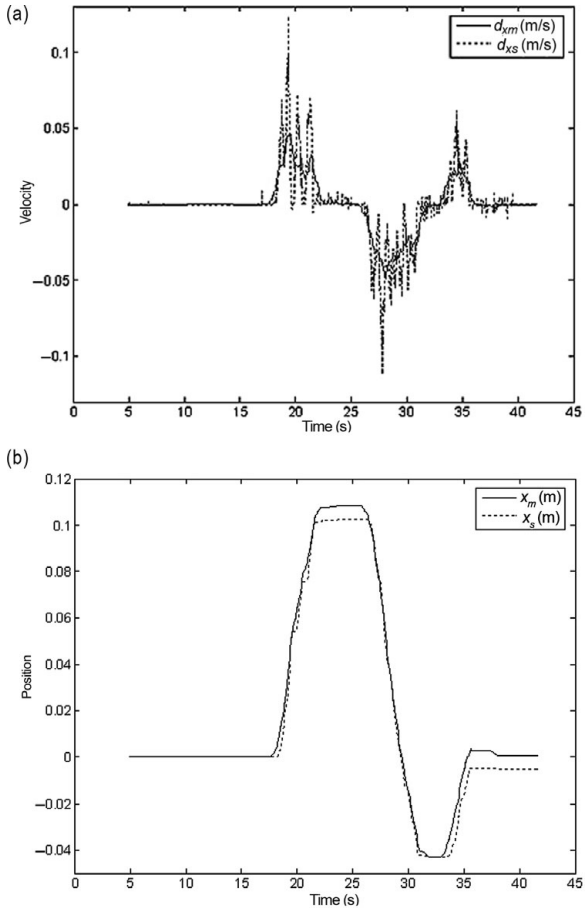


Fig. 12. The experiment result for the teleoperator without compensator. (a) Velocity of the master (solid) and the slave (dashed). (b) Displacement of the master (solid) and the slave (dashed).

The contact virtue Touch toolbox makes it easy to control Phantom™ device with simulink. It generates real-time codes to interface with the Phantom™ device by calling the Visual C++ program in Simulink. The model for Phantom™ applies the forces to the Phantom™ device and outputs the joint and Cartesian positions. The joint velocity signals are obtained by differentiating the joint positions. In order to compare the effect of the compensator, we performed the experiments with and without the compensator, respectively. The trajectories of manipulators are similar to those obtained through simulation.

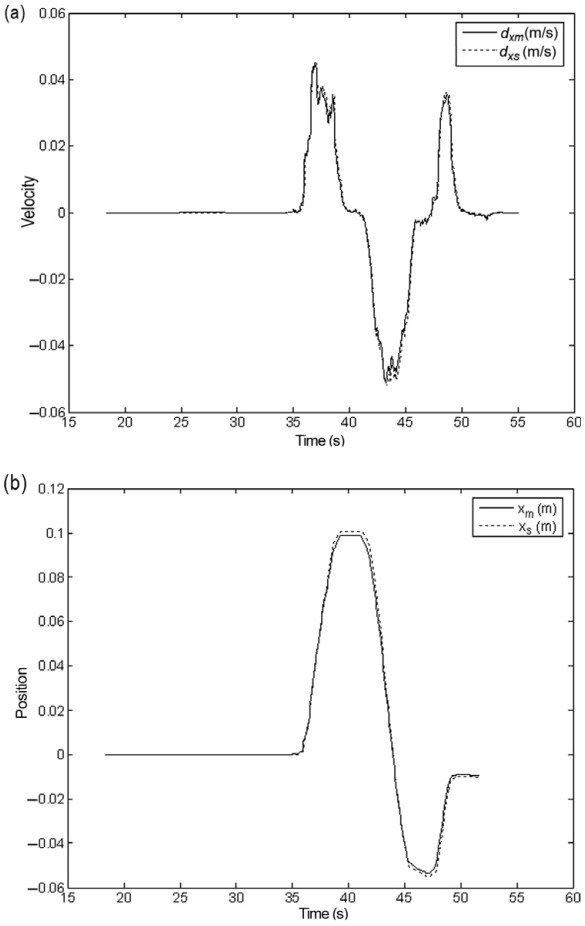


Fig. 13. The experiment result for the teleoperator with compensator. (a) Velocity of the master (solid) and the slave (dashed). (b) Displacement of the master (solid) and the slave (dashed).

First, the experiment was conducted without the compensator. The velocity and the displacement are shown in Fig. 12. The master velocity is the delayed one, i.e., $\dot{x}_m(t-T)$, $x_m(t-T)$. The solid line is for the master, and the dashed is for the slave. According to Fig. 12(a), there is distortion between the slave velocity and the master velocity. The reason has been given in Section 3. So does the displacement, which is shown in Fig. 12(b).

Next, we did the experiment with the compensator developed in this paper. The result is shown in Fig. 13. As shown in Fig. 13(a), the distortion between the slave and master velocities is almost corrected by the compensator. The slave velocity can track the master velocity very well. The trajectory tracking is significantly better than the teleoperator without the compensator, which is shown in Fig. 13(b).

7. Conclusion

A compensating scheme is developed to cancel the inherent distortion, which is introduced by the wave variable communication between the master and slave velocities (displacements) for time-delay teleoperation systems. In order to maintain system passivity, the key idea is to use a properly designed filter. In practice, the choice of the magnitude of the filter parameter λ depends on specific applications. For instance, if the system stability

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is the dominating problem (such as in many industrial applications), we can use a relatively small value of λ. On the other hand, we can choose a larger one if the system transparency (i.e., the fidelity of force interaction) is the main concern, such as telesurgery and telediagnosis.

Since the passivity of the whole system can always be ensured by choosing the proper filter parameter λ, the stability of the system can be always guaranteed. We can either plot the curve of $|V_m(s)/U_m(s)|_{s=jw}$ or use a trial-and-error method to determine the proper value of λ.

While the tracking is improved significantly compared to the conventional wave-variable-based teleoperation systems without distortion compensation, the system transparency is not compromised much. In fact, the simulation results show that the system transparency is almost the same for both the cases with and without a compensator. At the same time, the actual experiments have shown that the trajectory tracking is much improved with the compensator.

Acknowledgments

This work was supported by the National Basic Research Program of China 2011CB302400,the Education Department of Jiangxi Province of China under Grant GJJ09015 and the Science and Technology Department of Jiangxi Province of China under grants CB200920364 and 2010GQC0157.

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