A wave variable approach with multiple channel architecture for teleoperated system

Jing Luo, Chao Liu, Ning Wang, Chenguang Yang

To cite this version:

Jing Luo, Chao Liu, Ning Wang, Chenguang Yang. A wave variable approach with multiple channel architecture for teleoperated system. IEEE Access, 2019, 7, pp.143912-143920. 10.1109/ACCESS.2019.2945674 . lirmm-02315649

IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received September 17, 2019, accepted September 29, 2019, date of publication October 4, 2019, date of current version October 16, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2945674

A Wave Variable Approach With Multiple Channel Architecture for Teleoperated System

JING LUO[1], (Student Member, IEEE), CHAO LIU[2], (Senior Member, IEEE), NING WANG[3], (Member, IEEE), AND CHENGUANG YANG[3], (Senior Member, IEEE)

[1]Key Laboratory of Autonomous Systems and Networked Control, College of Automation Science and Engineering, South China University of Technology, Guangzhou 510640, China
[2]Department of Robotics, LIRMM, UMR5506, University of Montpellier-CNRS, 34095 Montpellier, France
[3]Bristol Robotics Laboratory, University of the West of England, Bristol BS16 1QY, U.K.

Corresponding author: Chenguang Yang (cyang@ieee.org)

This work was supported in part by the Engineering and Physical Sciences Research Council (EPSRC) under Grant EP/S001913, in part by CNRS-NSFC under Grant PRC2104, and in part by the National Natural Science Foundation of China under Grant 61811530281.

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 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

The associate editor coordinating the review of this manuscript and approving it for publication was Tai-Hoon Kim.

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]

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

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

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 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].

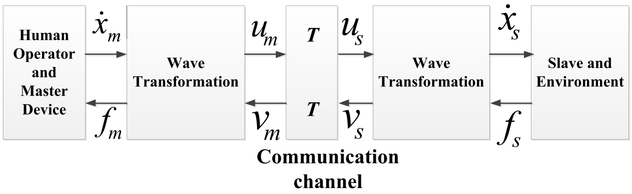


FIGURE 1. Traditional teleoperated system.

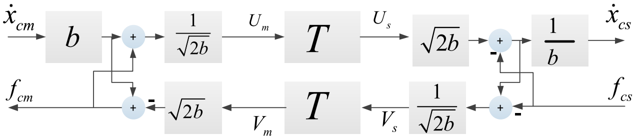


FIGURE 2. The general wave variable method.

- *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.

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

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

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

$$V_s = \frac{b}{\sqrt{2b}}\dot{x}_{cs} - \frac{1}{\sqrt{2b}}f_{cs} \tag{6}$$

where wave impedance $b > 0$.

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

$$U_s(t) = U_m(t - T) \tag{7}$$

$$V_m(t) = V_s(t - T) \tag{8}$$

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.

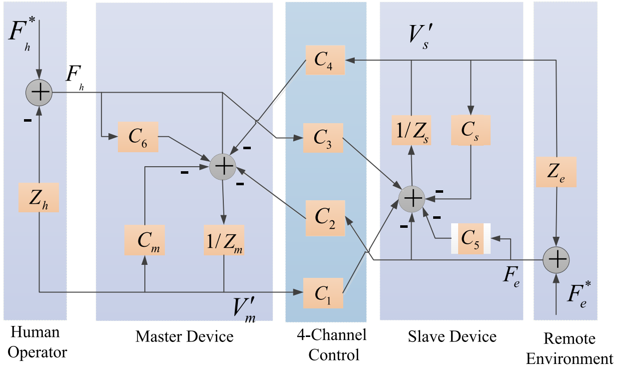


FIGURE 3. **The general 4-channel control teleoperation system without time delay.**

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

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

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

C. FOUR CHANNEL TELEOPERATION SYSTEM

Fig. 3 presents the general four channel teleoperated architecture.

The dynamics of four channel architecture can be represented as

$$F_h' = F_h + Z_h V_m' \tag{11}$$

$$F_e' = F_e + Z_e V_s' \tag{12}$$

$$Z_{cm} V_m' + C_4 V_s' = (1+C_6)F_h - C_2 F_e \tag{13}$$

$$C_1 V_m' - Z_{ce} V_s' = (1+C_5)F_e - C_3 F_h \tag{14}$$

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

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

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

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

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

$$U_m = \frac{b}{\sqrt{2b}}\dot{x}_{cm} \tag{18}$$

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

$$V_s = -\frac{1}{\sqrt{2b}}f_{cs} \tag{20}$$

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

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

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

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

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

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

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

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

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

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

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

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

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

$$V_1 = C_3 F_h + C_1 V_m' \tag{29}$$

---

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

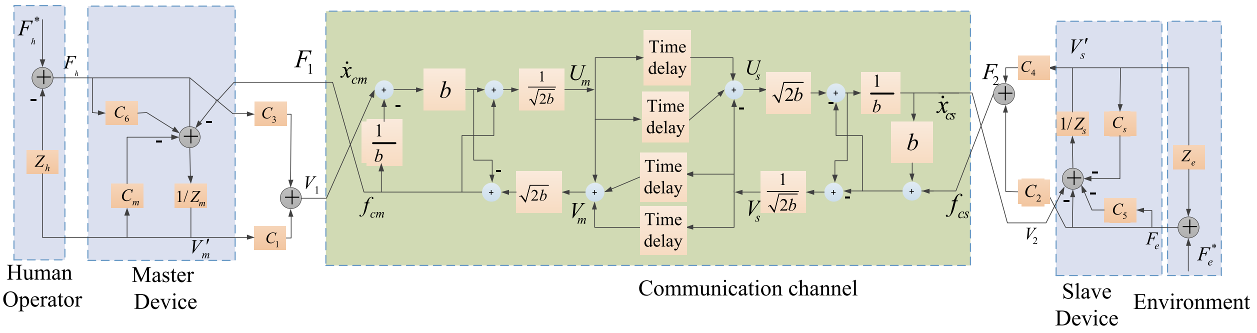


FIGURE 4. The proposed control architecture contains a four-channel scheme with wave variable method for the teleoperation system.

$$F_2 = C_2F_e + C_4V_s' \tag{30}$$
$$V_m'Z_m = -V_m'C_m + F_h(1+C_6) - F_1 \tag{31}$$
$$V_s'Z_s = -V_s'C_s - F_e(1+C_5) + V_2 \tag{32}$$
$$F_1 = F_h(1+C_6) - V_m'Z_{tm} \tag{33}$$
$$V_2 = F_e(1+C_5) + V_s'Z_{te} \tag{34}$$

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

$$\frac{2bV_2(t) + F_2(t)}{\sqrt{2b}} = 2\frac{bV_1(t-T)}{\sqrt{2b}} - (-\frac{F_2(t)}{\sqrt{2b}}) \tag{39}$$
$$-V_2(t) = -V_1(t-T) \tag{40}$$
$$-V_2 = -V_1e^{-sT} \tag{41}$$

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

$$\frac{bV_1(t) - 2F_1(t)}{\sqrt{2b}} = 2(-\frac{F_2(t-T)}{\sqrt{2b}}) + \frac{bV_1(t)}{\sqrt{2b}} \tag{42}$$
$$F_1(t) = F_2(t-T) \tag{43}$$
$$F_1 = F_2e^{-sT} \tag{44}$$

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., $V_h = V_e, Z_{t0} = Z_e, Z_{te} = Z_h$.

$$Z_{t0} = \frac{F_e}{V_e} = \frac{h_{11} + \Delta hZ_e}{1 + h_{22}Z_e} \tag{48}$$
$$Z_{te} = \frac{F_h}{V_h} = \frac{h_{11} + Z_h}{\Delta h + h_{22}Z_h} \tag{49}$$

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

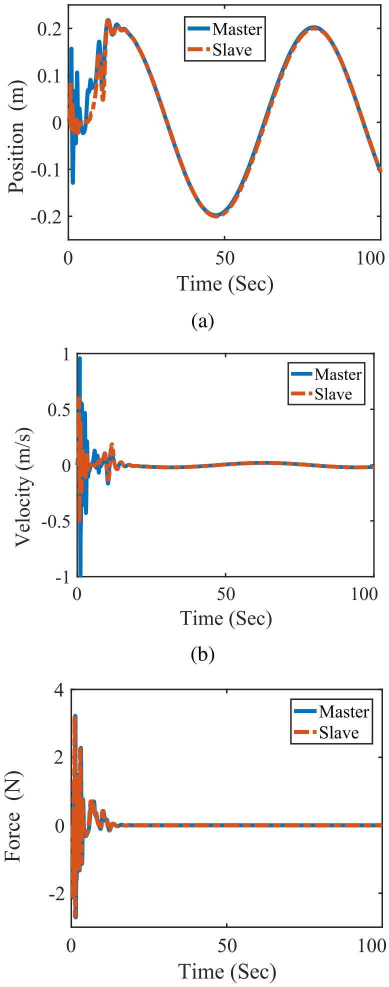
The parameters of the teleoperated system are chosen based on pilot experiment beforehand. Specifically, $b = 800$ N-s/m. The time delays are set as 200ms, 400ms, 800ms, and 1200ms. We assume that the external incentive F_h is a sine function. The slave follows the master's free motion. The parameters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

B. PERFORMANCE ANALYSIS

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

---

[2] We can choose the appropriate values of $C_1 - C_6$ to achieve a good transparency of the teleoperated system.

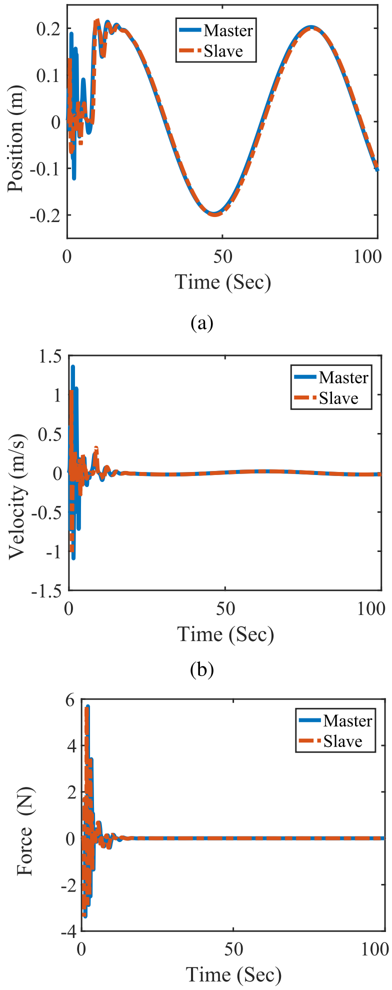


(a)

(b)

(c)

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).**



(a)

(b)

(c)

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

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|z_i - \hat{z}_i| \tag{54}$$

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

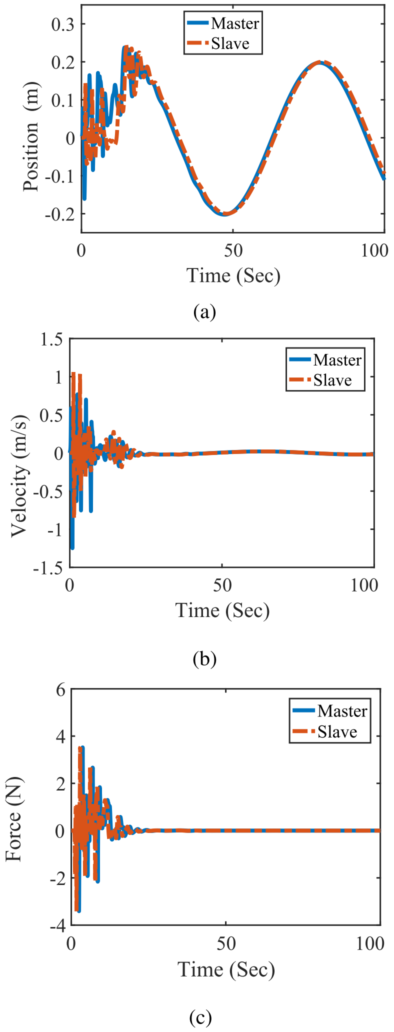
1) CASE 1-PERFORMANCE TRACKING UNDER TIME DELAY 200MS

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



(a)

(b)

(c)

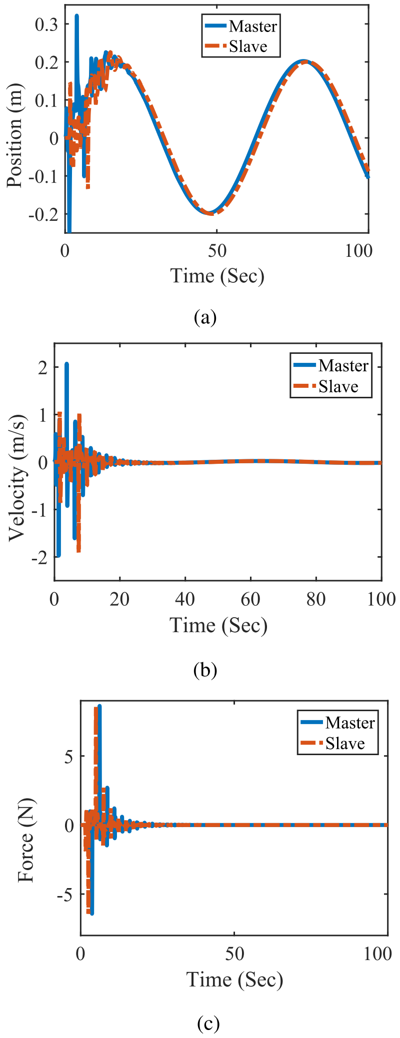
FIGURE 7. Tracking performance under time delay 800ms. (a) Trajectory tracking for the master (blue) and the slave (red). (b) Velocity tracking for the master and the slave. (c) Force tracking for the master (blue) and the slave (red).

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).



(a)

(b)

(c)

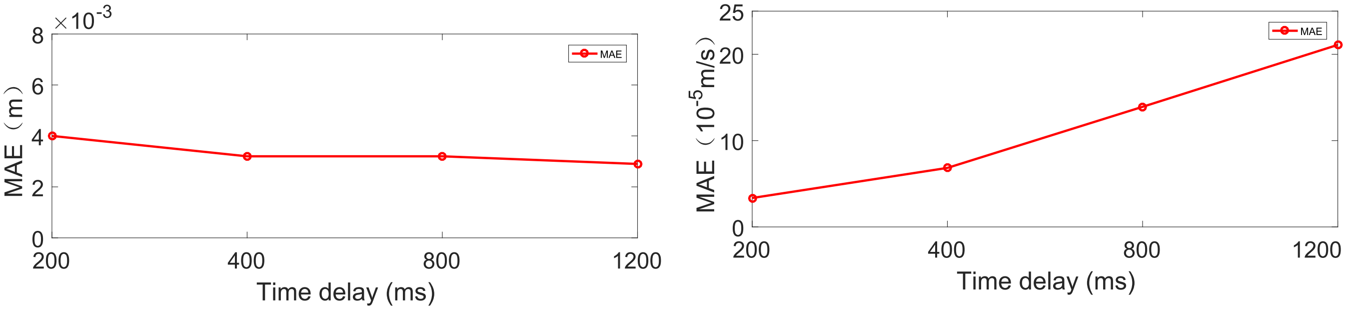
FIGURE 8. Tracking performance under time delay 1200ms. (a) Trajectory tracking for the master (blue) and the slave (red). (b) Velocity tracking for the master and the slave. (c) Force tracking for the master (blue) and the slave (red).

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



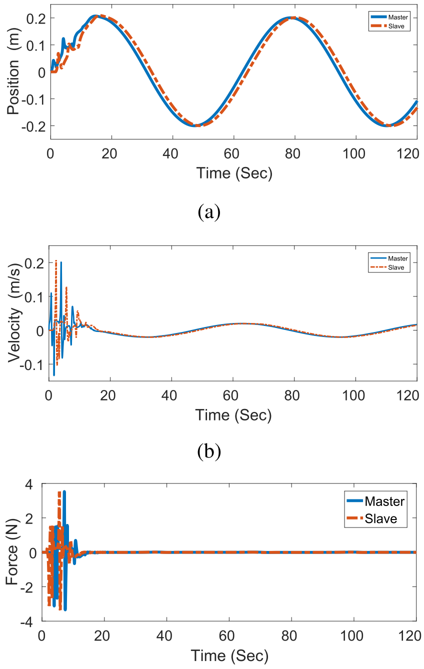
(a)

(b)

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}



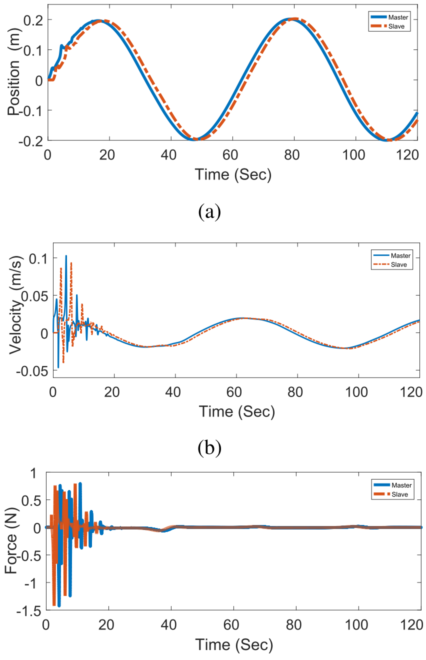
(c)

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).**

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.

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



(c)

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).**

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.

REFERENCES

[1] J. Artigas and G. Hirzinger, "A brief history of DLR's space telerobotics and force feedback teleoperation," *Acta Polytechnica Hungarica*, vol. 13, no. 1, pp. 239–249, Jan. 2016.

[2] M. L. Gernhardt, E. Z. Crues, P. Bielski, D. Dexter, H. L. Litaker, S. P. Chappell, K. H. Beaton, and O. S. Bekdash, "Simulation based studies of low latency teleoperations for NASA exploration missions," NASA Johnson Space Center, Inst. Elect. Electron. Eng., Houston, TX, USA, Tech. Rep. JSC-CN-36630, 2017.

[3] M. V. Jakuba, C. R. German, A. D. Bowen, L. L. Whitcomb, K. Hand, A. Branch, S. Chien, and C. McFarland, "Teleoperation and robotics under ice: Implications for planetary exploration," in *Proc. IEEE Aerosp. Conf.*, Mar. 2018, pp. 1–14.

[4] I. Kardan and A. Akbarzadeh, "Output feedback assistive control of single-DOF SEA powered exoskeletons," *Ind. Robot, Int. J.*, vol. 44, no. 3, pp. 275–287, May 2017.

[5] T. Kot and P. Novák, "Application of virtual reality in teleoperation of the military mobile robotic system TAROS," *Int. J. Adv. Robotic Syst.*, vol. 15, no. 1, Jan. 2018, Art. no. 1729881417751545.

[6] R. M. Murray, *A Mathematical Introduction to Robotic Manipulation*. Boca Raton, FL, USA: CRC Press, 2017.

[7] J. M. Aitken, S. M. Veres, A. Shaukat, Y. Gao, E. Cucco, L. A. Dennis, M. Fisher, J. A. Kuo, T. Robinson, and P. Mort, "Autonomous nuclear waste management," *IEEE Intell. Syst.*, vol. 33, no. 6, pp. 47–55, Nov./Dec. 2018.

[8] P. Arbeille, K. Zuj, A. Saccomandi, E. Andre, C. De La Porte, and M. Georgescu, "Tele-operated echography and remote guidance for performing tele-echography on geographically isolated patients," *J. Clin. Med.*, vol. 5, no. 6, p. 58, Jun. 2016.

[9] J. A. Camacho, C. D. Chamorro, J. A. Sanabria, N. G. Caicedo, and J. I. Garcia, "Implementation of o service-oriented architecture for applications in physical rehabilitation," *Facultad De Ingeniería*, vol. 26, no. 46, pp. 113–121, Sep./Dec. 2017.

[10] C. Yang, J. Luo, Y. Pan, Z. Liu, and C.-Y. Su, "Personalized variable gain control with tremor attenuation for robot teleoperation," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 48, no. 10, pp. 1759–1770, Oct. 2018.

[11] Q. Lin and C. Kuo, "On applying virtual reality to underwater robot Teleoperation and pilot training," *Int. J. Virtual Reality (IJVR)*, vol. 5, no. 1, pp. 71–91, 2015.

[12] P. Huang, M. Sithu, and Y. Ishibashi, "Media synchronization in networked multisensory applications with haptics," in *MediaSync*. Berlin, Germany: Springer, 2018, pp. 295–317.

[13] C. Yang, J. Luo, C. Liu, M. Li, and S.-L. Dai, "Haptics electromyogrphy perception and learning enhanced intelligence for teleoperated robot," *IEEE Trans. Autom. Sci. Eng.*, to be published.

[14] J. Luo, C. Yang, N. Wang, and M. Wang, "Enhanced teleoperation performance using hybrid control and virtual fixture," *Int. J. Syst. Sci.*, vol. 50, no. 3, pp. 451–462, 2019.

[15] Z. Li and C.-Y. Su, "Neural-adaptive control of single-master–multiple-slaves teleoperation for coordinated multiple mobile manipulators with time-varying communication delays and input uncertainties," *IEEE Trans. Neural Netw. Learn. Syst.*, vol. 24, no. 9, pp. 1400–1413, Sep. 2013.

[16] Z. Lu, P. Huang, and Z. Liu, "Relative impedance-based internal force control for bimanual robot teleoperation with varying time delay," *IEEE Trans. Ind. Electron.*, vol. 67, no. 1, pp. 778–789, Jan. 2020.

[17] Z. Lu, P. Huang, and Z. Liu, "Predictive approach for sensorless bimanual teleoperation under random time delays with adaptive fuzzy control," *Trans. Ind. Electron.*, vol. 65, no. 3, pp. 2439–2448, Mar. 2018.

[18] Z. Li, Y. Xia, and F. Sun, "Adaptive fuzzy control for multilateral cooperative teleoperation of multiple robotic manipulators under random network-induced delays," *IEEE Trans. Fuzzy Syst.*, vol. 22, no. 2, pp. 437–450, Apr. 2014.

[19] Z. Lu, P. Huang, P. Dai, Z. Liu, and Z. Meng, "Enhanced transparency dual-user shared control teleoperation architecture with multiple adaptive dominance factors," *Int. J. Control, Autom. Syst.*, vol. 15, no. 5, pp. 2301–2312, Oct. 2017.

[20] R. Oboe and P. Fiorini, "A design and control environment for Internet-Based telerobotics," *Int. J. Robot. Res.*, vol. 17, no. 4, pp. 433–449, Apr. 1998.

[21] N. Chopra, P. Berestesky, and M. W. Spong, "Bilateral teleoperation over unreliable communication networks," *IEEE Trans. Control Syst. Technol.*, vol. 16, no. 2, pp. 304–313, Mar. 2008.

[22] H. Sakai, D. Tomizuka, and K. Ohnishi, "Compliance control for stabilization of bilateral teleoperation system in the presence of time delay," in *Proc. IEEE Int. Conf. Mechatronics (ICM)*, Feb. 2017, pp. 62–67.

[23] S. F. Atashzar, I. G. Polushin, and R. V. Patel, "A small-gain approach for nonpassive bilateral telerobotic rehabilitation: Stability analysis and controller synthesis," *IEEE Trans. Robot.*, vol. 33, no. 1, pp. 49–66, Feb. 2017.

[24] N. A. Tanner and G. Niemeyer, "Improving perception in time-delayed telerobotics," *Int. J. Robot. Res.*, vol. 24, no. 8, pp. 631–644, 2005.

[25] 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, Feb. 2018.

[26] C. Yang, X. Wang, Z. Li, Y. Li, and C.-Y. Su, "Teleoperation control based on combination of wave variable and neural networks," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 47, no. 8, pp. 2125–2136, Aug. 2017.

[27] Y. Yuan, Y. Wang, and L. Guo, "Force reflecting control for bilateral teleoperation system under time-varying delays," *IEEE Trans. Ind. Informat.*, vol. 15, no. 2, pp. 1162–1172, Feb. 2019.

[28] S. Soyguder and T. Abut, "Haptic industrial robot control with variable time delayed bilateral teleoperation," *Ind. Robot, Int. J.*, vol. 43, no. 4, pp. 390–402, 2016.

[29] Y. Ye and P. X. Liu, "Improving haptic feedback fidelity in wave-variable-based teleoperation orientated to telemedical applications," *IEEE Trans. Instrum. Meas.*, vol. 58, no. 8, pp. 2847–2855, Aug. 2009.

[30] Y. Ye and P. X. Liu, "Improving trajectory tracking in wave-variable-based teleoperation," *IEEE/ASME Trans. Mechatronics*, vol. 15, no. 2, pp. 321–326, Apr. 2010.

[31] Z. Chen, Y.-J. Pan, and J. Gu, "Integrated adaptive robust control for multilateral teleoperation systems under arbitrary time delays," *Int. J. Robust Nonlinear Control*, vol. 26, no. 12, pp. 2708–2728, Aug. 2016.

[32] D. Sun, F. Naghdy, and H. Du, "Transparent four-channel bilateral control architecture using modified wave variable controllers under time delays," *Robotica*, vol. 34, no. 4, pp. 859–875, 2016.

[33] D. Sun, F. Naghdy, and H. Du, "Wave-variable-based passivity control of four-channel nonlinear bilateral teleoperation system under time delays," *IEEE/ASME Trans. Mechatronics*, vol. 21, no. 1, pp. 238–253, Feb. 2016.

[34] D. Sun, F. Naghdy, and H. Du, "Neural network-based passivity control of teleoperation system under time-varying delays," *IEEE Trans. Cybern.*, vol. 47, no. 7, pp. 1666–1680, Jul. 2017.

[35] A. Haddadi and K. Hashtrudi-Zaad, "Robust stability of teleoperation systems with time delay: A new approach," *IEEE Trans. Haptics*, vol. 6, no. 2, pp. 229–241, Apr. 2013.

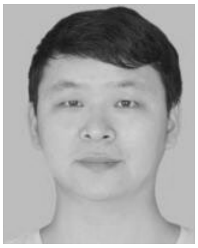
[36] B. Yalcin and K. Ohnishi, "Stable and transparent time-delayed teleoperation by direct acceleration waves," *IEEE Trans. Ind. Electron.*, vol. 57, no. 9, pp. 3228–3238, Sep. 2010.

[37] P. Pitakwatchara, "Wave correction scheme for task space control of time-varying delayed teleoperation systems," *IEEE Trans. Control Syst. Technol.*, vol. 26, no. 6, pp. 2223–2231, Nov. 2018.

[38] J. Luo, C. Yang, Q. Li, and M. Wang, "A task learning mechanism for the telerobots," *Int. J. Humanoid Robot.*, vol. 16, no. 2, 2019, Art. no. 1950009.

[39] D.-H. Zhai and Y. Xia, "Finite-time control of teleoperation systems with input saturation and varying time delays," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 47, no. 7, pp. 1522–1534, Jul. 2017.

[40] D.-H. Zhai and Y. Xia, "Adaptive finite-time control for nonlinear teleoperation systems with asymmetric time-varying delays," *Int. J. Robust Nonlinear Control*, vol. 26, no. 12, pp. 2586–2607, 2016.
[41] D.-H. Zhai and Y. Xia, "Adaptive control for teleoperation system with varying time delays and input saturation constraints," *IEEE Trans. Ind. Electron.*, vol. 63, no. 11, pp. 6921–6929, Nov. 2016.
[42] H. Li and K. Kawashima, "Achieving stable tracking in wave-variable-based teleoperation," *IEEE/ASME Trans. Mechatronics*, vol. 19, no. 5, pp. 1574–1582, Oct. 2014.
[43] J. Guo, C. Liu, and P. Poignet, "Scaled position-force tracking for wireless teleoperation of miniaturized surgical robotic system," in *Proc. 36th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, Aug. 2014, pp. 361–365.
[44] R. Anderson and M. W. Spong, "Bilateral control of teleoperators with time delay," *IEEE Trans. Autom. Control*, vol. 34, no. 5, pp. 494–501, May 1989.
[45] Z. Chen, F. Huang, W. Sun, and W. Song, "An improved wave-variable based four-channel control design in bilateral teleoperation system for time-delay compensation," *IEEE Access*, vol. 6, pp. 12848–12857, 2018.
[46] J. Luo, C. Yang, H. Su, and C. Liu, "A robot learning method with physiological interface for teleoperation systems," *Appl. Sci.*, vol. 9, no. 10, p. 2099, May 2019.
[47] H. Su, C. Yang, G. Ferrigno, and E. De Momi, "Improved human–robot collaborative control of redundant robot for teleoperated minimally invasive surgery," *IEEE Robot. Autom. Lett.*, vol. 4, no. 2, pp. 1447–1453, Apr. 2019.
[48] H. Su, J. Sandoval, P. Vieyres, G. Poisson, G. Ferrigno, and E. De Momi, "Safety-enhanced collaborative framework for tele-operated minimally invasive surgery using a 7-DoF torque-controlled robot," *Int. J. Control, Automat. Syst.*, vol. 16, no. 6, pp. 2915–2923, 2018.
[49] H. Lee, C. Ju, S. Park, S. Park, and H. I. Son, "Preliminary user evaluation of inaccuracy in haptic guidance for teleoperated maintenance task of nuclear power plant," in *Proc. 14th Int. Conf. Ubiquitous Robots Ambient Intell. (URAI)*, Jul. 2017, pp. 467–469.
[50] D. Buongiorno, E. Sotgiu, D. Leonardis, S. Marcheschi, M. Solazzi, and A. Frisoli, "WRES: A novel 3 DoF wrist exoskeleton with tendon-driven differential transmission for neuro-rehabilitation and teleoperation," *IEEE Robot. Autom. Lett.*, vol. 3, no. 3, pp. 2152–2159, Jul. 2018.



JING LUO (S'17) is currently pursuing the Ph.D. degree with the South China University of Technology and the Ph.D. degree with the Imperial College of Science, Technology, and Medicine. His research interests include robotics, teleoperation, haptics, nonlinear control theory, machine learning, and human–robot interaction.

CHAO LIU (S'02–M'05–SM'13) received the Ph.D. degree in electrical and electronic engineering from Nanyang Technological University, Singapore, in 2006.

He is currently a CR Research Scientist with the LIRMM, French National Center for Scientific Research (CNRS), Department of Robotics, University of Montpellier, Montpellier, France. His research interests include surgical robotics, teleoperation, haptics, and nonlinear control theory and its applications.

NING WANG (M'10) received the Ph.D. degree in electronics engineering with The Chinese University of Hong Kong, in 2011. She was a Postdoctoral Research Fellow on machine learning with The Chinese University of Hong Kong, as a Research fellow on human–robot interaction with the Centre for Robotics and Neural Systems, University of Plymouth. She is currently a Senior Lecturer in robotics with the Bristol Robotics Laboratory, University of the West of England, U.K. Her research interests include intelligent systems and robotics, in particular on human–robot interaction. She has rich project experience, and was a key member of EU FP7 Project ROBOT-ERA, EU Regional Development Funded Project ASTUTE 2020, and industrial projects with U.K. companies. She has been awarded several awards, including the Best Paper Award of ICIRA'15, the Best Student Paper Award nomination of ISCSLP'10, and the award of merit of 2008 IEEE Signal Processing Postgraduate Forum.

CHENGUANG YANG (M'10–SM'16) received the Ph.D. degree in control engineering from the National University of Singapore, Singapore, in 2010, and the Ph.D. degree in human robotics from the Imperial College London, London, U.K., from 2009 to 2010.

He is currently a Professor of robotics with the Bristol Robotics Laboratory, University of the West of England, Bristol, U.K. His research interest include human–robot interaction and intelligent system design. He has been awarded the EU Marie Curie International Incoming Fellowship, the U.K. EPSRC UKRI Innovation Fellowship, and the Best Paper Award for the IEEE Transactions on Robotics as well as over ten conference best paper awards.

• • •