Time Delayed Bilateral Teleoperation Based On A Novel Wave Variable Architecture With Position Compensation

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***Abstract*—It is well known that one of the most important issues in teleoperation systems is the communication delay, which significantly affects the stability of the system. The stability of the teleoperation system can be guaranteed by using a passivity based wave variable approach, but wave reflection may occur, which can seriously distort the operator, and serious position drift occurs when the communication delay is time varying. In this paper, a novel wave variable approach 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 guarantees the stability of the teleoperation system while the transparency of the system is obviously improved.**

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

I. INTRODUCTION

In a bilateral teleoperation system, the operator operates the master device, and through the communication channel, the slave devices are able to follow the signals from the master while interacting with the 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 caused by the communication channel, which may deteriorate the transparency of the teleoperation system and even lead to the instability of the whole system [3].

Over the past decades, researchers have come up with a number of innovative and effective solutions to improve the stability and transparency of teleoperation system, such as “move and wait” strategy [4], adaptive control and wave variable approach, of which the wave variable approach is theoretically based on the fact that passivity [5]. However, using the basic wave variable approach will result in wave reflections, which can lead to the decreasing of system transparency. In [6],damping elements were used to match the impedance of the master and slave to reduce wave reflection. In order to reduce the influence of the unknown environment on the teleoperation system, a approach to adjust the structure of the basic wave variable by removing the velocity term in the backward channel has been proposed [7]. In order to guarantee the passivity of the whole teleoperation system and to eliminate distortions, a low-pass filter is designed and compensated for the slave side of the basic wave variable architecture in [8]. A simpler wave variable structure was proposed and can be adjusted to satisfy different transparency requirements by tuning two parameters [9]. Subsequently, an improved four-channel control design based on the wave variable method was proposed, which designed a passive based time delay compensator to reduce wave reflections, thus further improving the stability and transparency of teleoperation system [10]. To cope with the time delay problem a modified wave variable approach was proposed, which effectively reduces the position and force tracking errors while guaranteeing stability [11]. In [12],a compensator based on wave variable on a one degree of freedom experimental platform was designed, which effectively compensates for the effects of time delay. 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 transparency of the teleoperation system or even lead to instability.

This paper is dedicated to solving these problems mentioned above to improve the transparency of teleoperation system. Under the condition of guaranteeing the stability of the teleoperation system, first of all, the circulating wave reflection is reduced by removing the force term present in the forward wave. Subsequently, in order to solve the problem of position drift under time-varying delay, a compensation term is added to the forward wave at the slave side based on the position error between the master and slave.

The rest of this paper is organized as follows: Section II introduces the wave variable and associated knowledge. The teleoperation control system is designed based on the novel proposed wave variable approach with position compensation, and the stability and transparency of the system are analyzed in Section III,which is followed by the simulation verification of the proposed scheme in Section IV. Finally, Section V summarizes the findings and provides concluding remarks.

II. Wave Variable Transform

A. Basic Wave Variable Transform

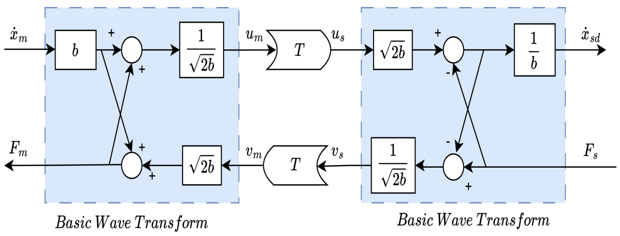


Fig. 1. Bilateral teleoperation with basic wave transform

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 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 :

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

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

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 first 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 [7], which will lead to disorientation of human operators using the teleoperation system.

B. Modified Wave Transform

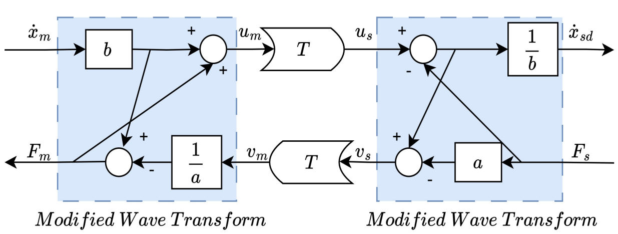


Fig. 2. Bilateral teleoperation with modified wave transform

As mentioned above, the basic wave variable approach loses performance to ensure the stability of the system. As shown in Fig. 2, a modified wave variable approach 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:

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

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

In addition, the reference signals on both sides of the channel are changed compared to the basic wave variable, which are defined as follows:

$$\dot{x}_{sd} = \frac{F_m(t-T)}{b} - \frac{F_s(T)}{b} + \dot{x}_m(t-T) \tag{7}$$

$$F_m = b\dot{x}_m(t) - \frac{b}{a}\dot{x}_{sd}(t-T) + F_s(t-T) \tag{8}$$

Although the method guarantees the stability and improves the transparency of the system, which only considers constant delay and does not take into account position drift due to time-varying delay.

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

A. Novel Wave Variable Architecture

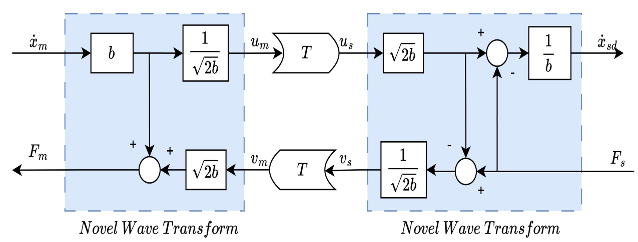


Fig. 3. Bilateral teleoperation with novle wave transform

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

$$u_m = \sqrt{\frac{b}{2}}\dot{x}_m \tag{9}$$

$$v_s = \frac{F_s - b\dot{x}_m(t-T)}{\sqrt{2b}} \tag{10}$$

The novel incoming wave variables can be written as:

$$v_m = \frac{F_m - b\dot{x}_m}{\sqrt{2b}} \tag{11}$$

$$u_s = \frac{F_s + b\dot{x}_{sd}}{\sqrt{2b}} \tag{12}$$

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

$$u_s = u_m(t-T) \tag{13}$$

$$v_m = v_s(t-T) \tag{14}$$

Equation (9) indicates that the novel wave variable u_m only contains velocity information and no more force information, which means the master outgoing wave variable no longer contains the master incoming wave variable v_m. Consequently, circulating wave reflections are mitigated by decoupling velocity and force on the master side. With the newly introduced wave variables, the reference signals on both sides of the channel are derived as follows:

$$\dot{x}_{sd} = -\frac{F_s}{b} + \dot{x}_m(t-T) \tag{15}$$

$$F_m = -b\dot{x}_m(t-2T) + b\dot{x}_m + F_s(t-T) \tag{16}$$

From (15), we can see that one can adjust the value of b to meet the requirement for positional accuracy. Meanwhile, (16) shows that the force feedback value is also accurate if the master manipulator moves slowly.

B. Control Design of Teleoperation

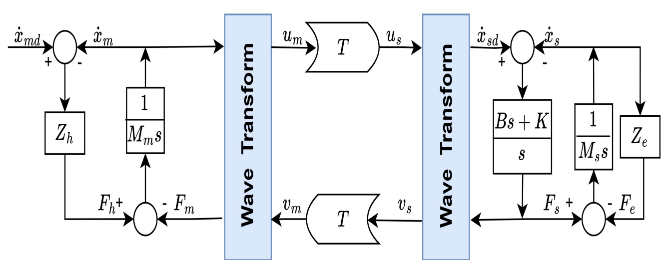


Fig. 4. Control design with novle wave transform

For the sake of simplicity and fairness of comparison(as shown in Fig. 4), this paper uses a common wave variable based teleoperation control system. The dynamics of the master and slave are modeled as follows:

$$M_m\ddot{x}_m(t) = F_h(t) - F_m(t) \tag{17}$$

$$M_s\ddot{x}_s(t) = F_s(t) - F_e(t) \tag{18}$$

In addition, in order to be able to track the desired velocity signal x_{sd} from the master, the slave uses a PD controller.

C. Stability

The wave variable based teleoperation system can guarantee the stability of system with constant or unknown communication delay. According to scattering theory [7], When the scattering norm is less than or equal to one i.e.$\|S(s)\| \leq 1$, the teleoperation system will satisfy passivity, then the system is stable.

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

$$S(s) = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} [H(s) - I] [H(s) + I]^{-1} \tag{19}$$

The hybrid matrix $(H(s)$ in a teleoperation system, which relates velocity and force, is defined as follows:

$$\begin{bmatrix} F_m(s) \\ -\dot{x}_{sd}(s) \end{bmatrix} = H(s) \begin{bmatrix} \dot{x}_m(s) \\ F_s(s) \end{bmatrix} \tag{20}$$

Thus, as shown in "Fig. 4",the hybrid matrix of the teleoperation system is derived as follows:

$$H(s) = \begin{bmatrix} b(1-e^{2Ts}) & e^{-Ts} \\ -e^{-Ts} & \frac{1}{b} \end{bmatrix} \tag{21}$$

Defining $s = j\omega$, ω is the angular frequency, which influences the scattering norm through $e^{j\omega T}$. Besides,as $e^{j\omega T}$ is periodic and has a period of 2π, then the scattering norm is likewise periodic. From equation (21), it can be seen that the time delay T only affects the the scattering norm with respect to the magnitude of the period of ω. Let $T = 1s$,$b = 1 \sim 200$,$\omega = 1 \sim 5$ as the only variable.As a result, Fig. 5 illustrates that the scattering norm of the proposed teleoperation system is coherent not greater than one. Thus,for any constant delay time, the proposed novel teleoperation system is passive and stable .

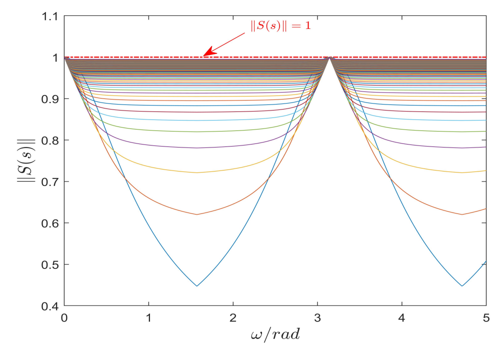


Fig. 5. Scattering norm of novel teleoperation

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, a compensation term is added to the forward wave at the slave side (as shown in Fig. 6) to improve position tracking [15].

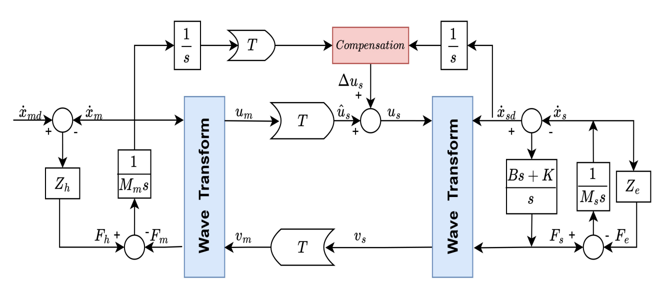


Fig. 6. Control design with novle wave transform and compensation

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

$$u_s = \hat{u}_s + \Delta u_s \tag{22}$$

Additional compensation term inevitably inject energy into the system and may destroy the passivity of the whole teleoperation system, which can lead to system instability. Hence, an energy reservoir based regulator is designed to guarantee the passivity of the system, where the energy reservoir is used for tracking how much net energy is consumed by the slave system, which is defined as follows:

$$E_r(t) = E_r(0) + \int_0^t (\hat{u}_s^2 - v_s^2) d\tau \tag{23}$$

The compensation term is defined as follows:

$$\Delta u_s = \gamma \left[1 - e^{-\delta E_r(t)}\right] * \sqrt{\frac{b}{2}} \left\{x_m(t-T) - x_{sd}(t)\right\} \tag{24}$$

Where δ,γ 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 teleoperation 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 (9) and (11),we have:

$$u_m = \hat{u}_s = \frac{1}{\sqrt{2b}} \left(F_m - \frac{1}{\sqrt{2b}} v_s\right) \tag{25}$$

Substituting (22) and (11) into (12) 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:

$$\Delta u_s = \frac{1}{\sqrt{2b}}(b\dot{x}_{sd} + \frac{F_s}{2b}) \tag{26}$$

Note $\theta = \frac{F_s}{2b}$,substituting (22) into (24) 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:

$$\dot{x}_{sd} + \frac{\theta}{b} = \gamma \left(x_m - x_{sd}\right) \tag{27}$$

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 $\frac{\theta}{b} = \frac{F_s}{2b^2} \rightarrow 0$ and (27) can be written as:

$$\dot{x}_{sd} \approx \gamma \left(x_m - x_{sd}\right) \tag{28}$$

At this point, it is easy to see how (24) enables x_{sd} to asymptotically converge to x_m. In addition, it is advisable to cap the energy reservoir to be on the safe side. However, the cap should not be set too low, as the reservoir may be exhausted before the wave variable that on the master side reaches the slave side, thus shutting off the compensation term early.

It is worth noting that this compensation method has two strengths. First of all, this position compensation scheme does not care about the drift source, it only depends on the measured difference between the desired positions of the master and slave. Subsequently, even if the positions of the master and slave do not coincide in the initial conditions, the compensation term is able to quickly drives the slave's position to the master's, keeping the two synchronized.

On the other hand,when the velocity is slowly time varying or time-invariant , from (16) we can get 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

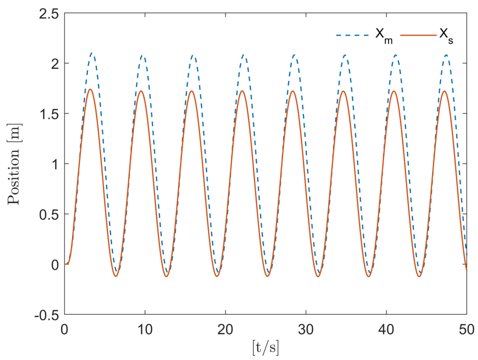
In this section,we will demonstrate the performance of the teleoperation system based on the modified wave variable and the teleoperation system based on the novel wave variable(both with and without position compensation) will be compared by simulation in different situations, including constant delay and time varying delay.

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. Moreover, the human operator is considered as a system consisting of a spring and a damper, which in this paper we set to $Z_h = \frac{20s+10}{s}$. The reference velocity x_{md} at the master side is set to sine curve $sinx$.

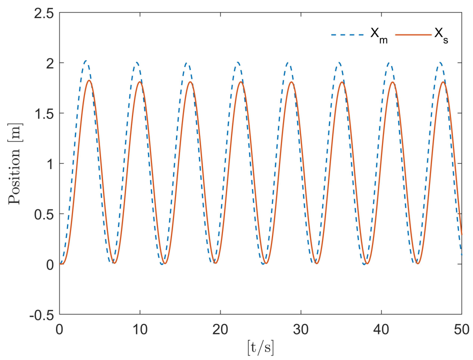
Situation 1: The time delay is set to a fixed $200ms$ and other parameters refer to Table. I.

Situation 2: The time delay is set to the time-varying delay($0.2 \pm 0.15s$) as shown in Fig. 11 and other parameters remain the same with Situation 1.

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 use of the modified wave variable method, because of the reduction 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 time, the force feedback tracking also maintains a good curve, as shown in Fig. 8(a) and Fig. 8(b).

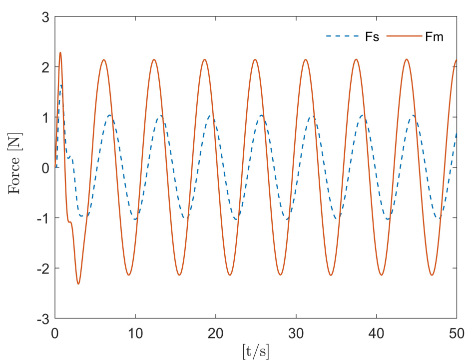


(a) Modified wave variable [11]

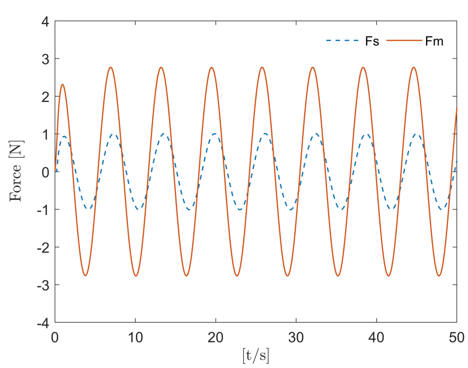


(b) Novel wave variable

Fig. 7. Position tracking in Situation 1

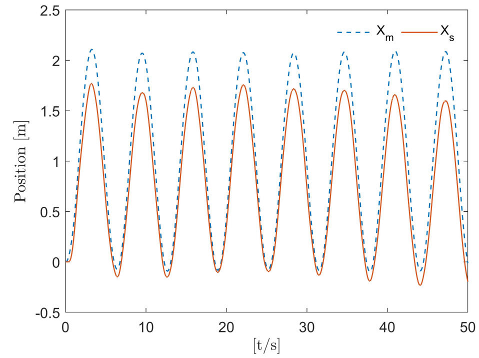


(a) Modified wave variable [11]

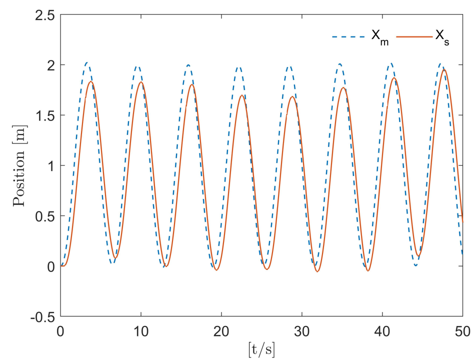


(b) Novel wave variable

Fig. 8. Force tracking in Situation 1



(a) Modified wave variable [11]



(b) Novel wave variable

Fig. 9. Position tracking in Situation 2

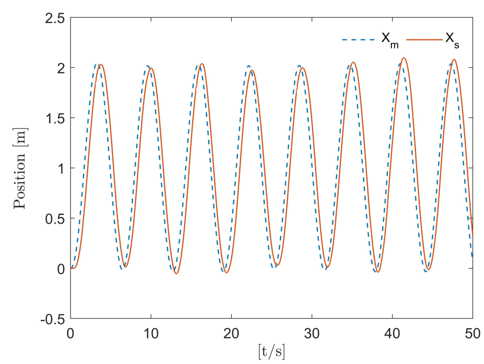


Fig. 10. Novel wave variable with compensation in Situation 2

Fig. 9(a) and Fig. 9(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 (24). As explained in the transparency analysis, the compensation term at the slave side will render the slave's position gradually follow the master's position as

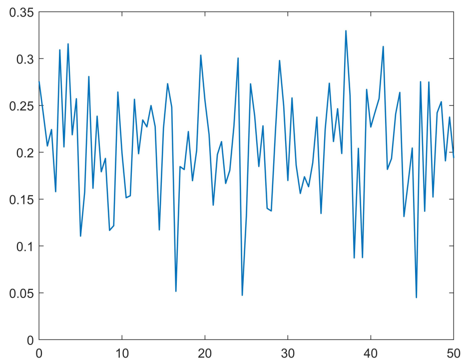


Fig. 11. Time-varying delay

time goes by.

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

V. Conclusion

In this paper, a novel wave variable approach is proposed and applied to bilateral teleoperation system control, which efficiently addresses the wave reflection problem. To address position drift due to time varying delay, an energy reservoir is designed to compensate the forward wave while guaranteeing the system passivity. Detailed theoretical derivations and proofs are given for the stability and transparency of teleoperation system. The effectiveness of the proposed schemes are also 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 condition. Besides, the performance of position tracking can be guaranteed by the compensation term even under time varying delay condition.

In the future, we will focus our work on experimental validation and further investigate force feedback tracking based on this paper.

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