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Type-2 Fuzzy Logic based Time-delayed Shared Control in Online-switching Tele-operated and Autonomous Systems

Da SUN and Qianfang LIAO

Abstract – This paper develops a novel shared control scheme for online-switching tele-operated and autonomous system with time-varying delays. Type-2 Takagi-Sugeno (T-S) fuzzy model is used to describe the dynamics of master and slave robots in this system. A novel non-singular fast terminal sliding mode (NFTSM)-based algorithm combined with an extended wave-based time domain passivity approach (TDPA) is presented to enhance the master-slave motion synchronization in the tele-operated mode and reference-slave motion synchronization in the autonomous mode, while simultaneously ensuring the stability of the overall system in the presence of arbitrary time delays. In addition, based on the Type-2 Fuzzy model, a new torque observer is designed to estimate the external torques and then the torque tracking method is employed in the control laws to let the slave apply the designated force to further improve the operator's force perception for the environment. The stability of the closed-loop system is proven using the Lyapunov-Krasovskii functions. Finally, experiments using two haptic devices prove the superiority of the proposed strategy.

Index terms – Online-switching tele-operated and autonomous system, Type-2 T-S Fuzzy System, Time-varying delays.

1. Introduction

The bilateral teleoperation system, which generally composed of five components, a human operator, a local master robot, the communication channels, a remote slave robot and a remote target, has been found in a broad spectrum of applications ranging from space/ocean exploration, bomb disposal, nuclear reactor, and rehabilitation, to minimally invasive surgery [1]. One of the main downsides of tele-operated robot is the requirement of large amounts of training and practising in order to achieve accurate performance in the tasks. Especially for the delicate minimally invasive surgery using the tele-surgical robot within a confined space [2]-[3], those psychological and physical workloads may lead to increased failure rate in several significant aspects of the operation. In order to address this shortage and simultaneously improve the operational accuracy, the autonomous mode that performing certain tasks automatically by the teleoperation system itself has been investigated [4]. To the best of authors' knowledge, the studies of shared control strategies for the systems with semi-teleoperation and semi-automation are still in the initial stage and leave a large space for development.

The online-switching tele-operated and autonomous system has to face challenges in larger shared controller design than the pure teleoperation system or the pure autonomous system. In the tele-operated mode, due to the existence of time delays, especially time-varying delays, the trade-off has to be made between stability and transparency, which can seriously degrade the system performance without a proper algorithm. A variety of control algorithms have been developed to improve the delay-based system performance. To maintain the delay-based stability, in [5], A PD-like control algorithm is proposed that aims to

achieve the stable behavior with no delayed derivative action. In [6], a stability criteria used to derive the maximal transmission delay with a P+d controller is presented. The stability for the closed-loop teleoperation systems under symmetrical and unsymmetrical time-varying delays is explored in [7]. In the above mentioned studies, however, the environmental feedback forces are not considered, and the human and the environmental force are assumed to be passive, which may not work for real applications. The passivity-based approaches are extended to the mobile robots in [40]-[42] in order to main stability under various criteria. To enhance the system transparency, a closed-loop teleoperation systems under time-varying delays with P+d control are given in [8]. To achieve more precise and faster position convergence performances, the terminal sliding mode control (TSMC) methods are studied in [9]. In [10] and [11], globally continuous non-singular TSMC methods are developed to deal with the singularity problem. A new non-singular fast terminal sliding mode (NFTSM)-based teleoperation system is investigated in [12] to enhance the position tracking. Later, the approach is improved by adding the synchronization error constraint [13]. The shortcoming of the above sliding mode control algorithms is that the time-varying delayed system performance cannot be guaranteed. By adding additional buffers to keep the delays constant, the NFTSM-based teleoperation system in [14] can work under time-varying delays. However, this method increases the overall time delays and make the system redundant.

When directly switching to the autonomous mode, it is inappropriate to employ most of the teleoperation algorithms because: Firstly, the autonomous control algorithms are usually set at the slave side that manipulate the slave to the designated spot. In order to allow the human operator to fluently perform the remaining tasks when switching back to the tele-operated mode, the master should closely track the slave's motion without position drift. Hence, the roles of the slave and the master are mutually exchanged in the autonomous mode and the active energy is feedback from the slave to the master side. Under time delay condition, since most of the approaches assume the passive environment (energy will not be fed back from the slave side to the master side), stability condition will be seriously compromised in the autonomous mode. Although the autonomous control algorithm can be still set at the master side such as [15], due to the influence of time-varying delays, the slave may be not possible to accurately follow the reference signals and achieve the ideal performance. Time delay issue is not included in the approach in [15]. Secondly, in the autonomous mode, the slave not only need to follow the reference signals to the designated spot, but also need to apply the designated force (e.g. target tissue manipulation). The force control algorithm becomes crucially important, otherwise the slave can only stay at the designated spot without applying any force that does not meet the requirement of the autonomous control. However, the force/torque transmission is rarely applied in the teleoperation systems since the external noise may significantly affect the

overall stability. Also, the force/torque signals convergence is also a big challenge.

In addition, it is inevitable that the nonlinear robotic systems contain dynamic uncertainties and external disturbances. How to compensate for the dynamic uncertainties is an important issue. A number of approaches use neural network [13], adaptive control [16] and fuzzy logic system [32]-[35] to deal with this problem. Among these approaches, fuzzy logic system has salient features: i) fuzzy model can be built to a high degree of accuracy (universal approximator) based on data samples, expert experience or a combination of both [17]-[19]; ii) fuzzy logic system has been proven to be a powerful tool to handle the noises and disturbances [20]. Consequently, the fuzzy model based control requires no accurate mathematical functions/models of the system, and is robust to uncertainties. The traditional (Type-1) fuzzy model with crisp fuzzy memberships may be limited in describing a system where large uncertainties appear, subsequently its controller design may provide degraded performance. In order to overcome this limitation, an extension work, called Type-2 fuzzy model [21]-[28], is proposed that has the fuzzy memberships themselves fuzzy to provide additional design degrees to describe the inexactness for controller to compensate for the uncertainties. A completed theory of Type-2 Mamdani fuzzy logic systems have been developed in [21] and the introduction of Type-2 Takagi-Sugeno (T-S) fuzzy model is given in [25]. Compared to Mamdani fuzzy model, T-S fuzzy model using a group of linear local models blended by fuzzy membership functions to describe a global nonlinear system has the advantages that requiring less fuzzy rules and providing a platform for optimization, stability analysis and controller design using traditional linear algorithms [20]. Several results in [29]-[31] have demonstrated that Type-2 T-S fuzzy systems are superior over their Type-1 counterparts with respect to robustness in modeling and controller design. Currently only a few methods using fuzzy logic based algorithms for robotic system control have been found. In [32]-[34], Mamdani fuzzy model based control methods are proposed in order to compensate for the uncertainties. A T-S fuzzy model based controller is developed in [35] using Type-1 fuzzy logic to describe the overall system for controller design without considering the dynamical uncertainties.

In this paper, a novel online-switching tele-operated and autonomous shared control system is proposed that allows free switch between the tele-operated mode and the autonomous mode. A decentralized Type-2 T-S modelling algorithm is developed to transfer the nonlinear system to multiple linear systems connected by the fuzzy memberships, and the extended wave-based time domain passivity approach (TDPA) is applied to ensure the passivity of the communication channels in order to maintain stability in the two modes with arbitrary time delays. By virtue of the Type-2 T-S fuzzy model and the guaranteed passivity of TDPA, NFTSM is applied to achieve accurate master-slave position tracking as well as reference-slave position tracking. Meanwhile, a new Type-2 fuzzy model based torque observer is applied to estimate the external torques and the torque control method is also applied to let the slave apply the designated force and improve the perception of the operator on the environment. Lyapunov-Krasovskii functions are used to analyze the system stability with dynamic uncertainties. The superiority of the proposed approach is demonstrated by a bilateral experimental platform consisting two haptic devices.

2. Type-2 T-S fuzzy logic based dynamic models

The dynamics of the master/slave robot in the bilateral teleoperation system are described as follows:

$$M_i(q_i)\ddot{q}_i + C_i(q_i, \dot{q}_i)\dot{q}_i + g_i(q_i) + f_i\dot{q}_i + f_{ci}(\dot{q}_i) + F_i^d = \tau_i + \tau_j \quad (1)$$

where $i = m, s$ represents master and slave, and $j = h, e$ indicates human and environment. $\ddot{q}_i, \dot{q}_i, q_i \in R^n$ stand for the joint acceleration, velocity and position signals, respectively. $M_i(q_i) \in R^{n \times n}$ and $C_i(q_i, \dot{q}_i) \in R^{n \times n}$ are the inertia matrices and Coriolis/centrifugal effects, respectively. $g_i(q_i) \in R^n$ is the gravitational force. $f_i\dot{q}_i$ and $f_{ci}(\dot{q}_i)$ denote the viscous friction and Coulomb friction, respectively. F_i^d is the unknown disturbance. τ_i is the control signal, and τ_j is the external human or environmental torques that $\tau_j = \tau_j^* + \Delta\tau_j$, where τ_j^* is the measured torque and $\Delta\tau_j$ is the measurement error.

The interval Type-2 T-S fuzzy models [25] is employed to describe the bilateral teleoperation system for controller design. The fuzzy rules of an interval Type-2 T-S fuzzy model are:

Rule l : IF $x(k)$ is $\tilde{S}^l$, THEN

$$\tilde{y}^l(k) = \tilde{a}_0^l + \tilde{a}_1^l x_1(k) + \tilde{a}_2^l x_2(k) + \dots + \tilde{a}_n^l x_n(k) \quad (2)$$

where, $l = 1, \dots, c$, c is the number of fuzzy rules; $x(k) \in R^n$ is the input vector, $x(k) = [x_1(k) \ x_2(k) \ \dots \ x_n(k)]^T$; $\tilde{S}^l$ is an interval Type-2 fuzzy set where the fuzzy membership of $x(k)$ is an interval denoted as $\tilde{\mu}^l(x(k)) = [\underline{\mu}^l(x(k)), \overline{\mu}^l(x(k))]$, $\underline{\mu}^l(x(k))$ and $\overline{\mu}^l(x(k))$ are lower and upper bounds respectively that $0 \leq \underline{\mu}^l(x(k)) \leq \overline{\mu}^l(x(k)) \leq 1$; The coefficients of the local models are also intervals as $\tilde{a}_r^l = [\underline{a}_r^l, \overline{a}_r^l]$, $r = 0, 1, \dots, n$. The local output $\tilde{y}^l(k) = [\underline{y}^l(k), \overline{y}^l(k)]$ is derived by:

$$\begin{cases} \underline{y}^l(k) = \underline{a}_0^l + \underline{a}_1^l x_1(k) + \underline{a}_2^l x_2(k) + \dots + \underline{a}_n^l x_n(k) \\ \overline{y}^l(k) = \overline{a}_0^l + \overline{a}_1^l x_1(k) + \overline{a}_2^l x_2(k) + \dots + \overline{a}_n^l x_n(k) \end{cases} \quad (3)$$

Blending the c fuzzy rules as in (2) produces a type-reduced set which is an interval and denoted as $\tilde{y}(k) = [\underline{y}(k), \overline{y}(k)]$. $\underline{y}(k)$ and $\overline{y}(k)$ can be calculated by:

$$\begin{cases} \underline{y}(k) = (\sum_{l=1}^c \underline{\mu}^l(x(k)) \underline{y}^l(k)) / (\sum_{l=1}^c \underline{\mu}^l(x(k))) \\ \overline{y}(k) = (\sum_{l=1}^c \overline{\mu}^l(x(k)) \overline{y}^l(k)) / (\sum_{l=1}^c \overline{\mu}^l(x(k))) \end{cases} \quad (4)$$

Defuzzifying $\tilde{y}(k)$ gives the crisp output $y(k)$:

$$y(k) = 0.5\underline{y}(k) + 0.5\overline{y}(k) \quad (5)$$

A data-driven procedure to identify a Type-2 fuzzy model is introduced as follows:

i). Collect N data samples from the original system as: $z(k) = [x^T(k) \ y(k)]^T \in R^{n+1}$, $k = 1, \dots, N$. Determine the number of fuzzy rules c .

ii). Use a clustering algorithm, such as the Gustafson-Kessel method in [40], to locate c fuzzy cluster centers, denoted by $z_c^l = [(x_c^l)^T \ y_c^l]^T$, and subsequently to provide a fuzzy membership matrix $U = [\mu^l(z(k))]_{c \times N}$, where $0 \leq \mu^l(z(k)) \leq 1$ and $\sum_{l=1}^c \mu^l(z(k)) = 1$.

iii). Determine a blurring radius of fuzzy membership in l th fuzzy cluster $0 \leq \Delta\mu^l \leq 1$ to extend $\mu^l(z(k))$ to an interval $\tilde{\mu}^l(z(k))$ by:

$$\begin{cases} \underline{\mu}^l(z(k)) = \max\{0, \mu^l(z(k)) - \Delta\mu^l\} \\ \bar{\mu}^l(z(k)) = \min\{1, \mu^l(z(k)) + \Delta\mu^l\} \end{cases} \quad (6)$$

iv). Determine a blurring radius of output $\Delta y > 0$, and then use weighted least square to identify the local model's coefficients:

$$\begin{cases} \underline{a}^l = (X^T W^l X)^{-1} X^T W^l \underline{Y} \\ \bar{a}^l = (X^T W^l X)^{-1} X^T W^l \bar{Y} \end{cases} \quad (7)$$

where, $\underline{a}^l = [\underline{a}_0^l \ \dots \ \underline{a}_n^l]^T$, $\bar{a}^l = [\bar{a}_0^l \ \dots \ \bar{a}_n^l]^T$, $X = [\hat{x}(1) \ \dots \ \hat{x}(N)]^T \in R^{N \times (n+1)}$, in which $\hat{x}(k) = [1 \ x_1(k) \ \dots \ x_n(k)]^T \in R^{n+1}$, $\underline{Y} = [(y(1) - \Delta y) \ (y(2) - \Delta y) \ \dots \ (y(N) - \Delta y)]^T$, $\bar{Y} = [(y(1) + \Delta y) \ (y(2) + \Delta y) \ \dots \ (y(N) + \Delta y)]^T$, and $W^l = \text{diag}[\mu^l(z(1)) \ \mu^l(z(2)) \ \dots \ \mu^l(z(N))]$.

For a master or a slave of the teleoperation system as in (1) with the degree of freedom as n^f , collect the joint positions $q_i(k) = [q_{i,a}^l(k)]_{n^f \times 1}$, joint velocities $v_i(k) = [v_{i,a}^l(k)]_{n^f \times 1}$ and torques $(\tau_i(k) + \tau_j^*(k)) = [(\tau_{i,a}(k) + \tau_{j,a}^*(k))]_{n^f \times 1}$, $a = 1, \dots, n^f$, $k = 1, \dots, N$, to form the data samples as $z_i(k) = [x^T(k) \ (\tau_i(k) + \tau_j^*(k))]^T$, where $x_i(k) = [ac_i^T(k) \ v_i^T(k) \ q_i^T(k)]^T$, $ac_i(k) = (v_i(k) - v_i(k-1))/\Delta T$ can represent the joint accelerations when the sampling period ΔT is sufficiently small. The rules of its Type-2 T-S fuzzy model can be expressed as:

Rule l : IF $x_i(k)$ is $\tilde{S}_i^l$, THEN

$$\tilde{M}_i^l ac_i(k) + \tilde{C}_i^l v_i(k) + \tilde{D}_i^l q_i(k) + \tilde{E}_i^l = \tilde{\tau}_i^l(k) + \tau_j(k) \quad (8)$$

where $\tilde{M}_i^l = [\underline{M}_i^l, \ \bar{M}_i^l]$, $\tilde{C}_i^l = [\underline{C}_i^l, \ \bar{C}_i^l]$, $\tilde{D}_i^l = [\underline{D}_i^l, \ \bar{D}_i^l]$ and $\tilde{E}_i^l = [\underline{E}_i^l, \ \bar{E}_i^l]$, $\underline{M}_i^l, \bar{M}_i^l, \underline{C}_i^l, \bar{C}_i^l, \underline{D}_i^l, \bar{D}_i^l \in R^{n^f \times n^f}$ and $\underline{E}_i^l, \bar{E}_i^l \in R^{n^f}$. The local model in (1) can be rewritten as a combination of two linear functions as:

$$\begin{cases} \underline{M}_i^l ac_i(k) + \underline{C}_i^l v_i(k) + \underline{D}_i^l q_i(k) + \underline{E}_i^l = \underline{\tau}_i^l(k) + \tau_j(k) \\ \bar{M}_i^l ac_i(k) + \bar{C}_i^l v_i(k) + \bar{D}_i^l q_i(k) + \bar{E}_i^l = \bar{\tau}_i^l(k) + \tau_j(k) \end{cases} \quad (9)$$

To further simplify the fuzzy model based controller design, we create a nominal model using decentralized structure keeping the diagonal elements of $\tilde{M}_i^l$, $\tilde{C}_i^l$ and $\tilde{D}_i^l$ and discarding the rest. The relative gain array (RGA) [36] is employed to compensate the interacting effects on diagonal elements. For an $n \times n$ MIMO system, the RGA, denoted by Λ , can be calculated by:

$$\Lambda = [\lambda_{ab}]_{n \times n} = G \otimes G^{-T} \quad (10)$$

where $\lambda_{ab} = g_{ab}/\hat{g}_{ab}$, $a, b = 1, \dots, n$, g_{ab} is the steady-state gain of the channel connecting a th output and b th input without coupling effects from other channels, while $\hat{g}_{ab}$ is the apparent steady-state gain of this channel bearing interacting effects. $G = [g_{ab}]_{n \times n}$, $\otimes$ is the element-by-element product, G^{-T} is the transpose matrix of the inverse of G .

Let $ac_{i,a}(k) = (q_{i,a}(k) - 2q_{i,a}(k-1) + q_{i,a}(k-2))/\Delta T^2$, $v_i(k) = (q_{i,a}(k) - q_{i,a}(k-1))/\Delta T$, by virtue of Z-transform, the two equations in (9) can be rewritten as:

$$\begin{cases} \underline{G}_i^l(z) q_i(k) = \underline{\Pi}_i^l(k) \\ \bar{G}_i^l(z) q_i(k) = \bar{\Pi}_i^l(k) \end{cases} \quad (11)$$

where $\underline{G}_i^l(z) = \frac{\underline{M}_i^l}{\Delta T^2} + \frac{\underline{C}_i^l}{\Delta T} + \underline{D}_i^l + \left(\frac{-2\underline{M}_i^l}{\Delta T^2} + \frac{-\underline{C}_i^l}{\Delta T} \right) z^{-1} + \frac{\underline{M}_i^l}{\Delta T^2} z^{-2}$, $\bar{G}_i^l(z) = \frac{\bar{M}_i^l}{\Delta T^2} + \frac{\bar{C}_i^l}{\Delta T} + \bar{D}_i^l + \left(\frac{-2\bar{M}_i^l}{\Delta T^2} + \frac{-\bar{C}_i^l}{\Delta T} \right) z^{-1} + \frac{\bar{M}_i^l}{\Delta T^2} z^{-2}$, $\underline{\Pi}_i^l(k) = \underline{\tau}_i^l(k) + \tau_j^*(k) - \underline{E}_i^l$ and $\bar{\Pi}_i^l(k) = \bar{\tau}_i^l(k) + \tau_j^*(k) - \bar{E}_i^l$. Two steady-state gain matrices can be obtained from (11):

$$\begin{cases} \underline{G}_i^l = \underline{G}_i^l(z)|_{z=1} = \underline{D}_i^l \\ \bar{G}_i^l = \bar{G}_i^l(z)|_{z=1} = \bar{D}_i^l \end{cases} \quad (12)$$

Afterwards two RGAs can be derived using (10) and denoted by

$$\begin{cases} \underline{\Lambda}_i^l = [\underline{\lambda}_{i,ab}^l]_{n^f \times n^f} = \underline{G}_i^l \otimes \underline{G}_i^{l-T} = \underline{D}_i^l \otimes (\underline{D}_i^l)^{-T} \\ \bar{\Lambda}_i^l = [\bar{\lambda}_{i,ab}^l]_{n^f \times n^f} = \bar{G}_i^l \otimes \bar{G}_i^{l-T} = \bar{D}_i^l \otimes (\bar{D}_i^l)^{-T} \end{cases} \quad (13)$$

From the RGAs $\underline{\Lambda}_i^l$ and $\bar{\Lambda}_i^l$ in (13) we have

$$\begin{cases} \underline{\hat{D}}_{i,aa}^l = \underline{D}_{i,aa}^l / \underline{\lambda}_{i,aa}^l \\ \bar{\hat{D}}_{i,aa}^l = \bar{D}_{i,aa}^l / \bar{\lambda}_{i,aa}^l \end{cases} \quad (14)$$

where the subscript aa means diagonal element, and $\underline{\hat{D}}_{i,aa}^l$ and $\bar{\hat{D}}_{i,aa}^l$ are coefficients after compensation. Using (14), a nominal Type-2 fuzzy model with decentralized structure can be derived:

Rule l : IF $x_i(k)$ is $\tilde{S}_i^l$, THEN

$$\tilde{M}_i^l ac_i(k) + \tilde{C}_i^l v_i(k) + \tilde{D}_i^l q_i(k) + \tilde{E}_i^l = \tilde{\tau}_i^l(k) + \tau_j(k) \quad (15)$$

where $\tilde{M}_i^l = [\underline{\hat{M}}_i^l, \ \bar{\hat{M}}_i^l]$, $\tilde{C}_i^l = [\underline{\hat{C}}_i^l, \ \bar{\hat{C}}_i^l]$ and $\tilde{D}_i^l = [\underline{\hat{D}}_i^l, \ \bar{\hat{D}}_i^l]$, $\underline{\hat{X}}_i^l = \text{diag}\{\underline{\hat{x}}_{i,11}^l, \ \underline{\hat{x}}_{i,22}^l, \ \dots \ \underline{\hat{x}}_{i,n^f n^f}^l\}$, $\bar{\hat{X}}_i^l = \text{diag}\{\bar{\hat{x}}_{i,11}^l, \ \bar{\hat{x}}_{i,22}^l, \ \dots \ \bar{\hat{x}}_{i,n^f n^f}^l\}$, $\mathcal{X} = M, C$ and D . The sampling time for bilateral system is generally counted in milliseconds. In this paper, the sampling time is 1ms, which is sufficiently small to the extent that the local model can be expressed by the following two continuous functions:

$$\begin{cases} \underline{\hat{M}}_i^l \ddot{q}_i + \underline{\hat{C}}_i^l \dot{q}_i + \underline{\hat{D}}_i^l q_i + \underline{\hat{E}}_i^l = \underline{\tau}_i^l + \tau_j \\ \bar{\hat{M}}_i^l \ddot{q}_i + \bar{\hat{C}}_i^l \dot{q}_i + \bar{\hat{D}}_i^l q_i + \bar{\hat{E}}_i^l = \bar{\tau}_i^l + \tau_j \end{cases} \quad (16)$$

Treating $M_i = \frac{1}{2}(\underline{\hat{M}}_i + \bar{\hat{M}}_i) = \frac{\sum_{l=1}^c \underline{\mu}^l(x_i(k)) \underline{\hat{M}}_i^l}{2 \sum_{l=1}^c \underline{\mu}^l(x_i(k))} + \frac{\sum_{l=1}^c \bar{\mu}^l(x_i(k)) \bar{\hat{M}}_i^l}{2 \sum_{l=1}^c \bar{\mu}^l(x_i(k))}$,

$$C_i = \frac{1}{2}(\underline{\hat{C}}_i + \bar{\hat{C}}_i) = \frac{\sum_{l=1}^c \underline{\mu}^l(x_i(k)) \underline{\hat{C}}_i^l}{2 \sum_{l=1}^c \underline{\mu}^l(x_i(k))} + \frac{\sum_{l=1}^c \bar{\mu}^l(x_i(k)) \bar{\hat{C}}_i^l}{2 \sum_{l=1}^c \bar{\mu}^l(x_i(k))}, \quad D_i = \frac{1}{2}(\underline{\hat{D}}_i + \bar{\hat{D}}_i) = \frac{\sum_{l=1}^c \underline{\mu}^l(x_i(k)) \underline{\hat{D}}_i^l}{2 \sum_{l=1}^c \underline{\mu}^l(x_i(k))} + \frac{\sum_{l=1}^c \bar{\mu}^l(x_i(k)) \bar{\hat{D}}_i^l}{2 \sum_{l=1}^c \bar{\mu}^l(x_i(k))}, \quad E_i = \frac{1}{2}(\underline{\hat{E}}_i + \bar{\hat{E}}_i) =$$

$$\frac{\sum_{l=1}^c \underline{\mu}^l(x_i(k)) \underline{\hat{E}}_i^l}{2 \sum_{l=1}^c \underline{\mu}^l(x_i(k))} + \frac{\sum_{l=1}^c \bar{\mu}^l(x_i(k)) \bar{\hat{E}}_i^l}{2 \sum_{l=1}^c \bar{\mu}^l(x_i(k))}, \quad \text{and} \quad \tau_i = \frac{\sum_{l=1}^c \underline{\mu}^l(x_i(k)) \underline{\tau}_i^l(k)}{2 \sum_{l=1}^c \underline{\mu}^l(x_i(k))} + \frac{\sum_{l=1}^c \bar{\mu}^l(x_i(k)) \bar{\tau}_i^l(k)}{2 \sum_{l=1}^c \bar{\mu}^l(x_i(k))}, \text{ the nominal Type-2 fuzzy model becomes:}$$

$$(M_i + \Delta M_i) \ddot{q}_i + (C_i + \Delta C_i) \dot{q}_i + (D_i + \Delta D_i) q_i + (E_i + \Delta E_i) = \tau_i + \tau_j \quad (17)$$

where $\Delta M_i = \frac{1}{2} \lambda (\bar{\hat{M}}_i - \underline{\hat{M}}_i)$, $\Delta C_i = \frac{1}{2} \lambda (\bar{\hat{C}}_i - \underline{\hat{C}}_i)$, $\Delta D_i = \frac{1}{2} \lambda (\bar{\hat{D}}_i - \underline{\hat{D}}_i)$, $\Delta E_i = \frac{1}{2} \lambda (\bar{\hat{E}}_i - \underline{\hat{E}}_i)$. $\lambda \in [-1, 1]$ is an unknown variable. ΔM_i , ΔC_i , ΔD_i , and ΔE_i are the unknown estimation errors with known upper and lower bounds. Due to the small

interval of each fuzzy rule, ΔM_i , ΔC_i , ΔD_i , and ΔE_i are neighbouring zero.

3. Guarantee for passivity of communication channels

The designed online-switching system possesses two modes. One is the tele-operated mode, which allows the human operator to remotely control the slave and simultaneously receive the feedback from the slave. The other is the autonomous mode, where the slave follows the reference signals trained by the master's previous motion and remotely controls master's motion in order to let master follow the slave's motion. It is easy to learn that in the autonomous mode, the roles of the two robots are mutually exchanged: the slave becomes the master while the master becomes the slave. Since active power flow transmitted either from master or from the slave, the passivity of the communication channels must be guaranteed in both of the modes in order to further ensure the overall system's stability.

Remark 1: The differentials of $T_1(t)$ and $T_2(t)$ are bounded by positive constants $\bar{d}_1$ and $\bar{d}_2$, respectively. That is, $0 \leq |\dot{T}_{1,2}(t)| \leq \bar{d}_{1,2}$.

In this paper, the wave-based TDPA proposed in [37] is further extended in order to transmit the position, velocity and torque signals. The extended wave variable transformation is shown in Fig. 1, where $b, \lambda_{11}, \lambda_{21}, \lambda_{12}, \lambda_{22} > 0$. The wave variable scheme is used to encode the transmitted position, velocity and torque signals, where ${}^1V_{A1} = \dot{q}_m$, ${}^1I_{A2} = -\dot{q}_s$, ${}^2V_{A1} = \tau_h^*$, ${}^2I_{A2} = -\dot{q}_s$, ${}^1V_{B1} = q_m$, ${}^1I_{B2} = \dot{q}_s$, ${}^2V_{B1} = \dot{q}_m$, ${}^2I_{B2} = \tau_e^*$. ${}^\ell u_{m1}^T$, ${}^\ell u_{m2}^T$, ${}^\ell u_{s1}^T$, ${}^\ell u_{s2}^T$ are the wave variables. ($\ell = 1$ or 2).

Fig. 1. Extended wave transformation

Therefore, the control signals after transmission in Fig. 1 can be derived as:

$$\begin{aligned} {}^1I_{A1}(t) &= b\lambda_{11}\dot{q}_m(t) - q_s(t - T_2(t)) \\ {}^1V_{A2}(t) &= \dot{q}_m(t - T_1(t)) + \frac{1}{b\lambda_{11}}(q_s(t) - q_s(t - \hat{T}_2(t))) \\ {}^2I_{A1}(t) &= b\lambda_{21}\tau_h^*(t) - \dot{q}_s(t - T_2(t)) \end{aligned}$$

$$\begin{aligned} {}^2V_{A2}(t) &= \tau_h^*(t - T_1(t)) + \frac{1}{b\lambda_{21}}(\dot{q}_s(t) - \dot{q}_s(t - \hat{T}_2(t))) \\ {}^1I_{B1}(t) &= \dot{q}_s(t - T_2(t)) + \frac{b}{\lambda_{12}}(q_m(t) - q_m(t - \hat{T}_1(t))) \\ {}^1V_{B2}(t) &= -\frac{\lambda_{12}}{b}\dot{q}_s(t) + q_m(t - T_1(t)) \\ {}^2I_{B1}(t) &= \tau_e^*(t - T_1(t)) + \frac{b}{\lambda_{22}}(\dot{q}_m(t) - \dot{q}_m(t - \hat{T}_1(t))) \\ {}^2V_{B2}(t) &= -\frac{\lambda_{22}}{b}\tau_e^*(t) + \dot{q}_m(t - T_1(t)) \end{aligned} \quad (18)$$

where $\hat{T}_2(t) = T_2(t) + T_1(t - T_2(t))$, $\hat{T}_1(t) = T_1(t) + T_2(t - T_1(t))$.

The wave variable transformation in Fig. 1 can be treated as the combination of four 2-port networks. Inspired by [37] the power flow in the wave variable transformation is defined as:

$$P_{flow}(t) = {}^1P_1(t) + {}^2P_1(t) + {}^1P_2(t) + {}^2P_2(t)$$

$$\begin{aligned} {}^\ell P_1(t) &= {}^\ell V_{A1}(t) {}^\ell I_{A1}(t) - {}^\ell V_{A2}(t) {}^\ell I_{A2}(t) \\ &= \frac{d}{dt} \int_{t-T_1(t)}^t \lambda_{\ell 1} {}^\ell u_{m1}^T(\eta) {}^\ell u_{m1}(\eta) d\eta + \\ &\frac{d}{dt} \int_{t-T_2(t)}^t \frac{1}{\lambda_{\ell 1}} {}^\ell v_{s1}^T(\eta) {}^\ell v_{s1}(\eta) d\eta + \frac{1}{\lambda_{\ell 1}} ({}^\ell v_{m1}(t) - \\ &\lambda_{\ell 1} {}^\ell u_{m1}(t))^T ({}^\ell v_{m1}(t) - \lambda_{\ell 1} {}^\ell u_{m1}(t)) + \frac{1}{\lambda_{\ell 1}} ({}^\ell v_{s1}(t) - \\ &\lambda_{\ell 1} {}^\ell u_{s1}(t))^T ({}^\ell v_{s1}(t) - \lambda_{\ell 1} {}^\ell u_{s1}(t)) - \\ &\lambda_{\ell 1} \dot{T}_1(t) {}^\ell u_{s1}^T(t) {}^\ell u_{s1}(t) - \frac{1}{\lambda_{\ell 1}} \dot{T}_2(t) {}^\ell v_{m1}^T(t) {}^\ell v_{m1}(t) \\ &= \frac{d {}^\ell E_1(t)}{dt} + {}^\ell P_1^{diss}(t) \end{aligned} \quad (19)$$

$$\begin{aligned} {}^\ell E_1(t) &= \frac{d}{dt} \int_{t-T_1(t)}^t \lambda_{\ell 1} {}^\ell u_{m1}^T(\eta) {}^\ell u_{m1}(\eta) d\eta + \\ &\frac{d}{dt} \int_{t-T_2(t)}^t \frac{1}{\lambda_{\ell 1}} {}^\ell v_{s1}^T(\eta) {}^\ell v_{s1}(\eta) d\eta \end{aligned} \quad (20)$$

$$\begin{aligned} {}^\ell P_1^{diss}(t) &= \frac{1}{\lambda_{\ell 1}} ({}^\ell v_{m1}(t) - \lambda_{\ell 1} {}^\ell u_{m1}(t))^T ({}^\ell v_{m1}(t) - \\ &\lambda_{\ell 1} {}^\ell u_{m1}(t)) + \frac{1}{\lambda_{\ell 1}} ({}^\ell v_{s1}(t) - \lambda_{\ell 1} {}^\ell u_{s1}(t))^T ({}^\ell v_{s1}(t) - \\ &\lambda_{\ell 1} {}^\ell u_{s1}(t)) - \lambda_{\ell 1} \dot{T}_1(t) {}^\ell u_{s1}^T(t) {}^\ell u_{s1}(t) - \\ &\frac{1}{\lambda_{\ell 1}} \dot{T}_2(t) {}^\ell v_{m1}^T(t) {}^\ell v_{m1}(t) \end{aligned} \quad (21)$$

$$\begin{aligned} {}^\ell P_2(t) &= {}^\ell V_{B1}(t) {}^\ell I_{B1}(t) - {}^\ell V_{B2}(t) {}^\ell I_{B2}(t) \\ &= \frac{d}{dt} \int_{t-T_1(t)}^t \frac{1}{\lambda_{\ell 2}} {}^\ell u_{m2}^T(\eta) {}^\ell u_{m2}(\eta) d\eta + \\ &\frac{d}{dt} \int_{t-T_2(t)}^t \lambda_{\ell 2} {}^\ell v_{s2}^T(\eta) {}^\ell v_{s2}(\eta) d\eta + \lambda_{\ell 2} ({}^\ell v_{m2}(t) - \\ &\frac{1}{\lambda_{\ell 2}} {}^\ell u_{m2}(t))^T ({}^\ell v_{m2}(t) - \frac{1}{\lambda_{\ell 2}} {}^\ell u_{m2}(t)) + \lambda_{\ell 2} ({}^\ell v_{s2}(t) - \\ &\frac{1}{\lambda_{\ell 2}} {}^\ell u_{s2}(t))^T ({}^\ell v_{s2}(t) - \frac{1}{\lambda_{\ell 2}} {}^\ell u_{s2}(t)) - \\ &\frac{1}{\lambda_{\ell 2}} \dot{T}_1(t) {}^\ell u_{s2}^T(t) {}^\ell u_{s2}(t) - \lambda_{\ell 2} \dot{T}_2(t) {}^\ell v_{m2}^T(t) {}^\ell v_{m2}(t) \\ &= \frac{d {}^\ell E_2(t)}{dt} + {}^\ell P_2^{diss}(t) \end{aligned} \quad (22)$$

$$\begin{aligned} {}^\ell E_2(t) &= \frac{d}{dt} \int_{t-T_1(t)}^t \frac{1}{\lambda_{\ell 2}} {}^\ell u_{m2}^T(\eta) {}^\ell u_{m2}(\eta) d\eta + \\ &\frac{d}{dt} \int_{t-T_2(t)}^t \lambda_{\ell 2} {}^\ell v_{s2}^T(\eta) {}^\ell v_{s2}(\eta) d\eta \end{aligned} \quad (23)$$

$$\begin{aligned} P_2^{diss}(t) &= \lambda_{\ell 2} ({}^\ell v_{m2}(t) - \frac{1}{\lambda_{\ell 2}} {}^\ell u_{m2}(t))^T ({}^\ell v_{m2}(t) - \\ &\frac{1}{\lambda_{\ell 2}} {}^\ell u_{m2}(t)) + \lambda_{\ell 2} ({}^\ell v_{s2}(t) - \frac{1}{\lambda_{\ell 2}} {}^\ell u_{s2}(t))^T ({}^\ell v_{s2}(t) - \\ &\frac{1}{\lambda_{\ell 2}} {}^\ell u_{s2}(t)) \end{aligned}$$

$$\frac{1}{\lambda_{\ell 2}} \ell u_{s2}(t) \Big) - \frac{1}{\lambda_{\ell 2}} \dot{T}_1(t) \ell u_{s2}^T(t) \ell u_{s2}(t) - \lambda_{\ell 2} \dot{T}_2(t) \ell v_{m2}^T(t) \ell v_{m2}(t) \quad (24)$$

According to (20) and (24), in the tele-operated mode, the net energy flows are absolutely positive. According to the definition of passivity and assuming $\ell E_\ell(0) = 0$, the energy flow is derived as:

$$E_{flow}(t) = \int_0^t P_{flow}(\eta) d\eta = \int_0^t ({}^1P_1(\eta) + {}^2P_1(\eta) + {}^1P_2(\eta) + {}^2P_2(\eta)) d\eta = {}^1E_1(t) + {}^2E_1(t) + {}^1E_2(t) + {}^2E_2(t) - {}^1E_1(0) - {}^2E_1(0) - {}^1E_2(0) - {}^2E_2(0) - \int_0^t ({}^1P_1^{diss}(\eta) + {}^1P_2^{diss}(\eta) + {}^2P_1^{diss}(\eta) + {}^2P_2^{diss}(\eta)) d\eta \geq \int_0^t ({}^1P_1^{diss}(\eta) + {}^1P_2^{diss}(\eta) + {}^2P_1^{diss}(\eta) + {}^2P_2^{diss}(\eta)) d\eta \quad (25)$$

Therefore, in the situation that ${}^1P_1^{diss}(t) + {}^1P_2^{diss}(t) + {}^2P_1^{diss}(t) + {}^2P_2^{diss}(t) \geq 0$, the energy flow $E_{flow}(t)$ in (25) is no less than zero and the passivity of the time delayed network can be guaranteed in the tele-operated mode.

Based on (21) and (24) and **Remark 1**, four passivity observers are designed in each terminal of the communication channels in order to observe the passivity of the power flow.

$$P_{obs(\ell 1)}^m(t) = \frac{1}{\lambda_{\ell 1}} \left(\ell v_{m1}(t) - \lambda_{\ell 1} \ell u_{m1}(t) \right)^T \left(\ell v_{m1}(t) - \lambda_{\ell 1} \ell u_{m1}(t) \right) - \frac{\bar{d}_2}{\lambda_{\ell 1}} \ell v_{m1}^T(t) \ell v_{m1}(t) \quad (26)$$

$$P_{obs(\ell 2)}^m(t) = \lambda_{\ell 2} \left(\ell v_{m2}(t) - \frac{1}{\lambda_{\ell 2}} \ell u_{m2}(t) \right)^T \left(\ell v_{m2}(t) - \frac{1}{\lambda_{\ell 2}} \ell u_{m2}(t) \right) - \lambda_{\ell 2} \bar{d}_2(t) \ell v_{m2}^T(t) \ell v_{m2}(t) \quad (27)$$

$$P_{obs(\ell 1)}^s(t) = \frac{1}{\lambda_{\ell 1}} \left(\ell v_{s1}(t) - \lambda_{\ell 1} \ell u_{s1}(t) \right)^T \left(\ell v_{s1}(t) - \lambda_{\ell 1} \ell u_{s1}(t) \right) - \lambda_{\ell 1} \bar{d}_1 \ell u_{s1}^T(t) \ell u_{s1}(t) \quad (28)$$

$$P_{obs(\ell 2)}^s(t) = \lambda_{\ell 2} \left(\ell v_{s2}(t) - \frac{1}{\lambda_{\ell 2}} \ell u_{s2}(t) \right)^T \left(\ell v_{s2}(t) - \frac{1}{\lambda_{\ell 2}} \ell u_{s2}(t) \right) - \frac{\bar{d}_1}{\lambda_{\ell 2}} \ell u_{s2}^T(t) \ell u_{s2}(t) \quad (29)$$

By using the passivity observer, the related passivity controllers are as follows:

$$\begin{aligned} \ell \hat{I}_{A1}(t) &= \ell I_{A1}(t) + \ell \Gamma_{A1}(t) \ell V_{A1}(t) \\ \ell \hat{I}_{B1}(t) &= \ell I_{B1}(t) + \ell \Gamma_{B1}(t) \ell V_{B1}(t) \\ \ell \hat{V}_{A2}(t) &= \ell V_{A2}(t) + \ell \Gamma_{A2}(t) \ell I_{A2}(t) \\ \ell \hat{V}_{B2}(t) &= \ell V_{B2}(t) + \ell \Gamma_{B2}(t) \ell I_{B2}(t) \end{aligned} \quad (30)$$

where $\ell \hat{I}_{A1}(t)$, $\ell \hat{I}_{B1}(t)$, $\ell \hat{V}_{A2}(t)$ and $\ell \hat{V}_{B2}(t)$ are the final control signals to master and slave terminals after modification by the passivity controllers. $\ell \Gamma_{A1}(t)$, $\ell \Gamma_{B1}(t)$, $\ell \Gamma_{A2}(t)$ and $\ell \Gamma_{B2}(t)$ are derived as:

$$\ell \Gamma_{A1}(t) = \begin{cases} 0, & \text{if } P_{obs(\ell 1)}^m(t) > 0 \text{ or } \ell V_{A1}(t) = 0 \\ -P_{obs(\ell 1)}^m(t) \left(\ell V_{A1}^T(t) \ell V_{A1}(t) \right)^{-1}, & \text{else} \end{cases} \quad (31)$$

$$\ell \Gamma_{B1}(t) = \begin{cases} 0, & \text{if } P_{obs(\ell 2)}^m(t) > 0 \text{ or } \ell V_{B1}(t) = 0 \\ -P_{obs(\ell 2)}^m(t) \left(\ell V_{B1}^T(t) \ell V_{B1}(t) \right)^{-1}, & \text{else} \end{cases} \quad (32)$$

$$\ell \Gamma_{A2}(t) = \begin{cases} 0, & \text{if } P_{obs(\ell 1)}^s(t) > 0 \text{ or } \ell I_{A2}(t) = 0 \\ P_{obs(\ell 1)}^s(t) \left(\ell I_{A2}^T(t) \ell I_{A2}(t) \right)^{-1}, & \text{else} \end{cases} \quad (33)$$

$$\ell \Gamma_{B2}(t) = \begin{cases} 0, & \text{if } P_{obs(\ell 2)}^s(t) > 0 \text{ or } \ell I_{B2}(t) = 0 \\ P_{obs(\ell 2)}^s(t) \left(\ell I_{B2}^T(t) \ell I_{B2}(t) \right)^{-1}, & \text{else} \end{cases} \quad (34)$$

Theorem 1. The designed passivity controller (31)-(34) can ensure the channels passivity in the presence of arbitrary time delays. The proof is similar as Theorem 3.1 in [38].

Remark 2. In the tele-operated mode, the proposed wave variable transformation can maintain the passivity of the communication channels under constant time delays and slow-varying delays to a certain extent. When the time delays vary sharper, the observers may detect negative power information so that the passivity controllers are activated by the observers to further guarantee the channel passivity. The passivity controller guarantees the channel passivity by degrading the transparency. Since in most cases, the information detected by the observers is active, the passivity controllers are not always activated and high transparency can be guaranteed. In the autonomous mode, since the slave driven by the reference signals to control the master, the roles of the master and slave are mutually switched and the power flow is from the slave to the master. The information observed by the observers are always negative and the passivity controller are always activated in this mode in order to guarantee the channel passivity. More analyses are in the following sections.

4. Control laws

Definition 1:

$$\text{sig}(\eta)^\alpha \triangleq [|\eta_1|^{\alpha_1} \text{sign}(\eta_1), \dots, |\eta_n|^{\alpha_n} \text{sign}(\eta_n)]^T$$

where $\eta = [\eta_1 \dots \eta_n]^T \in \mathbb{R}^n$, $\alpha = [\alpha_1 \dots \alpha_n]^T$, $\alpha_{1 \dots n}$ are positive constants. $\text{sign}(\cdot)$ is the standard signum function.

Lemma 1: Assume $\alpha_1 > 0$, $\alpha_2 > 0, \dots$, $\alpha_n > 0$, if $0 < c < 1$, then $(\alpha_1 + \dots + \alpha_n)^c \leq \alpha_1^c + \dots + \alpha_n^c$. If $1 < c < \infty$, then $(\alpha_1 + \dots + \alpha_n)^c \leq n^{c-1}(\alpha_1^c + \dots + \alpha_n^c)$.

Lemma 2: (reaching time): consider the dynamic model $\dot{x} = f(x)$, $f(0) = 0$ and $x \in \mathbb{R}^n$. If there is a positive definite function $V(x)$ such that $\dot{V}(x) \leq -\mathbb{R}V(x)^{\rho_1} - \mathbb{Z}V(x)^{\rho_2}$ where $\mathbb{R}, \mathbb{Z} > 0$, $\rho_1 > 1$, $0 < \rho_2 < 1$. Then the system is finite-time stable, Furthermore, the settling time is given by $T_r < \frac{1}{\mathbb{R}} \frac{1}{\rho_1 - 1} + \frac{1}{\mathbb{Z}} \frac{1}{1 - \rho_2}$

Lemma 3: (sliding time) Choose the terminal sliding mode as $s = \dot{x} + \alpha \text{sig}(x)^{\gamma_1} + \beta \text{sig}(x)^{\gamma_2}$. The convergence time T_s of x is $T_s < \frac{1}{\alpha} \frac{1}{\gamma_1 - 1} + \frac{1}{\beta} \frac{1}{1 - \gamma_2}$

In the tele-operated mode, we define the new variables representing position tracking in the master and slave sides as:

$$r_m = q_m(t) + {}^1\hat{I}_{A1}(t) = -q_s(t - T_2(t)) + q_m(t) + b\lambda_{11}\dot{q}_m(t) + {}^1\hat{I}_{A1}(t)\dot{q}_m(t) \quad (35)$$

$$r_s = q_s(t) - {}^1\hat{V}_{B2}(t) = -q_m(t - T_1(t)) + q_s(t) + \frac{\lambda_{12}}{b}\dot{q}_s(t) -$$

$${}^1\Gamma_{B2}(t)\dot{q}_s(t) \quad (36)$$

Based on (35)-(36), by setting small values of λ_{11} and λ_{12} , the bias term $b\lambda_{11}\dot{q}_m(t)$ and $\frac{\lambda_{12}}{b}\dot{q}_s(t)$ can be minimized. According to Section 3, ${}^1\Gamma_{A1}(t)\dot{q}_m(t)$ and ${}^1\Gamma_{B2}(t)\dot{q}_s(t)$ are the passivity controllers that guarantee the channel passivity, which are zero under constant or small-varying delays. The NFTSM for the tele-operated mode is defined as

$${}^1s_i(t) = k_i\dot{r}_i(t) + k_i\alpha_{i1}\text{sig}(r_i(t))^{\gamma_{i1}} + k_i\alpha_{i2}\text{sig}(r_i(t))^{\gamma_{i2}(t)} \quad (37)$$

where α_{i1} , α_{i2} , k_i are positive constants and $\gamma_{i1} > 1$. $\gamma_{i2}(t)$ are designed functions that will be introduced later. $\dot{r}_i(t)$ in (37) is derived as:

$$\dot{r}_m(t) = \dot{q}_m(t) - \dot{q}_s(t - T_2(t)) + b\lambda_{11}\dot{q}_m(t) - \left(\frac{d({}^1\Gamma_{A1}(t)\dot{q}_m(t))}{dt} - \dot{T}_2\dot{q}_s(t - T_2(t)) \right) \quad (38)$$

$$\dot{r}_s = \dot{q}_s(t) - \dot{q}_m(t - T_1(t)) + \frac{\lambda_{12}}{b}\ddot{q}_s(t) - \left(\frac{d({}^1\Gamma_{B2}(t)\dot{q}_s(t))}{dt} - \dot{T}_1\dot{q}_m(t - T_1(t)) \right) \quad (39)$$

According to Section 3 and **Theorem 1**, the passivity controllers are proposed to absolutely guarantee the passivity of the communication channels so that $\dot{T}_2\dot{q}_s(t - T_2(t))$ and $\dot{T}_1\dot{q}_m(t - T_1(t))$ can be seen as the extra energy inserted by the time-varying delays and can be compensated for by the passivity controllers. Therefore, the last terms of (38) and (39) can be ignored. By setting $0 < k_i \ll 1$, (34) approximately equals to:

$${}^1s_m(t) = k_m \left(\frac{1}{2} \left({}^1\hat{I}_{B1}(t) - {}^2\hat{I}_{A1}(t) \right) - \dot{q}_m(t) \right) + k_m\alpha_{m1}\text{sig}(r_m(t))^{\gamma_{m1}} + k_m\alpha_{m2}\text{sig}(r_m(t))^{\gamma_{m2}(t)} \quad (40)$$

$${}^1s_s(t) = k_s \left(\frac{1}{2} \left({}^2\hat{V}_{B2}(t) + {}^1\hat{V}_{A2}(t) \right) - \dot{q}_s(t) \right) + k_s\alpha_{s1}\text{sig}(r_s(t))^{\gamma_{s1}} + k_s\alpha_{s2}\text{sig}(r_s(t))^{\gamma_{s2}(t)} \quad (41)$$

$\gamma_{i2}(t)$ in (40)-(41) are proposed as (42).

$$\gamma_{i2}(t) = \text{Sat}'_1 \left(\frac{\varpi}{\|r_i(t)\|} \right) \quad (42)$$

$$\text{where } \text{Sat}'_1(\cdot) \triangleq \begin{cases} \varpi_1 \leq \frac{\varpi}{\|r_i(t)\|} \leq \varpi_2, \text{ when } \|r_i(t)\| \geq \varpi \\ \varpi_3 \leq \frac{\varpi}{\|r_i(t)\|} \leq \varpi_4, \text{ when } \|r_i(t)\| < \varpi \end{cases}$$

ϖ , ϖ_{1-4} are positive constants and satisfy $0 < \varpi_1 < \varpi_2 < 1 < \varpi_3 < \varpi_4$, $0 < \varpi \ll 1$. From (42), when $r_i(t)$ decrease to ϖ , $\gamma_{i2}(t)$ can increase from ϖ_1 to ϖ_2 ; and if $r_i(t)$ continue to decrease to zero, $\gamma_{i2}(t)$ will increase from ϖ_3 to ϖ_4 . This function is utilized to deal with the singularity if ${}^1s_i = 0$, $\dot{r}_i(t) = 0$ but $r_i(t) \neq 0$.

In the autonomous mode, define $e_{ref} = q_{ref} - q_s$, where q_{ref} is the reference position signal previously trained by the operator, the NFTSM for the autonomous mode is defined as:

$${}^2s_s(t) = \dot{e}_{ref}(t) + \alpha_3\text{sig}(e_{ref}(t))^{\gamma_3} + \alpha_4\text{sig}(e_{ref}(t))^{\gamma_4(t)} \quad (43)$$

where $\alpha_3, \alpha_4, \gamma_3 > 0$, and $\gamma_4(t)$ is designed similar as (42):

$$\gamma_4(t) = \text{Sat}'_2 \left(\frac{\varpi}{\|e_{ref}(t)\|} \right) \quad (44)$$

$$\text{where } \text{Sat}'_2(\cdot) \triangleq \begin{cases} \varpi_1 \leq \frac{\varpi}{\|e_{ref}(t)\|} \leq \varpi_2, \|e_{ref}(t)\| \geq \varpi \\ \varpi_3 \leq \frac{\varpi}{\|e_{ref}(t)\|} \leq \varpi_4, \|e_{ref}(t)\| < \varpi \end{cases}$$

Additionally, we define the new variables representing torque tracking for the master and slave as:

$$\mathcal{E}_m(t) = \tau_h^*(t) - {}^2\hat{I}_{B1}(t) = \tau_h^*(t) - \tau_e^*(t - T_1(t)) - \frac{b}{\lambda_{22}} \left(\dot{q}_m(t) - \dot{q}_m(t - \hat{T}_1(t)) \right) - {}^2\Gamma_{B1}(t)\dot{q}_m(t) \quad (45)$$

$$\mathcal{E}_s(t) = {}^2\hat{V}_{A2}(t) - \tau_e^*(t) = \tau_h^*(t - T_1(t)) - \tau_e^*(t) + \frac{1}{b\lambda_{21}} \left(\dot{q}_s(t) - \dot{q}_s(t - \hat{T}_2(t)) \right) - {}^2\Gamma_{A2}(t)\dot{q}_s(t) \quad (46)$$

In (45)-(46), by setting large values of λ_{22} and λ_{21} , the bias terms $\frac{b}{\lambda_{22}} \left(\dot{q}_m(t) - \dot{q}_m(t - \hat{T}_1(t)) \right)$ and $\frac{1}{b\lambda_{21}} \left(\dot{q}_s(t) - \dot{q}_s(t - \hat{T}_2(t)) \right)$ can be minimized. ${}^2\Gamma_{B1}(t)\dot{q}_m(t)$ and ${}^2\Gamma_{A2}(t)\dot{q}_s(t)$ are the passivity controllers guaranteeing channel passivity, which are zero under constant or small-varying delays.

Highly-transparent torque tracking can be derived when the tracking error $\mathcal{E}_i$ is restricted in a predefined small region that is shaped by a time-decaying function. The prescribed performance can be expressed as:

$$\begin{cases} -h\kappa_i(t) < \mathcal{E}_i < \kappa_i(t), \text{ if } \mathcal{E}_i(0) \geq 0 \\ -\kappa_i(t) < \mathcal{E}_i < h\kappa_i(t), \text{ if } \mathcal{E}_i(0) \leq 0 \end{cases} \quad (47)$$

where $0 < h < 1$ and $\kappa_i(t)$ is the performance function defined as.

$$\kappa_i(t) = (\kappa_{i0} - \kappa_{i\infty})e^{-\iota t} + \kappa_{i\infty} \quad (48)$$

where κ_{i0} , $\kappa_{i\infty}$ and ι are positive constants. κ_{i0} is the initial large value of the function $\kappa_i(t)$. $\kappa_{i\infty} = \lim_{t \rightarrow \infty} \kappa_i(t)$ is the predefined final constraint of $A(t)$ that usually is set to be very small. ι is the convergence velocity. We design the torque controllers for the master and the slave in the tele-operated mode as:

$${}^1\epsilon_i = R_i \left(\frac{\mathcal{E}_i}{\kappa_i(t)} \right) + \mathcal{E}_i \quad (49)$$

where $R_i(\cdot)$ is a smooth, strictly increasing function shown as

$$R_i \left(\frac{\mathcal{E}_i}{\kappa_i(t)} \right) = \tan \left(\frac{\pi \mathcal{E}_i}{2\kappa_i(t)p_i} \right) \quad (50)$$

The function R_i satisfies: $R_i: (-A_i, A_i) \rightarrow (-\infty, +\infty)$. When ${}^1\epsilon_i(t)$ converges to zero, $\mathcal{E}_i$ will also converge to zero so that the torque tracking errors also converge to zero.

Similarly, the torque controller for the reference torque and the slave in the autonomous mode is designed as

$${}^2\epsilon_i = R_i \left(\frac{e_t}{\kappa_i(t)} \right) + e_t \quad (51)$$

where e_t denotes $e_t = \tau_{ref} - \tau_s$.

Reconsidering (16), knowing that ΔM_i , ΔC_i , ΔD_i , and ΔE_i are neighbouring zero, $\Delta M_i\ddot{q}_i + \Delta C_i\dot{q}_i + \Delta D_iq_i + \Delta E_i$ is also neighbouring zero. Also, the applied NFTSM is used to force the sliding surface 1s_i and 2s_s to zero in a finite time so that ${}^1\dot{s}_i$ and ${}^2\dot{s}_s$ will also fast converge to zero. Consider

$$Y_m\theta_m = \Delta M_m\ddot{q}_m + \Delta C_m\dot{q}_m + \Delta D_mq_m + \Delta E_m - M_m {}^1\dot{s}_m \quad (52)$$

$$Y_s\theta_s = \Delta M_s\ddot{q}_s + \Delta C_s\dot{q}_s + \Delta D_sq_s + \Delta E_s - M_s(\alpha_0 {}^1\dot{s}_s + (1 -$$

$$\alpha_0 {}^2\dot{s}_s) \quad (53)$$

where θ_i is a unknown vector to be estimated. Based on the above description, the unknown vector θ_i is neighboring zero. Y_i is the matrix of known functions of the generalized coordinates and their higher derivatives. $\alpha_0(t)$ is the trigger signal send from the master to let the operator freely make a switch of the tele-operated mode and autonomous mode. $\alpha_0(t) = 0$ or 1 . In the tele-operated mode ($\alpha_0(t) = 1$), the dynamics can be written as:

$$M_i {}^1\dot{s}_i = -M_i\ddot{q}_i - C_i\dot{q}_i - D_iq_i - E_i + \tau_i + \tau_j - Y_i\theta_i \quad (54)$$

and in the autonomous mode,

$$M_s {}^2\dot{s}_s = -M_s\ddot{q}_s - C_s\dot{q}_s - D_sq_s - E_s + \tau_s + \tau_e - Y_s\theta_s \quad (55)$$

The overall control laws are written as

$$\begin{aligned} \tau_m = & -c_{m1}\text{sig}({}^1s_m)^{\delta_1} - c_{m2}\text{sig}({}^1s_m)^{\delta_2} - c_{m3} {}^1s_m + \\ & c_{m4} {}^1\epsilon_m + M_m\ddot{q}_m + C_m\dot{q}_m + D_mq_m + E_m - \tau_h^* - \\ & \varsigma_{m1}Y_m^TY_m {}^1s_m + Y_m\hat{\theta}_m \end{aligned} \quad (56)$$

$$\begin{aligned} \tau_s = & \alpha_0 \left(-c_{s1}\text{sig}({}^1s_s)^{\delta_1} - c_{s2}\text{sig}({}^1s_s)^{\delta_2} - c_{s3} {}^1s_s + \right. \\ & \left. c_{s4} {}^1\epsilon_s \right) + (1 - \alpha_0) \left(-c_{s5}\text{sig}({}^2s_s)^{\delta_1} - c_{s6}\text{sig}({}^2s_s)^{\delta_2} - \right. \\ & \left. c_{s7} {}^2s_s + c_{s8} {}^2\epsilon_s \right) + M_s\ddot{q}_s + C_s\dot{q}_s + D_sq_s + E_s - \tau_e^* - \\ & \varsigma_{s1}Y_s^TY_s(\alpha_0 {}^1s_s + (1 - \alpha_0) {}^2s_s) + Y_s\hat{\theta}_s \end{aligned} \quad (57)$$

where $c_{i1}, c_{i2}, c_{i3}, c_{i4}, c_{s5}, c_{s6}, c_{s7}, c_{s8}$ are positive diagonal matrices. For Type-2 fuzzy model, $c_{m1-4} = \frac{\sum_{l=1}^L \mu^l(x_m(k)) \underline{c}_{m1-4}^l}{2 \sum_{l=1}^L \mu^l(x_m(k))} + \frac{\sum_{l=1}^L \bar{\mu}^l(x_m(k)) \bar{\underline{c}}_{m1-4}^l}{2 \sum_{l=1}^L \bar{\mu}^l(x_m(k))}$, $c_{s1-8} = \frac{\sum_{l=1}^L \mu^l(x_s(k)) \underline{c}_{s1-8}^l}{2 \sum_{l=1}^L \mu^l(x_s(k))} + \frac{\sum_{l=1}^L \bar{\mu}^l(x_s(k)) \bar{\underline{c}}_{s1-8}^l}{2 \sum_{l=1}^L \bar{\mu}^l(x_s(k))}$, $\delta_1 > 1$, $0 < \delta_2 < 1$, $\hat{\theta}_i$ is used to estimate θ_i . ς_{i1} is a small constant gain. According to (52)-(53) and knowing θ_i is neighboring zero, using the following adaptive control law is enough to compensate for θ_i .

$$\begin{aligned} \dot{\hat{\theta}}_m = & -\psi Y_m^T {}^1s_m + \psi(\theta_m^* - \hat{\theta}_m) \\ \dot{\hat{\theta}}_s = & -\Lambda Y_s^T(\alpha_0 {}^1s_s + (1 - \alpha_0) {}^2s_s) + \Lambda(\theta_s^* - \hat{\theta}_s) \end{aligned} \quad (58)$$

where ψ and Λ are constant positive definite matrices. θ_i^* is the nominal values of θ_i that is also neighboring zero.

Inspired by [39] and according to the proposed Type-2 modelled dynamics (16), we propose the fuzzy model-based torque observer to estimate the external torques.

$$\begin{aligned} \tau_j^* = & Z_i - \mathcal{B}_i \\ \mathcal{B}_i = & \sigma \dot{q}_i, \quad \dot{\mathcal{B}}_i = \mathcal{F}_i M_i \ddot{q}_i \\ \mathcal{F}_i = & \frac{\sigma}{M_i} \end{aligned} \quad (59)$$

$$\dot{Z}_m = -\mathcal{F}_m Z_m + \mathcal{F}_m(\tau_m - C_m\dot{q}_m - D_mq_m - E_m - \mathcal{B}_m) + {}^1s_m \quad (60)$$

$$\dot{Z}_s = -\mathcal{F}_s Z_s + \mathcal{F}_s(\tau_s - C_s\dot{q}_s - D_sq_s - E_s - \mathcal{B}_s) + (\alpha_0 {}^1s_s + (1 - \alpha_0) {}^2s_s) \quad (61)$$

where σ is an arbitrary, positive constant gain. Based on (59)-(61), the deferential of the torque estimation errors $\Delta\tau_j$ can be derived as:

$$\Delta\dot{\tau}_h = \dot{\tau}_h - \dot{\tau}_h^* = \dot{\tau}_h - \dot{Z}_m - \dot{\mathcal{B}}_m = \dot{\tau}_h - \mathcal{F}_m\Delta\tau_h - {}^1s_m \quad (62)$$

$$\Delta\dot{\tau}_e = \dot{\tau}_e - \dot{\tau}_e^* = \dot{\tau}_e - \dot{Z}_s - \dot{\mathcal{B}}_s = \dot{\tau}_e - \mathcal{F}_s\Delta\tau_e - (\alpha_0 {}^1s_s + (1 - \alpha_0) {}^2s_s) \quad (63)$$

Remark 3: The designed control laws in (56)-(57) have the following purpose.

In the tele-operated mode ($\alpha_0 = 1$), the applied NFTSM is expected to let r_i converge to zero in a finite time. Based on (35)-(36), under constant or slowly-varying delays (passivity controllers are not automatically activated), by setting small values of λ_{11} and λ_{12} , the NFTSM can force the position tracking errors to fast converge to zero. Under sharply-varying delays (passivity controllers are activated), the passivity controllers in (35)-(36) actually are velocity dampers with variable gains that will not seriously influence the position tracking ability. Therefore, motion synchronization can still be achieved. The torque controller in (49) is expected to suppress the torque tracking errors in a predefined boundary. According to (45)-(46), in the presence of constant or slowly varying delays, by setting large values of λ_{21} and λ_{22} , the torque tracking errors are also neighboring zero at the steady state. In the presence of sharply-varying delays, the passivity controllers can affect the torque tracking. When the slave is conducting hard contact (the velocity becomes zero suddenly), highly accurate torque tracking can still be achieved. However, if the slave is conducting soft contact (the velocity becomes zero gradually), the passivity controllers may affect the accuracy.

In the autonomous mode ($\alpha_0 = 0$), as analysed before, due to the reverse direction of the power flow, the passivity controllers keep activated in order to guarantee the channel passivity. The purpose of the autonomous mode is to let the slave to follow the reference position control information (previously trained by the expert) that the human operator (trainee) can hardly achieve. Accordingly, the primary objective of this mode is the accurate position synchronization of the reference signal and the slave position. The second objective is the master accurately tracking the position of the slave in order to allow the human operator fluently conduct the remaining task when the mode is switched back to tele-operated mode. The NFTSM in the autonomous mode can also guarantee motion synchronization of the reference signal and the slave according to (43). As analysed, even the passivity controllers are activated, the velocity dampers with variable gains do not seriously affect the position synchronization. The master can still accurately follow the motion of the slave. In the autonomous mode, the human operator does not need to drive the master or to feel the force feedback. Therefore, torque tracking does not need to be considered in this mode.

5. Stability analysis

This section presents system stability analysis. Two theorems are proposed. **Theorem 2** proves that in the free space movement without external forces ($\tau_h(t) = \tau_e(t) = 0, \tau_h^*(t) = \tau_e^*(t) = 0$), the position synchronization errors can converge to zero in a finite time in the two modes. **Theorem 3** proves that when human and environmental forces are applied into the system, the system can still remain stable. Moreover, the measured torque errors can be restricted in a pre-defined boundary and converge to zero when time tends to infinity.

Theorem 2. Consider the system dynamics (53) and (54) with the control laws (56)-(57) in the absence of the human and environmental torques ($\tau_h(t) = \tau_e(t) = 0, \tau_h^*(t) = \tau_e^*(t) = 0$). The position tracking errors contained in the two modes can be

driven onto the sliding mode surface and converge to zero in finite time under time-varying delays.

Proof. With no human and environmental torques, the measured torques are also zero. Therefore, ϵ_i is zero. Consider a positive definite function V for the system as:

$$V = \frac{1}{2} {}^1s_m^T M_m {}^1s_m + \frac{1}{2} \alpha_0 {}^1s_s^T M_s {}^1s_s + \frac{1}{2} (1 - \alpha_0) {}^2s_s^T M_s {}^2s_s + \frac{1}{2} \tilde{\theta}_m^T \psi^{-1} \tilde{\theta}_m + \frac{1}{2} \tilde{\theta}_s^T \Lambda^{-1} \tilde{\theta}_s \quad (64)$$

where $\tilde{\theta}_i = \theta_i - \hat{\theta}_i$. In the tele-operated mode ($\alpha_0 = 1$),

$$\begin{aligned} \dot{V} \leq & {}^1s_m^T (-c_{m1} \text{sig}({}^1s_m)^{\delta_1} - c_{m2} \text{sig}({}^1s_m)^{\delta_2} - c_{m3} {}^1s_m) + \\ & {}^1s_s^T (-c_{s1} \text{sig}({}^1s_s)^{\delta_1} - c_{s2} \text{sig}({}^1s_s)^{\delta_2} - c_{s3} {}^1s_s) - \\ & {}^1s_m^T Y_m \tilde{\theta}_m - {}^1s_s^T Y_s \tilde{\theta}_s - \zeta_{m1} {}^1s_m^T Y_m^T Y_m {}^1s_m - \\ & \zeta_{s1} {}^1s_s^T Y_s^T Y_s {}^1s_s + {}^1s_m^T Y_m \tilde{\theta}_m + {}^1s_s^T Y_s \tilde{\theta}_s - \frac{1}{2} \tilde{\theta}_m^T \tilde{\theta}_m + \frac{1}{2} \tilde{\theta}_s^T \tilde{\theta}_s - \\ & \frac{1}{2} \tilde{\theta}_m^T \tilde{\theta}_m + \frac{1}{2} \tilde{\theta}_s^T \tilde{\theta}_s \end{aligned} \quad (65)$$

where $\bar{\theta}_i = \theta_i^* - \theta_i$. Since both θ_i and θ_i^* are neighboring zero, $\bar{\theta}_i$ is also neighboring zero. Treating $\zeta_{i1} {}^1s_i^T Y_i^T Y_i {}^1s_i > \frac{1}{2} \tilde{\theta}_i^T \tilde{\theta}_i$, we can derive

$$\begin{aligned} \dot{V} \leq & {}^1s_m^T (-c_{m1} \text{sig}({}^1s_m)^{\delta_1} - c_{m2} \text{sig}({}^1s_m)^{\delta_2}) + \\ & {}^1s_s^T (-c_{s1} \text{sig}({}^1s_s)^{\delta_1} - c_{s2} \text{sig}({}^1s_s)^{\delta_2}) \\ \leq & -c_{m1} \left(\frac{2}{M_m} \right)^{\frac{1+\delta_1}{2}} \left(\frac{1}{2} {}^1s_m^T M_m {}^1s_m \right)^{\frac{1+\delta_1}{2}} - \\ & c_{s1} \left(\frac{2}{M_s} \right)^{\frac{1+\delta_1}{2}} \left(\frac{1}{2} {}^1s_s^T M_s {}^1s_s \right)^{\frac{1+\delta_1}{2}} - \\ & c_{m2} \left(\frac{2}{M_m} \right)^{\frac{1+\delta_2}{2}} \left(\frac{1}{2} {}^1s_m^T M_m {}^1s_m \right)^{\frac{1+\delta_2}{2}} - \\ & c_{s2} \left(\frac{2}{M_s} \right)^{\frac{1+\delta_2}{2}} \left(\frac{1}{2} {}^1s_s^T M_s {}^1s_s \right)^{\frac{1+\delta_2}{2}} \\ \leq & -\mathbb{R} V^{\frac{1+\delta_1}{2}} - \mathbb{Z} V^{\frac{1+\delta_2}{2}} \end{aligned} \quad (66)$$

where $\mathbb{R} = \min \left\{ c_{m1} \left(\frac{2}{M_m} \right)^{\frac{1+\delta_1}{2}}, c_{s1} \left(\frac{2}{M_s} \right)^{\frac{1+\delta_1}{2}} \right\}$, $\mathbb{Z} = \min \left\{ c_{m2} \left(\frac{2}{M_m} \right)^{\frac{1+\delta_2}{2}}, c_{s2} \left(\frac{2}{M_s} \right)^{\frac{1+\delta_2}{2}} \right\}$. Based on **Lemma 2**, we can derive that during free space movement, the reaching time T_r is

$$T_r < \frac{1}{\mathbb{R}} \frac{2}{\delta_1 - 1} + \frac{1}{\mathbb{Z}} \frac{2}{1 - \delta_2} \quad (67)$$

And according to **Lemma 3**, the sliding time T_s is

$$T_s < \max \left\{ \frac{1}{\alpha_{m1}} \frac{1}{\gamma_{m1} - 1} + \frac{1}{\alpha_{m2}} \frac{1}{1 - \mu_2}, \frac{1}{\alpha_{s1}} \frac{1}{\gamma_{s1} - 1} + \frac{1}{\alpha_{s2}} \frac{1}{1 - \mu_{s2}} \right\} \quad (68)$$

Then the exact convergence time is $T_{r1} + T_{s1}$. The proof of stability of the autonomous mode is the same as the above analysis. This completes the proof. **Q.E.D.**

Remark 4: In the paper, the differential of the human and environmental torques are assumed to be bounded that

$$\exists \varpi_i > 0 \text{ such that } \|\dot{\tau}_j\| < \rho_i \quad (69)$$

$$\rho = \max\{\rho_m, \rho_s\}.$$

Theorem 3. When involving the human and the environmental forces, the system (54)-(55) with the control laws (56)-(63) can still remain stable and the torque tracking errors can be restricted in a pre-defined boundary and finally converge to zero at the

steady state during time-varying delays.

Proof. For tele-operated mode, define $e'(t) = {}^1s_m(t) - {}^1s_s(t)$, $\epsilon'(t) = \epsilon_m(t) - \epsilon_s(t)$. Accordingly, we define the control output as

$$e = \begin{bmatrix} e' \\ \epsilon' \end{bmatrix} = \begin{bmatrix} 1 & -1 \\ 0 & 0 \end{bmatrix} s + \begin{bmatrix} 0 & 0 \\ 1 & -1 \end{bmatrix} \epsilon = X_1 s + X_2 \epsilon \quad (70)$$

where $s = [{}^1s_m, {}^1s_s]^T$, $\epsilon = [\epsilon_m, \epsilon_s]^T$.

The goal is to minimize $\mathbf{E}$, which contains the position, velocity and torque tracking errors, by finding proper control gains c_{m1-4} and c_{s1-6} such that the system is stable and the following H_∞ performance requirement is achieved.

$$\int_0^\infty e^T(\eta) e(\eta) d\eta < \gamma^2 \int_0^\infty \epsilon^T(\eta) \epsilon(\eta) d\eta \quad (71)$$

According to (71), γ is the performance index of the system. More exactly smaller γ requires smaller $\mathbf{E}$, and the tracking errors can then be minimized. Consequently we are trying to find the optimized control gains c_{m1-4} and c_{s1-6} to satisfy the smallest γ .

Based on (59)-(62), we derive

$$M\dot{s} = -A_1 \text{sig}(s)^{\delta_1} - A_2 \text{sig}(s)^{\delta_2} - A_3 s + A_4 \epsilon + \Delta \tau \quad (72)$$

where $M = \text{diag}[M_m, M_s]$, $A_{1-4} = \text{diag}[c_{m1-4}, c_{s1-4}]$, $\Delta \tau = \text{diag}[\Delta \tau_h, \Delta \tau_e]$, $\tau = \text{diag}[\tau_h, \tau_e]$, $\mathcal{F} = \text{diag}[\mathcal{F}_m, \mathcal{F}_s]$. $Y_i \theta_i$ is proved to be compensated for by the adaptive laws in **Theorem 3**, therefore we do not consider it in this proof for simplicity.

Apply the following Lyapunov-Krasovskii function

$$V^* = s^T P s + \Delta \tau^T P M^{-1} \Delta \tau \quad (73)$$

$$\dot{V}^* < 2s^T P M^{-1} (-A_1 \text{sig}(s)^{\delta_1} - A_2 \text{sig}(s)^{\delta_2} - A_3 s + A_4 \epsilon + \Delta \tau) + 2\Delta \tau^T P M^{-1} \rho - 2\Delta \tau^T P M^{-1} \mathcal{F} \Delta \tau - 2\Delta \tau^T P M^{-1} s \quad (74)$$

Adding $e^T e - \gamma^2 \epsilon^T \epsilon$ to both sides of (74) yields

$$\begin{aligned} \dot{V}^* + e^T e - \gamma^2 \epsilon^T \epsilon & < 2s^T P M^{-1} (-A_1 \text{sig}(s)^{\delta_1} - \\ & A_2 \text{sig}(s)^{\delta_2} - A_3 s + A_4 \epsilon) + 2\Delta \tau^T P M^{-1} \omega - 2\Delta \tau^T P M^{-1} \mathcal{F} \Delta \tau + \\ & e^T e - \gamma^2 \epsilon^T \epsilon \\ & < \zeta_1^T \mathcal{E} \zeta_1, \forall \mathcal{N}^T \zeta_1 > \rho \end{aligned} \quad (75)$$

where $\mathcal{N} = [\mathcal{N}_1, \mathcal{N}_2, \mathcal{N}_3, \mathcal{N}_4, \mathcal{N}_5]$, $\zeta_1 = [s, s^{\frac{1+\delta_1}{2}}, s^{\frac{1+\delta_2}{2}}, \epsilon, \Delta \tau]^T$. Applying Schur compliments, $\mathcal{E}$ can be finally written as

$$\begin{bmatrix} \mathcal{E}_{11} & * & * & * & * & * \\ 0 & \mathcal{E}_{22} & * & * & * & * \\ 0 & 0 & \mathcal{E}_{33} & * & * & * \\ P M^{-1} A_4 & 0 & 0 & -\gamma^2 & * & * \\ \mathcal{N}_1^T P M^{-1} & \mathcal{N}_2^T P M^{-1} & \mathcal{N}_3^T P M^{-1} & \mathcal{N}_4^T P M^{-1} & \mathcal{E}_{55} & * \\ X_1 & 0 & 0 & X_2 & 0 & -I \end{bmatrix} < 0 \quad (76)$$

where $\mathcal{E}_{11} = -P^T M^{-1} A_3 - (M^{-1} A_3)^T P$, $\mathcal{E}_{22} = -P^T M^{-1} A_1 - (M^{-1} A_1)^T P$, $\mathcal{E}_{33} = -P^T M^{-1} A_2 - (M^{-1} A_2)^T P$, $\mathcal{E}_{55} = -P^T M^{-1} \mathcal{F} - (M^{-1} \mathcal{F})^T P + \mathcal{N}_5^T P M^{-1} + P^T \mathcal{N}_5 M^{-1}$. The proposed system with applied torque control is asymptotically stable if there exist matrix $P > 0$, such that LMI (76) holds. The proof of stability of the autonomous mode is the same as the above analysis. This completes the proof. **Q.E.D**

6. Experimental results

This section presents experiments to validate the proposed system online-switching tele-operated and autonomous system.

In the tele-operated mode, the operator is driving the master to let the slave conduct the designated motion. Meanwhile, the position and torque information of the slave in this mode is recorded for the following use of autonomous mode as the reference signals q_{ref} and τ_{ref} . Accordingly, the following criteria are applied to test the performance of the proposed system.

Criterion 1: In the tele-operated mode, the slave can accurately follow the motion of the master to reach the designated spot while recording the motion, and the position tracking errors must fast neighbor zero. After switching to the autonomous mode online, the slave must accurately follow the reference position signals (previous slave position in the tele-operated mode) with errors neighboring zero. In a real tele-surgery, without the fast and accurate motion synchronization between the slave and the reference position signal previously trained by the expert, the slave may reach the wrong spot that may largely increase the risk and failure of the surgery. Meanwhile, in this mode, the slave acts as the role of master to drive the master to track the slave's position in order to allow the operator to fluently perform the remaining task. Position drift is not allowed when switching between these two modes. Also, the stability of the system must be robustly guaranteed without large perturbation since active energy is feedback to the master.

Criterion 2: In a real tele-surgery, the slave is expected not only to move to the designated spot, but also to apply the designated force (e.g., intramuscular injection). This requires the accurate force/torque tracking between the master and the slave that allows the expert accurately apply the right force and simultaneously derive the perception of the remote dynamics in the tele-operated mode. In the autonomous mode, the reference torque signal previously trained by the expert can guide the slave to apply the same torque. The torque control method in the autonomous mode is extremely important, without which the slave may reach the right spot but is not able to apply any force to the extent that the task like intramuscular injection cannot be performed. Since in the autonomous mode the operator does not need to control the master or feel the remote environment, force feedback to the master becomes unimportant.

Criterion 3: The overall system is conducted in the presence of arbitrary time delays (constant, slowly or sharply varying delays). The stability of the overall system must be guaranteed in both of the modes without large perturbation even during the sharply varying delays, and the transparency of the system should be reasonable with any types of the time delays.

The applied experimental platform consists of two 3-DOF Omni Phantom haptic devices. For the proposed system, a Type-2 fuzzy model with nine fuzzy rules is constructed from the data samples where the sampling period is $\Delta T = 0.001$.

Based on the derived values of M_i^l , C_i^l , D_i^l and D_i^l from the designed numbers of fuzzy rules, the control gains $\bar{c}_{m1-4}^l$, $\underline{c}_{m1-4}^l$, $\bar{c}_{s1-8}^l$, $\underline{c}_{s1-8}^l$ can be derived using the LMI toolbox. The performance index γ is derived as 2.0053. In the first fuzzy rule,

$$\begin{aligned} \bar{c}_{m1}^1 &= \text{diag}[0.1532, 0.1567, 0.1571] & \underline{c}_{m1}^1 &= \text{diag}[0.1491, 0.1312, 0.1308], & \bar{c}_{m2}^1 &= \text{diag}[0.1202, 0.1361, 0.1433], \\ \underline{c}_{m2}^1 &= \text{diag}[0.1137, 0.1102, 0.1098] & \bar{c}_{m3}^1 &= \text{diag}[0.1009, 0.1031, 0.1297], & \underline{c}_{m3}^1 &= \text{diag}[0.1009, 0.0934, 0.1153], \\ \bar{c}_{m4}^1 &= \text{diag}[0.7459, 0.7076, 0.8575] & \bar{c}_{s1}^1 &= \text{diag}[0.1031, 0.1097, 0.1085], & \underline{c}_{s1}^1 &= \text{diag}[0.0921, 0.0983, 0.0878], \\ \bar{c}_{s2}^1 &= \text{diag}[0.1032, 0.1081, 0.1023], & \underline{c}_{s2}^1 &= \text{diag}[0.0732, 0.0712, 0.0999], & \bar{c}_{s3}^1 &= \text{diag}[0.1559, 0.1382, 0.1201], \\ \underline{c}_{s3}^1 &= \text{diag}[0.1249, 0.1384, 0.1483] & \bar{c}_{s4}^1 &= \text{diag}[0.5251, 0.5136, 0.4535], & \underline{c}_{s4}^1 &= \text{diag}[0.4449, 0.4996, 0.3971], \\ \bar{c}_{s5}^1 &= \text{diag}[0.1259, 0.1173, 0.1075], & \underline{c}_{s5}^1 &= \text{diag}[0.1046, 0.0972, 0.1075], & \bar{c}_{s6}^1 &= \text{diag}[0.1401, 0.1482, 0.1356], \\ \underline{c}_{s6}^1 &= \text{diag}[0.1232, 0.1175, 0.1309], & \bar{c}_{s7}^1 &= \text{diag}[0.1189, 0.1312, 0.1412], & \underline{c}_{s7}^1 &= \text{diag}[0.0941, 0.0965, 0.0871], \\ \bar{c}_{s8}^1 &= \text{diag}[0.8211, 0.7126, 0.7005], & \underline{c}_{s8}^1 &= \text{diag}[0.6409, 0.6294, 0.5801]. \end{aligned}$$

$$\begin{aligned} \bar{c}_{s4}^1 &= \text{diag}[0.5251, 0.5136, 0.4535], & \underline{c}_{s4}^1 &= \text{diag}[0.4449, 0.4996, 0.3971], & \bar{c}_{s5}^1 &= \text{diag}[0.1259, 0.1173, 0.1075], \\ \underline{c}_{s5}^1 &= \text{diag}[0.1046, 0.0972, 0.1075], & \bar{c}_{s6}^1 &= \text{diag}[0.1401, 0.1482, 0.1356], & \underline{c}_{s6}^1 &= \text{diag}[0.1232, 0.1175, 0.1309], \\ \bar{c}_{s7}^1 &= \text{diag}[0.1189, 0.1312, 0.1412], & \underline{c}_{s7}^1 &= \text{diag}[0.0941, 0.0965, 0.0871], & \bar{c}_{s8}^1 &= \text{diag}[0.8211, 0.7126, 0.7005], \\ \underline{c}_{s8}^1 &= \text{diag}[0.6409, 0.6294, 0.5801]. \end{aligned}$$

The remaining control parameters are set as $\lambda_{11} = 0.2$, $\lambda_{12} = 0.6$, $\lambda_{21} = 2.5$, $\lambda_{22} = 2$, $b = 2.5$, $\delta_1 = 1.8$ and $\delta_2 = 0.2$. The sliding mode surface parameters are $k_m = k_s = 0.01$, $\alpha_{m1} = \alpha_{s1} = 100$, $\alpha_{m2} = \alpha_{s2} = 100$, $\gamma_{m1} = \gamma_{s1} = 1.2$, $\mu_m = \mu_s = 0.01$, $\mu_{m1} = \mu_{s1} = 0.4$, $\mu_{m2} = \mu_{s2} = 0.9$, $\mu_{m3} = \mu_{s3} = 1.1$, $\mu_{m4} = \mu_{s4} = 5$, $\zeta_{i1} = 0.01$.

6.1. Free motion (criterion 1)

In the first experiment, the time delay (one way) in our system is about 100 ms with 50 ms variation. The operator firstly drive the master to conduct a free motion and meanwhile records the slave's motion, then directly activate the actuator to switch the tele-operated mode to the autonomous mode online to let the slave follow the reference signals (previous motion of the slave in the tele-operated mode). After that, the autonomous mode is switched back to the tele-operated mode and the system is operated by the operator to conduct a free motion again. Fig. 2 shows the position tracking and the tracking errors of the first experiment. According to Fig. 2, the proposed control algorithm can provide a highly accurate position tracking in the tele-operated mode and the tracking errors are neighbouring zero. Since the reference signals are recording the slave motion and are not activated in the mode, the values of the reference signals are keeping constant in this mode. During the switch between the two modes, no perturbation occurs. In the autonomous mode, the slave can also closely follow the reference position signals (previous position in the tele-operated mode) basically with no tracking errors that means no matter in the tele-operated mode or the autonomous mode, the slave can reach the designated spot. Meanwhile, the master can also follow the slave's motion in the autonomous mode. Since active energy is transmitted back by the slave and the passivity controllers are always activated in the autonomous mode which can influence the overall transparency, the tracking errors of the master and the slave becomes a little larger in this mode. However, after switching back to the tele-operated mode, high position synchronization between the master and the slave can still achieved without position drift or perturbation.

Fig. 2. Free motion of our system ($100 \text{ ms} \pm 50 \text{ ms}$)

Fig. 3. Free motion of system in [13] (100 ms)

Then the system in [13] conducts the same motion as shown in Fig. 3. NFTSM method is also used in [13] and the same method in [13] is also implemented in its autonomous mode. Since the NFTSM method cannot guarantee the stable performance in [13], the time delay is set to 100 ms constant delay. The NFTSM method can perform an accurate position tracking with position errors neighbouring zero in the teleoperation mode. However, in the autonomous mode, the slave conversely drives the master and the active energy is transmitted from slave to the master. Without a good approach like the wave-based TDPA that can efficiently eliminate the active energy, the system in [13] cannot remain stable in the autonomous mode and large perturbations occur.

6.2. Hard contact (criterion 2)

In the second experiment, the slave is controlled to contact to a solid wall. The time delay is 200 ms with 100 ms variation (one way). The requirement of this experiment becomes higher since the slave is not only required to reach the designated spot but also required to perform the designated force. The master driven by the operator firstly control the slave move to a solid wall to make a hard contact in the tele-operated mode and then in the autonomous mode, the slave follows the reference signals (previous position and torque of the slave) to contact to the wall again. Figs. 4 and 5 show the position and torque tracking and the related tracking errors, respectively. In Fig. 4, since the wall impede the slave's motion, position errors enlarged during hard contact of the tele-operated mode. After hard contact, the position errors directly converge to zero. When switching to the autonomous mode, the slave follows the reference position to the designated spot. Moreover, as shown in Fig. 5, accurate torque tracking between the master and the slave as well as between the reference and the slave is achieved in these two modes and the tracking errors are neighbouring zero. It means the proposed system can not only allow the operator to have a good perception about the environment but also let the slave to apply the designated force. Since in the tele-operated mode, the master is controlling the slave, while in the autonomous mode, it is being controlled by the slave, that is why the torque of master has the reverse direction in the autonomous mode and has no influence since the operator is not controlling the master.

Then the system in [16] conducts the same motion as shown in Figs. 6 and 7. The system in [16] designs an auxiliary switching filter to reduce the tracking errors in the steady state and the same method is also used in its autonomous mode. By using the auxiliary switching filter, fine position tracking is achieve in the

system in [16]. However, without a torque control method, the human torque cannot track the environment torque in the teleoperation mode. Moreover, in the autonomous mode, Since without proper torque control method, control method in [16] can only let the slave move to the designated spot without exerting any force. The slave torque cannot track the reference torque. Therefore, the system lose the capacity to affect the environment (e.g. injection in tele-surgery). Also, the system in [16] has no superiority on eliminating the active converse energy from slave to master so that the system is not robustly stable and signal perturbation is still occur.

Fig. 4. Hard contact of our system ($200 \text{ ms} \pm 100 \text{ ms}$, position)

Fig. 5. Hard contact of our system ($200 \text{ ms} \pm 100 \text{ ms}$, torque)

Fig. 6. Hard contact of system in [16] ($200 \text{ ms} \pm 100 \text{ ms}$, position)

Fig. 7. Hard contact of system in [16] (200 ms $\pm$ 100 ms, torque)

6.3. Sharply-varying delay (criterion 3)

The third experiment test the performance in the presence of the large and sharply varying delays. The time delay (one way) is about 1.5 s with 1100 ms variation. To our best knowledge, there seldom have articles on nonlinear teleoperation that can deal with the time delays with rate larger than 1. In the tele-operated mode, the system firstly conducts a free motion and from the 11th second to the 16th second, the slave contacts a solid wall. The slave then repeats this action in the autonomous mode. Figs.8 and 9 show the position and torque tracking and the related tracking errors. In such sharply-varying delays, the passivity controllers are activated in most of the time in order to guarantee the passivity of the communication channels. Since the passivity controllers for the position signals transmission are actually velocity controllers with variable gains that will not largely affect the position tracking. Therefore, reasonable position tracking can still be achieved in both of the mode as shown in Fig. 8. However, the large time delays and the passivity controllers can inevitably affect the transparency of the tele-operated mode, the torque tracking between the master and the slave is a little degraded but still reasonable as shown in Fig. 9. Since the time delays do not affect the performance of the autonomous mode, the position and torque tracking between the reference signal and the slave is still neighbouring zero.

Fig. 8. Free motion + hard contact (1.5s $\pm$ 1100 ms, position)

Fig. 9. Free motion + hard contact (1.5 ms $\pm$ 1100 ms, torque)

7. Conclusion

This study investigate a Type-2 fuzzy model based shared control strategy for online-switching tele-operated and autonomous system. The tele-operated mode supports bilateral teleoperation that allows the operator to remotely control the slave and to have a perception on the environment; while in the autonomous mode, the roles of master and slave mutually exchange that the slave follows the reference signals to perform task and the master follows the slave. A Type-2 T-S fuzzy modelling algorithm using RGA theory for decentralization is introduced to describe the master and slave robots. Extended waved-based TDPA is applied to guarantee the passivity of communication channels with arbitrary time-varying delays. NFTSM is selected to ensure the accurate position tracking between the master and slave in both tele-operated and autonomous modes. A torque observer based on the proposed Type-2 T-S fuzzy model is used to estimate the external torques. At the same time, the torque control algorithms are also employed to let the slave apply the designated force. The system stability is analysed using Lyapunov functions, and LMI toolbox is used to derive series of optimized main control parameters. The experiments using two haptic devices are given to demonstrate the effectiveness and superiority of the proposed system.

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