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A Multilateral Impedance-Controlled System for Haptics-Enabled Surgical Training and Cooperation in Beating-Heart Surgery

Lingbo Cheng, Mahdi Tavakoli*

Lingbo Cheng and Mahdi Tavakoli are with the Department of Electrical and Computer Engineering, University of Alberta, Edmonton, Alberta, T6G 1H9 Canada.
*Corresponding author. (e-mails: mahdi.tavakoli@ualberta.ca, phone: +1- 780-492-8935)

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Abstract—In this paper, an impedance-controlled multi-master/single-slave telerobotic system is developed for haptics-enabled surgical training and cooperation in beating-heart surgery. This system not only can enable automatically motion compensation for the beating heart's motion as well as non-oscillatory force feedback to the human operators but can also enable training and cooperation for multiple users. A multi-user shared control architecture is developed, and a multilateral impedance-controlled strategy is employed for this architecture. The desired objectives of the proposed system are a) providing position guidance to the trainees during training procedure, b) providing force feedback to all human operators (trainer and trainees) regardless of their levels of authority over the slave robot, c) motion compensation for the heart's motion, and d) reflecting only the non-oscillatory force portion of the slave-heart tissue interaction force to all human operators. To this end, virtual fixtures and a dominance factor are introduced, and a reference impedance model with adjusted parameters is designed for each master or slave robot. The proposed impedance-based control methodology is evaluated experimentally. The experimental results demonstrated that the proposed method could be used for surgical training and cooperation in beating-heart surgery by providing appropriate position guidance and environmental force feedback to the human operators.

Keywords—Motion compensation, haptic feedback, impedance model, teleoperation system, medical robots.

I. INTRODUCTION

In recent years, research on multilateral teleoperation systems have moved to the applications of surgical procedures such as teleoperated surgical training [1], [2] and telerehabilitation therapy [3]. This research provides an opportunity to promote the development of robotic-assisted technology for beating-heart surgery.

Beating-heart surgery has significant advantages over conventional arrested-heart surgery. For instance, it could enable intraoperative evaluation of the beating heart and eliminate adverse effects such as long-term cognitive loss and neurologic dysfunction [4]. Nevertheless, due to the fast motions induced by respiration and heartbeat, performing a surgical procedure on a beating-heart tissue is extremely difficult for the human operator (surgeon). To eliminate the physiological motions, a mechanical stabilizer [5] is come up with, but residual movements still exist. Alternatively, robotic-assisted surgical systems for beating-heart surgery are proposed by developing a surgical robot attached by a surgical tool to compensate for the complex physiological motions automatically. By using these systems, the human operator can have a feeling of operating on a seemingly arrested heart. The robotic-assisted system, however, introduces another issue: haptic feedback. To provide haptic feedback to the human operator, a force sensor is usually attached to the surgical robot to register forces. When the surgical robot's motions are synchronized with the heart's motions, the force sensor inertia will cause oscillatory forces, which should not be transmitted to the human operator. In other words, the haptic feedback should only contain the non-oscillatory portion of the environmental forces.

To this end, various configurations of the robotic-assisted system have been proposed. Position-based surgical systems obtain the physiological motions by observation [6], prediction [7], and estimation [8]. The employed sensors are varied from sonomicrometry crystals [9], high-speed cameras [10], [11], infrared radiometer [12], to Ultrasound machine [13], [14]. Force-based surgical systems [8], [15], [16] employ force sensors to make the contact forces track the desired forces. Additionally, to control the dynamic behavior between the surgical robot and heart tissue, impedance-controlled systems [13], [17], [18] are presented subsequently. All the past work focused on the hand-held devices or single-master-single-slave teleoperation systems to perform surgical tasks. These systems provide the expert human operators assistance in the beating-heart surgical procedure, but they cannot provide training opportunities for the novice operators. This leads us to come up with the idea that in addition to developing advanced surgical systems for beating-heart surgery, training the novices to use such systems proficiently is equally important and necessary. Moreover, in realistic beating-heart surgery, human operators usually need to perform complex tasks within a limited workspace. Therefore, an effective expert-in-the-loop surgical training for novice human operators plays an essential role in decreasing potential risks during operation.

In addition, the systems of the past work are only suitable for a single human operator instead of multiple human operators, which lead them cannot allow for cooperative task performance like a multi-user teleoperation system. Particularly, if a task is super delicate and complex, two or more expert operators simultaneously perform the operation is necessary to minimize the risk of tissue injury and too-tissue collision. As a result, the interest of this paper focuses on developing a multi-user teleoperation system which enables expert-in-the-loop surgical training and multiple operators cooperatively perform a physical operation on the slave robot in the remote environment (beating-heart surgery). This requires the system not only to enable automatically motion compensation for the beating heart's motion as well as non-oscillatory force feedback to the human operators, but also to enable training and cooperation for multiple users.

The rest of the paper is organized as follows. Section II introduces the related work about multilateral teleoperation systems incorporating control architectures and control strategies in the literature. Section III describes the developed multilateral teleoperation system for surgical training and cooperation in beating-heart surgery and the desired objectives for the system. Section IV presents the control methodology for the master and slave robots, which includes the proposed reference impedance model for each robot and the parameter adjustment guidelines for the models. Section V shows the experimental results and discussion. Finally, Section VI contains concluding remarks.

II. RELATED WORK

A most common form of multi-user systems for surgical training and cooperation is the dual-user shared control system [19][20], which includes two master robots manipulated by a trainer and a trainee, respectively, and one slave robot to perform tasks. This system enables both operators to interact with the environment simultaneously by providing haptic feedback to them.

Various dual-user shared control architectures have been proposed. In [19], the authors initially introduced the dominance factor for the surgical training system to provide skill levels of control authority over the task to both trainer and trainee. In this system, the trainer and trainee perceived force feedback from the master robots instead of the remote slave robot. In [21], the authors using the three-port master-slave network model proposed the complementary linear combination architecture and the master's correspondence with environment transfer architecture for haptic training. The former proposed the desired position and force commands for each robot by using the weighted sum of positions and forces of the other two robots. The latter provided half environment forces to both operators regardless of their authority over the task. Based on [21], a six-channel dual-user shared control architecture was developed in [22]. Also, in [23], the authors developed an architecture that provides direct interaction between the operators and the slave robot by employing two dominance factors. In addition to the authority of the trainer over the trainee, the authority of the trainer over the slave robot was designed to adjust the supremacy of teleoperators. In [24], a dual-user teleoperated surgical training architecture incorporating virtual fixtures (active constraints) was proposed. This architecture enabled novice trainee to receive haptic virtual fixtures cueing so that the trainee can follow the right gesture of the trainer. After the trainee has authority over the task, an expertise-oriented training was used providing a weighted sum of forces of the environment and the force exerted by virtual fixtures to the trainee. In [25], the authors extended the work presented in [24] and evaluated the system by employing a surgical setup consisting of the classic da Vinci surgical system and the dV-Trainer master console. Moreover, in [26], the authors proposed an architecture for cooperation by providing each operator with a force authority factor over the task and providing them with the same position commands regardless of their exerted forces.

In addition to different dual-user shared control architectures, various control strategies for these architectures are proposed. H_∞-based shared control approach for haptic training and collaboration was proposed in [19]. For the six-channel dual-user teleoperation system shown in [22], a transparency-optimized distance transfer function was introduced to compare the performance of the proposed system with that of the transparency-optimized four-channel controller. In [27], a P + D controller involving gravity compensation for all the robots was proposed to guarantee the stability of the dual-user system. In [26], an adaptive nonlinear impedance control strategy was developed for the nonlinear teleoperated system, and the stability of uncertain teleoperation system has been proven via the Lyapunov theorem. Other research on sliding-mode-based control strategy [28], adaptive fuzzy force/motion control method [29], passivity-based approach based on the Port-Hamiltonian [30], and neural network-based control method [31] were presented successively.

As a special case of multi-user teleoperation system, dual-user shared control system has attracted extensive attention and discussion. However, to provide surgical training for a class of trainees and realize a common task performance for multiple operators, a general multi-user system is needed. Fortunately, much of the work on dual-user teleoperation systems can be extended to multi-user systems. For instance, in [32], the authors developed a robust stability analysis framework for unconditional stability analysis of multi-master/multi-slave teleoperation systems and verified it on two dual-user shared control architectures. In [33], a multi-master/single-slave system was developed for cooperative and training applications. The proposed architecture allowed each human operator to feel the environment force for having an ideal transparent operation and provided the slave robot with the weighted sum of the position of each operator.

In this paper, a multi-master/single-slave teleoperator system for haptics-enabled surgical training and cooperation in beating-heart surgery is developed. The desired objectives of the teleoperation system are a) providing position guidance to the trainees during the training procedure, b) providing force feedback to all human operators regardless of their levels of authority over the slave robot, c) motion compensation for the heart's motion, and d) non-oscillatory forces feedback to all human operators. Table 1 summarizes the above previous research and states if the desired objectives are satisfied and if the system can be extended to a multi-user system.

Table 1. Previous research has been divided into different categories based on the desired objectives and whether the system can be extended to a multi-user system

Previous research	Objectives			
	Position guidance to the trainees	Environmental force feedback	Motion compensation and non-oscillatory force feedback	Suitable for multi-user system
[19]	No	No	No	No
[21][22]	No	No	No	No
[23]	No	Yes	No	No
[24][25]	Yes	No	No	Yes
[26]	Yes	No	No	Yes
[32]	No	No	No	Yes
[33]	No	Yes	No	Yes
Proposed method	Yes	Yes	Yes	Yes

In [17], [18], a bilateral impedance-controlled system with two reference impedance models for the master and slave robots, respectively, was proposed such that beating-heart surgery is facilitated. The proposed bilateral teleoperation system takes advantage of the frequency range of the heart's motion to successfully realize motion compensation and non-oscillatory force feedback to the human operator. Different from [17], [18], this paper focuses on haptics-enabled surgical training and task cooperation in beating-heart surgery. Therefore, the bilateral teleoperation systems in [17], [18] must be replaced by a multilateral teleoperation system. The new framework builds on previous work of the authors and makes use of multi-user teleoperation scenario, allowing the presence of a trainer and multiple trainees in the training and cooperation loop.

In this paper, a reference impedance model is designed for each robot, and the corresponding parameters are adjusted to meet the requirements of motion compensation and non-oscillatory force feedback. For the sake of clarity, the operation procedure is divided into three scenarios: fundamental training, skills assessment, and task cooperation. The desired objectives for each scenario are defined and satisfied by using virtual fixtures and a dominance factor. After the trainees are sufficiently trained, the trainer and trainees collaboratively control the slave robot to perform common tasks on the beating-heart tissue. To the best knowledge of the authors, this is the first research framework for beating-heart surgical training and cooperation. In other words, this is an initial work for adapting a teleoperation system for beating-heart surgery to surgical training and cooperation purposes. The overall system not only requires motion compensation and non-oscillatory haptic feedback but should also be suitable for surgical training and task cooperation for multiple human operators simultaneously.

III. Multilateral Teleoperation Systems

The multilateral teleoperation system for beating-heart surgical training and cooperation involves n master robots that provide position commands and one slave robot that receives those commands and executes tasks on the beating-heart tissue. Fig. 1 shows the developed system, human operators, and beating heart. In the master site, human operator 1 is the trainer and manipulates master robot 1, and the other operators are trainees who manipulate their corresponding master robots. In the slave site, the slave robot works as a surgical robot and performs tasks inside or outside the beating heart.

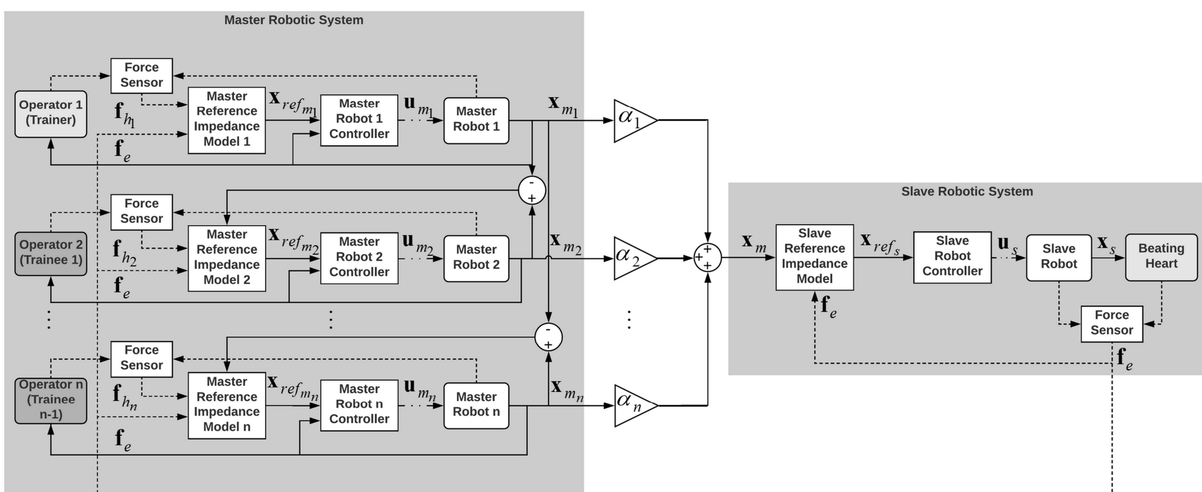

Figure 1. The block diagram of the multilateral teleoperation system for beating-heart surgical training with motion compensation models and non-oscillatory force feedback to the human operators. The solid, dashed, and dash-dotted lines indicate the position transfer paths, force transfer paths, and control signals, respectively.

A. Desired Objectives

In the developed system (Fig. 1), each robot is attached with a force sensor to measure the interaction force between the human operator and the master robot, $\mathbf{f}_{h_i}$ ($i = 1, \cdots, n$), or the interaction force between the slave robot and the heart tissue, $\mathbf{f}_e$. The positions of the master robots end-effectors, $\mathbf{x}_{m_i}$ ($i = 1, \cdots, n$), and the position of the slave robot end-effector, $\mathbf{x}_s$, can be measured and recorded by the robot encoders. Therefore, the measured interaction forces and end-effector positions of the robots can be transmitted through a communication channel to achieve the desired objectives for the beating-heart surgical training and cooperation system. Based on the divided three scenarios, the desired objectives for each scenario are as follows.

Scenario 1: Fundamental training. The skills levels of the trainees are assumed to be at the lowest (no skill). Only the trainer has authority over the surgical task. In other words, the trainer will teleoperate the slave robot alone and show the right gesture and exerted force to the trainees at the same time. The goals in this scenario include two parts. For the master site, the trainees should be guided to follow the position of the trainer, $\mathbf{x}_{m_1}$, to practice operation gesture. Also, all human operators should feel the (possibly scaled) non-oscillatory (low-frequency) portion of the slave-heart interaction forces. Note that the movements and applied forces by the trainees do not affect the movements and performance of the trainer and the slave robot. Therefore, there is no risk imposed by the trainees to the beating-heart tissue. Therefore, for the slave site, the movements of the slave robot, $\mathbf{x}_s$, is only affected by the trainer's motion, $\mathbf{x}_{m_1}$. At the same time, the slave robot should compensate for the motion of the beating heart, $\mathbf{x}_e$.

Scenario 2: Skills assessment. After the trainees are trained, the skills levels of the trainees will be assessed. A dominance factor, α_i (i = 1, ⋯, n), is defined to represent the skills level of each trainee, and it will be used for task cooperation. The dominance factor for each trainee should satisfy the equation $\sum_{i=1}^{n} \alpha_i = 1, \alpha_i \geq 0$. The transmitted position of the master robots to the slave robot in scenario 3 can be expressed as $\mathbf{x}_m = \alpha_1 \mathbf{x}_{m_1} + \alpha_2 \mathbf{x}_{m_2} + \cdots + \alpha_n \mathbf{x}_{m_n}$. Therefore, scenario 1 is a special case when $\alpha_1 = 1$ and $\alpha_i = 0$ (i = 2, ⋯, n). As the skills assessment is not the research focus of this paper, the series dominance factors in the experiments are assigned randomly.

Scenario 3: Task cooperation. Based on the skills level of each trainee, the trainees and trainer can cooperate to accomplish one task. In this scenario, both trainer and trainees can fully feel the (possibly scaled) non-oscillatory slave-heart interaction force and have authorities over the task according to their corresponding skills levels. The main difference between scenario 1 and scenario 3 is that the former provides position guidance from the trainer to the trainees, but the latter does not. For the sake of clarity, the above objectives are summarized in Table 2.

Table 2. Objectives for the multilateral teleoperation system

Scenarios	Objectives	
	Master site	Slave site
Scenario 1: Fundamental training	**Position guidance for the trainees:** $\mathbf{x}_{m_i} = \mathbf{x}_{m_1}$, **(*i* = 2, ⋯, *n*)**	**Transmitted master robots' position to the slave site:** $\mathbf{x}_m = \mathbf{x}_{m_1}$
	Non-oscillatory force feedback to all operators	Motion compensation for the beating heart: $\mathbf{x}_s$ complies with $\mathbf{x}_e$ during interaction
Scenario 2: Skills assessment	Obtain dominance factor α_i such that $\sum_{i=1}^{n} \alpha_i = 1, \alpha_i \geq 0$	
Scenario 3: Task cooperation	**No position guidance for the trainees:** $\mathbf{x}_{m_i} \neq \mathbf{x}_{m_1}$, **(*i* = 2, ⋯, *n*)**	**Transmitted master robots' position to the slave site:** $\mathbf{x}_m = \alpha_1 \mathbf{x}_{m_1} + \alpha_2 \mathbf{x}_{m_2} + \cdots + \alpha_n \mathbf{x}_{m_n}$
	Non-oscillatory force feedback to all operators	Motion compensation for the beating heart: $\mathbf{x}_s$ complies with $\mathbf{x}_e$ during interaction

B. Control Strategy Overview

The control of the multilateral teleoperation system is the most important issue to perform beating-heart surgical training and tasks cooperation successfully. In Fig. 1, a reference impedance model is proposed to design for each master or slave robot.

The reference impedance model for each master robot incorporates the forces applied by the corresponding human operator and the heart tissue and dictates the haptic force feedback from the heart tissue to the operator. As mentioned above, the non-oscillatory force feedback can be achieved by appropriately adjusting the parameters of the reference impedance model. The adjusted reference impedance model generates the desired position for the corresponding master robot i (i = 1, ⋯, n), $\mathbf{x}_{ref_{m_i}}$. A master robot controller is used for the master robot to track the desired position. The actual position of the master robot is $\mathbf{x}_{m_i}$, and $\mathbf{u}_{m_i}$ is the control signal to the master robot.

The reference impedance model for the slave robot provides the flexibility of the slave robot in tracking the master robots' position, $\mathbf{x}_m$, in response to the slave-heart interaction force. By appropriately adjusting its parameters, the slave robot can compensate for the beating-heart motion perfectly. The slave robot controller receives the slave robot desired trajectories generated by the impedance model ($\mathbf{x}_{ref_s}$) and actual trajectories ($\mathbf{x}_s$), and outputs the control signal $\mathbf{u}_s$ to the slave robot. The reference impedance models and their parameter adjustments and controllers are presented in Section IV in detail.

IV. Control Methodology

Algorithms presented in this section focuses on the reference impedance models for the master and slave robots presented in Section IV-A and the parameter adjustment guidelines for the impedance models presented in Section IV-B.

A. Reference Impedance Models

The reference impedance model for each master robot in Cartesian coordinates includes the human-master interaction force, the scaled slave-heart interaction force, and the desired master response trajectory. The relationships can be expressed as

$$\mathrm{M}_{m_1}\ddot{\mathbf{x}}_{ref_{m_1}} + \mathrm{C}_{m_1}\dot{\mathbf{x}}_{ref_{m_1}} + \mathrm{K}_{m_1}\mathbf{x}_{ref_{m_1}} = \mathbf{f}_{h_1} - k_{\mathrm{f}}\mathbf{f}_e \tag{1a}$$

$$\mathrm{M}_{m_i}\ddot{\mathbf{x}}_{ref_{m_i}} + \mathrm{C}_{m_i}\dot{\mathbf{x}}_{ref_{m_i}} + \mathrm{K}_{m_i}\mathbf{x}_{ref_{m_i}} = \mathbf{f}_{h_i} - k_{\mathrm{f}}\mathbf{f}_e - \beta\mathbf{f}_{v_i} \tag{1b}$$

$$\mathbf{f}_{v_i} = \mathrm{M}_m^v\ddot{\mathbf{e}}_{m_i} + \mathrm{C}_m^v\dot{\mathbf{e}}_{m_i} + \mathrm{K}_m^v\mathbf{e}_{m_i} \tag{1c}$$

where M_{m_i}, C_{m_i}, and K_{m_i} are the virtual mass, damping, and stiffness of the i^{th} master impedance model. The subscript $i = 1$ refers to the human operator 1 that is the trainer, and $i = 2, \cdots, n$ refers to the human operator $2, \cdots, n$, which are trainees. Scalars k_{f} and β are two force scaling factors. The interaction forces ($\mathbf{f}_{h_i} \in \mathbb{R}^{6\times1}$, $\mathbf{f}_e \in \mathbb{R}^{6\times1}$) and the desired master response ($\mathbf{x}_{ref_{m_i}} \in \mathbb{R}^{6\times1}$) are vectors. Here, $\mathbf{f}_{v_i}$ is a designed virtual force generated by a virtual fixture designed to guide the trainees along the right path of the surgery, and $\mathbf{e}_{m_i} = (\mathbf{x}_{m_i} - \mathbf{x}_{m_1})$ is the position tracking error between trainer and each trainee. Also, M_m^v, C_m^v, and K_m^v correspond to the impedance characteristics of the virtual fixture model. As the robots' accelerations are hard to measure, M_m^v is set to be 0. According to the desired objectives for the trainees, scalar β is set to be 1 for training scenario and 0 for cooperation scenario.

The reference impedance model for the slave robot is concerned with the slave-heart interaction force and the desired slave impedance model's response deviation from the trajectory of the master robot. The model can be expressed as

$$\mathrm{M}_s\ddot{\tilde{\mathbf{x}}}_{ref_s} + \mathrm{C}_s\dot{\tilde{\mathbf{x}}}_{ref_s} + \mathrm{K}_s\tilde{\mathbf{x}}_{ref_s} = -\mathbf{f}_e \tag{2}$$

where $\tilde{\mathbf{x}}_{ref_s} = \mathbf{x}_{ref_s} - k_{\mathrm{p}}\mathbf{x}_m$, and k_{p} is the position scaling factor. Here, $\mathbf{x}_m \in \mathbb{R}^{6\times1}$ is the position vector of the master robot. Also, M_s, C_s, and K_s are the virtual mass, damping and stiffness of the slave impedance model.

B. Parameter Adjustments

To illustrate the parameter adjustment guidelines for the reference impedance models clearly, damping ratios and natural frequencies of the reference impedance models are introduced. For each master robot, the damping ratio is given by $\xi_{m_i} = \mathrm{C}_{m_i}/2\sqrt{\mathrm{M}_{m_i}\mathrm{K}_{m_i}}$, and the natural frequency is given by $\omega_{n_{m_i}} = \sqrt{\mathrm{K}_{m_i}/\mathrm{M}_{m_i}}$. For the slave robot, the damping ratio is $\xi_s = \mathrm{C}_s/2\sqrt{\mathrm{M}_s\mathrm{K}_s}$, and the natural frequency is $\omega_{n_s} = \sqrt{\mathrm{K}_s/\mathrm{M}_s}$. In the following, only the damping ratios, the natural frequencies, and the stiffnesses are chosen to be adjusted.

1) Fundamental training

The reference impedance model for master robot 1 (1a) aims to avoid possible fatigue and exhaustion caused by the oscillatory slave-heart interaction force feedback to the trainer. Also, the reference impedance model for the other master robot (1b) aims to provide position guidance to all trainees from the trainer, and meanwhile all trainees should feel the non-oscillatory force feedback. Therefore, a virtual force, $\mathbf{f}_{v_i}$ (1c), is designed so that each trainee's motion can follow the position command of the trainer. The desired objective is $\mathbf{f}_{v_i} \to 0$ as $\mathbf{e}_{m_i} \to 0$, so the impedance characteristics of the virtual force are set to be moderate. If $\mathbf{f}_{v_i}$ equals 0 is achieved, equations (1a) and (1b) have the same expressions and goal, so the parameters of (1a) and (1b) are adjusted to be the same. To be more specific, a well-trained trainee will perfectly follow the trainer's position commands which means $\mathbf{f}_{v_i}$ will be 0 so that the trainee can perceive the same force feedback as the trainer perceived. In other words, the virtual force $\mathbf{f}_{v_i}$ can be treated as an evaluation indicator of the trainee's skill level. Both high and low $\mathbf{f}_{v_i}$ mean the trainee is unskilled and provides the trainee with a clue to change his/her position. Therefore, firstly, ξ_{m_i} is chosen to be 0.7 to get a fast behaviour in response to the harmonic force of the human operator. Secondly, to filter out the high frequency of the slave-heart interaction force and achieve $(\mathbf{f}_{h_i} - k_{\mathrm{f}}\mathbf{f}_e^L) \to 0$, the natural frequencies of (1a) and (1b) ($\omega_{n_{m_1}}$ and $\omega_{n_{m_i}}$) should be several times smaller than the rate of the heart motion ($\omega_{n_{m_1}} = \omega_{n_{m_i}} \ll \omega_h$) and the stiffnesses of models (1a) and (1b) (K_{m_i}) are chosen small.

The goal of the slave impedance model (2) is to make the slave robot comply with the beating heart's motion during the contact procedure. Based on (2), the deviation from the scaled master trajectory ($\tilde{\mathbf{x}}_{ref_s} = \mathbf{x}_{ref_s} - k_\mathrm{p}\mathbf{x}_m$) provides the flexibility of the slave robot. As for the training scenario, only the trainer has authority over the surgical task, the position commands transmitted to the slave robot, $\mathbf{x}_m$, is $\mathbf{x}_{m_1}$. Note that the flexibility of the slave robot can neither be too small nor too large. If the slave robot is too flexible, it cannot apply enough forces on the heart surface to perform tasks. If the slave robot is too rigid, the motion compensation cannot be achieved. Therefore, the stiffness of the slave impedance model (K_s) should be adjusted to be moderate. Also, the natural frequency of (2) (ω_{n_s}) should be several times greater than the rate of the heart motion ($\omega_{n_s} \gg \omega_h$). Here, ξ_{s_i} is chosen to be 0.7.

2) Task cooperation

For task cooperation, both trainer and trainee have authority over the surgical task. The goal is that all operators can feel the same non-oscillatory force feedback, but they can provide different position commands to the slave robot. The position transmitted to the slave robot is the weighted sum of every operator's position. The only difference between training and cooperation is that the virtual force for cooperation is set to be zero; that is, β is equal to 0. The rest parameters of models (1a), (1b) and (2) are selected the same as those for the training scenario. Table 3 summarizes the parameter adjustments guidelines for the reference impedance models.

Table 3. Parameter adjustments for the reference impedance models

Scenarios	Objectives & Adjusted Parameters			
	Master site		Slave site	
Scenario 1: Fundamental training	Objectives	Position guidance for the trainees	Objectives	$\mathbf{x}_m = \mathbf{x}_{m_1}$
	Parameters	• $\beta = 1$	Parameters	• $\alpha_1 = 1, \alpha_i = 0, (i = 2, \cdots, n)$
	Objectives	Non-oscillatory force feedback	Objectives	Motion compensation
	Parameters	• Small K_{m_i} to achieve $\mathbf{f}_{h_i} \to k_\mathrm{f}\mathbf{f}_e$ • Small $\omega_{n_{m_i}}$ ($\ll \omega_h$) to filter out the high-frequency portion of $\mathbf{f}_e$	Parameters	• Moderate K_s to exert appropriate force • Large ω_{n_s} ($\gg \omega_h$) to make the slave robot comply with the heart motion
Scenario 2: Skills assessment	Obtain dominance factor α_i such that $\sum_{i=1}^{n} \alpha_i = 1, \alpha_i \geq 0$			
Scenario 3: Task cooperation	Objectives	No position guidance for the trainees	Objectives	$\mathbf{x}_m = \alpha_1\mathbf{x}_{m_1} + \alpha_2\mathbf{x}_{m_2} + \cdots + \alpha_n\mathbf{x}_{m_n}$
	Parameters	• $\beta = 0$	Parameters	• $\sum_{i=1}^{n} \alpha_i = 1, \alpha_i \geq 0$
	Objectives	Non-oscillatory force feedback	Objectives	Motion compensation
	Parameters	• Small K_{m_i} to achieve $\mathbf{f}_{h_i} \to k_\mathrm{f}\mathbf{f}_e$ • Small $\omega_{n_{m_i}}$ ($\ll \omega_h$) to filter out the high-frequency portion of $\mathbf{f}_e$	Parameters	• Moderate K_s to exert appropriate force • Large ω_{n_s} ($\gg \omega_h$) to make the slave robot comply with the heart motion

C. Controllers

The dynamics of the master and slave robots in the Cartesian space can be expressed as

$$\mathbf{M}_{\mathbf{x},m}(\boldsymbol{\theta}_m)\ddot{\mathbf{x}}_m + \mathbf{C}_{\mathbf{x},m}(\boldsymbol{\theta}_m,\dot{\boldsymbol{\theta}}_m)\dot{\mathbf{x}}_m + \mathbf{G}_{\mathbf{x},m}(\boldsymbol{\theta}_m) + \mathbf{F}_{\mathbf{x},m}(\dot{\boldsymbol{\theta}}_m) = \mathbf{f}_m + \mathbf{f}_h \tag{3}$$

$$\mathbf{M}_{\mathbf{x},s}(\boldsymbol{\theta}_s)\ddot{\mathbf{x}}_s + \mathbf{C}_{\mathbf{x},s}(\boldsymbol{\theta}_s,\dot{\boldsymbol{\theta}}_s)\dot{\mathbf{x}}_s + \mathbf{G}_{\mathbf{x},s}(\boldsymbol{\theta}_s) + \mathbf{F}_{\mathbf{x},s}(\dot{\boldsymbol{\theta}}_s) = \mathbf{f}_s - \mathbf{f}_e \tag{4}$$

Here $\boldsymbol{\theta}_i$ is the joint angle of the robot's end-effector, $\mathbf{f}_i$ is the control torque of the robot, and $\mathbf{M}_{\mathbf{x},i}(\boldsymbol{\theta}_i)$, $\mathbf{C}_{\mathbf{x},i}(\boldsymbol{\theta}_i,\dot{\boldsymbol{\theta}}_i)$, $\mathbf{G}_{\mathbf{x},i}(\boldsymbol{\theta}_i)$ and $\mathbf{F}_{\mathbf{x},i}(\dot{\boldsymbol{\theta}}_i)$ are the inertia matrix, the centrifugal and Coriolis term, the gravity term, and the friction torque, respectively. Note that $i = m$ for the master and $i = s$ for the slave.

To track the ideal responses of the reference impedance models for the master and slave robots, the proportional-integral-derivative (PID) controllers are employed for each master and slave robot. In the experiments, the parameters of PID controllers for the master robot 2 are $K_{\mathrm{p}_m} = 1000$, $K_{\mathrm{i}_m} = 200$, $K_{\mathrm{d}_m} = 1$. The PID controller parameters for the master robot 1 and the slave robot are $K_{\mathrm{p}_s} = 1000$, $K_{\mathrm{i}_s} = 0$, $K_{\mathrm{d}_s} = 20$.

V. Experiments

The experiments are conducted to evaluate the proposed multilateral impedance-based control method for surgical training and cooperation. Fig. 2 shows the experimental setup which consists of a Phantom Premium 1.5A robot

(Geomagic Inc., Wilmington, MA, USA) as the master robot 1 and two Quanser robots (Quanser Consulting Inc., Markham, ON, Canada) as the master robot 2 and the slave robot, separately. Two human operators are employed to implement training and cooperation tasks. The human operator manipulated the master robot 1 is treated as the trainer, and the other operator is treated as the trainee. The beating-heart is simulated by a custom-built mechanical cam whose end is attached a plastisol-based tissue to simulate the heart tissue. This heart simulator generates continuous heart motion signals with a fundamental frequency of 64 bpm to simulate the real-heart motion [34]. To measure the human operator-master robot interaction forces and the slave robot-heart tissue interaction force, a 50M31 force/torque sensor (JR3 Inc., Woodland, CA, USA) and an ATI Gamma Net force/torque sensor (ATI Industrial Automation, Inc., Apex, NC, USA) are attached to the end-effectors of the master robot 1 and 2, separately. Another ATI Gamma Net force/torque sensor (ATI Industrial Automation, Inc., Apex, NC, USA) is attached to the end-effector of the slave robot. For the sake of brevity, the experiments only present the motion along the *x*-axis to evaluate the feasibility of the proposed method. It is straightforward to extend the proposed method from one-degree-of-freedom (DOF) to multiple-DOF. The adjusted parameters of the reference impedance models in (1) and (2) are listed in Table 4.

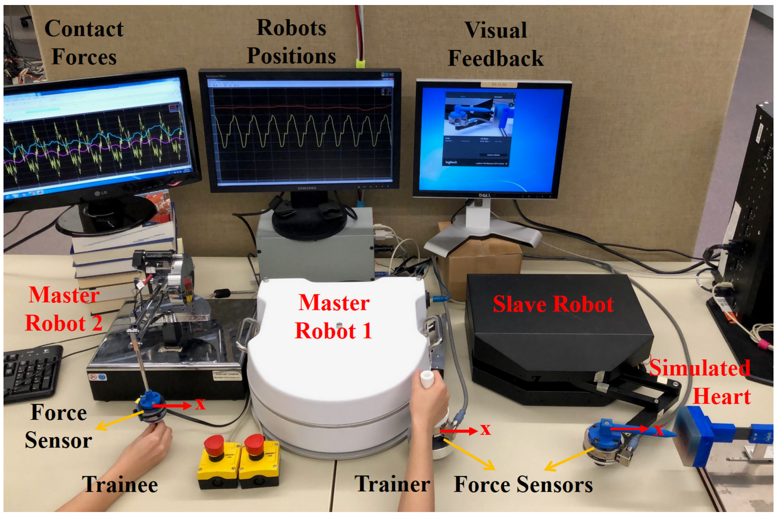

Fig. 2. Experimental setup.

Table 4. Parameters of the reference impedance models

Impedance Model (1a)	**Impedance Model (1b)**	**Impedance Model (1c)**	**Impedance Model (2)**
K_{m_1} = 10 N/m $\omega_{n_{m_1}}$ = 0.5 rad/sec ξ_{m_1} = 0.7 C_{m_1} = 28 Ns/m M_{m_1} = 40 kg k_f = 1	K_{m_2} = 10 N/m $\omega_{n_{m_2}}$ = 0.5 rad/sec ξ_{m_2} = 0.7 C_{m_2} = 28 Ns/m M_{m_2} = 40 kg	K_m^v = 30 N/m C_m^v = 0.1 Ns/m	K_s = 160 N/m ω_{n_s} = 20 rad/sec ξ_s = 0.7 C_s = 11.2 Ns/m M_s = 0.4 kg k_p = 1

A. Training Results

The experiments include two scenarios: surgical training and task cooperation. In the surgical training scenario, three groups of the experiments which consist of two unskilled-trainee cases and one skillful-trainee case are simulated. For all these experiments, only the trainer has authority over the slave robot. Based on the description in IV-B, the force feedback perceived by the trainee will change according to different cases. Only when the trainee follows the trainer's position commands perfectly, the trainee can perceive the same force feedback as the trainer perceived, which means the trainee is well trained.

The first unskilled-trainee case requires the trainee to keep the master robot 2 at the original point. Fig. 3 shows the positions and contact forces of the master and slave robots in this experiment. As can be seen in Fig. 3, the virtual force generated by a virtual fixture model, $\mathbf{f}_{v_2}$, stays negative due to the distance between the two master robots. This virtual force mainly leads the force perceived by the trainee to be lower than the trainer-master1 contact force. Also, due to the designed reference impedance models for the master and slave robots, the slave robot complies with the heart's motion perfectly and the forces perceived by the human operators are both non-oscillatory which is possible to increase the robot operability for human operators.

The second unskilled-trainee case requires the trainee to make the master robot 2 go farther than the trainer's robot (master robot 1). The experimental results are shown in Fig. 4. In this experiment, $\mathbf{f}_{v2}$ keeps positive which mainly leads the force perceived by the trainee to be higher than the trainer-master1 contact force. To simulate a skillful performance for the trainee, the trainee is asked to follow the position of the trainer, and Fig. 5 shows the results. In Fig. 5, the virtual force is almost 0 due to the trainer's perfect position tracking. Therefore, the trainee-master2 contact force is almost the same as the trainer-master1 contact force. The above three training cases show that the advantage of the virtual fixture guidance force is to provide a position clue to the trainee when his/her position goes too far away from the trainer's position.

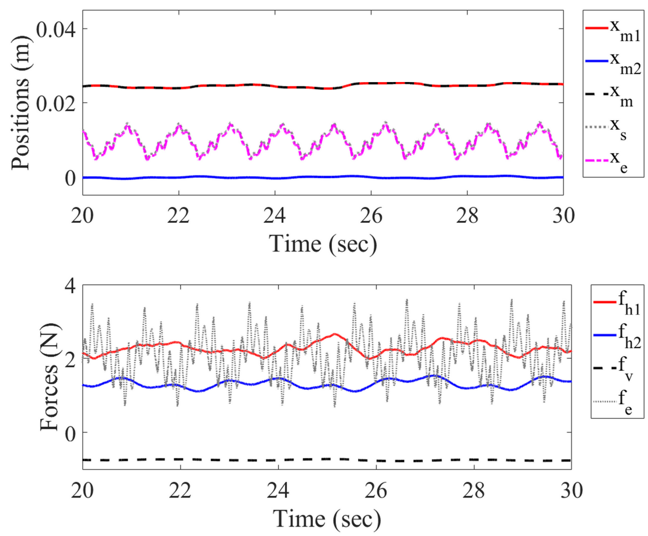

Fig. 3. Training Results of the first unskilled-trainee case.

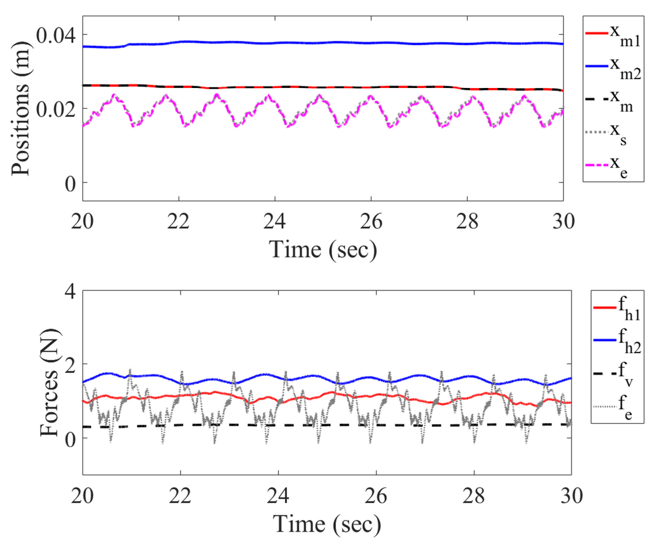

Fig. 4. Training Results of the second unskilled-trainee case.

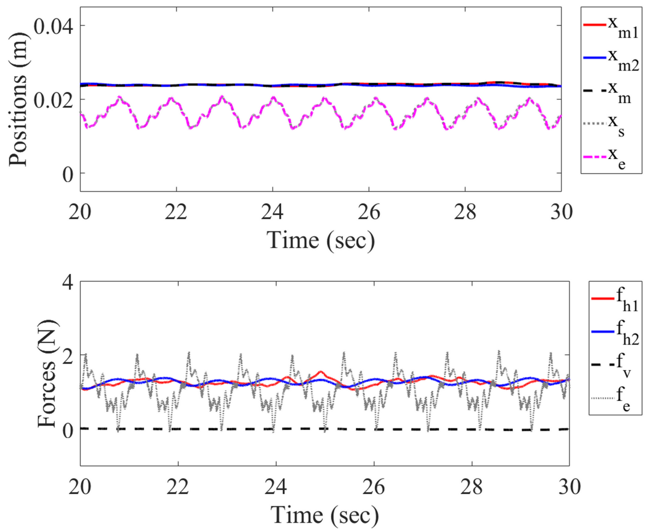

Fig. 5. Training Results of the skillful-trainee case.

B. Cooperation results

To investigate the behavior of the system with different dominance factor, the experiments are divided into two groups to be conducted. For the experiment in each group, three phases are included. In phase I, only the master robot 1 moves and the master robot 2 is kept at the original point. In phase II, only the master robot 2 moves and the master robot 1 is kept at the original point. In phase III, both master robot 1 and 2 move cooperatively, and they are asked to take the same path. In the experiments, the task is to move in both free motion and contact motion interaction with the simulated beating-heart tissue.

Fig. 6 shows the results of the experiment in the first group. The dominance factors are set as $\alpha_1 = \alpha_2 = 0.5$, which means the two human operators have the same level of authority over the slave robot. When the slave robot moves in free motion, it simply tracks the weighted sum of the two master robots' positions, x_m. While when the slave robot contacts the beating-heart tissue, it begins to comply with the heart's motion. Additionally, in Fig. 6, the human-master robot contact forces are relatively steady compared to the oscillatory slave-heart contact force. Note that, in phase I and phase II, the two human-master robot contact forces are not close to each other with the differences caused by the reference impedance models for the two master robots (1a) and (1b). The distances between the two master robots lead to the differences between the left sides of (1a) and (1b). These differences can be reduced by decreasing the parameters of models (1a) and (1b). In this paper, however, considering the limitation of the robots, the adjusted parameters in Table 4 are the optimal values. In phase III, as the two master robots have almost the same positions, the left sides of (1a) and (1b) are basically the same. Therefore, the two human-master robot contact forces are basically the same.

The experiment in the second group is conducted with dominance factors of $\alpha_1 = 0.3$ and $\alpha_2 = 0.7$. The positions and forces results are presented in Fig. 7. In this experiment, the master robot 2 has more authority over the slave robot than the master robot 1. Therefore, in phase I, the master robot 1 must go much farther than the distance went by the master robot 2 in phase II to make the slave robot contact with the beating-heart tissue. In phase III, the position commands transmitted from the master robots to the slave robot, x_m, are the same as the two master robots' positions. This performance is the same as that shown in phase III of Fig. 6 although the dominance factors are different. It is concluded that as long as the positions of the two master robots are the same (phase III), x_m will be the same as the two master robots' positions regardless of the skills levels of the operators.

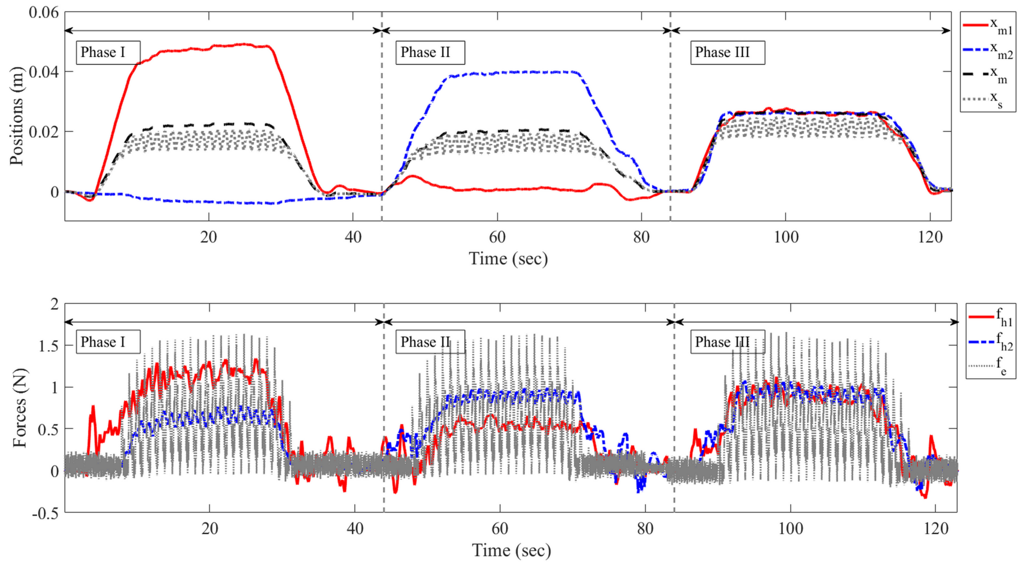

Fig. 6. Cooperation results of the experiment in the first group with dominance factors of $\alpha_1 = \alpha_2 = 0.5$.

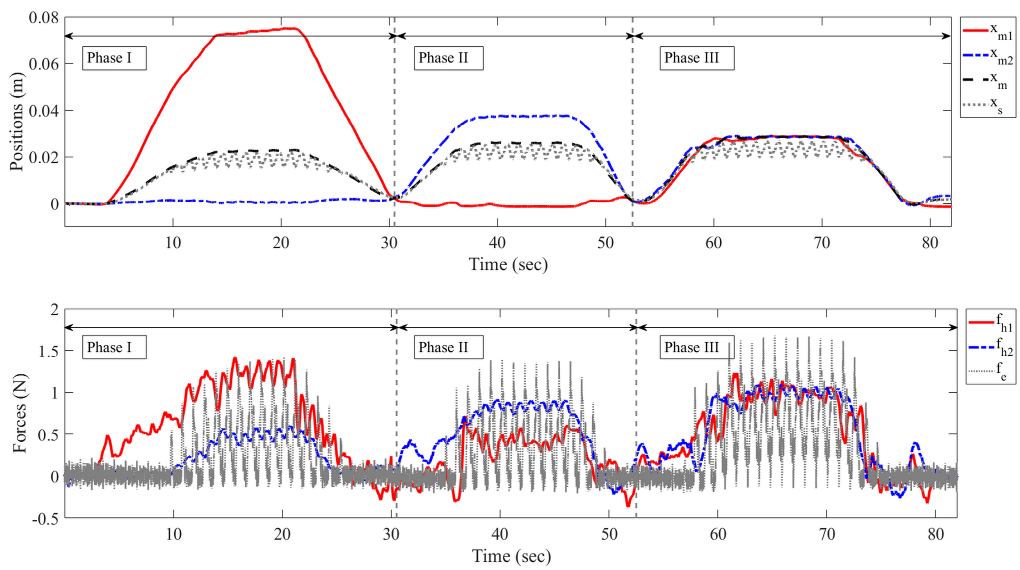

Fig. 7. Cooperation results of the experiment in the second group with dominance factors of $\alpha_1 = 0.3$ and $\alpha_2 = 0.7$.

VI. Conclusion

A multilateral impedance-controlled telerobotic system is proposed for surgical training and cooperation in beating-heart surgery. This system not only enables motion compensation and non-oscillatory haptic feedback but is also suitable for surgical training and task cooperation for multiple human operators simultaneously. By designing the reference impedance model with adjusted parameters for each master or slave robot, motion compensation and non-oscillatory haptic feedback in beating-heart surgery are achieved. In a training procedure, the virtual fixture guidance force provides each trainee with a position clue when his/her position goes too far away from the trainer's position, so that position and force tracking can be realized. The trainees can perceive full non-oscillatory force feedback and implement cooperative tasks. Difference dominance factors are set for the two human operators, and the experimental results demonstrated that the proposed method could be used for surgical training and cooperation in beating-heart surgery perfectly. Future work will involve exploring the method's potential uses in real surgical robots, i.e., da Vinci surgical systems.

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**Lingbo Cheng** received her B.Sc. and M.Sc. degrees in Vehicle Engineering and Safety Engineering from Beijing Institute of Technology, Beijing, China, in 2012 and 2014, respectively. She is currently pursuing a Ph.D. in Electrical and Computer Engineering at the University of Alberta. Her research interests are in force feedback for image-guided robot-assisted surgery.

**Mahdi Tavakoli** is a Professor in the Department of Electrical and Computer Engineering, University of Alberta, Canada. He received his BSc and MSc degrees in Electrical Engineering from Ferdowsi University and K.N. Toosi University, Iran, in 1996 and 1999, respectively. He received his PhD degree in Electrical and Computer Engineering from the University of Western Ontario, Canada, in 2005. In 2006, he was a post-doctoral researcher at Canadian Surgical Technologies and Advanced Robotics (CSTAR), Canada. In 2007-2008, he was an NSERC Post-Doctoral Fellow at Harvard University, USA. Dr. Tavakoli's research interests broadly involve the areas of robotics and systems control. Specifically, his research focuses on haptics and teleoperation control, medical robotics, and image-guided surgery. Dr. Tavakoli is the lead author of Haptics for Teleoperated Surgical Robotic Systems (World Scientific, 2008).