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Single Master Bimanual Teleoperation System with Efficient Regulation

Da Sun, Qianfang Liao and Amy Loutfi

Abstract—This paper proposes a new single master bimanual teleoperation (SMBT) system with an efficient position, orientation and force regulation strategy. Unlike many existing studies that solely support motion synchronization, the first contribution of the proposed work is to propose a solution for orientation regulation when several slave robots have differing motions. In other words, we propose a solution for self-regulated orientation for dual-arm robots. A second contribution in the paper allows the master with fewer degrees of freedom to control the slaves (with higher degrees of freedom), while the orientation of the slaves is self-regulated. The system further offers a novel force regulation that enables the slave robots to have a smooth and balanced robot-environment interaction with proper force directions. Finally, the proposed approach provides adequate force feedback about the environment to the operator and assists the operator in identifying different motion situations of the slaves. Our approach demonstrates that the forces from the slaves will not interrupt the operator's perception of the environment. To validate the proposed system, experiments are conducted using a platform consisting of two 7-Degree of Freedom (DoF) slave robots and one 3-DoF master haptic device. The experiments demonstrated good results in terms of position, orientation and force regulation.

Index Terms—Single master bimanual teleoperation, force control, orientation regulation

I. INTRODUCTION

A. Background

In recent years, research on teleoperation in the robotics and automation community has been extensively explored [1]–[4]. Unlike purely autonomous robotic systems that are limited in their performance for jobs requiring complex movements and high-level dexterity, teleoperation involving human intelligence can effectively and safely realize greater robustness and reliability [5]. In certain cases, human factors (e.g., muscle activation) are also involved in teleoperation research to ease potential burdens and to improve operation [6]–[8]. A particular subset of teleoperation research considers bimanual teleoperation, which allows the operator to remotely drive a dual-arm robot, which can improve efficacy, precision, dexterity, loading capacity and handling capability [9], [10]. Currently, bimanual teleoperation has a wide variety of applications, including handling toxic and hazardous materials, robotic rehabilitation, underwater exploration and telesurgery [11]–[15].

In a bimanual teleoperation system, control strategy design is difficult due to the complex structures and mechanisms of multiple robots. Nevertheless, significant contributions have

been made to delay-based stability and motion synchronization in previous studies. For example, to guarantee the stability of a bimanual system, passivity-based approaches were explored in [16]–[19]. Furthermore, the coupled stability of multilateral linear systems was analyzed in [20], [21]. Additionally, in [3], [22], a neural network was employed to guarantee the stability of the bimanual system under contact motion. The motion consensus problem of multiple slave robots under time-varying delays was also studied in [23]–[27]. Moreover, the problems of motion tracking under uncertainties (e.g., dynamics, kinematics, dead-zone and input saturation) and state constraints in bimanual teleoperation systems were analyzed in [1], [28]–[31] by building Mamdani fuzzy models. Combining the main contributions of the above studies, the previous systems have stable motion synchronization under time delays, system uncertainties, external disturbances and state constraints. However, the issues of orientation and force regulation between the slaves should be further studied.

At the same time, force control and feedback are also crucial to a bimanual teleoperation system, without which the system cannot make a transient response to the changing environment or provide a good force feedback to the operator [32]. As outlined in [9], [33], the difficulty of designing force control algorithms in a bimanual teleoperation system, is much greater than that in an ordinary teleoperation system for the following two reasons. First, unlike a single slave in bilateral teleoperation, a good force control algorithm in bimanual teleoperation must be able to build a bridge among the slaves to adaptively regulate and balance their forces in the correct directions on the task object. Second, it must categorize the forces from different slaves and provide good force feedback to the operator without interruption from diverse slaves' forces. Significant contributions to force control in bimanual teleoperation systems have been developed in some studies. In [33], a force-based sliding mode controller with variable dominance factors was proposed that allows the operator to use multiple masters to drive the grippers for grasping irregular-shaped objects. In [34], [35], force observer-based controllers were proposed to enhance the local force control of a dual-master-bimanual teleoperation system, which was further improved for environmental compliance by adding impedance control in [36]. However, the above approaches require equal numbers of masters to slaves and do not consider kinematic redundancy (the joints of a slave robot are more than those of a master).

In practical applications, simultaneously operating multiple master robots can add to the burden of the operator because s/he may be distracted by multiple motions of masters [37]. This burden can be further intensified when the scales,

The authors are with the Center for Applied Autonomous Sensor Systems (AASS), Örebro university, Sweden. (Corresponding author: Qianfang Liao)
E-mail: Da.Sun@oru.se, Qianfang.Liao@oru.se, Amy.Loutfi@oru.se.

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Fig. 1. Draft diagram of the proposed SMBT. POFDS denotes the strategy for deriving the desired positions, orientations and forces; SMC denotes sliding mode control; VC denotes velocity controller, FC denotes force controller; PCv denotes the position controller with a variable gain; P_d , O_d , and F_d denote desired positions, orientations, and forces, respectively; P , O , and F denote actual positions, orientations, and forces, respectively

structures, number of joints, dynamics and kinematics of the masters and the slaves differ. An SMBT system is usually more user-friendly for a single operator than multimaster bimanual teleoperation systems in [33]–[36], since the operator only needs to control one master. However, as analyzed above, most of the existing bimanual teleoperation systems focus on motion synchronization of slave robots under time delays, uncertainties and constraints, but a complex task usually needs to be performed by more than one slave robot with different motions and variable orientations and with balanced forces in correct directions, which basically cannot be performed by using those previous approaches. For the instance of a common lift-and-place task, the systems for motion synchronization without position regulation such as [18], [38], [39] have strong motion limitations, in which the slave robots are unable to move in different directions for cooperatively lifting the object located at an arbitrary place within the robots' workspace. The systems without orientation regulation, such as [36], [40] can lift and place the object with a fixed orientation so that the object with arbitrary orientations cannot be handled optimally. Another problem is that systems without force regulation, such as [22], [24] assume that all manipulators are always rigidly attached to the object without relative motion, which violates reality. Using the slaves in these systems can easily drop the task object, and the operator can hardly obtain good force feedback from the environment to know the slave robots' situations. More efforts are needed for the position, orientation and force coordination of an SMBT system. The operation of an SMBT system can become more challenging when kinematic redundancy exists in which the operator cannot control the slaves' orientation by using a master haptic device with fewer joints. For the instance of telesurgery, the slave robots' structure (e.g., da Vinci surgical robots) can be completely different from the master, where the slave's DoF is more than the master's DoF. Consequently, the master cannot handle both position and orientation of the slave, which leads to limited teleoperation performance [11], [41], [42]. In fact, even when the master has equal numbers of joints as the slave, simultaneously handling both the position and orientation of one or more slaves is still an exhausting job [37], [43]. Further studies are desired to address the kinematic redundancy problem.

In this paper, we propose a new SMBT system to address the above issues; its goal is to 1) support the slave robots'

coordination with different motions and self-regulated orientation in the existence of kinematic redundancy; 2) have an efficient force regulation strategy that allows the slave robots in different motions and poses to have smooth and balanced robots-environment interaction with proper force directions; 3) provide the operator with good perception about the remote environment without the interruption of forces from different slave robots.

B. Brief description of the proposed system

The diagram of the proposed system is shown in Fig. 1. On the slave side, the final slaves' control torque inputs are derived from three control layers. The main contribution of the proposed system is *Layer 1*, which acts as the "coordinator" of the bimanual system. We define the algorithm in *Layer 1* to be Position, Orientation, Force Determination Strategy (POFDS) that determines the desired positions, orientations and forces of the two slave robots based on the input information of the master haptic device. *Layer 2* is a sliding mode controller utilized to guarantee position tracking between the slave robots and their desired position commands. *Layer 3* is a combination of a velocity controller and a force controller that is used to regulate the robot's velocity in case of a sharp position jump and to allow the slave robot to apply the desired forces. On the master side, the control algorithm consists of a sliding mode position controller with a force-based variable gain and a force controller that can provide the operator with a good perception of the environment.

During the work procedure, the movement of the proposed SMBT system is categorized into two motion styles, decoupled motion and coupled motion. Decoupled motion denotes that the two slave robots and the task object are decoupled, and their motions are different according to different task requirements. Coupled motion denotes that the two slave robots load the task object by mutually contacting each other and then conduct a combined motion together. During decoupled motion, the proposed system allows the two slave robots to approach the target with different motions with their optimal orientations, and then gently contact and lift the object with balanced forces using the proposed force regulation strategy. The operator detects the contact force from the environment and can classify the environmental forces from different slaves using one master haptic device. Then, during coupled motion, the proposed system integrates the slaves and the task object

Fig. 2. Position coordination of the proposed SMBT system. For each coordinate frame, red, green and blue arrows denote the X-, Y-, and Z-axis, respectively.

as a whole robot. When the operator is driving this large robot in free motion, s/he feels little force, and when the large robot is in contact motion (e.g., placing the object), the proposed system can offer the operator a force feedback in the correct directions so that the operator is not adversely affected by the interaction force among the slave robots and the object.

The proposed SMBT system has the following merits:

1). Unlike the majority of multirobot systems in previous studies (e.g. [1], [16], [17], [23]–[26], [28]–[30], [44]) focusing on motion synchronization, the proposed SMBT allows the dual-arm slave robots driven by one master to simultaneously conduct different motions according to different task requirements.

2). Kinematic redundancy is addressed in this paper. The slave robots in our system can self-regulate their orientations based on the task object, while the operator only needs to handle the position of the master, which efficiently reduces the operator's burden.

3). Unlike the previous studies [33]–[36] that require multiple masters to separately coordinate the slaves' forces, the proposed system enables the slaves to mutually apply and balance their forces in reasonable directions. Following the human reference force from the master, the slave robots can smoothly and stably contact the task object.

4). The proposed system provides a good force perception of the environment and a clear classification of different situations of the robots to the operator so that the forces of the slave robots in different directions and values will not interrupt the operator's perception of the environment.

In the remainder of this paper, Section II introduces the proposed POFDS, and Section III presents the control laws. The experimental results are demonstrated in Section IV. Some conclusions are drawn in Section V.

II. ROBOTS' COORDINATION IN COUPLED AND DECOUPLED MOTION

This section introduces POFDS in *Layer 1* for deriving the desired positions, orientations and forces of the dual-arm slaves in SMBT, which are the reference signals for later

controller design. POFDS is used to regulate and determine the robot's reference position, orientation and forces in decoupled motion and coupled motion, which can be separated into four aspects: pose coordination in decoupled motion, force coordination in decoupled motion, slaves' coordination in coupled motion, and master's force feedback in coupled motion.

In the overall system, six coordinate frames are involved: master frame bL_m , slave1 base frame $^bL_{s1}$, slave1 tool frame $^tL_{s1}$, slave2 base frame $^bL_{s2}$, slave2 tool frame $^tL_{s2}$, and the object frame L_{ob} . The slave1 base frame $^bL_{s1}$ is treated as the global coordinate frame whose origin is taken as $[0; 0; 0]$. For the successful collaboration of the two slave robots, slave2 with its base frame $^bL_{s2}$ is located within the practical workspace of slave1. The kinematics of all the robots are known, from which the heterogeneous transformation matrices $RM_{s1} \in R^{4 \times 4}$ from slave1's tool and $RM_{s2} \in R^{4 \times 4}$ from slave2's tool to the slave1 base can be derived. The master robot is a 3-DoF haptic device with its joint position $q_m \in R^{3 \times 1}$. The two slaves are N -DoF ($N > 5$) robots with their joint positions $q_{s1}, q_{s2} \in R^{N \times 1}$. $X_{st1} \in R^{3 \times 1}$ and $X_{st2} \in R^{3 \times 1}$ are the tool positions of slave1 and slave2. $X_{sf1} \in R^{3 \times 1}$ and $X_{sf2} \in R^{3 \times 1}$ are the flange positions of slave1 and slave2, respectively. A slave robot's orientation can be determined by mapping its tool's and flange's positions.

The object frame L_{ob} can be set up using computer vision technology [45]. The estimated position of the center of the object is derived as $X_{ob} \in R^{3 \times 1}$, which may contain errors compared to its real value X_{real} . Additionally, the heterogeneous transformation matrix from L_{ob} to $^bL_{s1}$ is derived as $RM_{ob} \in R^{4 \times 4}$.

The forward and backward time-varying delays between slave1 and master are T_{f1} and T_{b1} , and the forward and backward time-varying delays between slave2 and master are T_{f2} and T_{b2} . T_{s1} is the delay from slave1 to slave2 and T_{s2} is the delay from slave2 to slave1.

We define the real human/environmental force as $F_{h/e1/e2}$, which cannot be exactly measured. The estimated human force, environmental force of slave1 and environmental force of slave2 are defined as F_h^* , F_{e1}^* and F_{e2}^* , respectively, which can be derived using force sensors or observation methods. In this paper, these estimated forces are derived using the force observer in [32], which has high estimation accuracy and has the advantage of noise suppression.

A. Pose coordination in decoupled motion

The pose coordination of the proposed SMBT system in decoupled motion is shown in Fig.2. The two slaves are controlled by the master to conduct free motion, and their positions, orientations and forces can be totally diverse and variable. For pose coordination of the two slave arms, we treat slave1 as the main arm, where its tool position tracks the master's position but is also affected by slave2's position, and its orientation targets toward the object, while slave2 is the arm that provides auxiliary supports to slave1 whose position and orientation are regulated according to different task demands.

The strategy for the two slaves pose coordination in decoupled motion includes the following tasks.

Fig. 3. Tools adjustment. The object frame L_{ob} denotes the location of the object. The surface S_{xy} is defined by the X- and Y-axis of L_{ob} . The main idea is to find optimal joint positions q_{ds1} and q_{ds2} to ensure that any points (${}^{ob}X_{tool}$) on the Y-axis of the tool frame (yellow dotted line) have the same distance to S_{xy} .

Task A1: Position determination. Define the desired tool positions of slave1 and slave2 as ${}^dX_{st1}$ and ${}^dX_{st2}$, respectively.

For slave2, ${}^dX_{st2}$ is codetermined by the object's position X_{ob} , the master position X_m and its current position X_{st2} as

$${}^dX_{st2} = A_{tr}[X_{ob}, X_m(t - T_{f2}), X_{st2}]^T \quad (1)$$

where A_{tr} is the transformation matrix that can be variable based on the demands of different objectives. For instance, set A_{tr} as

$$A_{tr} = [2(1 - \mu_F), -(1 - \mu_F), \mu_F] \quad (2)$$

where $\mu_F = (k_{sc}F_{e2}^*)^{\delta_{sc}}$

where $\delta_{sc} > 1$, k_{sc} is a scaling factor that makes $0 \leq |k_{sc}F_{e2}^*| \leq 1$. The logic is that when slave2 is in free motion (μ_F is close to 0), the motion of slave2 assists that of slave1 to allow the object to be in the center between the two robots, as illustrated in Fig. 2; when slave2 is in hard contact (μ_F is close to 1), it stops at its current position. From (1), we can also derive a relationship between X_{st2} and the master reference position $X_m(t - T_{f2})$, which are written as $X_{st2} = P_{tr}(X_m(t - T_{f2}))$, where P_{tr} is the transformation function based on A_{tr} .

For slave1, the desired position ${}^dX_{st1}$ is coaffected by the transmitted master position $X_m(t - T_{f1})$ and the transmitted inversely transformed slave2 position $P_{tr}^{-1}(X_{st2})(t - T_{s2})$ as

$${}^dX_{st1} = (1 - \mu_F(t - T_{s2}))X_m(t - T_{f1}) + \mu_F(t - T_{s2})P_{tr}^{-1}(X_{st2})(t - T_{s2}) \quad (3)$$

From (3), during free motion ($\mu_F \rightarrow 0$ according to (2)), ${}^dX_{st1}$ is determined by the master. When slave2 has an environmental contact and stops, the motion of slave1 is also affected by $P_{tr}^{-1}(X_{st2})$ and then stops based on $\mu_F \rightarrow 1$.

Task A2: Tools adjustment. As shown in Fig. 3, the slaves' tools are parallel with a predefined surface S_{xy} for better grasping by regulating the end joints of slave1 and slave2, $q_{s1}(N)$ and $q_{s2}(N)$, to track the desired joint positions q_{ds1} and q_{ds2} . The surface S_{xy} is built up by the X- and Y-axes of

the object frame L_{ob} . (If the object stands up at the ground, S_{xy} is exactly the ground.)

We use slave1 as an example to present the procedure as follows. Define a point that is aligned with the tool frame ${}^tL_{s1}$ as ${}^tX_{tool} = [0, 1, 0]^T$. Then, transfer ${}^tX_{tool}$ from ${}^tL_{s1}$ to L_{ob} to be $[{}^{ob}X_{tool}, 1] = RM_{ob}^{-1}RM_{s1}[{}^tX_{tool}, 1]^T$. To let the tool (Y-axis of the tool frame) be parallel to the surface S_{xy} , the height (position at Z axis) of the tool in L_{ob} must be equal to ${}^{ob}X_{tool}(3)$ (position at Z axis) in L_{ob} . Therefore, by solving the equation ${}^{ob}X_{tool}(3) = {}^{ob}X_{s1}(3)$ where $[{}^{ob}X_{s1}, 1]^T = RM_{ob}^{-1}[X_{st1}, 1]^T$, the desired joint position q_{ds1} can be derived.

Task A3: Orientation determination. The tools of the two slaves must point to the estimated object position X_{ob} , as in Fig. 2. To achieve this, the desired position ${}^dX_{sf1}$ and ${}^dX_{sf2}$ of the two slaves' flanges must satisfy

$$\begin{aligned} {}^dX_{sf1} &= \text{argmin} \| {}^dX_{sf1} - X_{sf1} \|_2 \\ \text{s.t. } X_{ob} - {}^dX_{st1} &= k(X_{sf1} - {}^dX_{st1}) \end{aligned} \quad (4)$$

$$\begin{aligned} \text{s.t. } \|X_{sf1} - {}^dX_{st1}\|_2 &= d_{ft1} \\ \text{s.t. } \|X_{sf1} - X_{ob}\|_2 &\geq d_{ft1} \end{aligned}$$

$$\begin{aligned} {}^dX_{sf2} &= \text{argmin} \| {}^dX_{sf2} - X_{sf2} \|_2 \\ \text{s.t. } X_{ob} - {}^dX_{st2} &= k(X_{sf2} - {}^dX_{st2}) \\ \text{s.t. } \|X_{sf2} - {}^dX_{st2}\|_2 &= d_{ft2} \\ \text{s.t. } \|X_{sf2} - X_{ob}\|_2 &\geq d_{ft2} \end{aligned} \quad (5)$$

where k is an arbitrary constant. d_{ft1} and d_{ft2} denote the length of the link between the tool and the flange of slave1 and that of slave2, respectively.

Task A4: Position correction for the object. Tasks A1-A3 make the position and orientation of each slave mutually associated with each other so that the robots at the right positions have matched orientations. However, they cannot handle the error of the estimated object position; consequently, the robot gives the desired orientation at an incorrect position. For this issue, we design this task to decouple the orientations from the positions to allow the operator to match the orientations with the correct target positions.

When slave1 moves to X_{ob} , the position error exists ($X_{ob} \neq X_{real}$). Record the current position errors ${}^ft_{e_{s1}} = X_{sf1} - X_{st1}$ and ${}^ft_{e_{s2}} = X_{sf2} - X_{st2}$, which are used to lock the desired orientation. The desired positions ${}^dX_{sf1}$ and ${}^dX_{sf2}$ are then derived as

$$\begin{aligned} {}^dX_{sf1} &= {}^ft_{e_{s1}} + {}^dX_{st1} \\ {}^dX_{sf2} &= {}^ft_{e_{s2}} + {}^dX_{st2} \end{aligned} \quad (6)$$

B. Force coordination in decoupled motion

In this section, we discuss how to derive the transmitted reference force F_{htr} , F_{e2tr} and F_{e1tr} for further force controller setup. For the force control during decoupled motion, due to the different positions and orientations of the robots, simultaneously transmitting the human force to all the slave robots and simultaneously feeding all the slave's force back to the master as in [16], [33] is likely to apply inaccurate force to the task, and the operator may obtain unreal force feedback.

Fig. 4. Force coordination of the proposed SMT system. Red solid lines denote the real applied active forces. White dotted lines denote the electrically transmitted force signals. The master sends the operator's force to slave2, slave2 applies force to the object, the object applies force to slave1, and finally slave2 feeds the force back to the master. F_{htr} , F_{e2tr} and F_{e1tr} are the transmitted force signals for further force controllers setup.

In fact, the bimanual slave robotic system can be imagined as the two hands of our bodies. In our daily life, when we are doing something using two hands, such as shooting a basketball, we usually use one hand to passively fix the position and the other to actively apply force. This principle can be directly used in our system, in which slave1 is used to fix the object's position, and slave2 applies active force.

We design a force cycling strategy, as shown in Fig. 4, where the transmitted reference force F_{htr} is derived from the estimated human force F_h^* to control slave2. Afterward, the transmitted reference force F_{e2tr} is derived from the estimated environmental force of slave2 F_{e2}^* to control slave1. Finally, slave1 feeds reference force F_{e1tr} derived from the estimated environmental force of slave1 F_{e1}^* back to the master. In practice, as in Fig. 4, the active force is sent by the master, followed by slave2 to the object, then from the object to slave1 to the extent that each robot (slave1, slave2, and the object) in the proposed system only receives one active force, which benefits the system's stability. If the active force is sent from both slave1's side and slave2's side, the two active forces mutually affecting each other can destabilize the robots, and moreover, the object can be "double" squeezed. (Like a human's two hands squeezing an object using large force.)

Due to the different positions and orientations of the slave robot, directly transmitting force signals in different directions from one side to another will cause incorrect force control. Therefore, all of the force signals need to be transformed before further control.

For master-slave2 force control, the position and orientation of slave2 are related to A_{tr} in (2), which can be freely designed for different usages. It is hard to directly map the human force to slave2 in the base coordinate frame ${}^bL_{s2}$ due to the varying orientation of slave2. Otherwise, the mapped human force will lead slave2 in an incorrect direction. However, A_{tr} is defined and the primary purpose of slave2 is to use its tool to

apply force to the object. Mapping the human force to the tool frame ${}^tL_{s2}$ to lead slave2 can build a reasonable force control with proper force direction. Unlike the force tracking in the slave base frame that is affected by the robot's orientation, mapping the force to the slave tool frame ${}^tL_{s2}$ allows slave2 to apply force in its tool's direction when the operator is moving the master manipulator forward. Accordingly, we build a connection between the transmitted human force $F_h^*(t - T_{f2})$ and the desired slave position ${}^{t2}X_{d1}$ for slave2's tool in ${}^tL_{s2}$ using impedance control as

$$F_h^*(t - T_{f2}) = Z_{e2}s({}^{t2}X_{d1} - [0, 0, 0]^T) \quad (7)$$

where s denotes the Laplace operator. $Z_{e2} = M_{e2}\frac{1}{s} + B_{e2}$ denotes the control impedance with constant gains M_{e2} and B_{e2} . $[0, 0, 0]^T$ denotes the current tool position in slave2 tool frame ${}^tL_{s2}$, which is always zero. ${}^{t2}X_{d1}$ is the desired position for slave2's tool in ${}^tL_{s2}$, which can be calculated from (7).

Then, by transforming ${}^{t2}X_{d1}$ from ${}^tL_{s2}$ to slave1 base frame ${}^bL_{s1}$ using

$$[{}^{b1}X_{d1}^T, 1]^T = RM_{s2} * [{}^{t2}X_{d1}^T, 1]^T \quad (8)$$

The transformed human force F_{htr} can be derived as

$$F_{htr} = Z_{e2}s({}^{b1}X_{d1} - X_{st2}) \quad (9)$$

F_{htr} can be used for further force control for slave2.

For transmitting slave2's force to slave1, the transmitted force signal from slave2 should be ideally equal to the real object's contact force to slave1, which cannot be achieved in reality because the object is affected not only by the active force from slave2 but also by real environmental disturbances such as friction. Hence, the force from the object to slave1 will not be equal to that from slave2 to the object. Additionally, directly transmitting F_{e2}^* to control slave1 is not helpful because of their different directions.

The above issue can be effectively addressed by transforming F_{e2}^* from ${}^bL_{s1}$ to ${}^tL_{s1}$ using impedance control since it is the "tool-to-tool" contact, as shown in Fig. 4.

We build a connection between slave2's force F_{e2}^* and the desired slave position ${}^{b2}X_{d2}$ using impedance control

$$F_{e2}^* = Z_{e1}s({}^{b2}X_{d2} - X_{st2}) \quad (10)$$

where $Z_{e1} = M_{e1}\frac{1}{s} + B_{e1}$ is the impedance control gain with constant terms M_{e1} and B_{e1} . Then, the desired position ${}^{b2}X_{d2}$ is transformed from the base frame ${}^bL_{s1}$ to slave2 tool frame ${}^tL_{s2}$ as

$$[{}^{t2}X_{d2}^T, 1]^T = RM_{s2}^{-1} * [{}^{b2}X_{d2}^T, 1]^T \quad (11)$$

Then, the position error from ${}^{t2}X_{d2}^T$ to the origin of ${}^tL_{s2}$ is equal to the error from the desired position of slave1 ${}^{t1}X_{d2}^T$ to the origin of ${}^tL_{s1}$. That is, ${}^{t1}X_{d2} = {}^{t2}X_{d2}(t - T_{s2})$.

The final force reference F_{e2tr} for later force control of slave1 is

$$F_{e2tr} = Z_{e1}s({}^{b1}X_{d2} - {}^tX_{s1}) \quad (12)$$

where $[{}^{b1}X_{d2}^T, 1]^T = RM_{s1} * [{}^{t1}X_{d2}^T, 1]^T$

For slave1-master force control, since the motion of slave1 closely tracks the motion of the master, the directions of their

Fig. 5. Position regulation during coupled motion. The relative displacement between the two slaves' tool always remains constant, which is guaranteed by X_{cmd1} . X_{cmd2} allows slave2's tool to apply force to the object. α_c weights the two-position command to determine the final desired tool position ${}^dX_{st2}$ that can balance the applied force.

applied force are the same. Therefore, the transmitted force F_{e1tr} from slave1 to the master for force control can be directly derived as

$$F_{e1tr} = F_{e1}^*(t - T_{b1}) \quad (13)$$

To enhance the operator's feeling about slave2, we also design a force-varying-based gain κ_f , which is treated as a stiffness function to affect the force feedback to the operator and is used by the position controller of the master (introduced in Section III) as

$$\kappa_f = |F_{e2tr}(t - T_{b1})|^{\epsilon_f} \cdot \text{sat}_1(\varrho_f - |F_{e1tr}|) \quad (14)$$

$$\text{where } \text{sat}_1(x) = \begin{cases} x & \text{if } x \geq 0 \\ 0 & \text{if } x < 0 \end{cases}$$

where $\epsilon_f > 1$. ϱ_f is a preset constant bound. (14) is used to work together with (3). When slave2 is blocked because of hard environmental contact but slave1 is in free motion ($\varrho_f \geq |F_{e1tr}|$), slave2 stops moving, which makes slave1 stop according to μ_F in (3). The enlarged force $F_{e2tr}(t - T_{b1})$ increases the value of κ_f . However, if slave1 is in hard contact ($\varrho_f < |F_{e1tr}|$), κ_f loses its weight and F_{e1tr} takes effect, which makes the human felt force still comes from slave1 as in (13). In the later controller design, the stiffness function κ_f is applied to the position controller of the master. The varying κ_f in different motions provides the operator with diverse feelings about free motion and contact.

C. Slaves' coordination in coupled motion

During the coupled motion, the two slaves and the object are combined to conduct motions (e.g., the two slave robots cooperate to lift an object and move together). During the whole coupled motion, the relative displacements and orientations among the tools of the two slaves and the object must always remain the same. Moreover, the two slave robots must keep applying stable forces to the object; otherwise, the object will drop. We propose the following strategy with hierarchical tasks for coupled motion of the bimanual slave system.

Task B1: Position determination. This task determines the desired tool positions of the two slaves according to the master position X_m . Slave1 is expected to closely track the master's motion so that the desired tool position ${}^dX_{st1}$ is derived as ${}^dX_{st1} = X_m(t - T_{f1})$. Slave2 always needs to keep the same relative displacement to the slave1's tool during coupled motion. However, finding this displacement and letting slave2 track the position is not enough because slave2 using this approach will no longer apply force to the object. Therefore, the desired position of slave2 must produce a smaller displacement than the real displacement between the two slaves to allow the two slaves to "hold" the object. Accordingly, we propose the following method to allow slave2 to always keep the same relative displacement as slave1's tool and keep applying stable force in the proper direction pointing to the object during coupled motion.

At the exact moment when the decoupled motion is switched to the coupled motion, we record the following information, which is calculated from (15).

1). Current position of slave2's tool ${}^{t1}X_{re2}$ in ${}^tL_{s1}$. ${}^{t1}X_{re2}$ is the recorded displacement from slave2's tool to slave1's tool in slave1's tool frame ${}^tL_{s1}$.

2). Current desired position of slave2's tool ${}^{t1}X_{red2}$ in ${}^tL_{s1}$. ${}^{t1}X_{red2}$ is the recorded displacement from ${}^{b1}X_{d2}$ in (12) to slave1's tool in ${}^tL_{s1}$.

3). Current applied force of slave2 F_{re2} .

Note that the recorded values ${}^{t1}X_{re2}$, ${}^{t1}X_{red2}$ and F_{re2} , calculated by (15), are used as constants during the coupled motion.

$$\begin{aligned} [{}^{t1}X_{re2}^T, 1]^T &= RM_{s1}^{-1}(t - T_{s1}) * [X_{st2}^T, 1]^T \\ [{}^{t1}X_{red2}^T, 1]^T &= RM_{s1}^{-1}(t - T_{s1}) * [{}^{b1}X_{d2}^T, 1]^T \\ F_{re2} &= F_{e2}^* \end{aligned} \quad (15)$$

During the coupled motion, from (15), we derive two command positions in ${}^bL_{s1}$.

$$\begin{aligned} [X_{cmd1}^T, 1]^T &= RM_{s1}(t - T_{s1}) * [{}^{t1}X_{re2}^T, 1]^T \\ [X_{cmd2}^T, 1]^T &= RM_{s1}(t - T_{s1}) * [{}^{t1}X_{red2}^T, 1]^T \end{aligned} \quad (16)$$

As shown in Fig. 5, X_{cmd1}^T allows the slave2's tool to always keep the "tool-to-tool" relative constant displacement with slave1's tool during coupled motion. X_{cmd2}^T is the desired position toward the center of the object, which allows slave2 to apply force to the object. Then, the desired tool position ${}^dX_{st2}$ can be derived by combining the above two command positions as

$$\begin{aligned} {}^dX_{st2} &= \alpha_c X_{cmd1} + (1 - \alpha_c) X_{cmd2} \\ \text{where } \alpha_c &= \text{sat}_2\left(\left(\frac{F_{e2}^*}{F_{re2}}\right)^{\epsilon_c}\right) \\ \text{and } \text{sat}_2 &= \begin{cases} x & \text{if } x \leq 1 \\ 1 & \text{if } x > 1 \end{cases} \end{aligned} \quad (17)$$

In (17), ϵ_c satisfies $0 < \epsilon_c < 1$. α_c is the dominance factor that is used to balance the two command positions. If $F_{e2}^* \rightarrow F_{re2}$, X_{cmd1} takes charge of control to prevent slave2's tool from squeezing the object too hard. If $F_{e2}^* \rightarrow 0$, X_{cmd2} is in charge of control to allow slave2's tool to apply more force. Based

Fig. 6. Orientation regulation during coupled motion. The slave robots and the object in transparent gray area at the current poses, while the slave robots and the object in orange denote the target poses.

on (17), the robots can apply a balanced force to the object during coupled motion.

Task B2: Orientation regulation. This strategy allows the operator to change the object's pose during the coupled motion by simultaneously regulating the orientations of both slave robots, as shown in Fig. 6. It includes the following two steps.

Step 1: At the current positions, for slave1, a vector with a constant length d_k is created that starts from the flange along the link d_{f1} to the endpoint $\mathcal{O}_1$. $\mathcal{O}_1$ is used to regulate the object's orientation in the next step.

For slave2, we record the current relative displacement ${}^{t2}X_{re2}$ between slave2's flange and tool in slave2 tool frame ${}^tL_{s2}$ as $[{}^{t2}X_{re2}^T, 1]^T = RM_{s2}^{-1} * [X_{sf2}^T, 1]^T$. ${}^{t2}X_{re2}$ is leveraged as a constant vector in the next step.

Step 2: When slave1 moves to ${}^dX_{st1}$, the desired flange position ${}^dX_{sf1}$ must satisfy

$$\begin{aligned} {}^dX_{sf1} &= \text{argmin} \| {}^dX_{sf1} - X_{sf1} \|_2 \\ \text{s.t. } \mathcal{O}_1 - X_{st1} &= k(X_{st1} - X_{sf1}) \\ \text{s.t. } \|\mathcal{O}_1 - X_{st1}\|_2 &= d_k \\ \text{s.t. } \|\mathcal{O}_1 - X_{sf1}\|_2 &> d_k \end{aligned} \quad (18)$$

For slave2, since its desired tool position ${}^dX_{st2}$ was determined in Task B1, by transforming the recorded displacement ${}^{t2}X_{re2}$ between the tool and flange from ${}^tL_{s2}$ to ${}^bL_{s1}$, the desired flange position ${}^dX_{sf2}$ is derived as

$$[{}^dX_{sf2}^T, 1] = RM_{s2} * [{}^{t2}X_{re2}^T, 1]^T \quad (19)$$

Using these two steps, orientation regulation of the object in Fig. 6 can be achieved.

It should be noted that during the orientation regulation, ${}^{t1}X_{red2}$ in (15) that determines the actively applied force to the object follows the object's varying pose. Therefore, the relative direction of the applied force to the object is not influenced by the varying pose of the object.

Task B3: Orientation determination. This task is used to fix the robots' orientations after the orientation regulation. At the exact moment when the object is regulated to a desired orientation, we record the current position errors between the tool and flange $e_{re1} = X_{sf1} - X_{st1}$ for slave1 and $e_{re2} =$

Algorithm 1 Position, Orientation, Force Determination Strategy (POFDS)

Input: $X_{st1}, X_{st2}, X_{sf1}, X_{sf2}, X_{ob}, F_h^*, F_{e1}^*, F_{e2}^*, RM_{s1}, RM_{s2}, q_m, q_{s1}, q_{s2}$.

Output: ${}^dX_{st1}, {}^dX_{st2}, {}^dX_{sf1}, {}^dX_{sf2}, F_{htr}, F_{e1tr}, F_{e2tr}, \kappa_f$.

In decoupled motion Section A:

- 1: Derive ${}^dX_{st1}$ from (3) and derive ${}^dX_{st2}$ from (1). Move slave1's tool to X_{ob} with slave2 reaching the desired position.
- 2: $q_{s1}(N) = q_{ds1}, q_{s2}(N) = q_{ds2}$. Let the two slaves' tools be parallel to the predefined surface $\mathbb{S}_{xy}$.
- 3: **if** $X_{ob} = X_{real}$ **then**
- 4: Derive ${}^dX_{sf1}$ from (4) and ${}^dX_{sf2}$ from (5).
- 5: **else**
- 6: Derive ${}^dX_{sf1}$ and ${}^dX_{sf2}$ from (6).
- 7: Move slave1's tool to X_{real} .
- 8: **end if**
- 9: Update: $X_{ob} = X_{real}$.

In decoupled motion Section B:

- 10: Derive F_{htr} from (9) for master-slave2 force tracking.
- 11: Derive F_{e2tr} from (12) for slave1-slave2 force tracking.
- 12: Derive F_{e1tr} from (13) for slave2-master force tracking.
- 13: Derive the master force feedback based on κ_f from (14).

In coupled motion Section C:

- 14: Record ${}^{t1}X_{re2}, {}^{t1}X_{red2}$ and F_{re2}
- 15: Set $F_{htr} = 0, F_{e1tr} = 0$, keep F_{e2tr} (internal force).
- 16: ${}^dX_{st1} = X_m(t - T_{f1})$
- 17: Derive ${}^dX_{st2}$ from (17) by using the recorded values ${}^{t1}X_{re2}, {}^{t1}X_{red2}$ and F_{re2} .
- 18: **if** Object's orientation needs to be regulated **then**
- 19: Derive ${}^dX_{sf1}$ and ${}^dX_{sf2}$ from (18) and (19).
- 20: **else**
- 21: Derive ${}^dX_{sf1}$ and ${}^dX_{sf2}$ from (20).
- 22: **end if**

In coupled motion Section D:

- 23: Record the current environmental force $F_{re} = F_{e1}^*(t - T_{b1})$
- 24: Derive the master force feedback based on the F_{re} based gain κ_f from (21).

$X_{sf2} - X_{st2}$ for slave2. Then, the desired flange positions can be derived as

$$\begin{aligned} {}^dX_{sf1} &= e_{re1} + {}^dX_{st1} \\ {}^dX_{sf2} &= e_{re2} + {}^dX_{st2} \end{aligned} \quad (20)$$

Then, the slaves follow these regulated orientations set by the relative displacement of the tools and flanges of the slaves in the following motions.

D. Master's force feedback in coupled motion

During the coupled motion, the two slaves and the object are connected to conduct motion. Accordingly, the overall slave system (two slaves and the object) can be regarded as one large robot, and the forces applied to each other are internal forces. Therefore, the task of the operator for driving two robots to contact the object becomes driving one large slave to conduct motion. Since the forces applied to the object become internal

forces, this large robot conducts free space movement. At the steady state of the slave coordination in the coupled motion, the mutual internal forces are balanced so that the human force must not be transmitted to the slave side to break this balance. Therefore, F_{htr} is zero at the coupled motion. Additionally, the operator should not feel the internal forces ($F_{e1tr} = 0$). Moreover, when this large robot contacts something (e.g., the two slave robot puts the object onto a table), the operator should feel force feedback with a correct direction that is not affected by the internal forces. We propose the strategy as follows.

Step 1: After the orientation regulation in Task B2, we record the current feedback force $F_{re} = F_{e1}^*(t - T_{b1})$ at this exact moment. During the free motion with the fixed orientation, the internal force applied by slave1 F_{e1}^* has a small variation based on this recorded force F_{re} with the known upper bound $b_{fu} > |F_{re} - F_{e1}^*|$.

Step 2: Instead of directly transmitting the environmental force feedback F_{e1}^* which is nonzero and variable (the variable internal forces can disturb human perception), the force-varying-based gain κ_f in the coupled motion is designed as

$$\kappa_f = \left| \frac{F_{re} - F_{e1}^*(t - T_{f1})}{b_{fu}} \right|^{\epsilon_f} \quad (21)$$

During free motion where $b_{fu} > |F_{re} - F_{e1}^*|$, κ_f is close to zero, while during hard contact, F_{e1}^* sharply changes and $b_{fu} < |F_{re} - F_{e1}^*|$, κ_f increases to be larger than 1.

Based on the above, the pseudocode of POFDS is summarized as Algorithm 1.

III. CONTROLLER DESIGN

The overall dynamic models of the SMBT system are

$$\mathbf{M}_i(q_i)\ddot{q}_i + \mathbf{C}_i(q_i, \dot{q}_i)\dot{q}_i + \mathbf{G}_i(q_i) + \mathbf{B}_i(q_i, \dot{q}_i) = \tau_i + J_i^T F_{h/e1/e2} \quad (22)$$

where $i = s1, s2$ and m represent slave1, slave2 and master, respectively, $q_i, \dot{q}_i$ and $\ddot{q}_i$ are the robots' joint position, velocity and accelerations. $\mathbf{M}_i(q_i)$ and $\mathbf{C}_i(q_i, \dot{q}_i)$ denote the inertia matrix, and centrifugal and coriolis matrices, respectively. $\mathbf{G}_i(q_i)$ is the gravity, and $\mathbf{B}_i(q_i, \dot{q}_i)$ denotes bounded disturbances, including robot frictions. $\mathbf{M}_i(q_i)$, $\mathbf{C}_i(q_i, \dot{q}_i)$, $\mathbf{G}_i(q_i)$, and $\mathbf{B}_i(q_i, \dot{q}_i)$ denote the totally unknown dynamics. τ_i denotes the control torque. J_i is the Jacobian matrix mapping from the tool to the base. We also define J_{fi} as the Jacobian matrix mapping from the flange to the base.

The dynamics of master and slave in (22) can be estimated by the Type-2 fuzzy neural network modeling method presented in [32]. This modeling method works well in uncertainties compensation. As a result, the overall unknown nonlinear system dynamics can be represented by a fuzzy weighted sum of multiple linear models, which can be expressed as

$$M_i\ddot{q}_i + C_i\dot{q}_i + D_iq_i + E_i + \eta_i = \tau_i + J_i^T F_{h/e1/e2}^* \quad (23)$$

where M_i , C_i , D_i and E_i denote the weighted sums of the local models coefficients with fuzzy membership grades as weights. $q_i, \dot{q}_i$ and $\ddot{q}_i$ are robots' joint position, velocity and accelerations. The fuzzy membership grades are a group of

Fig. 7. Experimental example of proposed velocity boundary. $b_{vu} = 0.7\text{m/s}$, $b_{vl} = 0.1\text{m/s}$, $\sigma_{vu} = 6$, $\sigma_{vl} = 0.5$.

dynamic functions of the system inputs. Therefore, M_i , C_i , D_i and E_i are known time-varying coefficients to describe the nonlinear robotic system. η_i denotes the remaining small uncertainties including the force estimation errors and time delay differential errors with its known upper bound $\bar{\eta}_i$.

Layer 2 shown in Fig. 1 is applied to enhance the tracking ability and transfer the control terms from Cartesian space to joint space. Based on the derived desired positions and orientations ${}^dX_{sf1}$, ${}^dX_{sf2}$, ${}^dX_{st1}$, and ${}^dX_{st2}$, we define the following joint space errors ($j = 1, 2$)

$$\begin{aligned} e_{sj} &= {}^1e_{sj} + {}^2e_{sj} \\ \text{where } {}^1e_{sj} &= J_{sj}^+(X_{stj} - {}^dX_{stj}) \\ \text{and } {}^2e_{sj} &= J_{fsj}^+(X_{sfj} - {}^dX_{sfj}) \end{aligned} \quad (24)$$

J_{sj}^+ and J_{fsj}^+ denote the pseudoinverse Jacobian matrices. We can also use Hierarchical Quadratic Programming (HiQP) in [46] to determine the priority of ${}^1e_{sj}$ and ${}^2e_{sj}$.

To enhance the tracking ability, we define the sliding surface s_{sj} and the sliding mode controller τ_{Ssj} based on the above position errors as

$$\begin{aligned} s_{sj} &= c_1 \text{sig}(e_{sj})^{\gamma_1} + c_2 \text{sig}(e_{sj})^{\gamma_2} \\ \tau_{Ssj} &= -d_1 \text{sig}(s_{sj})^{\varpi_1} - d_2 \text{sig}(s_{sj})^{\varpi_2} - d_3 s_{sj} \end{aligned} \quad (25)$$

where $\text{sig}(x)^a = [|x_1|^{a_1} \text{sign}(x_1), \dots, |x_N|^{a_N} \text{sign}(x_N)]$. c_1 , c_2 , d_1 , d_2 and d_3 are control gains. $\gamma_1, \varpi_1 > 1$ and $\gamma_2, \varpi_2 < 1$. (γ_2 can be a variable function that when $e_{sj} \rightarrow 0$, γ_2 is enlarged higher than 1 to deal with nonsingularity as [33]).

Layer 3 in Fig. 1 is the final control layer that is used to regulate the slave robot's velocity and add the force control. We design a boundary function for the slave robots' velocities.

$$B_v = \frac{-(b_{vu} - b_{vl})|\mu_v - \frac{1}{2}|^{\sigma_v}}{|\frac{1}{2}|^{\sigma_v}} + b_{vu} \quad (26)$$

where b_{vu} and b_{vl} are the upper bound and lower bound, respectively, and μ_v is defined as

$$\mu_v = \frac{\|X_{stj} - X_{otj}\|_2 + \|X_{sfj} - X_{ofj}\|_2}{\|{}^dX_{stj} - X_{otj}\|_2 + \|{}^dX_{sfj} - X_{ofj}\|_2} \quad (27)$$

where X_{otj} and X_{ofj} are the initial positions of the tool and flange for every move, and they are updated when $X_{otj} = X_{stj}$ and $X_{ofj} = X_{sfj}$. μ_v is 0 at the beginning of every move and increases to 1 in the end. σ_v is defined as

$$\sigma_v = (\sigma_{vu} - \sigma_{vl}) * \mu_v + \sigma_{vl} \quad (28)$$

where $\sigma_{vu} > 1$ and $0 < \sigma_{vl} < 1$ are constants.

Fig. 7 shows an example of the proposed bell-shaped velocity boundary curve in (26)-(28). When the slave robots are at their initial positions, the fuzzy membership μ_v is close to zero, which makes the boundary B_v its lower bound (e.g., 0.1m/s). Additionally, the change rate σ_{vu} is low at the beginning of motion to avoid the sudden jump of the slave robots. During the movement, the velocity boundary increases to its upper bound (e.g., 0.7m/s) to accelerate the slave robots, and the changing rate σ_{vu} also becomes high enough to allow the robots to have a fast speed during movement. When the robots are close to their desired poses, μ_v reaches 1, which slows down the velocity by lowering the velocity boundary B_v .

We design the velocity controllers for the slaves as

$$\tau_{vj} = Z_v(\beta_v \tau_{Ssj} - \dot{q}_{sj}) \quad (29)$$

where $Z_v = K_I \frac{1}{s} + K_P$. K_P and K_I are control gains. $\beta_v = \text{diag}[(\frac{B_v^2 - \dot{q}_{sj,1}^2}{B_v^2}, \dots, \frac{B_v^2 - \dot{q}_{sj,N}^2}{B_v^2})]$. The velocity controllers allow the slave robots to follow the position command with regulated velocities as in Fig. 7

We also define the force controllers for the two slaves as

$$\begin{aligned} \tau_{f1} &= J_{s1}^T(F_{e2tr} - F_{e1}^*) \\ \tau_{f2} &= J_{s2}^T(F_{htr} - F_{e2}^*) \end{aligned} \quad (30)$$

The final torque input τ_{sj} can be derived as

$$\tau_{sj} = \tau_{vj} + \tau_{fj} + \Omega_{sj}(q_{sj}, \dot{q}_{sj}, \ddot{q}_{sj}) \quad (31)$$

where $\Omega_{sj}(q_{sj}, \dot{q}_{sj}) = M_{sj}\ddot{q}_{sj} + C_{sj}\dot{q}_{sj} + D_{sj}q_{sj} + E_{sj} - M_{sj}\ddot{s}_{sj}$. $\Omega_{sj}(q_{sj}, \dot{q}_{sj})$ acts as a compensator to compensate for the side effect of dynamics.

For the master, defining the position error $e_m = J_m^+(X_m - X_{st1}(t - T_{b1}))$, the master control torque is designed as

$$\begin{aligned} \tau_m &= \kappa_f \tau_{Sm} + J_m^T(-F_{e1tr} - F_h^*) + \Omega_m(q_m, \dot{q}_m, \ddot{q}_m) \\ \text{where } \tau_{Sm} &= -d_1 \text{sig}(s_m)^{\varpi_1} - d_2 \text{sig}(s_m)^{\varpi_2} - d_3 s_m \quad (32) \\ \text{and } s_m &= c_1 \text{sig}(e_m)^{\gamma_1} + c_2 \text{sig}(e_m)^{\gamma_2} \end{aligned}$$

$\Omega_m(q_m, \dot{q}_m, \ddot{q}_m) = M_m\ddot{q}_m + C_m\dot{q}_m + D_mq_m + E_m - M_m\ddot{s}_m$ acts as a compensator to compensate for the dynamics.

From (32), the operator receives feedback from slave1 since slave1 always has the same motion as the master. In the decoupled motion, the transformed force F_{e1tr} takes effect that allows the operator to feel the interaction force between slaves and the object. Additionally, according to (3) and (14), when slave2 is in hard contact and slave1 is in free motion ($F_{e1tr} = 0$), the stopped slave1 and the enlarged κ_f enhance the value of $J_m^+ \kappa_f \tau_{Sm}$. The operator will obtain a spring-like force that makes the master stop. In other words, (3) and (14) can force the whole system to stop if any robot is blocked and the operator is informed by the force feedback from $\kappa_f \tau_{Sm}$.

The stability of the slave and master control laws in (31)-(32) is shown in the Appendix.

Remark 1: In decoupled motion, the position controller $\kappa_f \tau_{Sm}$ and the force controller $J_m^T(-F_{e1tr} - F_h^*)$ provide different types of forces from the two slaves. For slave1, the operator obtains the real force feedback according to F_{e1tr} . For slave2, the operator receives spring-like force feedback according to the variable gain κ_f in (14). Based on the two

Fig. 8. First experiment. The master controls the two slave robots (slave1: left, slave2: right) to move toward the heavy object for three rounds.

different forces, the operator can classify the two slaves' contact situations. In the coupled motion when the slaves move with the object together, F_{e1tr} does not take effect ($F_{e1tr} = 0$) and κ_f in (21) is close to zero during free motion (the big slave robot (slave1 + slave2 + the object) does not contact any external environment) that makes the operator feel nothing. When the big slave robot hits the environment (e.g., placing the object onto a table), κ_f increases and $\kappa_f \tau_{Sm}$ makes the operator feel a spring-like force feedback.

IV. EXPERIMENTS

This section validates the proposed SMBT system. The overall experimental platform contains a 3-DoF master haptic device (Geomagic contact), two 7-DoF slave robots (Franka Panda robot). Three computers are utilized to control the three robots, and the communication network between the computers is the internet. The time delay between the slaves and the master is approximately 200 ms. In all experiments, the positions of slave1 and slave2 can be different, and the orientations of the two robots are opposite.

The control parameters for the experiments are as follows. In POFDS, the impedance terms Z_{e1} and Z_{e2} are set as $Z_{e1,2} = 10 \frac{1}{s} + 1.5$. $\epsilon_f = 2$, $\epsilon_c = 0.5$. $\rho_f = 0.5N$, $b_{fu} = 0.3N$. For the sliding mode controller, $c_1 = 1$, $c_2 = 0.8$, $d_{1,2} = \text{diag}([10, 35, 20, 30, 20, 20, 15])$, $d_3 = 22$. For the velocity controllers, $K_I = \text{diag}([5, 10, 5, 10, 5, 5, 3])$, $K_P = \text{diag}([2, 5, 2, 5, 2, 2, 1])$, $b_{vu} = 0.7m/s$, $b_{vl} = 0.1m/s$, $\sigma_{vu} = 6$, $\sigma_{vl} = 0.5$.

A. Free motion and hard contact in decoupled motion

One of the most considerable challenges for an SMBT system is how to provide the operator with appropriate feedback to classify different remote situations that cannot be messed up by multiple slave robots. This section tests the slaves' coordination and the master's force feedback in decoupled motion, as shown in Fig. 8 to demonstrate the system's performance for dealing with this challenge. The strategy leveraged in this system is that slave1, which has the same motion as the master, is the main arm to provide force feedback to the master so that the operator can feel the condition of slave1, while slave2, based on (3) and (14) by taking slave1 as the medium, can also influence the feedback derived by the operator.

Fig. 9. Free motion and hard contact of the proposed system in the first experiment. The first figure shows the tool position signals at the Y-axis of bL_m (red: master position X_m ; blue: slave1 tool position X_{st1} ; green: transformed slave2 tool position $P_{tr}^{-1}(X_{st2})$). The second figure shows the related tool position errors (red: tool position error between the master and slave1; blue: tool position error between slave1 and slave2). The third figure shows the human/environment forces (red: human felt force; blue: environment force of slave1; green: environmental force of slave2). The fourth figure shows the force errors between the human force and each of the slaves (red: $F_h^* + F_{e2}^* - F_{e1}^*$; blue: $F_h^* - F_{e1}^*$).

The two slave robots are controlled by the master to move toward a heavy object between the two slaves (move in the Y-axis of ${}^bL_{s1}$) three times. In the three rounds, the location of the object is different, which leads to the following three conditions: In the first round (0 s - 35 s), there is no object in the middle of the robots so that the two slave robots conduct free motion without forces. In the second round (35 s - 80 s), the object is close to slave2, which puts slave2 in hard contact, but slave1 is in free motion. In the third round (80 s - 120 s), the object is close to slave1, which puts slave1 in hard contact, but slave2 in free motion. In this experiment, the two slaves' directions are opposite to each other with fixed orientations.

Fig. 9 shows the position and force tracking of the proposed system. Note that the position and orientation of slave2 are completely different from slave1, as shown in the last figure of Fig. 9, so we show the transformed signal $P_{tr}^{-1}(X_{st2})$ instead of its tool position X_{st2} . In the first round, all the robots are in free motion and closely track their desired position. The position tracking errors are smaller than 0.01 m and basically zero at steady state. Additionally, the operator receives no force feedback.

In the second round, slave2 is blocked by the object, while slave1 is in free motion (no force). When slave2 stops moving, the enlarged force of slave2 increases the dominance factor μ_F , which makes the stopped slave2's tool position completely determine the desired position of slave1. From the first figure in Fig. 9, the transformed slave position $P_{tr}^{-1}(X_{st2})$ always remains the same as slave1's tool position. Due to the different positions and orientation of slave2, its force can also have different shapes and directions from slave1 and the human force. Therefore, directly feeding slave2's force back to the master can interrupt the operator's force perception. In this study, the enlarged force of slave2 increases the variable gain κ_f in (14) so that the position error between the master and slave1 determines the master's force feedback. The stopped slave1's position enlarges the position error, which acts as a damper to make the operator feel a spring-like force feedback.

In the third round, slave1 is blocked by the object, while

slave2 is in free motion (no force). The amplitude and shape of the human felt force closely follow slave1's real force that contributes to the motion synchronization between the master and slave1. Then, slave2 is affected by the master's motion, which also stops when slave1 is in hard contact.

Based on the above experiment, the proposed system provides a clear classification of the different forces from the slaves to the operator. The same motion and direction of slave1 and the master enables slave1 to directly feed the environmental force back to the operator. Due to the different motion and directions, slave2 cannot directly feed its environmental force to the operator, but instead, it treats slave1 as a medium and sends a spring-like force to the operator. Therefore, these two kinds of forces allow the operator to identify the different situations of the slaves.

B. Orientation regulation in decoupled motion

Another challenge that is seldom considered by most of the existing studies on SMBT is the desired orientation regulation. This section demonstrates the performance of the proposed system on orientation regulation in decoupled motion (Task A1-Task A4), as shown in Fig 10. Fig 10A→B (0 s-50 s) shows that the orientations of the slaves are coupled with their positions so that the operator can regulate the desired orientations by changing their positions. Fig 10B→C (50 s-70 s) shows that the orientations of the slaves are decoupled from their positions and fixed. Then, the operator can move the target position (center between the two slaves' tool positions $\frac{X_{st1} + X_{st2}}{2}$) from the estimated position with errors (X: 0.45 m, Y: 0.34 m) to the real object position (X: 0.56 m, Y: 0.34 m). Fig 10C→D (70 s-100 s) shows that the two slaves start to contact and grasp the object, which means the decoupled motion is switched to coupled motion. Then, the operator moves the object from the real position back to the estimated position. In the whole experiment, the tools of the two slaves are parallel to the surface S_{xy} (set to be the ground) based on Task A2 for better grasping the object.

Figs. 11 and 12 show the performance of the proposed system in this section. In the period of 0 s-50 s, the orientations of the two slaves are regulated according to the changing positions of the two slaves, and the two robots' tips point to the estimated object position. The orientations of the two slaves are variable during this period but remain opposite. Therefore, the orientation error in the Y-axis (slave1 + slave2) is always around zero. Since the robots are conducting free motion, the forces of all the robots are close to zero. At the end of this period, the two slave robots are regulated to their optimal orientations, as shown in Fig. 10B, but the target position is at an incorrect object position.

In the period of 50 s-70 s, the orientations of the two slaves are decoupled from their positions and fixed. Then, the operator moves the two slaves with a fixed orientation to the real object's position. This demonstrates that the proposed strategy POFDS has the ability to locate the object's position with the optimal orientation of the slaves.

The period of 70 s-100 s can be separated into two periods: 70 s-80 s and 80 s-100 s. The first period (70 s-80 s)

Fig. 10. Second experiment. A→B: The two slave robots regulate their optimal orientations. B→C: The two slave robots correct their target position. C→D: Decoupled motion switches to coupled motion.

Fig. 11. Practical positions of the robots in the second experiment. The left two figures are the practical tool positions X_{st1} and X_{st2} of slave1 (blue) and slave2 (green) in the X- and Y-axes of ${}^bL_{s1}$. In the right two figures, the black curve is the target position (the center of the two robots' tool position $\frac{X_{st1} + X_{st2}}{2}$); the red curve is the real object position; the blue curve is the estimated object position; the yellow curve in the last figure denotes the estimated and real object positions which are the same.

is still in decoupled motion when the two robots begin to contact the object, and all the robots on the slave side (slave1, slave2 and the object) apply forces to each other. Using the force coordination strategy in POFDS, the human felt force closely tracks slave1's force; moreover, due to the opposite orientation and motion of slave1 to slave2, the proposed force coordination strategy allows slave2 to apply force with the same shape and amplitude but in the opposite direction to the force of slave1. Therefore, the object can be stably grasped by the two slave robots. During the free motion and contact, the positions of the robots (master X_m , slave1's tool position X_{st1} and the transformed tool position of slave2 $P_{tr}^{-1}(X_{st2})$) closely track each other, and their errors are basically zero.

In the second period (80 s-100 s), the decoupled motion is switched to coupled motion. This switch is triggered by the grippers grasping the object. In the coupled motion, all the robots on the slave side (slave1, slave2 and the object) are combined as a large slave robot, and the forces applied to each robot are treated as internal forces, which do not need to be felt by the operator. Therefore, the human felt force rapidly converges to zero.

This experiment shows the following advantages of the proposed system. 1). Unlike the existing approaches, the operator in the proposed system can regulate multiple slaves' orientations by using a haptic device with fewer joints. There-

Fig. 12. Position, orientation, force and the tracking errors of the proposed system in the second experiment. The upper two figures are the position tracking among the master X_m , slave tool position X_{st1} and the transformed tool position $P_{tr}^{-1}(X_{st2})$, and the related position tracking errors (master - slave1, slave1 - slave2). The middle two figures are orientations in the quaternion of the two slaves on the Y-axis and the orientation errors (slave1 + slave2). The last two figures are the human felt force (red), environmental force of slave1 (blue) and environmental force of slave2 (green), and the force errors (red: human force - slave1's force, blue: slave1's force + slave2's force)

fore, the kinematical redundancy problem is solved. 2). This system allows the operator to freely decouple or couple the slaves' orientations from their positions, which can efficiently solve the problem of object position error. 3). This system provides the operator with diverse force perceptions about the decoupled and coupled motions. In the decoupled motion, the operator can clearly feel the remote contact force, and the accurate force tracking performance allows the operator to regulate the slaves' applied force. In the coupled motion, the operator does not need to be concerned with the "internal" forces among the slaves and the object, which allows the operator to easily move and place the object.

C. Coupled motion

The third experiment tests the coupled motion of the proposed system, as shown in Fig. 13, which can be separated into the following periods.

Period 1 (0 s-30 s, Fig. 13A→B): Decoupled motion is switched to coupled motion.

Period 2 (30 s-100 s, Fig. 13C→D): The large slave robot conducts free motion with fixed orientation.

Period 3 (100 s-150 s, Fig. 13E→F): The large slave regulates its orientation in coupled motion.

Period 4 (150 s-185 s, Fig. 13G→H): The object is placed at the target place with right orientation.

To make the experiment more challenging, the applied grippers only apply small forces that are used to fix the object, while the forces lifting and moving the object are mainly the contact forces of the slave robots.

Figs. 14 and 15 demonstrate the performance of the proposed system in coupled motion. In all of the periods, accurate position tracking between the master and the big slave robot is achieved with little effect from the "internal" force among the three robots (slave1, slave2 and the object) on the slave side. In Period 1, the master controls the two slaves to move

Fig. 13. Third experiment: coupled motion. A→B: The decoupled motion is switched to coupled motion. C→D: The large slave robot (slave1 + slave2 + the object) conducts free motion with fixed orientation. E→F: The large slave robot regulates the object's orientation. G→H: The large slave robot gently places the object on the table. By feeling the force feedback, the operator switches the decoupled motion back to coupled motion. The task is accomplished

Fig. 14. Position and orientation of the proposed system in the third experiment. In the first six figures, the red curves are the master's positions in the X-, Y- and Z-axes of ${}^bL_{s1}$; the black curves are the positions of the large slave robot containing slave1, slave2 and the object (this position is derived as an average value between the slave1 position and the transformed slave2 position); blue curves are the related position errors. The seventh figure shows the orientation of slave1 and slave2 on the Y-axis, and the eighth figure shows the orientation errors (slave1 + slave2).

toward the object and then apply force. The force is mainly applied on the Y-axis, and the human felt force closely tracks the slave1's force, which gradually increases to 1N. By feeling this force, the operator knows that the object is tightly held by the two slaves and then switches the decoupled motion into coupled motion. Period 2 is the coupled motion, in which the human felt force decreases to zero so that the operator is not affected by the "internal" forces existing in the big slave robot. From Period 2 to Period 3, the human felt force remains at zero. In Period 3, the operator starts to regulate the object's orientation. During this period, the slave1's and slave2's force

Fig. 15. Forces of the proposed system in the third experiment in X-, Y-, and Z-axes of ${}^bL_{s1}$ and the related force errors between the two slaves. Red: human felt force; blue: environmental force of slave1; green: environmental force of slave2.

remains stable with similar amplitudes, and the force errors are under 0.5. In Period 4, after the operator corrects the object's orientation, the master drives the big slave robot to gently put the object in the desired place. Based on the master's force feedback strategy in coupled motion in POFDS, the enlarged κ_f increases the position errors between the master and the slave so that the operator can feel a spring-like force feedback to know that the object has already been placed on the table. Finally, the coupled motion is switched to the decoupled motion, and the task is accomplished.

In most of the previous multirobot systems (e.g., [1], [23]–[26], [28], [28]–[30]), the force regulation and control presented in our study are usually not considered. By treating human and environmental forces as external disturbances, their approaches mainly focus on guaranteeing system stability under these disturbances to achieve motion synchronization. However, without a good force regulation strategy, the slave

Fig. 16. Forces of the system for comparison in the third experiment in the X-, Y-, and Z-axis of ${}^bL_{s1}$ and the related force errors between the two slaves. Red: human felt force; blue: environmental force of slave1; green: environmental force of slave2.

Fig. 17. Position and orientation of the system for comparison in the third experiment. The red curves are the master's positions in the X-, Y- and Z-axes of ${}^bL_{s1}$; the black curves are the positions of the large slave robot (this position is derived as an average value between the slave1's position and the transformed slave2's position); blue curves are the related position errors.

robots can hardly cooperate to perform a complex task as the third experiment. In the following experiment, we conduct a similar experiment but without our proposed force coordination strategy in POFDS. (The other proposed strategies in POFDS are still employed. We cannot completely follow the approaches in the above references because they cannot support the operator to drive the slaves to conduct different motions with variable orientation.)

Figs. 16 and 17 show the performances of the system for comparison. Without the proposed force strategy, the operator cannot derive reasonable force feedback with proper directions. Without proper force feedback, the performances of the two slave robots cannot be clearly known by the operator. Moreover, unbalanced and sharply varying forces are applied by the two slave robots, which directly influence the motion of the overall slave bimanual system. Large position tracking errors are generated, and the object cannot be lifted and moved to the desired location, which fails the task.

The overall experiments show the following advantages of the proposed system.

1. The coupled motion supported by POFDS allows the operator to simultaneously control the three slave robots (slave1, slave2 and the object) similar to controlling one slave robot. The strategy of slave coordination in coupled motion in POFDS allows the large slave robot to closely track the motion of the master regardless of the side effect of the “internal” forces.

2. The strategy of slaves' coordination in coupled motion in POFDS has the ability of orientation regulation in the coupled motion, which improves the novelty of the proposed system on regulating both the object's position and orientation.

3. The force coordination strategy in POFDS allows the slave robots and the object to interact with each other with stable and smooth forces with correct directions, which enhances the cooperation ability of the slave robots and avoids the task failure caused by an unbalanced force.

4. The master force feedback strategy in POFDS prevents the operator from being adversely affected by the “internal” forces among the slaves. Moreover, it enables the operator to feel the external forces applied to the big slave robot, which helps the operator perform the correct movements.

V. CONCLUSION AND FUTURE WORK

In this paper, a new SMBT system is proposed with a novel strategy to regulate the system's positions, orientations and forces. For position regulation, unlike most of the existing studies more concentrating on synchronization, the proposed system allows slave robots driven by one master to simultaneously conduct different motions based on the task requirement. For orientation regulation, kinematic redundancy is addressed. The slave robots can autonomously regulate their orientations for tasks so that the operator only needs to handle the position of the master, which can potentially reduce the operator's burden. For force regulation, the slave robots' forces in different directions can be controlled and balanced and properly applied to the object. Moreover, the operator can derive good environmental force feedback without the interruption of forces from different slave robots. The experiment on the system consisting of two 7-DoF Franka robots and one 3-DoF Geomagic Touch demonstrates the feasibility of the proposed system. In future work, more human factors, such as muscle activation, will be involved to ease the operating burden. Trajectory learning approaches will also be further studied to improve the coordination of multiple slave robots.

APPENDIX A STABILITY PROOF

In this paper, we assume the differential of the time delays unitless. The differential of time delays can be estimated by using the time delay differential estimator in [47].

Based on the final control laws in (31)-(32), the Type-2 fuzzy neural network modeled master and slaves dynamics in (23) can be rewritten as

$$\begin{aligned}
M_{s1}\dot{s}_{s1} + \eta_{s1} &= Z_v(\beta_v\tau_{Ss1} - \dot{q}_{s1}) + J_{s1}^T F_{e2tr} \\
M_{s2}\dot{s}_{s2} + \eta_{s2} &= Z_v(\beta_v\tau_{Ss2} - \dot{q}_{s2}) + J_{s2}^T F_{e2tr} \\
M_m\dot{s}_m + \eta_m &= \kappa_f\tau_{Sm} - J_m^T F_{e1tr}
\end{aligned} \quad (33)$$

Define a Lyapunov function V_1 as

$$V_1 = \frac{1}{2}s_{s1}^T M_{s1}s_{s1} + \frac{1}{2}s_{s2}^T M_{s2}s_{s2} + \frac{1}{2}s_m^T M_m s_m \quad (34)$$

Its differential can be derived as

$$\begin{aligned}
\dot{V}_1 &= s_{s1}^T (Z_v(\beta_v\tau_{Ss1} - \dot{q}_{s1}) + J_{s1}^T F_{e2tr} - \eta_{s1}) + \\
& s_{s2}^T (Z_v(\beta_v\tau_{Ss2} - \dot{q}_{s2}) + J_{s2}^T F_{e2tr} - \eta_{s2}) + \\
& s_m^T (\kappa_f\tau_{Sm} - J_m^T F_{e1tr} - \eta_m) \\
& \leq -\kappa_f d_1 \left(\frac{2}{M_m}\right)^{\frac{1+\varpi_1}{2}} \left(\frac{1}{2}s_m^T M_m s_m\right)^{\frac{1+\varpi_1}{2}} \\
& - Z_v\beta_v d_1 \left(\frac{2}{M_{s1}}\right)^{\frac{1+\varpi_1}{2}} \left(\frac{1}{2}s_{s1}^T M_{s1}s_{s1}\right)^{\frac{1+\varpi_1}{2}} \\
& - Z_v\beta_v d_1 \left(\frac{2}{M_{s2}}\right)^{\frac{1+\varpi_1}{2}} \left(\frac{1}{2}s_{s2}^T M_{s2}s_{s2}\right)^{\frac{1+\varpi_1}{2}} \\
& - \kappa_f d_2 \left(\frac{2}{M_m}\right)^{\frac{1+\varpi_2}{2}} \left(\frac{1}{2}s_m^T M_m s_m\right)^{\frac{1+\varpi_2}{2}} \\
& - Z_v\beta_v d_2 \left(\frac{2}{M_{s1}}\right)^{\frac{1+\varpi_2}{2}} \left(\frac{1}{2}s_{s1}^T M_{s1}s_{s1}\right)^{\frac{1+\varpi_2}{2}} \\
& - Z_v\beta_v d_2 \left(\frac{2}{M_{s2}}\right)^{\frac{1+\varpi_2}{2}} \left(\frac{1}{2}s_{s2}^T M_{s2}s_{s2}\right)^{\frac{1+\varpi_2}{2}} \\
& - Z_v\beta_v d_3 s_{s1}^T s_{s1} - Z_v\beta_v d_3 s_{s2}^T s_{s2} - \kappa_f d_3 s_m^T s_m \\
& - Z_v\beta_v s_{s1}^T \dot{q}_{s1} - Z_v\beta_v s_{s2}^T \dot{q}_{s2} + s_{s1}^T J_{s1}^T F_{e2tr} + s_{s2}^T J_{s2}^T F_{htr} \\
& - s_m^T J_m^T F_{e1tr} - s_{s1}^T \eta_{s1} - s_{s2}^T \eta_{s2} - s_m^T \eta_m \\
& \leq -\mathbb{R}V_1^{\frac{1+\varpi_1}{2}} - \mathbb{Z}V_1^{\frac{1+\varpi_2}{2}} - Z_v\beta_v d_3 s_{s1}^T s_{s1} - Z_v\beta_v d_3 s_{s2}^T s_{s2} \\
& - \kappa_f d_3 s_m^T s_m - Z_v\beta_v s_{s1}^T \dot{q}_{s1} - Z_v\beta_v s_{s2}^T \dot{q}_{s2} + s_{s1}^T J_{s1}^T F_{e2tr} \\
& + s_{s2}^T J_{s2}^T F_{htr} - s_m^T J_m^T F_{e1tr} - s_{s1}^T \eta_{s1} - s_{s2}^T \eta_{s2} - s_m^T \eta_m
\end{aligned} \quad (35)$$

where $\mathbb{R} = \min\{\kappa_f d_1 \left(\frac{2}{M_m}\right)^{\frac{1+\varpi_1}{2}}, Z_v\beta_v d_1 \left(\frac{2}{M_{s1}}\right)^{\frac{1+\varpi_1}{2}}, Z_v\beta_v d_1 \left(\frac{2}{M_{s2}}\right)^{\frac{1+\varpi_1}{2}}\}$, $\mathbb{Z} = \min\{\kappa_f d_2 \left(\frac{2}{M_m}\right)^{\frac{1+\varpi_2}{2}}, Z_v\beta_v d_2 \left(\frac{2}{M_{s1}}\right)^{\frac{1+\varpi_2}{2}}, Z_v\beta_v d_2 \left(\frac{2}{M_{s2}}\right)^{\frac{1+\varpi_2}{2}}\}$. The differential of M_i depends on the fuzzy sets in Type-2 fuzzy modeling, which can be included into η_i .

By setting $d_3 > \max\{\frac{1}{2} + \frac{1}{Z_v\beta_v}, \frac{1}{2\kappa_f}\}$, (35) can be further simplified as

$$\dot{V}_1 \leq -\mathbb{R}V_1^{\frac{1+\varpi_1}{2}} - \mathbb{Z}V_1^{\frac{1+\varpi_2}{2}} + \bar{B} \quad (36)$$

where $\bar{B}$ is the upper bound of the terms $\frac{Z_v\beta_v}{2}\dot{q}_{s1}^T \dot{q}_{s1} + \frac{Z_v\beta_v}{2}\dot{q}_{s2}^T \dot{q}_{s2} + \frac{1}{2}(J_{s1}^T F_{e2tr})^T J_{s1}^T F_{e2tr} + \frac{1}{2}(J_{s2}^T F_{htr})^T J_{s2}^T F_{htr} + \frac{1}{2}(J_m^T F_{e1tr})^T J_m^T F_{e1tr} + \frac{1}{2}\eta_{s1}^T \eta_{s1} + \frac{1}{2}\eta_{s2}^T \eta_{s2} + \frac{1}{2}\eta_m^T \eta_m$. Knowing that a positive constant l_M exists that makes $-\mathbb{R}V_1^{\frac{1+\varpi_1}{2}} - \mathbb{Z}V_1^{\frac{1+\varpi_2}{2}} < -l_M V_1$, $\dot{V}_1$ becomes

$$\dot{V}_1 \leq -l_M V_1 + \bar{B} \quad (37)$$

Multiplying both sides in (37) by $e^{l_M t}$ leads to

$$\frac{d}{dt}(\dot{V}_1 e^{l_M t}) < \bar{B} e^{l_M t} \quad (38)$$

Integrating (38) over $[0, t]$ gets

$$0 \leq V_1(t) \leq (V_1(0) - \frac{\bar{B}}{l_M})e^{-l_M t} + \frac{\bar{B}}{l_M} \quad (39)$$

Accordingly

$$0 \leq V_1(t) \leq \bar{V}_1(0) \quad (40)$$

where $\bar{V}_1(0) = \frac{1}{2}s_{s1}^T(0)M_{s1}s_{s1}(0) + \frac{1}{2}s_{s2}^T(0)M_{s2}s_{s2}(0) + \frac{1}{2}s_m^T(0)M_m s_m(0) + \frac{\bar{B}}{l_M}$. From (40), the control signals' tracking is always bounded, which proves the stability of the system.

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Da Sun received B.Eng. and Ph.D. degrees in mechatronics from the University of Wollongong, Wollongong, NSW, Australia, in 2012 and 2016, respectively. From 2016 to 2017, he was a Research Fellow with the National University of Singapore, Singapore. He is currently a researcher at the Center for Applied Autonomous Sensor Systems (AASS) at Örebro University, Örebro, Sweden. His research interests include robotics learning, modelling, and control theory.

Qianfang Liao received a B.Eng. degree in automation from Wuhan University, Wuhan, China, in 2006, an M.Eng. degree in automation from Shanghai Jiao Tong University, Shanghai, China, in 2009, and a Ph.D. from the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore, in 2015. Currently, she is a researcher with Örebro University, Örebro, Sweden. Her research interests include fuzzy modeling, control theory, and computer vision.

Amy Loutfi is a professor in information technology at Örebro University with the Center for Applied Autonomous Sensor Systems (AASS), Sweden. Her general interests are in the integration of artificial intelligence with autonomous systems, and over the years, she has looked into applications where robots closely interact with humans in both industrial and domestic environments. She received her Ph.D. degree in computer science in 2006; her thesis focused on the integration of artificial olfaction into robotic and intelligent systems to enable good human-robot

interactions. Since then, she has examined various cases of human-robot interactions, including applications of telepresence.

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