A Wave Variable Approach With Multiple Channel Architecture for Teleoperated System

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ABSTRACT Performance of teleoperation can be greatly influenced by time delay in the process of tele-manipulation with respect to accuracy and transparency. Wave variable is an effective algorithm to achieve a good stable capability. However, some traditional wave variable methods may decrease the performance of transparency and suffer the impacts of wave reflection. To deal with the problem of stability and transparency in teleoperation, in this paper, a novel wave variable method with four channel is presented to achieve stable tracking in position and force. In addition, the proposed method can achieve the distortion compensation and reduce the impacts of wave reflection. The simulation experimental results verified the tracking performance of the proposed method.

INDEX TERMS Teleoperation, wave-variable-based method with four channel, stability and transparency, position tracking, force reflection.

I. INTRODUCTION

Over the past decades, the teleoperation technologies have been widely applied in various aspects, such as space maintenance [1], [2], ocean exploration [3], [4], military applications [5], hazardous material disposal [6], [7], tele-medicine [8], [9], education and entertainment [10]–[12]. Generally, a teleoperated system contains a master robot with a human operator, a slave robot with remote environment, communication channel. In teleoperation, the human operator can control a remote robot by operating a master robot. The human operator can safely conduct a certain task in the remote unknown or dangerous environments. The human operator can concentrate on the interaction with the external environments to enhance one's telepresence for the complicated tasks based on the feedback. The feedback including vision information, audio display, tactile and so on [13], [14].

While the teleoperation technology brings the benefits to humans, the performance of the teleoperated system is greatly influenced by the time delay of the communication channel of the system [15], [16]. It is noted that the stability of

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system is destabilized by the time delays in a closed-loop system [17]–[19]. Moreover, The stability and transparency of the system is sensitive to the communication time delay issue [20]. In order to guarantee the stable performance of the teleoperated system, many solutions have been introduced by related researches in the literatures such as scattering theory, network approach and passivity method. Chopra *et al.* proposed a framework of passivity with scattering formalism to guarantee the passivity of the system with the limitations of time delays and data loss [21]. In [22], a F-P (Transparency Optimized Control Architecture) architecture with compliance control was proposed to provide stability in different modes with small position error in the hard environment. A bilateral teleoperated architecture with a small gain method was developed to guarantee the safety of human-robot interaction in the presence of without passivity [23].

In the above-mentioned methods, the wave variable approach is significant because of its construction and passivity [24]. Huang *et al.* [25] proposed a method based on wave-variable to guarantee the stability and the tracking performance of position and force for dual-master-dual-slave (DMDS) system. A radial basis function neural networks (RBFNN) control method with wave variable was

developed to reduce the influences of the time delays and dynamics uncertainties [26]. Yuan *et al.* [27] developed a force observer with dynamic gain to collect the force reflection in a prescribed performance functions and to obtain a satisfactory manipulation performance. Soyguder and Abut [28] proposed a novel control method with time delay to ensure the stable performance of position tracking of the haptic industrial robot. A new wave variable method to strengthen the performance of haptic feedback and to reduce the bias portion and guarantee the steady-state position tracking in the teleoperation [29]. Additionally, in [30], an ideal method was proposed to augment the wave and a wave variable method was proposed to guarantee the tracking performance of the slave. Chen *et al.* [31] developed a integrated control method to deal with the issue of communication delays and to cooperatively handle a certain object for multi-slave manipulators in the multilateral teleoperated systems. Sun *et al.* [32], [33] proposed a new 4 channel architecture with modified wave variable controller to improve the stability and transparency of the teleoperated systems. In addition, the authors furtuer proposed a neural network (NN) with four channel method to ensure the passivity and high transparency of the systems and to estimate the dynamic uncertainties of the systems [34]. An approach with four channel structure of Lawrence was proposed to guarantee the passivity through the wave variable and the absolute stability of the system in terms of position and force [35]. In [36], a novel structure based on four channel was presented to enhance the tracking performance of position and force and to improve the transparency of the systems and to improve the perception bandwidth. Pitakwatchara [37] *et al.* developed a novel wave variable method with wave correction scheme to handle the problem of motion incongruity in task space for the teleoperated system.

In this paper, we proposed a wave variable method with four channel architecture to achieve a stable tracking performance in terms of position, velocity and force reflection under condition of constant time delay. The effectiveness of the proposed method verified by the simulation results.

After reading the details on teleoperated system and general wave variable method and passivity in Section II. Section III is to present the proposed approach. The simulation results of position/velocity tracking and force reflection to demonstrate the performance of the proposed wave variable methods in Section IV. Section V is the conclusion and future work.

II. BACKGROUND KNOWLEDGE
A. TELEOPERATED SYSTEM
As presented in Fig. 1, the dynamics of teleoperated system can be represented as [14], [38]

$$m_m(x_m)\ddot{x}_m + c_m(x_m, \dot{x}_m) + g_m(x_m) = f_m + f_h \quad (1)$$

$$m_s(x_s)\ddot{x}_s + c_s(x_s, \dot{x}_s) + g_s(x_s) = f_s - f_e \quad (2)$$

where m_m and m_s indicate the inertia matrix for the teleoperation system. c_m and c_s are the Coriolis and Centrifugal force
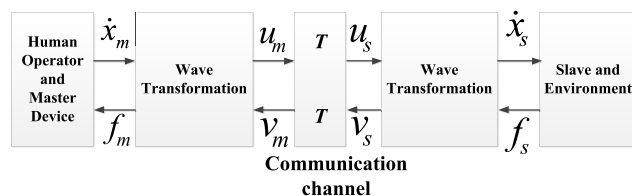

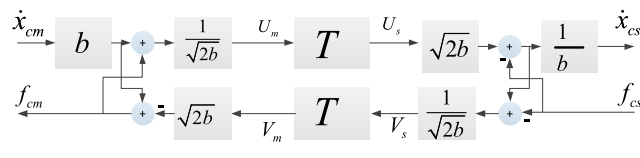**FIGURE 1.** Traditional teleoperated system.

FIGURE 2. The general wave variable method.

matrix of the master and the slave, respectively. g_m and g_s are the gravitational force matrix of the system. x_i is the position, $\dot{x}_i$ is the velocity, $\ddot{x}_m$ is the acceleration ($i = m, s$). f_m indicates the force of the master, while f_h is the applied force of the human operator. f_s and f_e represent force of the slave and interaction force of the operated system, respectively [39].

- *Property 1.* $m_i(x_i)$ is a symmetric positive-define matrix of the teleoperated system.
- *Property 2.* $z^T(\dot{m}_i(x_i) - 2c_i(x_i, \dot{x}_i))z = 0, \forall z \in R^n$.
- *Property 3.* m_i is a bounded term. g_i is also a bounded term. It satisfies $\forall x_i, \dot{x}_i \in R^n, \exists K_{ci} \in R > 0$ according to c_i, so that $\| c_i(x_i, \dot{x}_i) \| \leq K_{ci}|\dot{x}_i|$.

B. TRADITIONAL WAVE VARIABLE METHOD
Fig. 2 displays the general wave variable method for the teleoperated system [40], [41]. The wave variables U_m, V_m, U_s, and V_s can be defined as following.

$$U_m = \frac{b}{\sqrt{2b}}\dot{x}_{cm} + \frac{1}{\sqrt{2b}}f_{cm} \quad (3)$$

$$V_m = \frac{b}{\sqrt{2b}}\dot{x}_{cm} - \frac{1}{\sqrt{2b}}f_{cm} \quad (4)$$

$$U_s = \frac{b}{\sqrt{2b}}\dot{x}_{cs} + \frac{1}{\sqrt{2b}}f_{cs} \quad (5)$$

$$V_s = \frac{b}{\sqrt{2b}}\dot{x}_{cs} - \frac{1}{\sqrt{2b}}f_{cs} \quad (6)$$
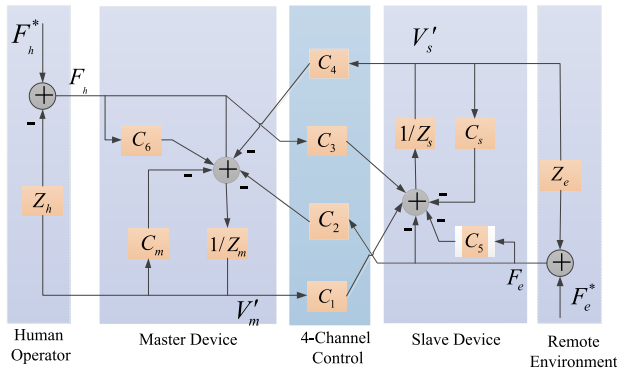
where wave impedance $b > 0$.

In Fig. 2, the wave variables based on time delay T can be represented as

$$U_s(t) = U_m(t - T) \quad (7)$$

$$V_m(t) = V_s(t - T) \quad (8)$$

where U_i and V_i ($i = m, s$) indicate the power variables which transferred between the velocity $\dot{x}_{ci}$ and the force f_{ci} of the master and the slave.

FIGURE 3. The general 4-channel control teleoperation system without time delay.

Based on Eqs. (3)-(8), the force f_{cm} and the velocity $\dot{x}_{cs}$ can be represented as

$$f_{cm}(t) = f_{cs}(t-T) + b\{\dot{x}_{cm}(t) - \dot{x}_{cs}(t-T)\} \quad (9)$$

$$\dot{x}_{cs}(t) = \dot{x}_{cm}(t-T) + \frac{1}{b}\{f_{cm}(t-T) - f_{cs}(t)\} \quad (10)$$

C. FOUR CHANNEL TELEOPERATION SYSTEM

Fig. 3 presents the general four channel teleoperated architecture.

The dynamics of four channel architecture can be represented as

$$F'_h = F_h + Z_h V'_m \quad (11)$$

$$F'_e = F_e + Z_e V'_s \quad (12)$$

$$Z_{cm}V'_m + C_4 V'_s = (1 + C_6)F_h - C_2 F_e \quad (13)$$

$$C_1 V'_m - Z_{ce} V'_s = (1 + C_5)F_e - C_3 F_h \quad (14)$$

where $Z_{cm} = Z_m + C_m, Z_{ce} = Z_s + C_s$. F'_h and F'_e indicate the applied force of the human operator and the environmental force or the environment. F_h is the interaction force of the human operator and the master device. F_e represents the interaction force of the environment and the slave device. Z_h is the impedance of the human operator. Z_e is the impedance of the environment. V'_m and V'_s indicate the velocities of the master device and the slave device. $C_1 - C_6$ are the enrollment parameters to impact the transparency performance of the teleoperated system[1]. Z_i and $C_i, (i = m, s)$ are the impedance parameters and the local position control parameters of the master device and the slave device.

III. METHOD
A. WAVE VARIABLE METHOD WITH FOUR CHANNEL ARCHITECTURE

Fig. 4 displays the proposed wave variable approach with 4 channel structure. Inspired by [42], [43], the relationship of intermediate variable U_s and V_m can be represented as

$$U_s(t) = 2U_{cm}(t-T) - V_{cs}(t) \quad (15)$$

$$V_m(t) = 2V_{cs}(t-T) + U_{cm}(t) \quad (16)$$

[1]Enrollment parameters $C_1 - C_6$ must be selected properly.

To reduce the impacts of wave reflections, impedance matching is employed. According to Fig. 4, U_m and V_s can be derived as

$$U_m = \{f_{cm} + b(\dot{x}_{cm} - \frac{1}{b}f_{cm})\}\frac{1}{2b} \quad (17)$$

$$U_m = \frac{b}{\sqrt{2b}}\dot{x}_{cm} \quad (18)$$

$$V_s = \frac{1}{\sqrt{2b}}\{-(b\dot{x}_{cs} + f_{cs}) + b\dot{x}_{cs}\} \quad (19)$$

$$V_s = -\frac{1}{\sqrt{2b}}f_{cs} \quad (20)$$

Based on Fig. 4 and Eqs. (17)-((20)), $f_{cm}, V_m, \dot{x}_{cs}$, and U_s can be represented as follows:

$$f_{cm} = -\sqrt{2b}V_m + b(\dot{x}_{cm} - \frac{1}{b}f_{cm}) \quad (21)$$

$$f_{cm} = \frac{1}{2}(b\dot{x}_{cm} - \sqrt{2b}V_m) \quad (22)$$

$$V_m = \frac{1}{\sqrt{2b}}(b\dot{x}_{cm} - 2f_{cm}) \quad (23)$$

$$\dot{x}_{cs} = \frac{1}{b}\{\sqrt{2b}U_s - (f_{cs} + b\dot{x}_{cs})\} \quad (24)$$

$$U_s = \frac{1}{\sqrt{2b}}(2b\dot{x}_{cs} + f_{cs}) \quad (25)$$

According to Eqs. (17)-(25), one has

$$\begin{cases} U_m = \dfrac{b\dot{x}_{cm}}{\sqrt{2b}} \\ V_s = \dfrac{-f_{cs}}{\sqrt{2b}} \\ V_m = \dfrac{b\dot{x}_{cm} - 2f_{cm}}{\sqrt{2b}} \\ U_s = \dfrac{2b\dot{x}_{cs} + f_{cs}}{\sqrt{2b}} \end{cases} \quad (26)$$

The wave variable method can be regarded as a two-port system. According to the passive theory, the power of the system can be calculated as

$$\begin{aligned} P &= P_{in} + P_{out} \\ &= \dot{x}_{cm}^T f_{cm} - \dot{x}_{cs}^T f_{cs} \\ &= U_m^T U_m + V_s^T V_s - U_m^T V_m + U_s^T V_s \end{aligned} \quad (27)$$

The energy E of the two-port system can be represented as

$$\begin{aligned} E &= \int_{t_0}^{\tau - t_0}(P_{in} + P_{out})dt \\ &= \int_{t_0}^{\tau - t_0}(\dot{x}_{cm}^T f_{cm} - \dot{x}_{cs}^T f_{cs})dt \\ &= \frac{1}{2}\int_{t_0}^{\tau - t_0} U_m^T U_m dt + \frac{1}{2}\int_{t_0}^{\tau - t_0} V_s^T V_s dt \end{aligned} \quad (28)$$

When $E > 0$, the teleoperated system is passive, therefore the stability can be guaranteed.

Based on the wave variable method [42], the four channel architecture can be represented as

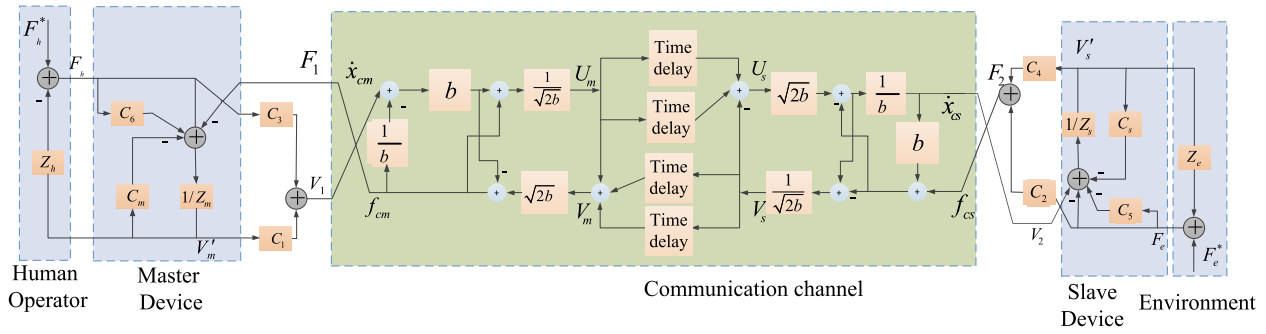$$V_1 = C_3 F_h + C_1 V'_m \quad (29)$$

FIGURE 4. The proposed control architecture contains a four-channel scheme with wave variable method for the teleoperation system.

$$F_2 = C_2 F_e + C_4 V_s' \tag{30}$$

$$V_m' Z_m = -V_m' C_m + F_h(1 + C_6) - F_1 \tag{31}$$

$$V_s' Z_s = -V_s' C_s - F_e(1 + C_5) + V_2 \tag{32}$$

$$F_1 = F_h(1 + C_6) - V_m' Z_{tm} \tag{33}$$

$$V_2 = F_e(1 + C_5) + V_s' Z_{te} \tag{34}$$

According to the proposed 4 channel control and wave-variable method, one has

$$U_m = \frac{bV_1}{\sqrt{2b}} \tag{35}$$

$$V_s = \frac{-F_2}{\sqrt{2b}} \tag{36}$$

$$V_m = \frac{bV_1 - 2F_1}{\sqrt{2b}} \tag{37}$$

$$U_s = \frac{2bV_2 + F_2}{\sqrt{2b}} \tag{38}$$

On the basis of Eq. (15) and Eqs. (35)-(38), it has

$$\frac{2bV_2(t) + F_2(t)}{\sqrt{2b}} = 2\frac{bV_1(t-T)}{\sqrt{2b}} - (-\frac{F_2(t)}{\sqrt{2b}}) \tag{39}$$

$$-V_2(t) = -V_1(t-T) \tag{40}$$

$$-V_2 = -V_1 e^{-sT} \tag{41}$$

According to Eq. (16) and Eqs. (35)-(38), it has

$$\frac{bV_1(t) - 2F_1(t)}{\sqrt{2b}} = 2(-\frac{F_2(t-T)}{\sqrt{2b}}) + \frac{bV_1(t)}{\sqrt{2b}} \tag{42}$$

$$F_1(t) = F_2(t-T) \tag{43}$$

$$F_1 = F_2 e^{-sT} \tag{44}$$

Then, based on Eq. (41) and Eq. (44), one has

$$\begin{bmatrix} F_1 \\ -V_2 \end{bmatrix} = \begin{bmatrix} 0 & e^{-sT} \\ -e^{-sT} & 0 \end{bmatrix} \begin{bmatrix} V_1 \\ F_2 \end{bmatrix} \tag{45}$$

Thus, the scattering norm can be derived as

$$H(s) = \begin{bmatrix} 0 & e^{-sT} \\ -e^{-sT} & 0 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \tag{46}$$

Let $s = jw$, then

$$sup^{\frac{1}{2}}[H^*(jw)H(jw)] = sup^{\frac{1}{2}} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} = 1 \tag{47}$$

According to the [44], [45], $sup^{\frac{1}{2}}[H^*(jw)H(jw)] = 1$ indicates that the teleoperated system is passive.

B. PERFORMANCE EVALUATION
In order to obtain a good transparency of the teleoperated system, the parameters must be satisfied the conditions, i.e., $V_h = V_e, Z_{t0} = Z_e, Z_{te} = Z_h$.

$$Z_{t0} = \frac{F_e}{V_e} = \frac{h_{11} + \Delta h Z_e}{1 + h_{22} Z_e} \tag{48}$$

$$Z_{te} = \frac{F_h}{V_h} = \frac{h_{11} + Z_h}{\Delta h + h_{22} Z_h} \tag{49}$$

where $\Delta h = h_{11}h_{22} - h_{12}h_{21}$.

A perfect transparency can be achieved when $h_{11} = h_{22} = 0, h_{12}h_{21} = -1$.

The desired transparency conditions of the teleoperated system with four channel architecture can be acquired as

$$C_1 = Z_{cs} = Z_s + C_s \tag{50}$$

$$C_2 = (1 + C_6) \tag{51}$$

$$C_3 = (1 + C_5) \tag{52}$$

$$C_4 = -Z_{cm} = -Z_m - C_m \tag{53}$$

where $C_2 = 0$ and $C_3 = 0$ can not be true at the same time.[2]

IV. SIMULATION RESULTS
A. SIMULATION SETUP
The parameters of the teleoperated system are chosen based on pilot experiment beforehand. Specifically, $b = 800$ N-s/m. The time delays are set as 200ms, 400ms, 800ms, and 1200ms. We assume that the external incentive F_h is a sine function. The slave follows the master's free motion. The parameters are selected as: $C_2 = C_3 = 0.495$. $C_5 = C_6 = -0.495$. The masses $M_m = M_s = 0.95kg$. $C_m = 50M_m(1 + s)/s$, $C_s = 50M_s(1 + s)/s$. $Z_m = M_m s$, $Z_s = M_s s$.

B. PERFORMANCE ANALYSIS
In order to verify the performance of the proposed method under different time delays, mean absolute error (MAE) of

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[2]We can choose the appropriate values of $C_1 - C_6$ to achieve a good transparency of the teleoperated system.
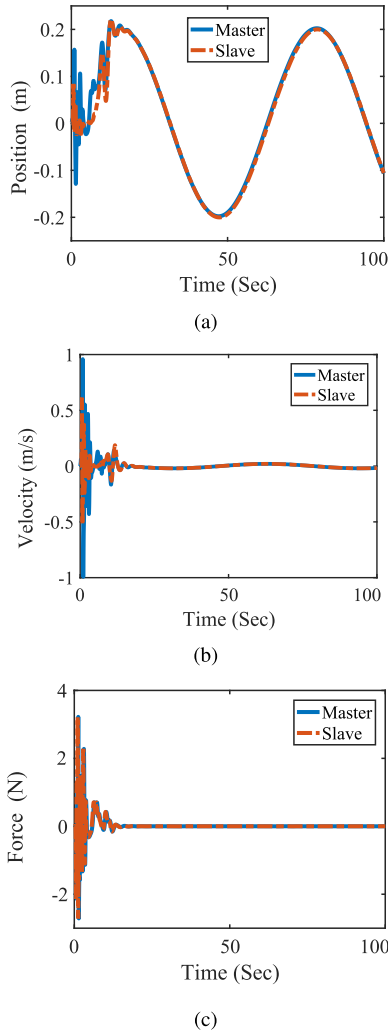
FIGURE 5. Tracking performance under time delay 200ms. (a) Trajectory tracking for the master (blue) and the slave (red). (b) Velocity tracking for the master and the slave. (c) Force tracking for the master (blue) and the slave (red).

FIGURE 6. Tracking performance under time delay 400ms. (a) Trajectory tracking for the master (blue) and the slave (red). (b) Velocity tracking for the master and the slave. (c) Force tracking for the master (blue) and the slave (red).

the tracking performance is introduced in this paper. MAE can be represented as
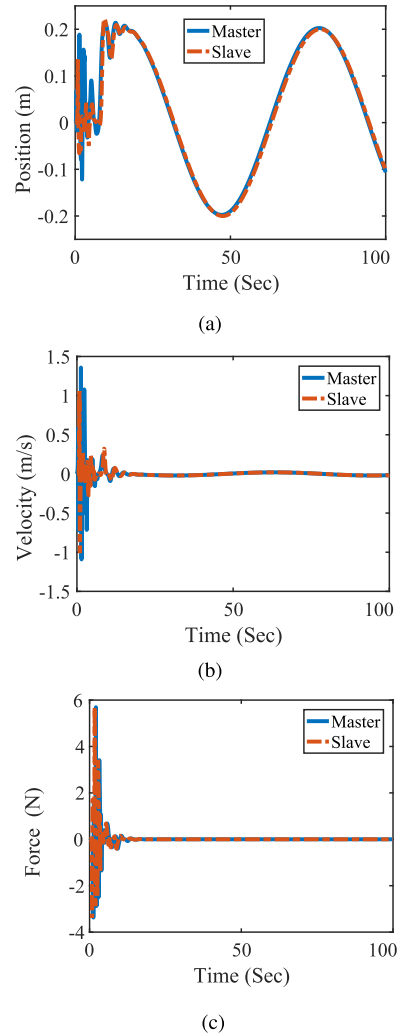
$$MAE = \frac{1}{N} \sum_{i=1}^{N} |z_i - \hat{z}_i| \qquad (54)$$

where z_i and $\hat{z}_i$ are the desired value and the actual value, respectively. N represents the number of sample value.

C. TRACKING PERFORMANCE

1) CASE 1-PERFORMANCE TRACKING UNDER TIME DELAY 200MS

Fig. 5(a) shows the position tracking performance of the teleoperated system with time delay 200ms. Blue curves and red curves are represent the performance of the master and the slave, respectively. It can be seen that the curves are oscillating at the beginning, but the slave can completely tracking the position of the master soon. In the Fig. 5(b),

the velocities of the system are very small, and the slave can track perfectly the master since the system employs a same structure for master-slave framework.

Fig. 5(c) shows the force reflection performance of the system. It can be seen that the slave can track the master perfectly. It can be concluded that the force line of the master and the slave have nearly no distortion. The performance of force tracking demonstrated the transparency of the teleoperated system can be guaranteed.

2) CASE 2-PERFORMANCE TRACKING UNDER TIME DELAY 400MS

The tracking performance of the master and the slave under time delay 400ms are presented in Figs. 6(a)-6(c), respectively. Figs. 6(a)-6(b) show that the trajectories tracking performance of the slave follow that of the master effectively, however, the process of position tracking are unstable due to the relatively large initial position difference. It can be drawn
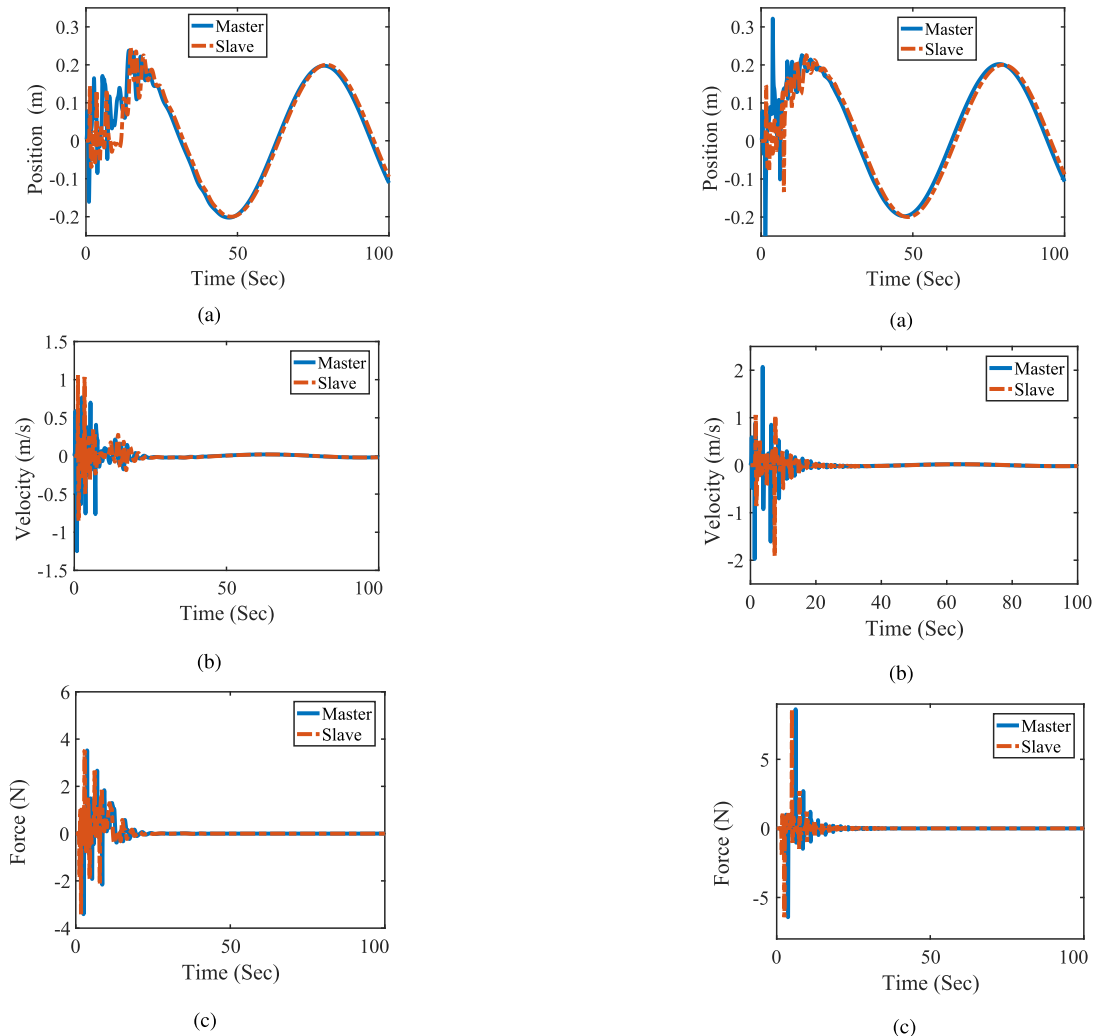
FIGURE 7. Tracking performance under time delay 800ms. (a) Trajectory tracking for the master (blue) and the slave (red). (b) Velocity tracking for the master and the slave. (c) Force tracking for the master (blue) and the slave (red).

FIGURE 8. Tracking performance under time delay 1200ms. (a) Trajectory tracking for the master (blue) and the slave (red). (b) Velocity tracking for the master and the slave. (c) Force tracking for the master (blue) and the slave (red).

a similar conclusion that the force tracking of the slave can track that of the master with no distortion in Fig. 6(c).

3) CASE 3-PERFORMANCE TRACKING UNDER TIME DELAY 800MS AND 1200MS

The tracking performance under time delay 800ms and 1200ms are shown in Figs. 7(a)-8(c). In Figs. 7(a)-7(b), the slave barely follows the movement of the master. In Figs. 8(a)-8(b), there are a little delay in the tracking performance for the master and the slave. In Figs. 7(a)-8(b), it has bigger delay in the tracking performance in comparison with that of time delay 800ms.

For the force tracking performance of the master and the slave under time delays 800ms and 1200ms, it has a similar conclusion that the process of force tracking are of relative distortion at the beginning, then the rest process becomes stable to the end, which are shown in Figs. 7(c) and 8(c).

Compared with the tracking performance of cases 1 and 2, the performance of case 3 are more rough. For the trajectories tracking, the performance under time delay 800ms are best in comparison with that of under time delay 1200ms.

Table 1 and Fig. 9 show the MAE of position and velocity. It can be seen that the values of MAE with related to position and velocity become larger follow the increasing of time delay. We can conclude that the performance of tracking get worse as the greater of time delay. The tracking performance with time delay 200ms perform best in comparison with those of 400ms, 800ms, and 1200ms.

4) CASE 4-COMPARATIVE EXPERIMENT

In this section, we perform a comparative test between a four-channel and proposed scheme. In this test, the delay time is set as 1000ms. Figs. 10 and 11 show the tracking performance by using the four-channel and proposed method. It can be seen that the four-channel scheme and proposed method
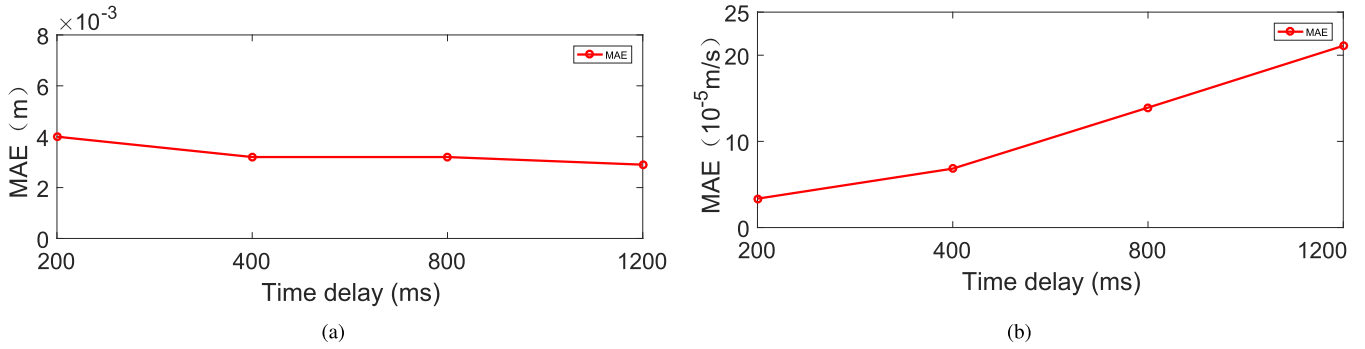
FIGURE 9. Performance analysis under different time delays. (a) MAE of position. (b) MAE of velocity.

TABLE 1. Mean absolute error of the tracking performance under different time delay conditions.

Time delay	Position	Velocity
200ms	0.0040	3.3503×10^{-05}
400ms	0.0032	6.8380×10^{-05}
800ms	0.0032	13.916×10^{-05}
1200ms	0.0029	21.090×10^{-05}

TABLE 2. Mean absolute error of the tracking performance between four-channel and proposed scheme.

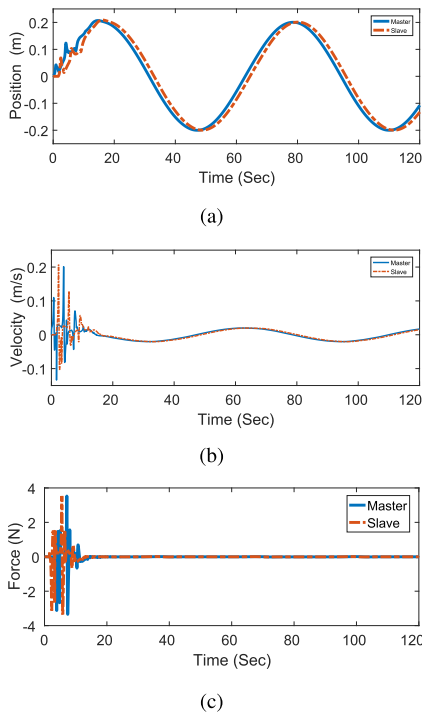| Scheme	Position	Velocity
Four-channel	0.0204	0.0060
Proposed	0.0200	0.0042

FIGURE 10. Tracking performance with four-channel scheme. (a) Trajectory tracking for the master (blue) and the slave (red). (b) Velocity tracking for the master and the slave. (c) Force tracking for the master (blue) and the slave (red).

FIGURE 11. Tracking performance with proposed scheme. (a) Trajectory tracking for the master (blue) and the slave (red). (b) Velocity tracking for the master and the slave. (c) Force tracking for the master (blue) and the slave (red).

can achieve good performance in the tracking test. However, it is shown that the proposed method can enhance the position and velocity tracking with smaller MAE in comparison with that of four-channel scheme in Table 2.
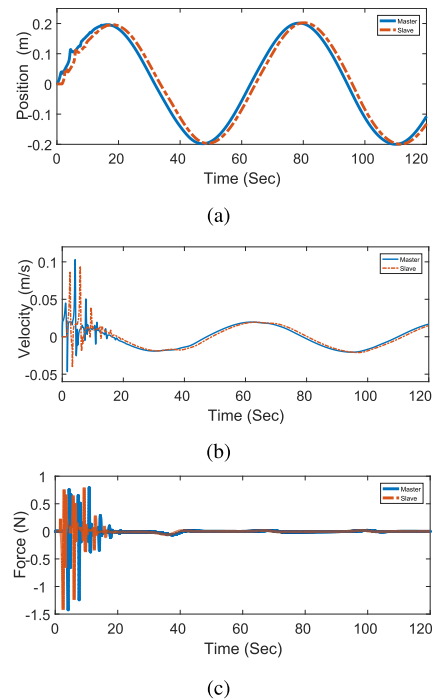
V. CONCLUSION AND FUTURE WORK

In this work, a novel wave variable approach with four channel architecture is proposed to cope with the problem of time delay of the communication channel in the teleoperated system. The proposed approach can compensate the influence of the time delay and can achieve good performance in position/velocity tracking and force reflection. In addition,

the stability and the transparency of the system can be guaranteed. The proposed algorithm is tested with time delays 200ms, 400ms, 800ms, and 1200ms. The simulation results verified the effectiveness and feasibility of the proposed method and it is demonstrated that the tracking performance is best when the time delay is 200ms. The proposed method provides a effective solution to deal with the time delay problem.

In future, the actual experimental application should be taken into consideration [46], such as teleoperated minimally invasive surgery system [47], [48], maintenance [49], and medical rehabilitation [50]. Furthermore, the different multiple channels and wave variable will be developed to deal with the issues of random time delay.
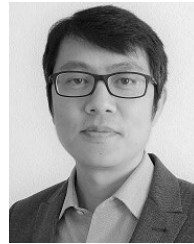
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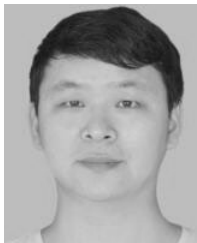
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