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

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***Abstract*—It is widely acknowledged that communication delay is a critical concern within teleoperation system, which significantly affects the stability of the system. With regard to the stability of the teleoperation system it 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 varies over time. Considering the above issues,this paper proposes an novel wave variable approach aimed at improving transparency of the system.Moreover, an energy reservoir is designed to compensate the forward wave. In conclusion, simulation results demonstrate that the proposed approach guarantees the stability of the teleoperation system while the transparency of the system is obviously improved.**

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

I. Introduction

For a typical bilateral teleoperation system, operators operate the master device and supported by the transmission of communication channel, the slave device is 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 highly susceptible to the time delay caused by communication channel, which may deteriorate the transparency of teleoperation system and even result in the instability of the whole system [3].

Over the past decades, researchers have come up with a number of innovative and effective solutions to cope with the two important issues of stability and transparency, such as “move and wait” strategy [4], adaptive control and wave variable approach, of which wave variable approach was developed from the theory of 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 mitigate the impact of the unknown environment, a approach to adjust the structure of the basic wave variable by discarding the velocity term in 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 wave variable approach was proposed, which designed a passive based time delay compensator to reduce wave reflections, thus both the stability and transparency has been further improved. [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 teleoperation system or even result in instability.

This paper is dedicated to solving these problems mentioned above to improve the transparency of teleoperation system. Under the condition of guaranteeing stability of teleoperation system, first of all, the circulating wave reflection is reduced by removing the force term present in the forward wave. Subsequently, to cope with the issue of position drift under time varying delay, an additional compensation term is incorporated to the forward wave at the slave side, which is designed for the position error between master side and slave side.

The subsequent sections of this paper are structured as follows: Section II describes the wave variable approach and associated knowledge. The teleoperation control system is designed based on the novel proposed wave variable approach with position compensation, which accompanied by the stability and transparency analysis of the system in Section III. In Section IV, the proposed scheme is demonstrated through simulation. Finally, Section V summarizes the findings and provides concluding remarks.

II. Wave Variable Transform

A. Basic Wave Variable Transform

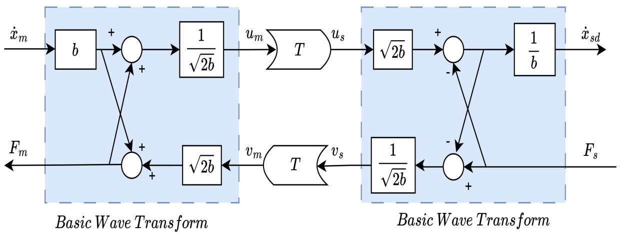


Fig. 1. Bilateral teleoperation with basic wave transform

A formula similar in concept to the scattering formula appears in [13], the so-called wave variable formualtion,which was proposed to solve the problem of teleoperation system instability due to time delay. As shown 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 either side of the communication channel respectively , which are derived as :

$$\dot{x}_{sd} = \frac{1}{b}\left[F_m(t-T) - F_s(T)\right] + \dot{x}_m(t-T) \tag{3}$$

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

Where b is called wave impedance,which is a fundamental tuning parameter. The characteristics of the system can be changed by choosing appropriate b, including the effective mass and the stiffness.

Although basic wave variable approach guarantees the passivity of the system [14], according to (3) and (4), the two preceding 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

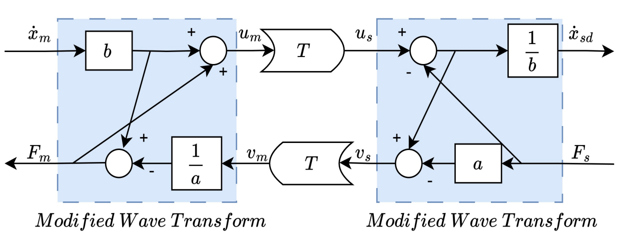


Fig. 2. Bilateral teleoperation with modified wave transform

As mentioned above, the basic wave variable approach loses performance to maintain the stability of the system. As shown in Fig. 2, a modified wave variable approach was proposed in [11] to solve the time delay problem. 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 signal on either side of the communication channel is changed compared to the basic wave variable approach, which are defined as follows:

$$\dot{x}_{sd} = \frac{1}{b}\left[F_m(t-T) - F_s(t)\right] + \dot{x}_m(t-T) \tag{7}$$

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

Although this method guarantees the stability and improves transparency of teleoperation 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

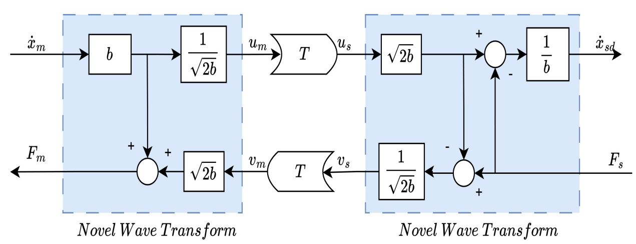


Fig. 3. Bilateral teleoperation with novle wave transform

As seen 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:

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

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

Define the time delay as T, then 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 just contains velocity term and no more force term, which means the outgoing wave variable u_m no longer contains incoming wave variable v_m. Consequently, circulating wave reflection is mitigated by separating the velocity term and force term on master side. With the newly introduced wave variables, the reference signal on either side of the communication channel can be written as:

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

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

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

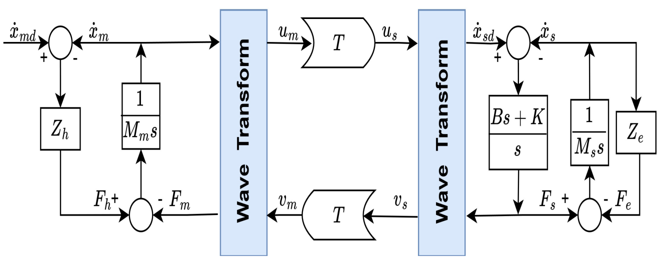


Fig. 4. Control design with novle wave transform

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. Considering the dynamics model of the master and slave 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 follow the desired velocity signal x_{sd} , the slave uses a PD controller.

C. Stability

The wave variable based teleoperation system can maintain stability of the system with constant or unknown communication delay. According to scattering theory [7], When the scattering norm is not more than or equal to one i.e.$\|S(s)\| \le 1$, the teleoperation system will satisfy passivity, then the system is stable.

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

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

Where $H(s)$ is called hybrid matrix in a teleoperation system, which is related to velocity and force can be written as:

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

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 $S(s)$ 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 is evident 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 $\|S(s)\|$ of the designed teleoperation system is coherent not more than one. Thus,for any constant delay time, the proposed novel teleoperation system is passive and stable .

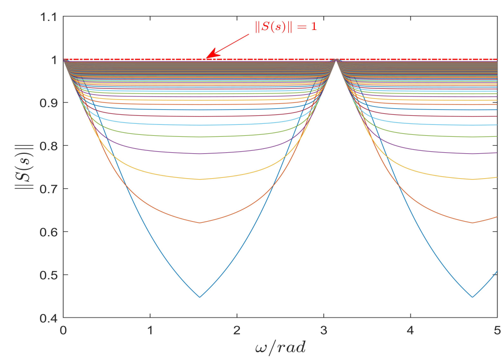


Fig. 5. Scattering norm of novel teleoperation

D. Forward Wave Variable Compensation

All of the above discussions are for the constant time delay, but if 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 response to this problem, a compensation term is added to the forward wave at the slave side (as seen in Fig. 6) to improve position tracking [15].

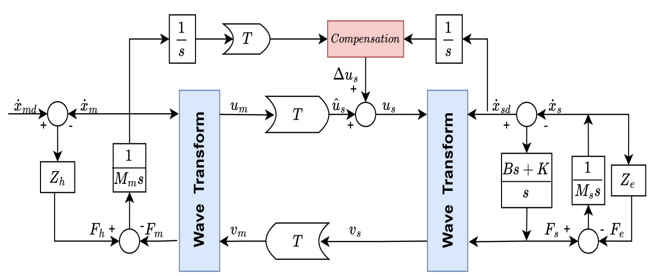


Fig. 6. Control design with novle wave transform and compensation

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 might destroy the passivity of the teleoperation system, which can result in system instability. Hence, A regulator utilizing energy reservoir is designed to maintain the passivity of the system., where the energy reservoir is used for tracking how much net energy is consumed by slave system, which is defined as follows:

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

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 for regualting the speed of compensation term. The energy reservoir term in brackets guarantees passivity,when $E_r(t) \to 0$, the $\Delta u_s \to 0$,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 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 $\frac{\theta}{b} = \frac{F_s}{2b^2} \to 0$ 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 at 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 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 slave's position to 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

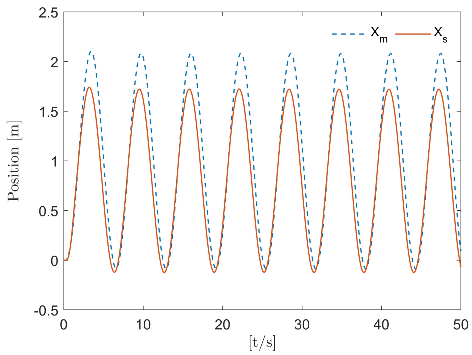
The performance of the teleoperation system based on modified wave variable approach and the teleoperation system based on novel wave variable approach(both with and without position compensation) will demonstrate in this section,which will be compared by simulation in two different situations, including 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, human operator in here 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 desired velocity x_{md} at master side is set to sine curve $sinx$. The simulation duration is set to $50s$ for both situations.

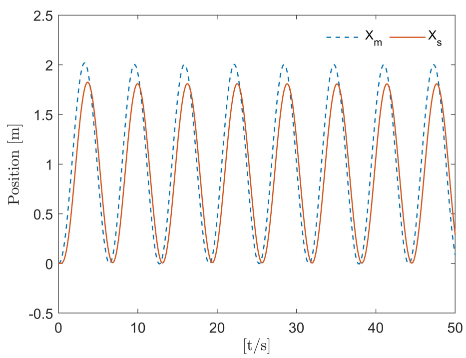
Situation 1: The time delay is set to a fixed $200ms$ and other parameters refer to Table. I.

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 approach and the novel wave variable approach in Situation 1, respectively. It can be seen that compared to the use of the modified wave variable approach, because of the reduction of wave reflection, the novel wave variable approach proposed in this paper has a significant improvement in position tracking under constant time delay. In the meantime, the force feedback tracking can maintain a good curve, as seen in Fig. 8(a) and Fig. 8(b).

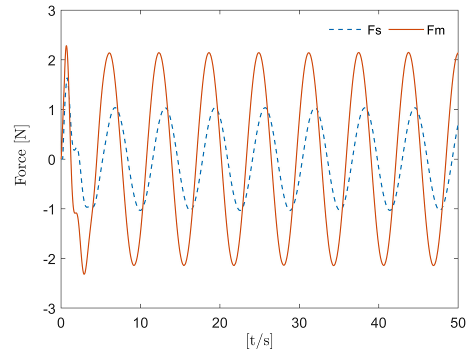


(a) Modified wave variable [11]

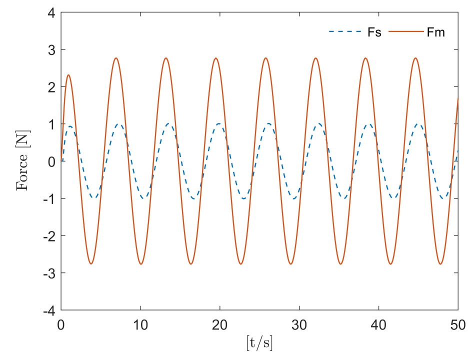


(b) Novel wave variable

Fig. 7. Position tracking in Situation 1



(a) Modified wave variable [11]

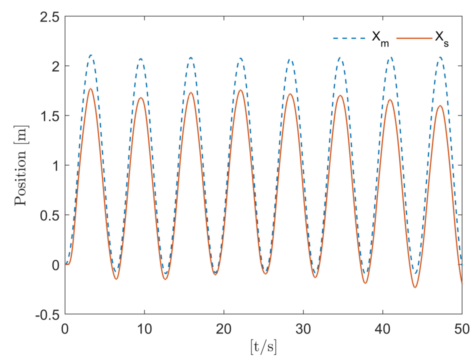


(b) Novel wave variable

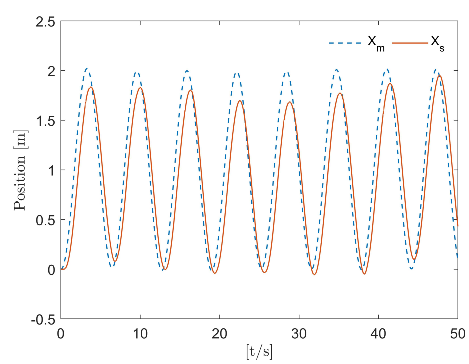
Fig. 8. Force tracking in Situation 1

Fig. 9(a) and Fig. 9(b) illustrate the positional tracking of based on the modified wave variable approach and the novel wave variable approach in Situation 2, respectively. It is obvious that at some point the position tracking curves of both approaches 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 time goes by.

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



(a) Modified wave variable [11]



(b) Novel wave variable

Fig. 9. Position tracking in Situation 2

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

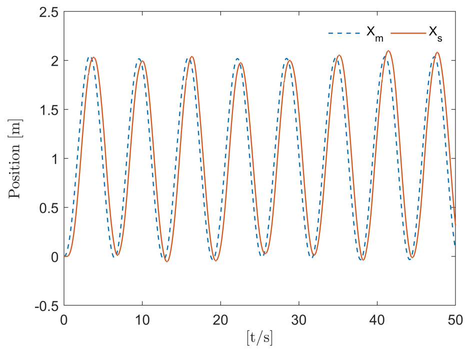


Fig. 10. Novel wave variable with compensation in Situation 2

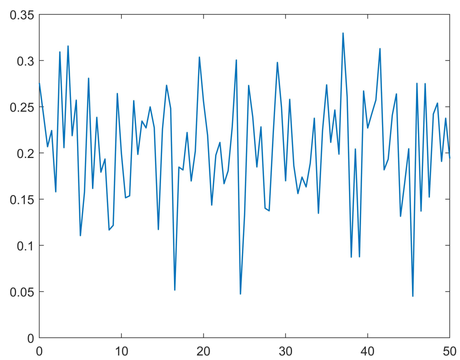


Fig. 11. Time-varying delay

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 simulation results also confirm the effectiveness of the proposed scheme, which show that the proposed novel wave variable approach 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.

References

[1] X. Bao, S. Guo, Y. Guo, and et al, "Multilevel operation strategy of a vascular interventional robot system for surgical safety in teleoperation," *IEEE Transactions on Robotics*, vol. 38, no. 4, pp. 2238–2250, 2022.

[2] Jianmin Li,Xuecheng Yang,Guangdi Chu and et al.,"Application of improved robot-assisted laparoscopic telesurgery with 5g technology in urology," *European Urology*, vol. 83, no. 1, pp. 41–44, 2023.

[3] D. A. Lawrence, "Stability and transparency in bilateral teleoperation," *IEEE transactions on robotics and automation*, vol. 9, no. 5, pp. 624–637, 1993.

[4] W. R. Ferrell, "Delayed force feedback," *Human factors*, vol. 8, no. 5, pp. 449–455, 1966.

[5] G. Niemeyer and J. J. Slotine, "Stable adaptive teleoperation," *IEEE Journal of oceanic engineering*, vol. 16, no. 1, pp. 152–162, 1991.

[6] G. D. Niemeyer, "Using wave variables in time delayed force reflecting teleoperation," Ph.D. dissertation, Massachusetts Institute of Technology, 1996.

[7] L. Bate, C. D. Cook, and Z. Li, "Reducing wave-based teleoperator reflections for unknown environments," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 2, pp. 392–397, 2009.

[8] L.Y. Hu, X. P. Liu, and G.P. Liu, "The wave-variable teleoperator with improved trajectory tracking," *IEEE ICCA*, pp. 322–327, 2010.

[9] Z. Chen, F. Huang, W. Sun and et al., "A novel wave variable based bilateral teleoperation control design for transparency improvement," *IEEE International Conference on Information and Automation (ICIA)*, pp. 1–6, 2018.

[10] Z. Chen, F. Huang, W. Sun, and et al., "An improved wave-variable based four-channel control design in bilateral teleoperation system for time-delay compensation," *IEEE Access*, vol. 6, pp. 12 848–12 857, 2018.

[11] C. Xu, X. Wang, X. Zhu, and B. Liang, "A modified wave variable method in bilateral teleoperation system with time delay," *Chinese Control And Decision Conference (CCDC)*, pp. 5143–5148, 2019.

[12] C. Gómez-Rosas and R. J. Portillo-Veléz, "Time delay compensation in a bilateral teleoperation system," *XXIII Robotics Mexican Congress (ComRob)*, pp. 13–18, 2021.

[13] R. J. Anderson and M. W. Spong, "Bilateral control of teleoperators with time delay," *Proceedings of the 1988 IEEE International Conference on Systems, Man, and Cybernetics*, vol. 1, pp. 131–138, 1988.

[14] G. Niemeyer and J. J. Slotine, "Stable adaptive teleoperation," *IEEE Journal of oceanic engineering*, vol. 16, no. 1, pp. 152–162, 1991.

[15] P. Huang, P. Dai, Z. Lu, and Z. Liu, "Asymmetric wave variable compensation method in dual-master-dual-slave multilateral teleoperation system," *Mechatronics*, vol. 49, pp. 1–10, 2018.