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SPECIAL SECTION ON ADVANCED MODELING AND CONTROL OF COMPLEX MECHATRONIC SYSTEMS WITH NONLINEARITY AND UNCERTAINTY

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A Novel Wave-Variable Based Time-Delay Compensated Four-Channel Control Design for Multilateral Teleoperation System

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ABSTRACT Multilateral teleoperation system, which is regarded as an extension of bilateral teleoperation system, is a significant issue and becomes a hotspot in recent years to improve the ability of multiple robots to coordinate and perform efficiently and accurately in the complicated, dangerous and remote working environment. In this paper, a four-channel multilateral teleoperation control problem is discussed, where n masters control the n slaves to handle dangerous, unknown, and complicated tasks remotely under time-varying delays in the communication channel. A novel multilateral teleoperation system combining the time-delay compensator by the novel wave transform and four-channel architecture is built to meet the demands of the communication among multiple masters and slaves, where the weighing coefficients are provided to perform different weighed commands. The two design parameters are provided separately in the time-delay compensator to optimize the signal transmission and guarantee the stability in the four-channel architecture, and the ideal transparency conditions are theoretically derived to simultaneously achieve the stability and good transparency performance for multilateral teleoperation system. The practical experiments are carried out on a 2-master-2-slave teleoperation system to vilify the effectiveness of the proposed control scheme.

INDEX TERMS Multilateral teleoperation, good transparency, wave variable, four channel.

I. INTRODUCTION

With the development of robotics and automation [1]–[8], the teleoperation technique, which relies on the human-machine interaction and provides human operators to handle the remote complicated working tasks, has been applied in numerous fields in visual reality, medical surgery and training, and some hazardous environments like underwater operation, space exploration and security inspection in the nuclear plants [9]–[12]. The bilateral teleoperation technique with force feedback, which generally deals with one single master and one single slave to implement some easy tasks, is not suitable in the increasing complicated requirements such as the large and multiple objects in the industrial situation like rehabilitation [13]–[15], and the precise surgical operations [16], [17]. Thus, the multilateral teleoperation technique, which is regarded as an extension of bilateral teleoperation technique, comes into being and aims to improve the ability of multiple robots to coordinate and perform efficiently and accurately in the complicated, dangerous and remote working environment [18], [19].

Though the multilateral teleoperation technique is introduced, few control designs of the multilateral teleoperation technique have been considered in the recent publications and have not been well developed yet. Sirouspour [20] proposed a μ-synthesis-based control for cooperative teleoperation system to maintain the robust stability in the presence of dynamic interaction between slave robots. Lo *et al.* [21] proposed a system via the Internet and vision to enable multiple operators at different sites to cooperatively control multiple robots with real-time force reflecting. Katsura and Ohnishi [22] designed an integrated multilateral teleoperation system with an observation method of the reaction force for robots to control a natural motion of contact. Khademian and Hashtrudi-Zaad [23] designed a six-channel multilateral shared control architecture for dual-user teleoperation systems, which allows the two users or the slave and environment to interact through a dominance factor that adjusts the authority of the users over the slave robot and environment. However, all the above-mentioned control designs have no consideration of time delay existing in the communication channel, which even exacerbate the problem of system's stability.

Communication time delay is a significant issue in the research of teleoperation systems [24]. Some passivity based control methods have been applied to deal with the instability problem of bilateral teleoperation system. Namely, Anderson and Spong [25], [26] proposed the stabilization method for teleoperation system with time delay based on the scattering operator and two-port network theory. Niemeyer and Slotine [27], [28] designed a wave-variable based control scheme by the enrollment of the wave transform, where the energy variables (velocity $\dot{x}$ and force F) were transformed into wave variables (u and v) in the communication channel. Hannaford and Ryu [29] proposed a time-domain passivity control, where the energy flow in the system was monitored via a passivity observer and the passivity controller is designed to dissipate the excessive energy when the energy flow is negative. A power-based time-domain passivity control was extended afterwards by Ye *et al.* [30], [31], where the passivity controller can be activated more smoothly. Though the above-mentioned methods can solve the instability problem of bilateral teleoperation system effectively, there will be more difficulties when extended the problem to the multilateral conditions as the communication channel between multiple masters and slaves is more complicated. Ye *et al.* [32] introduced a wave node for multilateral teleoperation system, where multiple wave-variable based transmission lines are connected and the stability of the system is maintained. Chen *et al.* [33] extended the power-based time-domain passivity control design to the multilateral conditions, and the weighing coefficients were designed to perform the weighted effects of different masters or slaves. However, these traditional wave-variable based control designs, which mainly cared about the system's stability, would cause wave reflection and position drift between the master and slave, resulting in the distortion of signals to exacerbate the systems' transparency performance.

Good transparency performance (e.g., position tracking and force feedback), which is regarded as another significant issue in the research of teleoperation system, has been developed in bilateral teleoperation system. Though some modifications of the wave variable architecture [34]–[36] were proposed for the purpose of enhancing the transparency of teleoperation system, the wave reflection problem still existed and exacerbated the systems' transparency performance. The four-channel architecture [37], [38], which comprises four kinds of data(velocity and force in both directions) transferred between the master and slave, was considered as an effective method to achieve the good transparency performance based on the impedance matching in view of the dynamics between the master and slave. However, the time delay in the communication channel was not considered in this kind of architecture, and the instability problems is essentially existing.

Therefore, the combination of four-channel architecture and the passivity based time-delay compensator was regarded as an intuitive idea to deal with the trade-off between system's stability and transparency, especially when the system is extended to multilateral conditions. Some passivity based time-delay compensator and four-channel architecture combined control designs for bilateral teleoperation system such as the time-domain passivity control based four-channel architecture [39], the wave-variable based control four-channel architectures [40], [41], the neural-network based passivity control and type-2 fuzzy modeling method combined four-channel architectures [42]–[44] and the adaptive inverse dynamics based four-channel controller [45] was proposed to deal with the trade-off between system's stability and transparency, to simultaneously achieves the stability and good transparency performance for four-channel multilateral teleoperation system is still challenging and becomes the research hotspots.

In this paper, focusing on the issue of instability resulting from time delay in the communication channel, the trade-off between stability and good transparency performance, and multi-robot cooperative collaboration, a novel wave-variable based time-delay compensated four-channel control design for multilateral teleoperation system to satisfy the multi-master-multi-slave communication is proposed. The weighing coefficients are provided for different operation requirements, where any master(slave) can receive different weighed commands and cooperate with each other by selecting the appropriate weighting coefficients. The passivity based time-delay compensator by the novel wave transform is modified from the previous ones, where the communication channel is simplified, and the two design parameters are provided for different transparency requirement, eliminate the negative phenomena of wave reflection and optimize the transmission of signals in the four-channel architecture. The ideal transparency conditions for the proposed multilateral teleoperation system are theoretically derived. Therefore, the stability of the designed multilateral teleoperation architecture and the good transparency performance for both position tracking and force feedback can be achieved simultaneously. The practical experiments are carried out on a 2-master-2-slave teleoperation system, and the results show that the slave can stably react the real operation commands from the master with larger weighed effects via the proposed multilateral teleoperation architecture, which verifies the effectiveness of the proposed method in the improvement of simultaneously achieving the stability and good transparency performance.

The rest of this paper is organized as follows. Section II introduces the basic passivity concepts and wave-variable based control designs. Section III presents the novel wave-variable based time-delay compensated control design of four-channel multilateral teleoperation system and theoretically presents the stability and transparency analyses of the proposed design. Section IV demonstrates the practical experiment, and the comparative results are obtained to show the advantages of our design. Section V presents the conclusions.

II. BASIC WAVE VARIABLES AND SCATTERING OPERATOR

Based on a typical architecture of 1-port network shown in Fig. 1, the concept of wave transform was proposed by Niemeyer and Slotine [27] to solve the instability problem caused by time delay in the communication channel of the bilateral teleopration system, where the energy variables (velocity $\dot{x}$ and force F) were transformed into the wave variables (u and v). The architecture of basic wave transform is shown in Fig. 2, and the definition of wave variable can be written as:

$$u_m(t) = \frac{b\dot{x}_m(t) + F_m(t)}{\sqrt{2b}}, u_s(t) = \frac{b\dot{x}_{sd}(t) + F_s(t)}{\sqrt{2b}} \quad (1)$$

$$v_m(t) = \frac{b\dot{x}_m(t) - F_m(t)}{\sqrt{2b}}, v_s(t) = \frac{b\dot{x}_{sd}(t) - F_s(t)}{\sqrt{2b}} \quad (2)$$

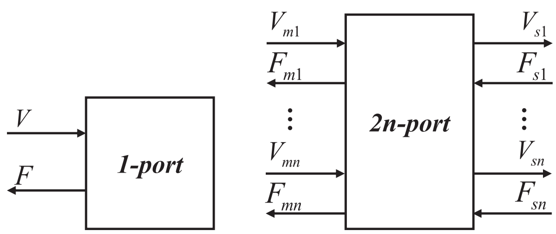

FIGURE 1. 1-port and 2n-port networks.

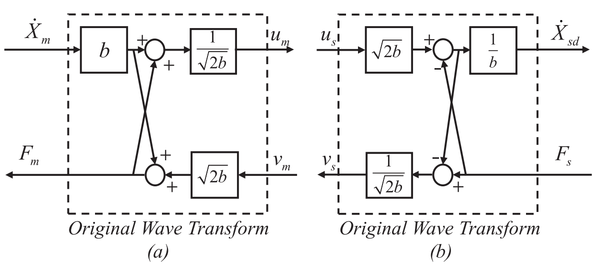

FIGURE 2. Basic wave transform for bilateral teleoperation system. (a) Master. (b) Slave.

Where b is the wave impedance parameter. Moreover,the 2n-port network shown in Fig. 1 can be extended as the basic architecture for wave-variable based multilateral teleoperation system.

For the purpose of proving the stability of teleoperation system with basic wave transform, the scattering operator [25] is introduced in the following.

Theorem 1: If the norm of the scattering matrix is no more than one, the teleoperation system is passive, that is $\|M_i\| \leq 1$ or $\sup \lambda^{\frac{1}{2}}[M_i^*(j\omega)M_i(j\omega)] \leq 1$, where $\lambda^{\frac{1}{2}}$ represents the square root of the largest characteristic value, $i = 1, \ldots, n$. ■

The scattering matrix M_i of the teleoperation system has the form as follows:

$$M_i(s) = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} [H_i(s) - I] [H_i(s) + I]^{-1} \quad (3)$$

Where $i = 1, \ldots, n$, which means the teleoperation system has n masters and n slaves. The hybrid matrix $H_i(s)$ relates the forces and velocities for n-master-n-slave teleoperation system is defined as follows:

$$\begin{bmatrix} F_{mi}(s) \\ -\dot{x}_{sdi}(s) \end{bmatrix} = H_i(s) \begin{bmatrix} \dot{x}_{mi}(s) \\ F_{si}(s) \end{bmatrix} \quad (4)$$

According to (4), the hybrid matrix of teleoperation system with basic wave transform($i = 1$) can be written as:

$$H(s) = \begin{bmatrix} btanh(sT) & -sech(sT) \\ sech(sT) & \frac{1}{b}tanh(sT) \end{bmatrix} \quad (5)$$

Therefore, the scattering operator can be derived as:

$$M(s) = \begin{bmatrix} 0 & e^{-sT} \\ e^{-sT} & 0 \end{bmatrix} \quad (6)$$

On the basis of Theorem 1, then

$$\begin{aligned} &\sup^{\frac{1}{2}} \left[M^*(jw) M(jw)\right] \\ &= \sup^{\frac{1}{2}} \left(\begin{bmatrix} 0 & e^{sT} \\ e^{sT} & 0 \end{bmatrix} - \begin{bmatrix} 0 & e^{-sT} \\ e^{-sT} & 0 \end{bmatrix} \right) \\ &= \sup^{\frac{1}{2}} \left(\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \right) = 1 \end{aligned} \quad (7)$$

Which demonstrates the teleoperation system with basic wave transform is passive.

However, for the teleoperation architecture with basic wave transform shown in Fig. 2, the velocity transfer equation and the force feedback equation are as follows:

$$\dot{x}_{sd}(t) = \dot{x}_m(t - T) - \frac{1}{b}[F_s(t) - F_m(t - T)] \quad (8)$$

$$F_m(t) = F_s(t - T) + b[\dot{x}_m(t) - \dot{x}_{sd}(t - T)] \quad (9)$$

Where $-\frac{1}{b}[F_s(t) - F_m(t - T)]$ and $b[\dot{x}_m(t) - \dot{x}_{sd}(t - T)]$ are the velocity and force distortion items, which will seriously attenuate the transparency of the system. Besides, when the wave impendence b is not perfectly matched, the wave reflection will occur and distort the position tracking and force feedback performance [28], and even worse performance when extended to the multilateral teleoperation system.

III. NOVEL WAVE-VARIABLE BASED FOUR-CHANNEL ARCHITECTURE FOR MULTILATERAL TELEOPERATION SYSTEM

There normally consists of the human operator, master, communication channel, salve and the working environment in a typical bilateral teleoperation system [14]. When extended to the multilateral teleoperation system, the architecture becomes more complicated, which includes the multiple

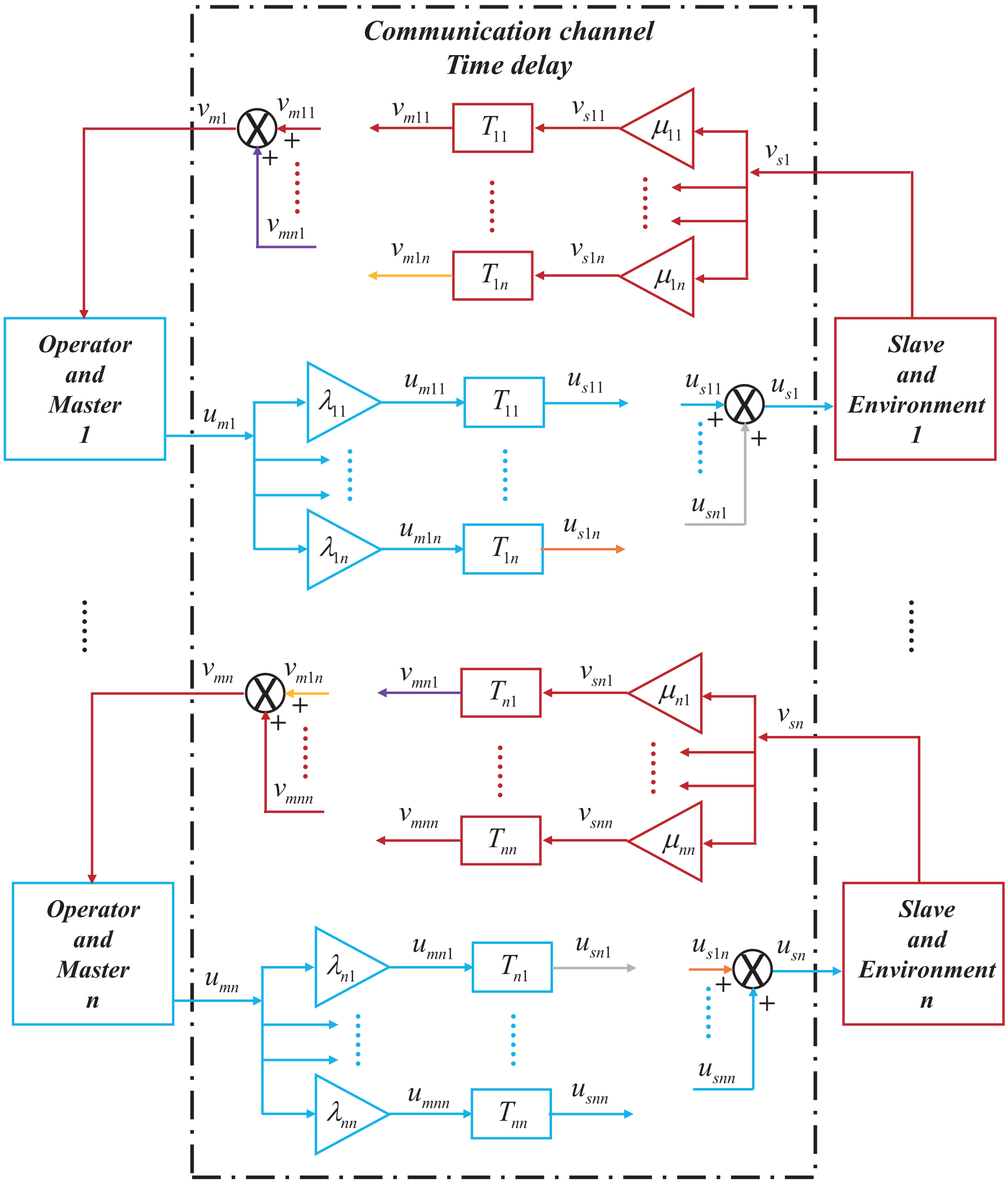

FIGURE 3. Weighed architecture for multilateral teleoperation system.

human operators, masters, slaves, and the working environments. In particular, as more signals transmitted in the communication channel between multiple masters and slaves, an appropriate communication channel, which includes the time delay and the weighed effects among different masters and slaves, should be designed. In this section, a n-master-n-slave teleoperation system is introduced shown in Fig. 3, and the weighing coefficients are designed to satisfy the different master/slave cooperation requirements.

A. NEW COMMUNICATION CHANNEL DESIGN

Fig. 3 shows a typical multilateral teleoperation system model, where the masters, communication channel and slaves are merged into a 2n-port network. The signal transmission and weights distribution are defined for the communication channel between the masters and slaves as follows:

$$u_{si}(t) = \sum_{j=1}^{n} u_{sij}(t),\ u_{mi}(t) = \sum_{j=1}^{n} u_{mij}(t) \tag{10}$$

$$u_{sij}(t) = \lambda_{ij} u_{mij}(t - T_{ij}) \tag{11}$$

$$v_{mi}(t) = \sum_{j=1}^{n} v_{mij}(t),\ v_{si}(t) = \sum_{j=1}^{n} v_{sij}(t) \tag{12}$$

$$v_{mij}(t) = \mu_{ij} v_{sij}(t - T_{ij}) \tag{13}$$

Where $i = 1, \ldots, n$, $j = 1, \ldots, n$, T_{ij} is time delay in the communication channel, $u_{mi}(t)$ is the forward wave channel from the i^{th} master, $u_{si}(t)$ is the forward wave channel from the

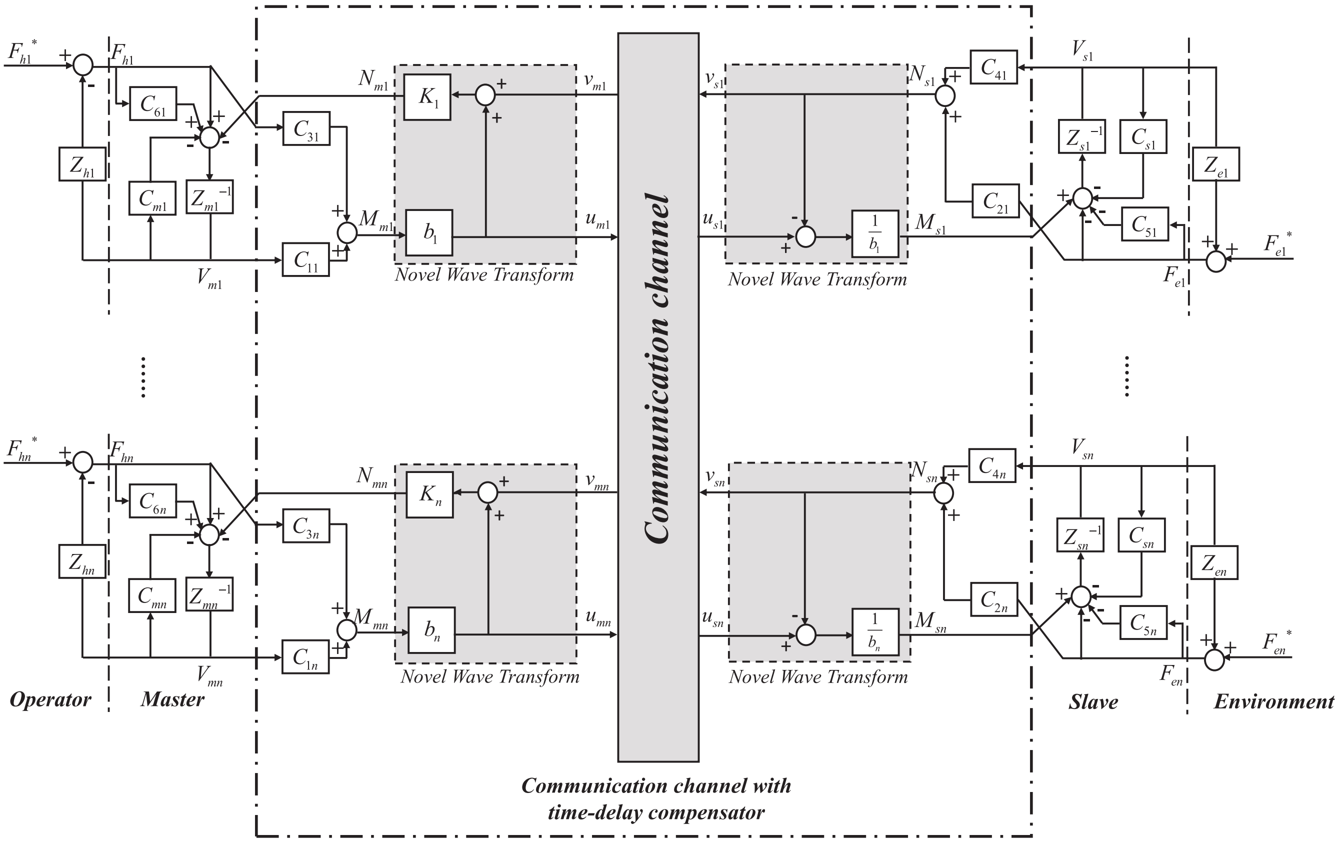

FIGURE 4. Four-channel multilateral teleoperation architecture with time-delay compensator by novel wave transform.

i^{th} slave, $v_{mi}(t)$ is the reverse wave channel from the i^{th} master, $v_{si}(t)$ is the reverse wave channel from the i^{th} slave, $u_{mij}(t)$ is the forward wave channel from the i^{th} master to the j^{th} slave, $v_{sij}(t)$ is the reverse wave channel from the i^{th} slave to the j^{th} master. λ_{ij} is the weighing coeffient from the i^{th} master to the j^{th} slave, and μ_{ij} is the weighing coeffient from the i^{th} slave to the j^{th} master. The different corporation requirements between the master and the slave can be satisfied by properly selecting the different weighing coefficients.

B. FOUR-CHANNEL MULTILATERAL TELEOPERATION ARCHITECTURE

As the stability of teleoperation system cannot be guaranteed in the basic four-channel architecture, a time-delay compensator by novel wave transform is introduced in this section to guarantee the system's stability and eliminate the wave reflection phenomena caused by the basic wave transform to enhance the transparency performance of the teleoperation system. Besides, the time-delay compensated four-channel architecture is extended for the multilateral teleoperation system, shown in Fig. 4, to satisfy the more complicated working requirements, which can still simultaneously achieve stability and good transparency performance.

Assume that the multiple masters and slaves interact with the operators and working environments respectively, thus the dynamics can be modeled by the impedance Z_{hi} and Z_{ei} as follows:

$$F_{hi} = F_{hi}{}^{*} - Z_{hi}V_{mi} \tag{14}$$

$$F_{ei} = F_{ei}{}^{*} + Z_{ei}V_{si} \tag{15}$$

Enable this compensator to be used in the four-channel teleoperation system, the communication channel of the system is separated into the 2n-port network architecture. Therefore, the i^{th} nonphysical input signal in the communication channel which combines the force and velocity signals simultaneously can be written as:

$$M_{mi} = C_{3i}F_{hi} + C_{1i}V_{mi} \tag{16}$$

$$N_{si} = C_{2i}F_{ei} + C_{4i}V_{si} \tag{17}$$

Since the i^{th} closed-loop functions of the master and slave can be written as:

$$V_{mi}Z_{mi} = -V_{mi}C_{mi} + F_{hi}(1 + C_{6i}) - N_{mi} \tag{18}$$

$$V_{si}Z_{si} = -V_{si}C_{si} - F_{ei}(1 + C_{5i}) + M_{si} \tag{19}$$

Then the nonphysical output signal in the communication channel which also combines the force and velocity signals simultaneously can be obtained as follows:

$$N_{mi} = F_{hi}(1 + C_{6i}) - V_{mi}Z_{cmi} \tag{20}$$

$$M_{si} = F_{ei}(1 + C_{5i}) + V_{si}Z_{cei} \tag{21}$$

Where $i = 1, \ldots, n, j = 1, \ldots, n$, V_{mi} and V_{si} are the velocities of the i^{th} master and i^{th} slave, Z_{hi} and Z_{ei} are the i^{th} operator's impendence and environment's impendence respectively, F_{hi} is the operating force exerted by the i^{th} operator, F_{ei} is the i^{th} environmental force generated when exposed to the working environment. $F_{hi}{}^*$ is the i^{th} interaction force between the i^{th} operator and master, and $F_{ei}{}^*$ is the i^{th} interaction force between the i^{th} slave and the working environment. $Z_{cmi} = Z_{mi}+C_{mi}$, $Z_{cei} = Z_{si}+C_{si}$, Z_{mi} and Z_{si} are the force-driven linear mass parameters of the i^{th} master and i^{th} slave, $Z_{mi} = m_{mi}s$, $Z_{si} = m_{si}s$, m_{mi} and m_{si} are the masses of the i^{th} master and i^{th} slave, C_{mi} and C_{si} are the position controller parameters of the i^{th} master and i^{th} slave, $C_{mi} = B_{mi} + K_{mi}/s$, $C_{si} = B_{si} + K_{si}/s$, $C_{1i} - C_{4i}$ are the four-channel controller parameters, C_{5i} and C_{6i} are the local force feedback parameters, respectively.

The definition of novel wave transform in Fig. 4 can be written as:

$$u_{mi}(t) = b_i M_{mi}(t) \quad (22)$$

$$v_{si}(t) = N_{si}(t) \quad (23)$$

$$v_{mi}(t) = -b_i M_{mi}(t) + \frac{N_{mi}(t)}{K_i} \quad (24)$$

$$u_{si}(t) = b_i M_{si}(t) + N_{si}(t) \quad (25)$$

Where b_i and K_i are the wave impendence and the secondary parameter, respectively.

It is clearly shown from (22) and (23) that the input wave variable u_{mi} contains only the forward signal information M_{mi}, and the output wave variable v_{si} contains only the reverse signal information N_{si}. Therefore, the wave variable u_{si} no longer reflects at v_{si}, and the wave variable v_{mi} no longer reflects at u_{mi}, which effectively reduces the wave reflection phenomena caused by then enrollment of wave transform, and further enhances the system's transparency performance when compared to the basic ones.

C. STABILITY ANALYSIS

Theorem 2: Choosing the wave impedance parameter and the secondary parameter satisfying $b_i \in (0, +\infty)$ and $K_i \in (0, 1]$, the novel wave-variable based four-channel mutilateral teleoperation subsystem is passive, where $i = 1, \ldots, n$. ■

Similarly to (4), the hybrid matrix of the novel wave-variable based multilateral teleoperation subsystem can be derived as:

$$\begin{bmatrix} N_{mi}(s) \\ -M_{si}(s) \end{bmatrix} = \begin{bmatrix} b_i K_i & K_i e^{-s\sum_{j=1}^{n}\mu_{ji}T_{ji}} \\ -e^{-s\sum_{j=1}^{n}\lambda_{ji}T_{ji}} & 1/b_i \end{bmatrix} \begin{bmatrix} M_{mi}(s) \\ N_{si}(s) \end{bmatrix} \quad (26)$$

Thus,

$$H_i(s) = \begin{bmatrix} b_i K_i & K_i e^{-s\sum_{j=1}^{n}\mu_{ji}T_{ji}} \\ -e^{-s\sum_{j=1}^{n}\lambda_{ji}T_{ji}} & 1/b_i \end{bmatrix} \quad (27)$$

Let $s = j\omega$, (27) shows that the scattering norm is influenced by the angular frequency ω. In view of the periodicity of $e^{-j\omega T}$, the scattering norm is periodic similarly. Besides, b_i and K_i are two parameters to be selected for the scattering norm.

Under the guidance of method proposed in [46], when $b_i > 0$, $0 < K_i \leqslant 1$, one can be obtained that the scattering norm is always less than one. It can also be checked by iterating on the different parameters of b_i, K_i, ω, and T_{ji} through Matlab toolbox. Specifically, in order to better show the value and periodicity of the scattering norm, a special case of $b_i = 3$, $K_i = 1$, $T_{ji} = 0.5$, $i = j = 1$ is taken, and the result is shown in Fig. 5 where the angular frequency ω is the only variable. It clearly shows the scattering norm is less than one even when K_i reaches 1. Therefore, the novel wave-variable based four-channel multilateral teleoperation system is passive, which demonstrates the correctness of Theorem 2.

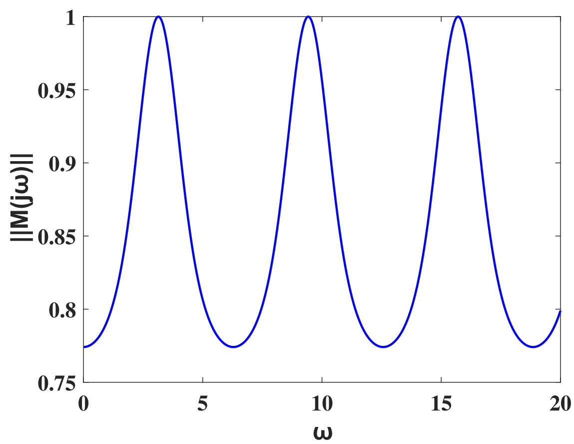

FIGURE 5. Scattering norm of novel wave transform.

Since the four-channel multilateral teleoperation architecture is stable when the time delay is ignored [23], the stability of proposed design under time delay can be achieved by adding the stable communication subsystem through the above novel wave transform.

D. TRANSPARENCY ANALYSIS

The functions of signal transmission in the communication subsystem shown in Fig. 4 are as follows:

$$M_{si}(t) = M_{mi}(t - \sum_{j=1}^{n}\lambda_{ji}T_{ji}) - \frac{N_{si}(t)}{b_i} \quad (28)$$

$$N_{mi}(t) = K_i \left[N_{si}(t - \sum_{j=1}^{n}\mu_{ji}T_{ji}) + b_i M_{mi}(t) \right] \quad (29)$$

Usually the wave impedance parameter b_i is small value in the previous architecture [27]. Since u_{si} no longer reflects at v_{si}, and v_{mi} no longer reflects at u_{mi} and enrollment of two design parameters in the time-delay compensator by the novel wave transform, the wave impedance parameter b_i can be selected more freely and the improvement of transparency

$$Z_{cmi}V_{mi}+(C_{4i}V_{si}+C_{2i}F_{ei})\,e^{-\left(\sum_{j=1}^{n}\mu_{ji}T_{ji}\right)s}+b_iK_i\,(C_{3i}F_{hi}+C_{1i}V_{mi})=(1+C_{6i})\,F_{hi} \tag{30}$$

$$Z_{cei}V_{si}+(1+C_{5i})\,F_{ei}=(C_{3i}F_{hi}+C_{1i}V_{mi})\,e^{-\left(\sum_{j=1}^{n}\lambda_{ji}T_{ji}\right)s}-\frac{C_{4i}V_{si}+C_{2i}F_{ei}}{b_i} \tag{31}$$

$$Z_{toi}=\left.\frac{F_{hi}}{V_{mi}}\right|_{F_{hi}^*=0}=\frac{b_i(Z_{cmi}Z_{cei}+C_{1i}C_{4i}e^{-2Ts})+[b_iK_i(1+C_{5i})Z_{cmi}+C_{1i}C_{2i}e^{-2Ts}]Z_{ei}+\Delta_{1i}}{[b_i(1+C_{6i})Z_{cei}-C_{3i}C_{4i}e^{-2Ts}]+[b_i(1+C_{5i})(1+C_{6i})-C_{2i}C_{3i}e^{-2Ts}]Z_{ei}+\Delta_{2i}} \tag{32}$$

$$Z_{tei}=-\left.\frac{F_{ei}}{V_{si}}\right|_{F_{ei}^*=0}=\frac{b_i(Z_{cmi}Z_{cei}+C_{1i}C_{4i}e^{-2Ts})+[b_iK_i(1+C_{6i})Z_{cei}-C_{3i}C_{4i}e^{-2Ts}]Z_{hi}+\Delta_{3i}}{[b_i(1+C_{5i})Z_{cei}+C_{1i}C_{2i}e^{-2Ts}]+[b_i(1+C_{5i})(1+C_{6i})-C_{2i}C_{3i}e^{-2Ts}]Z_{hi}+\Delta_{4i}} \tag{33}$$

performance can be shown from (28) and (29) when compared to the (8) and (9).

Obtained from the analysis, when the system starts to work, just make sure that the wave impendence parameter b_i is extremely large, which meet the needs for $N_{si}(t)/b_i \to 0$. Since b_i is extremely large, equation $N_{si}(t-\sum_{j=1}^{n}\mu_{ji}T_{ji})+b_iM_{mi}(t)$ will become extremely large. Refer to the system's passivity requirements $0 < K_i \leq 1$, by properly designing the parameter K_i, the demand $K_i\left[N_{si}(t-\sum_{j=1}^{n}\mu_{ji}T_{ji})+b_iM_{mi}(t)\right]\to N_{si}(t-\sum_{j=1}^{n}\mu_{ji}T_{ji})$ can be satisfied. Thus reducing the signal distortion and ensuring the system to have better signal transmission in the communication channel.

To better achieve the good transparency performance for the multilateral teleoperation system, the four-channel architecture is added in the above-mentioned control scheme, where the closed-loop dynamic functions of the i^{th} master and slave can be derived as (30) and (31), shown at the top of this page.

The transmitted impedances in the four-channel architecture are required to be matched as $Z_{toi}=Z_{ei}$ and $Z_{tei}=Z_{hi}$. Substitute (14) and (15) into (30) and (31), the transmitted impedances Z_{toi} and Z_{tei} can be derived as (32) and (33), shown at the top of this page.

Where $T=\sum_{j=1}^{n}(\lambda_{ji}+\mu_{ji})T_{ji}$, $i=1,\ldots,n$, $\Delta_{mi}(m=1,2,3,4)$, which are the error terms that can be neglected approximately in the transparency analysis. Besides, since the time delay term (e^{-2Ts}) takes little impact on the system's impedance matching equation (32) and (33) [40]. Assume $C_{1i}-C_{6i}$ are not the function of transmitted impedances Z_{toi} and Z_{tei}, the ideal transparency conditions for four-channel multilateral teleoperation system can be approximately obtained as follows:

$$\begin{cases} C_{1i}=Z_{cei}\\ C_{2i}=1+C_{6i}\\ C_{3i}=1+C_{5i}\\ C_{4i}=-Z_{cmi}\end{cases} \tag{34}$$

Where C_{2i} and C_{3i} are not simultaneously equal to zero. Thus, one remark can be obtained as follows:

Remark 1: By selecting b_i is extremely large to satisfy $N_{si}(t)/b_i \to 0$, designing the secondary parameter K_i to satisfy $K_i\left[N_{si}(t-\sum_{j=1}^{n}\mu_{ji}T_{ji})+b_iM_{mi}(t)\right]\to N_{si}(t-\sum_{j=1}^{n}\mu_{ji}T_{ji})$ under $K_i \in (0,1]$, and choosing $C_{1i}-C_{6i}$ to satisfy the ideal transparency conditions (34), where $i=1,\ldots,n$, the good transparency performance of both position tracking and force feekback for the novel wave-variable based four channel multilateral teleoperation system can be achieved simultaneously. ■

IV. EXPERIMENT

A. EXPERIMENTAL SETUP

The experiments are carried out on a 2-master-2-slave teleoperation real platform shown in Fig. 6, where two 3D Systems Phantom Premium haptic devices are set up as the masters and two 3D Systems Touch haptic devices are set up as the slaves. Each Premium haptic device and Touch provides the large workspace and high force while offering a wide range of force feedback, motion and varying stiffness, and can be used for trajectory planning and teleoperation applications. The QUARC real-time control systems which support signals transmission for both Premium haptic device and Touch are provided and installed in two computers, which are used to implement the control algorithms in the Matlab/Simulink. In the experiments, for the purpose of verifying the achievements of good transparency performance of

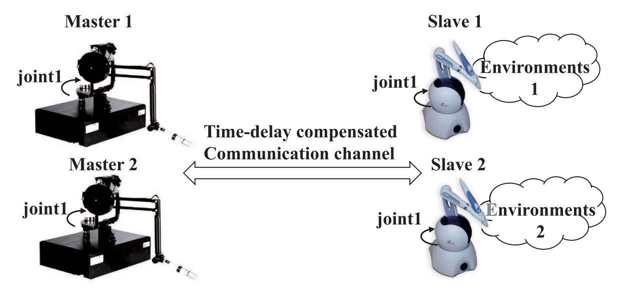

FIGURE 6. Testing platform of multilateral teleoperation system.

proposed architecture for multilateral teleoperation system, we use the Joint 1 of each device shown in Fig. 6 which simplifies the manipulator control problems.

To have a fair comparison, two controllers are compared in the following:

C1: The basic wave-variable based control design proposed by Ye *et al.* [32] to guarentee the stability for multilateral teleoperation system. The specific value of wave impedance b_i is chosen as $b_i = 5$. In order to reduce the degradation of system performance due to the wave reflection, the coefficients of the PI controller are chosen as $P_i = 0.3Ns/m$ and $I_i = 5N/m$, where $i = 1, 2$.

C2: The novel wave-variable based four channel control design proposed in this paper to achieve the good transparency performances of both position tracking and force feedback. In order to ensure the accurate transmission of signals in the communication channel, which requires the wave impedance b_i as large as possible, the specific value of b_i is chosen as $b_i = 200$, and the secondary parameter K_i is chosen as 0.248. The specific value of the masses of the i^{th} master and slave m_{mi} and m_{si} are chosen as $m_{mi} = 0.05kg$ and $m_{si} = 0.03kg$, then the force-driven linear mass parameters of the i^{th} master and slave Z_{mi} and Z_{si} are chosen as $Z_{mi} = m_{mi}s$ and $Z_{si} = m_{si}s$, the four-channel parameters C_{1i} and C_{4i} are chosen as $C_{1i} = 4m_{si}(10 + 1/s) + m_{si}s$ and $C_{4i} = -4m_{mi}(10 + 1/s) - m_{mi}s$, the position controller parameters C_{mi} and C_{si} are chosen as $C_{mi} = 4M_{mi}(1 + 1/s)$ and $C_{si} = 4M_{si}(1+1/s)$, the local force feedback parameters are chosen as $C_{5i} = C_{6i} = -0.5, C_{2i} = C_{3i} = 0.5$, respectively, where $i = 1, 2$.

In order to verify the effectiveness of the proposed control scheme under time-varying delays, the time delays are set as $0.5 \pm 0.1s$, and added into each communication channel. Specifically, the following experiment sets are conducted to vilify the system's ability to cooperate in the weighted environment:

Set1: $\lambda_{11} = 0.8, \lambda_{12} = 0.2, \lambda_{21} = 0.2, \lambda_{22} = 0.8$ and $\mu_{11} = 0.8, \mu_{12} = 0.2, \mu_{21} = 0.2, \mu_{22} = 0.8$, which means the 1st master assigns more weights on the 1st slaves, and the 2nd master assigns more weights to the 2nd slaves on the position command. The masters receive the similar weighs on the force feedback from the slaves.

Set2: $\lambda_{11} = \lambda_{21} = 0.5, \lambda_{12} = \lambda_{22} = 0.5$ and $\mu_{11} = \mu_{21} = 0.5, \mu_{12} = \mu_{22} = 0.5$, which means the two masters assign the weighs averagely to the two slaves on the position command, and the masters receive the weighs averagely from the slaves on the force feedback.

B. EXPERIMENTAL RESULTS

The experiment results of the basic wave-variable based control design (C1) for multilateral teleoperation system are shown in Fig. 7-Fig. 10.

Since all the position and force signals in the figures are bounded, the passivity of the multilateral teleoperation system under time-varying delays is guaranteed. Specifically, Fig. 7 and Fig. 8 shows the position tracking and force feedback performance where the 2-master-2-slave weighing coefficients are different. Due to the wave reflection problem caused by the enrollment of basic wave transform, the signal transmission distorts in the communication channel. Therefore, the 1st slave, which receives more weighs from the 1st master, cannot receive the accurate position command from the 1st slave, while the 1st master, which assigns more weighs on the 1st slave, cannot receive the accurate force feedback from the 1st slave, so do the 2nd master and 2nd slave. Fig. 9 and Fig. 10 shows the position tracking and force feedback performance where the 2-master-2-slave weighing coefficients are the same. Similarly, due to the wave reflection problem, the 1st and 2st slaves cannot receive the same position command and the 1st and 2st masters cannot receive the same force feedback in return, which definitely deteriorates the system's transparency performance, and even destroyed the perception of operators to the multilateral working

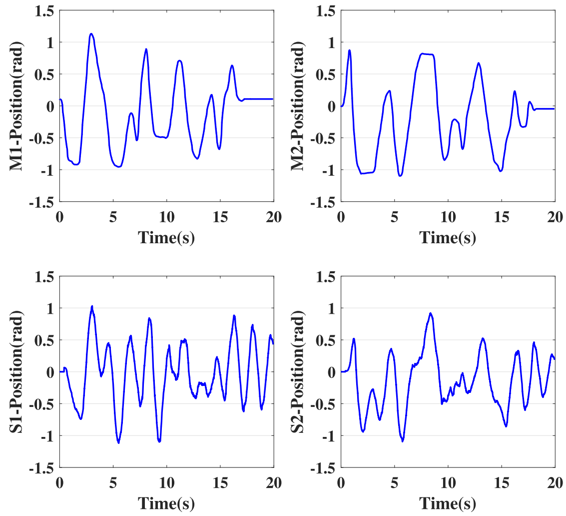

FIGURE 7. Experimental result of C1-Set1 in position tracking performance.

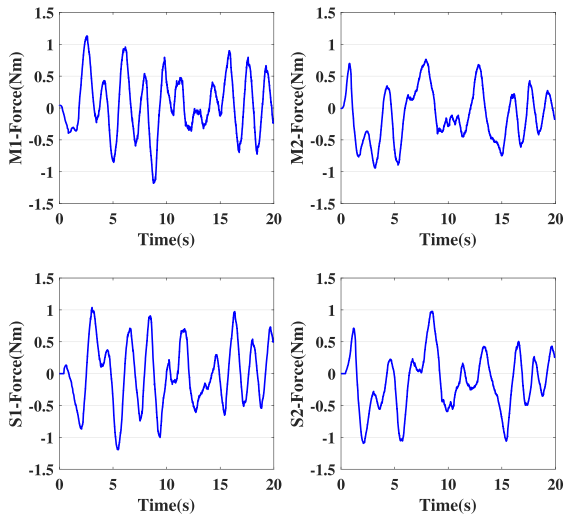

FIGURE 8. Experimental result of C1-Set1 in force feedback performance.

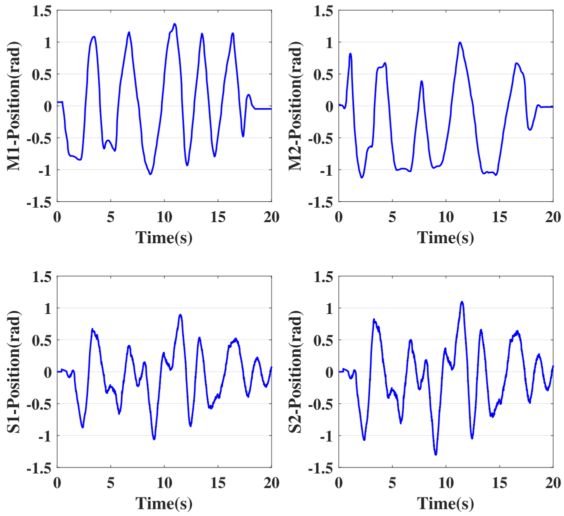

FIGURE 9. Experimental result of C1-Set2 in position tracking performance.

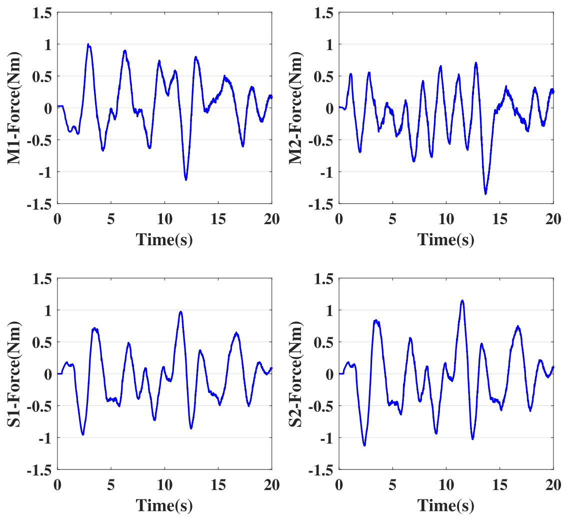

FIGURE 10. Experimental result of C1-Set2 in force feedback performance.

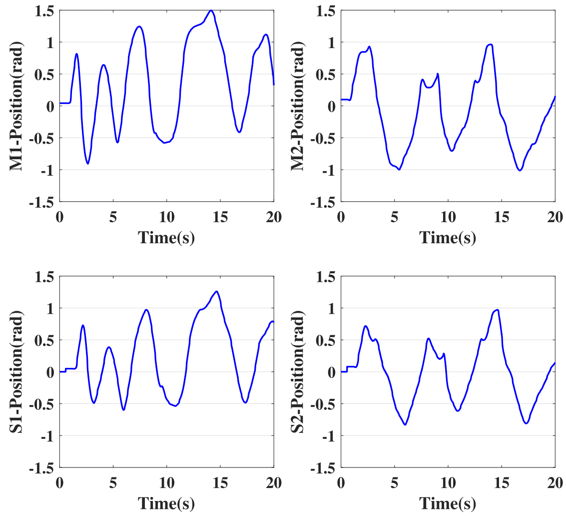

FIGURE 11. Experimental result of C2-Set1 in position tracking performance.

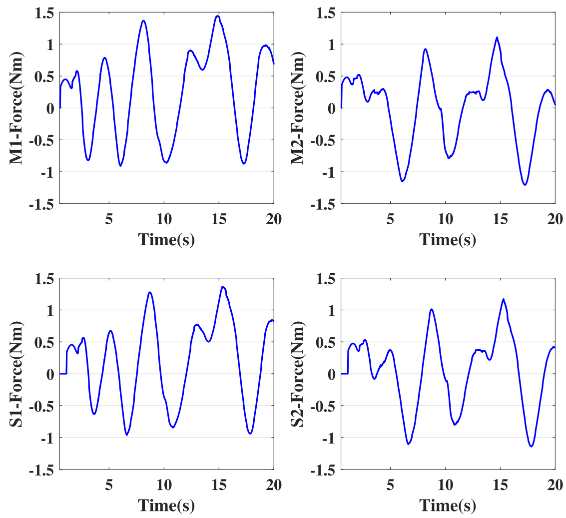

FIGURE 12. Experimental result of C2-Set1 in force feedback performance.

environments and the cooperation of multiple masters and slaves.

The experiment results of the novel wave-variable based four-channel control design (C2) for multilateral teleoperation system are shown in Fig. 11-Fig. 14.

Since all the position and force signals in the figures are bounded, the passivity of the multilateral teleoperation system under time-varying delays can be still guaranteed. Specifically, Fig. 11 and Fig. 12 shows the position tracking and force feedback performance where the 2-master-2-slave weighing coefficients are different. Due to the elimination of wave reflection problem by the enrollment of novel wave transform, the signals can accurately transmitted in the communication channel. Therefore, the 1st(2nd) slave, which receives more weighs from the 1st(2nd) master, can receive the accurate position command from the 1st master and correct operational intention from the 1st(2nd) operator, while the 1st(2nd) master, which assigns more weighs on the 1st(2nd) slave, can receive the accurate force feedback from the 1st(2nd) slave, since the signal waveforms of M1(M2)-Position(Force) and S1(S2)-Position(Force) are basically the same. Fig. 13 and Fig. 14 shows the position tracking and force feedback performance where the 2-master-2-slave weighing coefficients are the same. Similarly, due to the elimination of wave reflection problem, the 1st and 2st slaves can receive the identical position command, and the 1st and 2st masters cannot receive the identical force feedback in return, since the signal waveforms of S1-Position(Force) and S2-Position(Force) are basically the same, which definitely improves the system's transparency performance while the stability is theoretically guaranteed.

As shown from Fig. 7-Fig. 14, under the ideal transparency conditions (34), the slave can track the movement of the

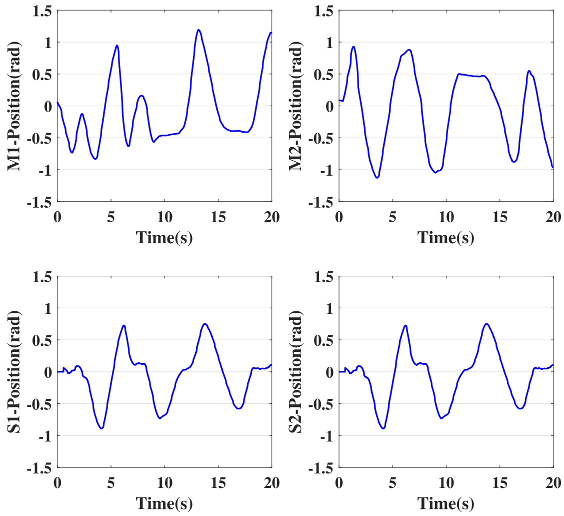

FIGURE 13. Experimental result of C2-Set2 in position tracking performance.

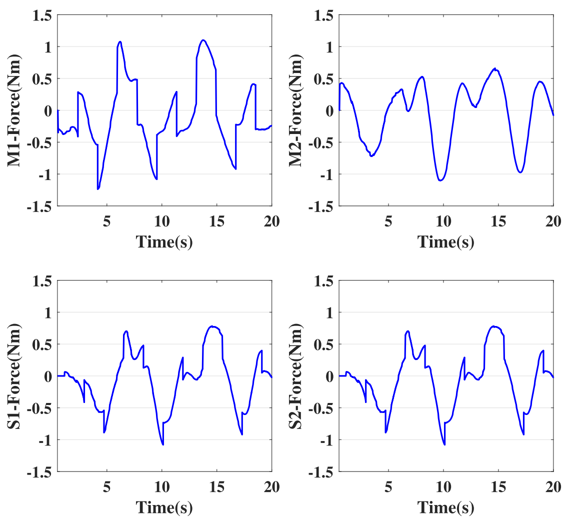

FIGURE 14. Experimental result of C2-Set2 in force feedback performance.

master manipulator and provide accurate force feedback to the master which assigns more weighs on itself via the novel architecture(C2), and cooperate with each other to handle the complicated remote tasks. Therefore, the effectiveness of the combination of the passivity based time-delay compensator by the novel wave transform and four-channel architecture for the multilateral teleoperation system to achieve the good transparency performance while the stability is guaranteed under time-varying delays.

V. CONCLUSION

In this paper, the control problem of a four-channel multilateral teleoperation system is discussed, where n masters remotely control the n slaves to cooperate and handle the dangerous, unknown and complicated tasks under time-varying delays in the communication channel. A novel wave-variable based time-delay compensated four-channel architecture for multilateral teleoperation system is built to meet the demands of the communication among multiple masters and slaves. The master(slave) can receive different weighed commands by selecting the appropriate weighing coefficients. The passivity based time-delay compensator by novel wave transform is introduced, where the two design parameters are provided to optimize the signal transmission and guarantee the stability in the four-channel architecture, and the ideal transparency conditions for the proposed multilateral teleoperation system are theoretically derived. Thus, the simultaneous stability and good transparency performance of multilateral teleoperation system can be achieved theoretically. The practical experiments are carried out on a 2-master-2-slave teleoperation system, and the results show the effectiveness of the proposed control scheme in the improvement of simultaneously achieving the stability and good transparency performance, enhancement of the operators perception and the cooperative collaboration ability of multiple masters and slaves.

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