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Bilateral teleoperation with reducing wave-based reflections

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Abstract This paper presents a wave-based bilateral teleoperation structure to reduce the wave reflection and enhance the force and speed tracking performance through adjusting the relative parameters. A time domain passive approach is also applied to deal with the passivity of whole system even with non passive environment. The efficiency of the proposed method is confirmed by some experimental results.

Keywords Teleoperation · Wave variable · Passivity

1 Introduction

The bilateral teleoperation system which consists of local master and remote slave robots enables the operator to feel the reaction force from the environment. This kind of human-in-the-loop system plays an important role in some challenging environments such as outer space, deep sea exploration, and hazardous material handling, and so on. A lot of significant research works have been conducted on the subject of teleoperation [1–12]. Anderson and Spong [1] introduced the two port scattering architecture, which was inspired by transmission line theory, to the problem of bilateral teleoperation. Based on this theory, the passivity of teleoperation can be guaranteed at any constant time-delay [1, 2]. Niemeyer and Slotine introduced the wave variable approach to the teleoperation system based on passivity theory, and the passivity can also be guaranteed at any constant time-delay. At same time, the performance can be improved by adjusting some parameters [3]. The basic wave based architecture of the bilateral teleoperation is presented in Fig. 1. The position tracking and force reflecting expressions are shown as follows

$$\dot{x}_{sd}(t)\dot{x}_{md}(t-T)\frac{f_{md}(t-T)-f_{sd}(t)}{b}, \tag{1}$$

$$f_{\mathrm{md}}(t)=b(\dot{x}_{\mathrm{md}}(t)-\dot{x}_{\mathrm{sd}}(t-T))+f_{\mathrm{sd}}(t-T), \tag{2}$$

where $\dot{x}_{\mathrm{m}}$ and f_{md} are velocity and force for the master manipulator, respectively; f_{sd} is force of the motor employed to the slave manipulator; $\dot{x}_{\mathrm{sd}}$ denotes the velocity command from the slave manipulator; f_{h} denotes the force employed by the operator; f_{e} denotes the force employed by the environment; u_{m}, v_{s} are the outgoing wave variables while u_{s}, v_{m} denote the corresponding incoming wave variable, respectively; m is the mass inertia and b denotes the characteristic impedance of the wave transmission.

However, wave-based teleoperation unavoids the reflections, which will corrupt the useful information flow or even cause the oscillatory behavior [11]. As shown in Fig. 2, there exist four paths of reflections in basic wave-based teleoperation. In order to eliminate the reflections an impedance matched method was introduced in Ref. [3]. As shown in Fig. 3, the outgoing wave variables u_{m} and v_{s} do not contain the information of u_{s} and v_{m} any more, i.e., they are decoupled. However, the velocity tracking $\dot{x}_{\mathrm{sd}}$ and force reflecting f_{md} has the following form

$$\dot{x}_{\mathrm{sd}}(t)=\frac{bx_{\mathrm{md}}(t-T)-f_{\mathrm{sd}}(t)}{2b}, \tag{3}$$

$$f_{\mathrm{md}}(t)=\frac{b\dot{x}_{\mathrm{md}}(t)+f_{\mathrm{sd}}(t-T)}{2}, \tag{4}$$

If $f_{\mathrm{sd}}\to 0$, then $\dot{x}_{\mathrm{md}}\to\frac{\dot{x}_{\mathrm{sd}}}{2}$. If $\dot{x}_{\mathrm{md}}\to 0$, i.e., when the master moves slowly, then $f_{\mathrm{md}}\to\frac{f_{\mathrm{sd}}}{2}$. Position tracking and force

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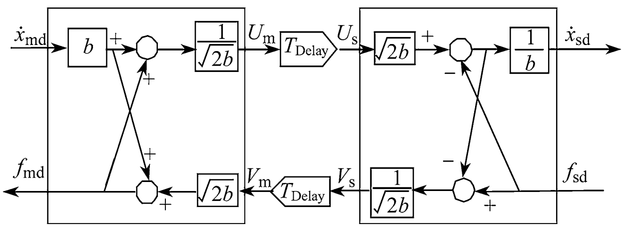

Fig. 1 Basic wave-based bilateral teleoperation architecture

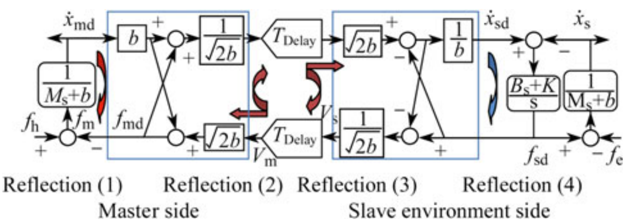

Fig. 2 Wave reflections of the teleoperation system

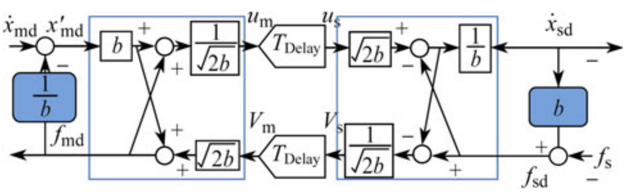

Fig. 3 Impedance matched teleoperator

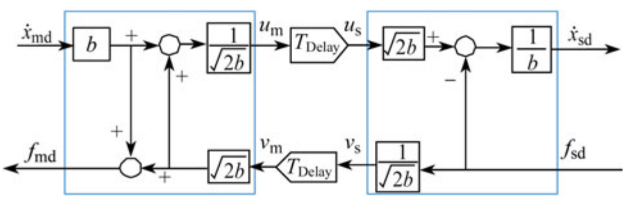

Fig. 4 Configuration of reducing wave-based teleoperator

reflecting stay only half of the expected value, that is, teleoperation does not well.

Bate et al. [11] proposed a reducing reflections scheme, as shown in Fig. 4. Through this configuration, reflections can be reduced. However when the characteristic impedance b gets greater, it can not get an effective force reflecting, for

$$F_{\mathrm{m}}(t) = b\dot{x}_{\mathrm{m}}(t) + F_{\mathrm{s}}(t - T). \tag{5}$$

If the characteristic impedance b gets smaller, it can not get effective velocity tracking, for

$$\dot{x}_{\mathrm{s}}(t) = \dot{x}_{\mathrm{m}}(t - T) + (F_{\mathrm{s}}(t - T) - F_{\mathrm{s}}(t))/b. \tag{6}$$

Furthermore, many literatures in teleoperation passive control architecture always assume the passivity of environment. However, it is not always consistent with the practical environment.

2 Wave reflection reducing configuration

The architecture of reducing wave reflection teleoperation is proposed in Fig. 5. From this structure, the combination of wave variables is as follows

$$u_{\mathrm{m}}(t) = \frac{1}{\sqrt{2b}}(\beta f_{\mathrm{sd}}(t - T) + b\dot{x}_{\mathrm{sd}}(t)), \tag{7}$$

$$u_{\mathrm{s}}(t) = \frac{1}{\sqrt{2b}}(\beta f_{\mathrm{sd}}(t) + b\dot{x}_{\mathrm{sd}}(t)), \tag{8}$$

$$v_{\mathrm{m}}(t) = \frac{1}{\sqrt{2b}}(f_{\mathrm{md}}(t) - \alpha b\dot{x}_{\mathrm{md}}(t)), \tag{9}$$

$$v_{\mathrm{s}}(t) = \frac{1}{\sqrt{2b}}f_{\mathrm{sd}}(t). \tag{10}$$

Equation (10) shows that v_{s} does not contain velocity information any more, i.e., the outgoing variable v_{s} of the slave side is independent on the incoming variable u_{s}, which means the path 3 of reflections is eliminated. Similarly, the influence between v_{m} and u_{m} gets smaller with the reflection adjusting factor β, for $0 < \beta < 1$, i.e., the path 2 of reflections in Fig. 2 has been attenuated. It is also clear that the dependence between f_{md} and $\dot{x}_{\mathrm{md}}$ becomes smaller with the reflection adjusting factor α, for $0 < \alpha < 1$, i.e., the path 1 of reflections in Fig. 2 has been reduced. The velocity tracking and force reflecting equations in Fig. 5 are as follows

$$\dot{x}_{\mathrm{sd}}(t) = \dot{x}_{\mathrm{md}}(t - T) + \frac{\beta(f_{\mathrm{sd}}(t - 2T) - f_{\mathrm{sd}}(t))}{b}, \tag{11}$$

$$f_{\mathrm{md}}(t) = \alpha b\dot{x}_{\mathrm{md}}(t) + f_{\mathrm{sd}}(t - T). \tag{12}$$

In order to guarantee the passivity of this control structure, Eqs. (11) and (12) are transformed by Lapalace and matrix form is used to describe them as follows

$$\begin{pmatrix} F_{\mathrm{md}}(s) \\ -X_{\mathrm{sd}}(s) \end{pmatrix} = \begin{pmatrix} \alpha b & \mathrm{e}^{-sT} \\ -\mathrm{e}^{-sT} & \frac{\beta(\mathrm{e}^{sT} - \mathrm{e}^{-sT})}{b\mathrm{e}^{sT}} \end{pmatrix} \begin{pmatrix} \dot{X}_{\mathrm{md}}(s) \\ F_{\mathrm{sd}}(s) \end{pmatrix} = \boldsymbol{H}(s) \begin{pmatrix} \dot{X}_{\mathrm{md}}(s) \\ F_{\mathrm{sd}}(s) \end{pmatrix}. \tag{13}$$

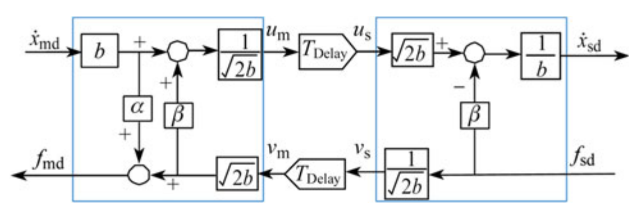

Fig. 5 Wave reflection reducing teleoperation

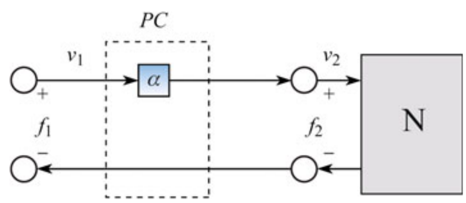

Fig. 6 Series configuration of PC for one-port networks

The scattering operator method can guarantee the passivity of the bilateral teleoperation system with communication time-delays. The form of scattering matrix is shown as follows:

$$\boldsymbol{\Xi}(s) = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} (\boldsymbol{H}(s) - \boldsymbol{I})(\boldsymbol{H}(s) - \boldsymbol{I})^{-1}. \tag{14}$$

Based on the passivity theory, suppose that the characteristic impedance $b > 0$, communication delay $T > 0$, if there exist $0 < \alpha < 1$, $0 < \beta < 1$, and inequality $\| \boldsymbol{\Xi}(s) \| \leq 1$ is satisfied, the two port control structure is passive.

3 Combination with energy-based time domain passivity control

Although the aforementioned control structure (see Fig. 5) can guarantee the two port network passivity, the stability of whole teleoperation system can not be guaranteed for the case when connecting with active environment port. In order to overcome this problem, energy-based time domain passivity control method can be combined with this structure.

Define the power P as the scalar product between the input velocity v and the output force f of the system

$$P = fv = \frac{\mathrm{d}E}{\mathrm{d}t} + P_{\mathrm{diss}}, \tag{15}$$

$$\int_0^t P\mathrm{d}\tau = \int_0^t fv\mathrm{d}\tau = E(t) - E(0) + \int_0^t P_{\mathrm{diss}}\mathrm{d}\tau = -E(0), \tag{16}$$

where E denotes the low-bounded energy stored in the system, $E(0)$ the initial energy, and P_{diss} the power dissipation that should be non-negative. Typically $E(0)$ is zero and the inequality (16) is simplified to $\int_0^t fv\mathrm{d}\tau \geq 0$ which states that the energy supplied to a passive system must be non-negative for all time.

Taking a series PC [12] (see Fig. 6), the environment of teleoperation system depicted as the block N. The dissipative element α is computed as follows:

When $v_2(n) \neq 0$, $v_1(n) = v_2(n)$, is the velocity input to the one-port network; $f_2(\mathrm{n}) = F(v_2(n))$, $F(\cdot)$ is the output force of the one-port network;

Calculate

$$P_{\mathrm{obsv}}(n) = f_2(n)v_1(n) - \frac{\mathrm{d}E}{\mathrm{d}t}(t). \tag{17}$$

Dissipative element $\alpha(n)$ are calculated as

$$\alpha(n) = \begin{cases} -P_{\mathrm{obsv}}(n)/v_2^2(n), & \text{if } P_{\mathrm{obsv}}(n) < 0, \\ 0, & \text{if } P_{\mathrm{obsv}}(n) \geq 0. \end{cases} \tag{18}$$

The adjusted output force is

$$f_1(n) = f_2(n) - \alpha(n)v_2(n) \Rightarrow \text{output}. \tag{19}$$

Using Eqs. (17) and (19), one can verify that the combination of the system and PC is passive at any time step, that is

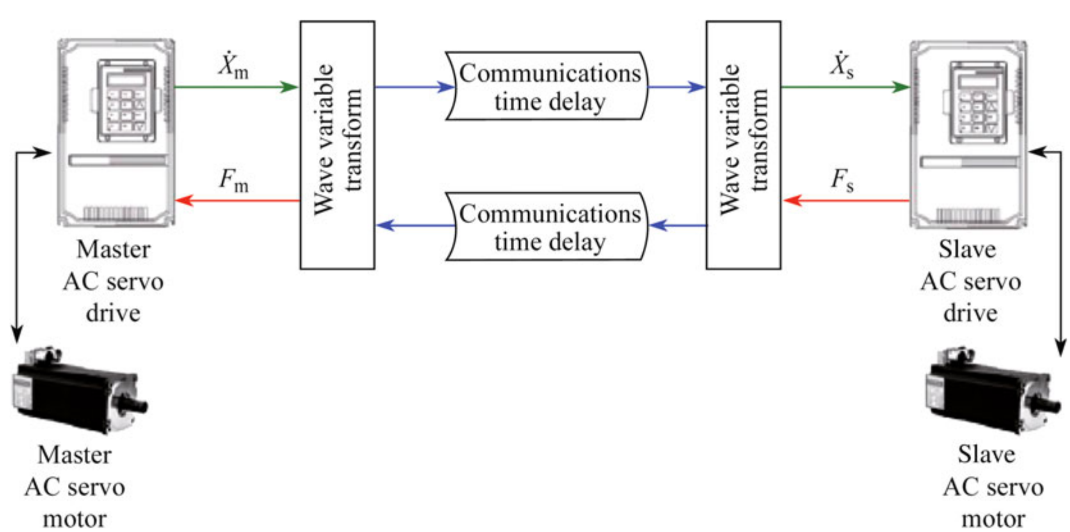

Fig. 7 Teleoperation test bed

$$f_1 v_1 - \frac{\mathrm{d}E}{\mathrm{d}t} = \begin{cases} f_2 v_1 - \frac{\mathrm{d}E}{\mathrm{d}t}, & \text{if } f_2 v_1 - \frac{\mathrm{d}E}{\mathrm{d}t} \geq 0, \\ 0, & \text{if } f_2 v_1 - \frac{\mathrm{d}E}{\mathrm{d}t} \leq 0, \end{cases} \tag{20}$$

when $v_2(n) = 0$, the PC is disable, and $f_1(n) = f_2(n)$.

4 Experiment results

In this section, experiments on position tracking and force reflecting are implemented. The experiments were carried out on a widely used test bed which consists of two AC servomotors represent master and slave manipulators. In order to simple the test process without lose of generality, one degree of freedom case is considered in this experiment.

The control loop is configured at a 2 kHz sampling rate, and communication time delay is set through the buffering techniques (Fig. 7).

Figure 8 shows position tracking performance by using the original wave-based teleoperation structure (Fig. 2).

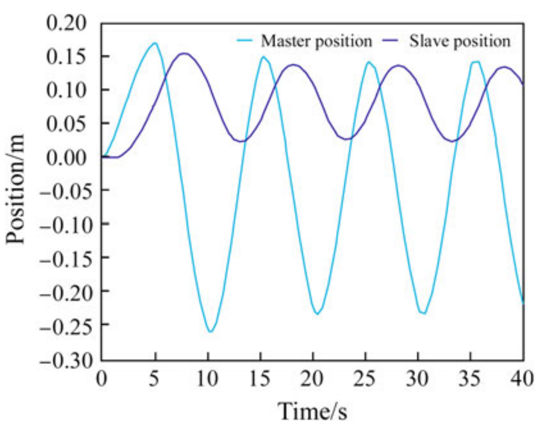

Fig. 8 Position tracking of original control structure

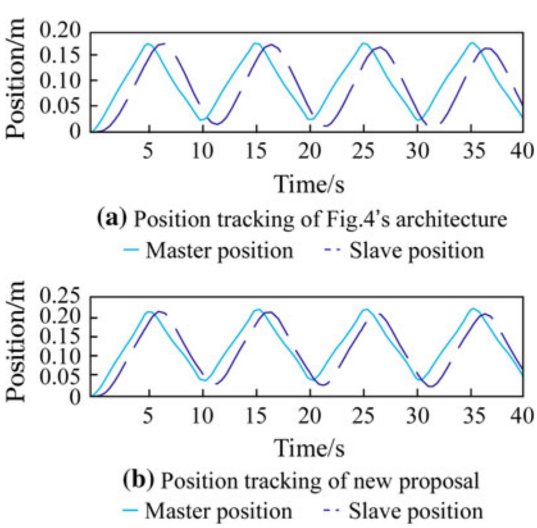

Fig. 9 Position tracking of Fig. 4's architecture and our method

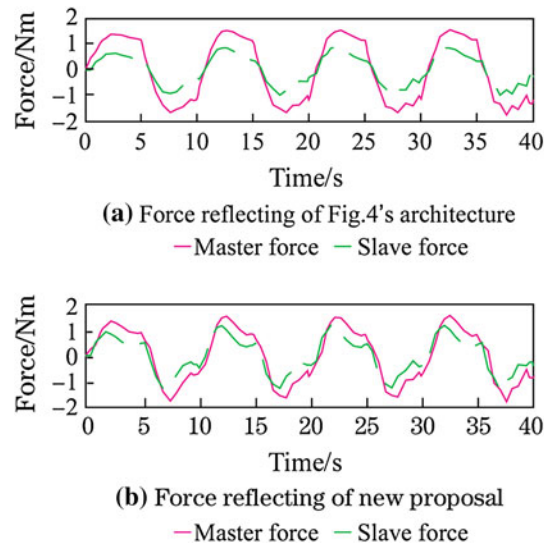

Fig. 10 Force reflecting of Fig. 4's structure and our method

Obviously, the tracking error is not satisfied, and the slave can not track well with the master.

In Figs. 9 and 10, position tracking and force reflecting of new proposed method are both compared with those in Fig. 4. Figures 9a and 10a denote the curves for the control structure as Fig. 4. Figures 9b and 10b denote the curves for our new proposed method. Herein, the reflection adjusting factors of new propose method are chosen as $\alpha = 0.7$, $\beta = 0.8$. The position tracking and force reflecting of new proposal are better by comparing Figs. 9 and 10.

5 Conclusions

The adjusting factor introduced architecture of wave-based bilateral teleoperation is proposed in order to reduce reflections and improve the tracking performance. Time domain passivity control method was also applied for guaranteeing the passivity of the whole teleoperation systems. These methods not only guarantee the stability of whole system, but also improve the tracking capability between master and slave.

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