Time delayed bilateral teleoperation based on a novel wave variable architecture with position compensation

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***Abstract*—Time delay is one of the most important issues in teleoperation system. Wave variable method based on passivity guarantees the stability of teleoperation system, but the resulting wave reflection seriously distorts the operator, and serious position drift occurs when the communication delay is time-varying. In this paper, a novel wave variable method is proposed to improve the transparency of the bilateral teleoperation system and an energy reservoir is designed to compensate the forward wave. In conclusion, simulation results show that the proposed scheme significantly improves the transparency of the system while guaranteeing the stability of the system.**

***Keywords*—teleoperation,wave variable,position compensation**

I. Introduction

A typical teleoperation system consists of operator, master device, slave device, communication channel and external environment. The appearance of teleoperation has brought new ideas for replacing human operators in unknown and complex environments, and as one of the core fields of robotics, it is now widely used in marine, medical, nuclear industries and so on [1], [2]. However, teleoperation system is very sensitive to time delay present in the communication channel, which may significantly reduce the transparency of the teleoperation system and even lead to system instability [3].

In order to guarantee the stability of teleoperation system under time delay, many solutions have been proposed including “move and wait” strategy [4], adaptive control and wave variable method, of which the wave variable method is based on the theory of passivity [5]. However, wave reflection occurs in the basic wave variable method, which can lead to the decreasing of system transparency. Niemeyer and Slotine used damping elements to match master and slave impedances to reduce wave reflection [6]. Bate modified the wave variable based teleoperation architecture by removing the velocity term in the backward channel to reduce the effect of the unknown environment on the teleoperation system [7]. Li designed two augmented wave variable terms in forward and backward waves to track position and force on single-travel time delay based on an impedance variable architecture [8]. Chen proposed a more simplified wave variable architecture and adjust two parameters to meet different transparency requirements. Chen then proposed an improved wave variable based four channel control design, which further improves the stability and transparency of the teleoperation system by providing a passive based time delay compensator to reduce wave reflections to compensate for distortion through a novel wave variable method and local force feedback [9], [10]. Xu proposed a modified wave variable method to deal with the time delay problem, which effectively reduces the force and position tracking errors while guaranteeing stability [11]. Gómez-Rosas designed a compensator based on wave variable on a one degree of freedom experimental platform that effectively compensates for the effects of time delay [12]. However,the methods mentioned above either do not take wave reflection into account or assume that the delay is constant, both of which can deteriorate the performance of the system or even lead to system instability.

In order to solve the above problems to improve the transparency of teleoperation system, this paper proposes a novel wave variable method to reduce the wave reflection, and compensate in the forward wave to solve the position drift problem caused by the time-varying delay.

The rest of this paper is organized as follows: Section II introduces the wave variable and associated knowledge. In Section III, the teleoperation control system is designed based on the novel proposed wave variable method and using position compensation, and the stability and transparency of the system are analyzed. Section IV demonstrates the proposed scheme through simulation. Finally, Section V summarizes the findings and provides concluding remarks.

II. Wave Variable Transform

A. Basic Wave Variable Transform

A formula similar in concept to the scattering formula appears in [13], the so-called wave variable formualtion,which was developed to solve the problem of teleoperation system instability due to time delay. As seen in Fig. 1, instead of

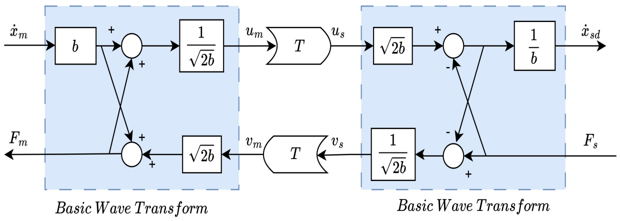


Fig. 1. Bilateral teleoperation with basic wave transform

transmitting the power variables $\dot{x}_m$ and $\dot{F}_m$, wave variables u_m and v_s are transmitted, which are given by:

$$u_m = \frac{F_m + b\dot{x}_m}{\sqrt{2b}} \tag{1}$$

$$v_s = \frac{F_s - b\dot{x}_{sd}}{\sqrt{2b}} \tag{2}$$

where u_s and v_m are the received signal and the reference signal on both side of the channel, which are derived as :

$$\dot{x}_{sd} = \dot{x}_m(t-T) - \frac{F_s(T)}{b} + \frac{F_m(t-T)}{b} \tag{3}$$

$$F_m = F_s(t-T) + b\dot{x}_m(t) - b\dot{x}_{sd}(t-T) \tag{4}$$

The fundamental tuning parameter is called wave impedance b, which allows the designer to trade off the effective mass and stiffness of the system characteristics.

Although the basic wave variable guarantees the passivity of the system [14], according to (3) and (4), the last two terms on the right-hand side of the equations are bias terms, which cause position drift. In addition, wave reflection occurs when b is not selected correctly [15], which will lead to disorientation of human operators using the teleoperation system.

B. Modified Wave Transform

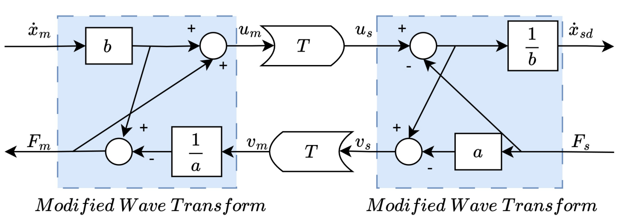


Fig. 2. Bilateral teleoperation with modified wave transform

As mentioned above, the traditional wave variable approach loses performance to guarantee the stability of the system. As shown in Fig. 2, a modified wave variable method was proposed in [11] to cope with the time delay. The outgoing wave variables can be adjusted to improve transient performance with two parameters, as follows:

$$u_m = F_m + b\dot{x}_m \tag{5}$$

$$v_s = -aF_s + b\dot{x}_{sd} \tag{6}$$

Although the method guarantees the stability and improves the transparency of the system, it only considers the constant delay and not the position drift caused by the time-varying delay condition.

III. Teleoperation Control Design With Novel Wave Variable and Position Compensation

A. Novel Wave Variable Architecture

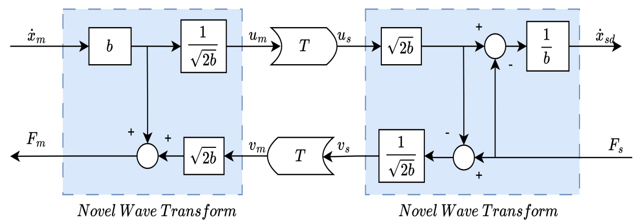


Fig. 3. Bilateral teleoperation with novle wave transform

The novel method alters the architecture of the basic wave variable, as shown in Fig. 3, the novel outgoing wave variables are as follows:

$$u_m = \sqrt{\frac{b}{2}}\dot{x}_m \tag{7}$$

$$v_s = \frac{F_s - b\dot{x}_m(t-T)}{\sqrt{2b}} \tag{8}$$

The novel incoming wave variables can be written as:

$$v_m = \frac{F_m - b\dot{x}_m}{\sqrt{2b}} \tag{9}$$

$$u_s = \frac{F_s + b\dot{x}_{sd}}{\sqrt{2b}} \tag{10}$$

If the time delay is T, the delay model of the transmitted wave variables through the communication channel can be written as:

$$u_s = u_m(t-T), v_m = v_s(t-T) \tag{11}$$

Equation (7) indicates that the novel wave variable u_m no longer carries any force information; therefore, this master outgoing wave variable no longer contains the master incoming wave variable v_m. As a result, circulating wave reflections are avoided due to the decoupling of force and velocity on the master side. With the newly introduced wave variables, the slave velocity tracking and master force feedback are as follows:

$$\dot{x}_{sd} = \dot{x}_m(t-T) - \frac{F_s}{b} \tag{12}$$

$$F_m = F_s(t-T) + b\dot{x}_m - b\dot{x}_m(t-2T) \tag{13}$$

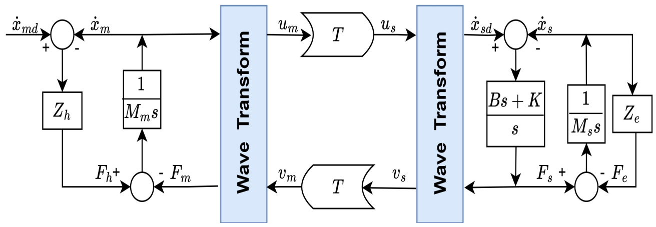


Fig. 4. Control design with novle wave transform

B. Control Design of Teleoperation

For the sake of simplicity and fairness of comparison(as shown in Fig. 4), a commonly used wave variable based teleoperation system is used. The dynamics of the master and slave are modeled as follows:

$$M_m\ddot{x}_m(t) = F_h(t) - F_m(t), M_s\ddot{x}_s(t) = F_s(t) - F_e(t) \quad (14)$$

In addition, a PD controller is designed for the slave manipulator in order to track the desired velocity x_{sd} of the slave manipulator.

C. Stability

The wave variable based teleoperation system guarantees the stability of the system with constant or unknown communication delays. According to scattering theory [7], if the scattering norm is less than or equal to one, i.e.$\|S(s)\| \leq 1$, then the teleoperation system will be passive and stable.

The scattering matrix $\|S(s)\|$ is defined as follows:

$$S(s) = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} [H(s) - I] [H(s) + I]^{-1} \quad (15)$$

The hybrid matrix $H(s)$ relating velocity and force in teleoperation system is defined as follows:

$$\begin{bmatrix} F_m(s) \\ -\dot{x}_{sd}(s) \end{bmatrix} = H(s) \begin{bmatrix} \dot{x}_m(s) \\ F_s(s) \end{bmatrix} \quad (16)$$

Thus, the hybrid matrix of the teleoperation system shown in “Fig. 4” can be written as:

$$H(s) = \begin{bmatrix} b(1 - e^{2sT}) & e^{-sT} \\ -e^{-sT} & \frac{1}{b} \end{bmatrix} \quad (17)$$

Defining $s = j\omega$, the angular frequency ω affects the scattering norm via the $e^{j\omega T}$. Due to the periodicity of $e^{j\omega T}$, the scattering norm is also periodic. Moreover, different time delay T only affects the scattering norm with respect to the magnitude of the period of ω. Let $T = 1s$,$b = 1 \sim 200$,ω as the only variable.As a result, Fig. 5 shows that the scattering norm of the proposed teleoperation system is consistent not to greater than unity. Thus, the proposed novel teleoperation system is passive and stable for any constant delay time.

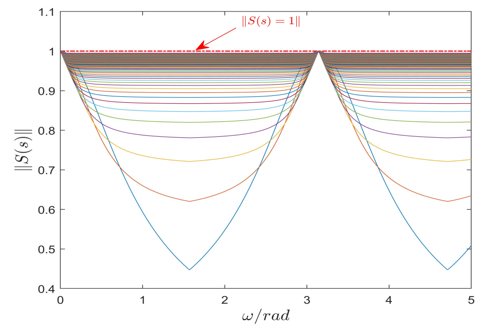


Fig. 5. Scattering norm of novel teleoperation

D. The Forward Wave Variable Compensation

All of the above discussions are for the constant time delay, but when the communication delay is variable, the teleoperation system may appear the position drift or even instability, and the greater the delay, the worse the impact. In order to solve this problem, this paper adds the forward wave compensation to the novel proposed wave variable architecture (as shown in Fig. 6) to improve position tracking [16].

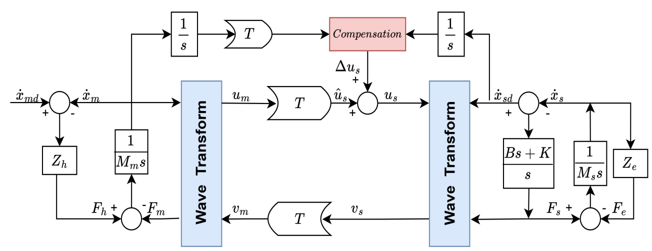


Fig. 6. Control design with novle wave transform and compensation

With the addition of the compensation term, the incoming wave at slave side u_s can be written as:

$$u_s = \hat{u}_s + \Delta u_s \quad (18)$$

Additional compensation term inevitably inject energy into the system and may destroy the passivity of the whole system leading to instability. In order to guarantee the passivity of the system, an energy reservoir based regulator is designed where the energy reservoir is used to track how much net energy is consumed by slave system, which is defined as follows:

$$E_r(t) = E_r(0) + \int_0^t (\hat{u}_s^2 - v_s^2) d\tau \quad (19)$$

The compensation term is defined as follows:

$$\Delta u_s = \gamma \left[1 - e^{-\delta E_r(t)}\right] * \sqrt{\frac{b}{2}} \left\{x_m(t - T) - x_{sd}(t)\right\} \quad (20)$$

Where γ,δ are positive constants used to adjust the speed of the compensation term. The energy reservoir term in brackets guarantees passivity,when $E_r(t) \rightarrow 0$, the $\Delta u_s \rightarrow 0$,which means that the compensation is cut off. Some of the parameters are given in Table. I.

E. Transparency

The control design with compensation is analyzed here. Considering approximate steady state,where the x_m and F_s are roughly constant. In this case, the transmission delay does not matter,then there is $u_m = \hat{u}_s, v_m = v_s$. Besides,it is assumed that the system has been running for a long enough time to render the energy reservoir large enough to satisfy $1 - e^{-\delta E_r(t)} \approx 1$.

According to (7) and (9),we have:

$$u_m = \hat{u}_s = \frac{1}{\sqrt{2b}} \left(F_m - \frac{1}{\sqrt{2b}} v_s \right) \tag{21}$$

Substituting (18) and (9) into (10) yields:

$$\begin{aligned} \dot{x}_{sd} &= \frac{1}{b}(\sqrt{2b}(\hat{u}_s + \Delta u_s) - F_s) \\ &= \frac{1}{b}(F_m - \frac{1}{\sqrt{2b}} v_s + \sqrt{2b}\Delta u_s - F_s) \\ &= \frac{1}{b}(\frac{1}{2}\dot{x}_m + \sqrt{2b}\Delta u_s - \frac{1}{2b}F_s) \end{aligned}$$

At steady state there is $\dot{x}_m \approx 0$, we have:

$$\Delta u_s = \frac{1}{\sqrt{2b}}(b\dot{x}_{sd} + \frac{F_s}{2b}) \tag{22}$$

Note $\theta = \frac{F_s}{2b}$,substituting (18) into (20) yields:

$$\frac{1}{\sqrt{2b}}(b\dot{x}_{sd} + \theta) = \gamma \left[1 - e^{-\delta E_r(t)} \right] * \sqrt{\frac{b}{2}} \{x_m(t-T) - x_{sd}(t)\}$$

After simplification, we have:

$$\dot{x}_{sd} + \frac{\theta}{b} = \gamma \left(x_m - x_{sd} \right) \tag{23}$$

The value of b is selected according to the demand for transparency, and if better positional tracking is desired then the value of b should be larger, then $\frac{\theta}{b} = \frac{F_s}{2b^2} \to 0$ and (23) can be written as:

$$\dot{x}_{sd} \approx \gamma \left(x_m - x_{sd} \right) \tag{24}$$

At this point, it is easy to see how (20) enables x_{sd} to asymptotically converge to x_m. The advantage of this position compensation scheme is that it does not care about the drift source. It only depends on the measured difference between the desired positions of the master and slave.

On the other hand,when the velocity is time-invariant or slowly time varying, (13) shows accurate or near accurate force tracking.

TABLE I
PARTIAL DESIGN PARAMETERS

Parameters	M_m	M_s	B	K	Z_e	δ	γ	b	a
Value	1	1	10	100	0.5	0.5	5	5	1.5

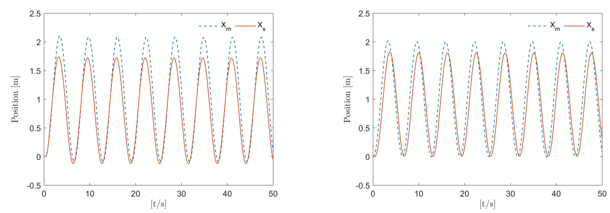
IV. Simulation

In this section, the performance of the teleoperation system based on the modified wave variable and the teleoperation system based on the novel wave variable(both with and without position compensation) will be compared by simulation in different situations, including constant delay and time-varying delay. Moreover, the human operator modeled as a system consisting of spring and damper($Z_h = \frac{20s+10}{s}$) and the reference velocity at the master is sine curve $sinx$.

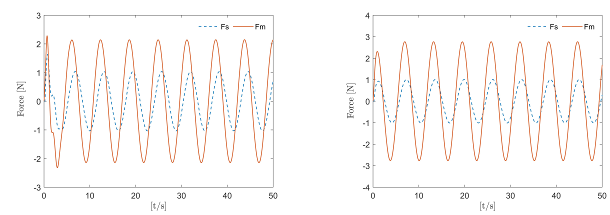
In each comparison simulation, all gain values of the controller remained unchanged. The only change in each comparison experiment is the change in the architecture of the wave variable, i.e. from basic wave variable to novel wave variable.

Situation 1: The time delay is set to a fixed $200ms$ and other parameters refer to Table. I.

Situation 2: The time delay is set as the time-varying delay($0.2 \pm 0.15s$) as shown in Fig. 10 and other parameters remain the same with Situation 1.

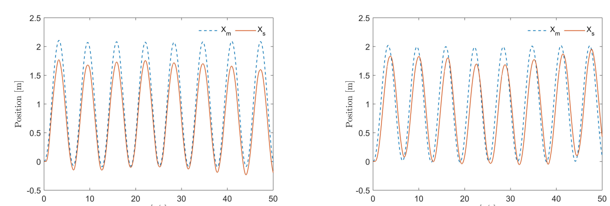


(a) Modified wave variable [11] (b) Novel wave variable



(c) Modified wave variable (d) Novel wave variable

Fig. 7. Position and force tracking in Situation 1



(a) Modified wave variable (b) Novel wave variable

Fig. 8. Position tracking in Situation 2

Fig. 7(a) and Fig. 7(b) illustrate the positional tracking of based on the modified wave variable and based on the novel wave variable in Situation 1, respectively. It can be seen that compared to the modified wave variable method, due to the elimination of wave reflection, the novel wave variable method proposed in this paper has a significant improvement in position tracking under constant time delay. At the same

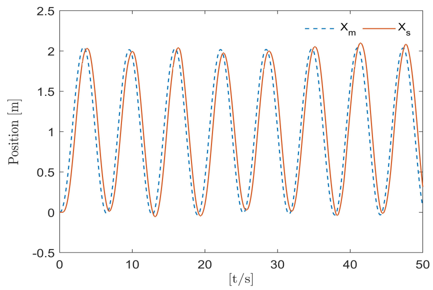


Fig. 9. Novel wave variable with compensation in Situation 2

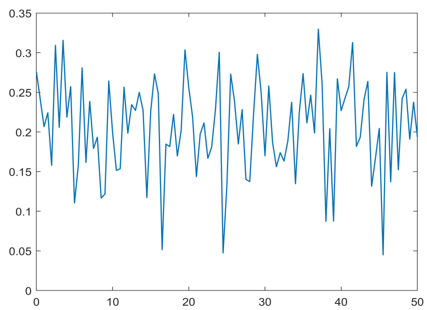


Fig. 10. Time-varying delay

time, the force feedback tracking also maintains a good curve, as shown in Fig. 7(c) and Fig. 7(d).

Fig. 8(a) and Fig. 8(b) illustrate the positional tracking of based on the modified wave variable and based on the novel wave variable with time varying delay in Situation 2, respectively. It can be seen that at some point the position tracking curves of both methods are distorted, and it can be believed that the longer the delay the worse the distortion is. However, with the addition of the positional compensation described in Section III , it can be seen that even in Situation 2 the slave is still able to track the master perfectly, which can be attributed to equation (20). The compensation term in forward wave variable makes position in slave gradually follow the position in slave along with time as explained in the transparency analysis.

Eventually, the effectiveness of the novel wave variable method and the position compensation scheme proposed in this paper are verified.

V. Conclusion

In this paper, a novel wave variable method is proposed and applied to bilateral teleoperation system control, which effectively solves the wave reflection problem. For the position drift caused by the time-varying delay, an energy reservoir is designed to compensate the forward wave while guaranteeing the system passivity. The effectiveness of the proposed schemes are verified by simulation. Simulation results show that the proposed novel wave variable method significantly improves the performance of position tracking while maintaining good force feedback tracking under constant time delay. Besides, under time-varying delay condition the performance of position tracking can be guaranteed by the compensation term.

In the future, we will experimentally validate the scheme proposed in this paper and focus on force feedback tracking based on it.

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