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Beating-heart robotic surgery using bilateral impedance control: Theory and experiments

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ABSTRACT

A bilateral impedance controller is presented to enable robot-assisted surgery of a beating heart. For this purpose, two desired impedance models are designed and realized for the master and slave robots interacting with the operator (surgeon) and the environment (heart tissue), respectively. The impedance models are designed such that (a) the slave robot complies with the oscillatory motion of the beating heart and (b) the surgeon perceives the non-oscillatory portion of the slave/heart contact force at the master robot implying arrested-heart surgery. These performance goals are achieved via appropriate adjustment of the impedance model parameters without any measurement or estimation of heart motion. Two nonlinear robust adaptive controllers are proposed for the master and slave robots to track their corresponding desired impedance responses in the Cartesian space. The stability, tracking convergence and the robustness against parametric and non-parametric modeling uncertainties are proven using the Lyapunov theorem and based on two types of adaptation laws. The stability of impedance models and nonlinear tele-operation system can enhance the patient's safety during the robotic surgery. Experimental results show that the proposed controller compensates for the beating motion and provides smooth force feedback to the surgeon.

1. Introduction

In recent years, teleoperation systems have been employed in biomedical applications such as minimally invasive robotic surgery [1], tele-rehabilitation [2–4] and tele-sonography [5,6] systems. Teleoperation-based surgery of the heart as a moving organ is challenging due to its movement velocity and acceleration which are more than 210 mm/s and 3800 mm/s^2 at the mitral valve annulus, respectively [7].

Arresting the heart to perform the surgery has undesirable side effects such as increased stroke risk [8] and long-time cognitive decline [9]. If the heart is allowed to beat freely during the surgery, these side effects would be alleviated. Moreover, the normal beating motion of the heart during the surgery is helpful for physiologic *intraoperative* evaluation of reconstructive procedures on dynamic heart structures such as the mitral valve, which is not possible in the arrested-heart surgery. Beating-heart surgery can be facilitated via a master-slave teleoperation system in which the slave robot automatically complies with the heartbeat-induced motion of the heart while the surgeon operates through the master robot without needing to manually compensate for the heart's beating motion.

In the past decade, various control methods have been proposed for linear and nonlinear robotic teleoperation systems such as [10–14] for position and force tracking. However, they cannot be used in tele-surgery on a moving organ (e.g., the heart) which require a motion or force compensation strategy in addition to stable control laws.

Different strategies [15,16] have been suggested for prediction and autonomous compensation of organ motion for robotic interactions using Model Predictive Control (MPC) methods and vision systems. Bachta et al. [17] have presented a piezo-actuated compliant mechanism for active stabilization of the beating heart using the MPC and H_∞ controllers. Bebek and Cavusoglu have measured the heart's position using sonomicrometry crystals [18] and a flexible whisker-like sensor [19] in order to not deal with ultrasound images, which involve acquisition and processing delays, for heart's position measurement. Ataollahi et al. [20] have also presented a new cardioscopic tool for optical imaging and tissue removal inside the beating-heart.

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A Smith predictor [21] and Kalman filtering [22] were suggested recently to predict and compensate for the organ motion under delayed vision and ultrasound images, respectively. However, these visual based methods have some drawbacks such as a) requiring a vision and/or ultrasound imager to follow artificial or natural landmarks inside the heart tissue, b) during interactions with the surgical instrument, the heart's soft tissue deforms, which increases errors of the vision systems, and c) the processing of some vision data like the ultrasound images is time-consuming and generate considerable delays, which cause problems for the feedback control system.

Some other control strategies [1,23–25] have been presented that do not have the above-mentioned drawbacks of visual-based position-control methods. The iterative learning control [26] and active observer (AOB) based force control [27] methods using Kalman Filter are used to compensate for the organ motion. The MPC method was also used as a linear predictive force controller [28] and its compensation performance was compared with the AOB approach in [29]. After that, a cascade force controller [30] was presented as a combination of the MPC and AOB approaches to compensate for physiological disturbances. Also, a force-based position tracking system [31,32] was developed using a catheter robotic system and ultrasound observations of the previous motion cycles. Lastly, Hasanzadeh and Janabi-Sharifi [33] have employed a low-dimensional model for intracardiac catheters behavior in order to estimate the interaction force during heart surgeries. In the above force-based controllers, the convergence and robustness of the observations/estimation algorithm together with the stability of employed controller were not proved analytically. Moreover, the rate of disturbance observation, estimation or prediction should be considerably faster than the heart rate in the above methods.

In this paper, a novel bilateral impedance control method is proposed for robotic surgery on the beating heart using the measured interaction forces and without any requirement for heart motion prediction, observation and/or learning. In this method, a virtual impedance model is defined and realized for the slave robot such that it can comply with the physiological force and/or disturbance of the beating heart while tracking the master robot's trajectory. Moreover, the surgeon can sense the non-oscillatory part of the slave/heart interaction force (such that the beating heart feels like a stationary heart) via implementing another impedance model for the master robot. Accordingly, the surgeon fatigue decreases and he/she does not need to manually compensate for the high-frequency oscillatory force and motion of the beating heart. For these purposes, the structure and parameters of the master and slave impedance models are designed such that they have desired responses with respect to the surgeon and heart forces.

The master and slave impedance models, that provide two relationships between the interaction forces and desired trajectories, are stable. These impedance models are realized for the multi-DOF master and slave robots with nonlinear dynamics using a bilateral adaptive controller. The stability of nonlinear tele-robotic system together with the proposed bilateral adaptive controller is proven via the Lyapunov method. Two kinds of adaptation laws are defined and employed in this controller to provide robustness against parametric and non-parametric modeling uncertainties of the system.

Accordingly, based on (a) the stability of impedance models, and (b) the Lyapunov-based stability proof for the proposed nonlinear robotic tele-surgery system, the patient safety can be enhanced during interaction with the slave robot using the presented impedance-based control strategy. Note that the communication delays are not considered in this work because the master/surgeon and slave/patient are close to each other in the most of real robot-assisted surgeries performed in medical clinics/hospitals. However, communication delays can be taken into account in future works for possible surgery operations on the remote patients.

2. Nonlinear dynamics of a master-slave robotic surgery system

The nonlinear model of an n-DOF tele-robotic system (master and slave robots) with parametric (structured) and unstructured uncertainties is expressed in the joint space as (chapter 9 of [34]):

$$\begin{aligned}&\mathbf{M}_{\mathbf{q},\mathrm{m}}(\mathbf{q}_m)\ddot{\mathbf{q}}_m+\mathbf{C}_{\mathbf{q},\mathrm{m}}(\mathbf{q}_\mathrm{m},\dot{\mathbf{q}}_m)\dot{\mathbf{q}}_m+\mathbf{G}_{\boldsymbol{q},m}(\mathbf{q}_m)+\mathbf{F}_{\boldsymbol{q},m}(\dot{\mathbf{q}}_m)\\&\quad=\boldsymbol{\tau}_m+\boldsymbol{\tau}_{sur}+\mathbf{d}_{\mathbf{q},\mathrm{m}}\end{aligned}\tag{1}$$

$$\begin{aligned}&\mathbf{M}_{\mathbf{q},s}(\mathbf{q}_s)\ddot{\mathbf{q}}_s+\mathbf{C}_{\boldsymbol{q},s}(\mathbf{q}_s,\dot{\mathbf{q}}_s)\dot{\mathbf{q}}_s+\mathbf{G}_{\boldsymbol{q},s}(\mathbf{q}_s)+\mathbf{F}_{\mathbf{q},s}(\dot{\mathbf{q}}_s)\\&\quad=\boldsymbol{\tau}_s-\boldsymbol{\tau}_{env}+\mathbf{d}_{\boldsymbol{q},s}\end{aligned}\tag{2}$$

where $\mathbf{q}_m$ and $\mathbf{q}_s \in \mathbb{R}^{n\times 1}$ are the joint positions, $\mathbf{M}_{\mathbf{q},m}(\mathbf{q}_m)$ and $\mathbf{M}_{\mathbf{q},s}(\mathbf{q}_s) \in \mathbb{R}^{n\times n}$ are the inertia/mass matrices, $\mathbf{C}_{\mathbf{q},m}(\mathbf{q}_m,\dot{\mathbf{q}}_m)$ and $\mathbf{C}_{\mathbf{q},s}(\mathbf{q}_s,\dot{\mathbf{q}}_s) \in \mathbb{R}^{n\times n}$ include the centrifugal and Coriolis terms, $\mathbf{G}_{\mathbf{q},m}(\mathbf{q}_m)$ and $\mathbf{G}_{\mathbf{q},s}(\mathbf{q}_s) \in \mathbb{R}^{n\times 1}$ are the gravity terms, $\mathbf{F}_{\mathbf{q},m}(\dot{\mathbf{q}}_m)$ and $\mathbf{F}_{\mathbf{q},s}(\dot{\mathbf{q}}_s) \in \mathbb{R}^{n\times 1}$ are the friction torques, and $\boldsymbol{\tau}_m$ and $\boldsymbol{\tau}_s \in \mathbb{R}^{n\times 1}$ are the control torques (originated from the actuators) of the master and the slave robots, respectively. Also, $\boldsymbol{\tau}_{sur} \in \mathbb{R}^{n\times 1}$ is the torque that the surgeon (human operator) applies to the master robot and $\boldsymbol{\tau}_{env} \in \mathbb{R}^{n\times 1}$ is the torque that the slave robot applies to the environment (heart tissue). The vectors of bounded unstructured modeling uncertainties and/or bounded exogenous disturbances of the system are also denoted by $\mathbf{d}_{\mathbf{q},m}$ and $\mathbf{d}_{\mathbf{q},s}$ for the master and slave robots, respectively. Then, the robots' end-effector equations of motion in the Cartesian space are represented as:

$$\begin{aligned}&\mathbf{M}_{\boldsymbol{x},m}(\mathbf{q}_m)\ddot{\mathbf{x}}_m+\mathbf{C}_{\mathbf{x},m}(\mathbf{q}_m,\dot{\mathbf{q}}_m)\dot{\mathbf{x}}_m+\mathbf{G}_{\mathbf{x},m}(\mathbf{q}_m)+\mathbf{F}_{\mathbf{x},m}(\dot{\mathbf{q}}_m)\\&\quad=\mathbf{f}_m+\mathbf{f}_{sur}+\mathbf{d}_{\mathbf{x},m}\end{aligned}\tag{3}$$

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

where $\mathbf{x}_m$ and $\mathbf{x}_s \in \mathbb{R}^{6\times 1}$ are the Cartesian positions of the master and slave robots' end-effectors, respectively. $\mathbf{f}_m$ and $\mathbf{f}_s \in \mathbb{R}^{6\times 1}$ are the generalized actuator forces of the master and slave robots defined in the Cartesian space, respectively. $\mathbf{f}_{sur}$ and $\mathbf{f}_{env} \in \mathbb{R}^{6\times 1}$ are the interaction forces that the surgeon applies to the master robot and the environment (heart tissue) applies to the slave robot, which are measured by two force sensors attached to the master and slave end-effectors, respectively.

Assumption. It is assumed that the unstructured modeling uncertainties and/or disturbances are bounded and there exist positive constants δ_m and δ_s such that:

$$\|\mathbf{d}_{\mathbf{x},m}\|_\infty\le\delta_m,\quad\|\mathbf{d}_{\mathbf{x},s}\|_\infty\le\delta_s\tag{5}$$

Using the subscript $i=m$ for the master and $i=s$ for the slave, the matrices of dynamic models in the joint space (Eqs. (1) and (2)) and the Cartesian space (Eqs. (3) and (4)) are related via the non-singular Jacobian matrices $\mathbf{J}_i(\mathbf{q}_i)$ as:

$$\begin{aligned}&\mathbf{M}_{\mathbf{x},i}(\mathbf{q}_i)=\mathbf{J}_i^{-T}\mathbf{M}_{\mathbf{q},i}(\mathbf{q}_i)\mathbf{J}_i^{-1},\quad\mathbf{G}_{\mathbf{x},i}(\mathbf{q}_i)=\mathbf{J}_i^{-T}\mathbf{G}_{\mathbf{q},i}(\mathbf{q}_i)\\&\mathbf{C}_{\mathbf{x},i}(\mathbf{q}_i,\dot{\mathbf{q}}_i)=\mathbf{J}_i^{-T}\left(\mathbf{C}_{\mathbf{q},i}(\mathbf{q}_i,\dot{\mathbf{q}}_i)-\mathbf{M}_{\mathbf{q},i}(\mathbf{q}_i)\mathbf{J}_i^{-1}\dot{\mathbf{J}}_i\right)\mathbf{J}_i^{-1}\\&\mathbf{F}_{\mathbf{x},i}(\mathbf{q}_i)=\mathbf{J}_i^{-T}\mathbf{F}_{\mathbf{q},i}(\mathbf{q}_i)\ ,\quad\mathbf{d}_{\mathbf{x},i}=\mathbf{J}_i^{-T}\mathbf{d}_{\mathbf{q},i}\\&\mathbf{f}_i=\mathbf{J}_i^{-T}\boldsymbol{\tau}_i\ ,\quad\mathbf{f}_{sur}=\mathbf{J}_m^{-T}\boldsymbol{\tau}_{sur}\ ,\quad\mathbf{f}_{env}=\mathbf{J}_s^{-T}\boldsymbol{\tau}_{env}\end{aligned}\tag{6}$$

with the following properties [34–36]: