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Tele-echography of moving organs using an Impedance-controlled telerobotic system[☆]

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ABSTRACT

A novel impedance-controlled teleoperation system is developed for robot-assisted tele-echography of moving organs such as heart, chest and breast during their natural motions (beating and/or breathing). The procedure of devising the two impedance models for the master and slave robots is developed such that (a) the slave robot holding the ultrasound (US) probe follows the master trajectory but complies with the oscillatory interaction force of the moving organ, and (b) the sonographer receives feedback from the non-oscillatory portion of the slave-organ interaction force via the master robot similar to the haptic feedback received in echography of a stationary organ. These goals are achieved via appropriate parameter adjustment in the desired impedance models without requiring any direct measurement and/or online prediction of the organ's motions. The stability and tracking convergence of the teleoperation system in the presence of communication delays and modeling uncertainties are proven in a Lyapunov-based framework. The performance of the proposed tele-echography system is evaluated experimentally using a master-slave telerobotic system, a US imaging system and a mechanical moving-organ simulator.

1. Introduction

In recent years, remote diagnosis and health monitoring has drawn great attention due to the practical challenges associated with delivering health services to remote areas. Accordingly, telerobotic systems have been developed for different biomedical applications such as tele-surgery [1,2], tele-rehabilitation [3,4] and tele-echography [5,6]. In a telerobotic system, the human operator applies forces to the master robot at the local site in order to control the position of the slave robot at the remote site which tracks the master robot's trajectory.

So far, some robot-assisted US imaging systems (e.g., [7,8]) have been proposed for scanning the stationary tissues. In [9,10], a force-based control strategy was employed for the robot to provide a specified interaction force between the US probe and the tissue while maintaining the contact. The telerobotic systems [5,6,11–18] have also been employed to perform remote ultrasound imaging using a slave robot based on the online motion measurement of the sonographer's hand interacting with the master robot. In these systems, position tracking controllers were implemented sometimes with reflecting the tissue force [5,11,14–16,18] to the sonographer.

While the above-mentioned works have focused on stationary organs, the remote US imaging (tele-echography) of the moving tissues such as the human heart and/or chest with a telerobotic system has remained as one of the challenging and open issues in the field of medical robotics. The ultrasound imaging of the heart during its normal beating will be significantly useful in the beating-heart surgeries (such as catheter ablation and mitral valve repair) for online detection of the catheter and/or surgery instrument inside the heart. Moreover, the tele-echography of other moving tissues inside the chest (e.g., lung) or outside it (e.g., breast) during normal respiration is useful for the intraoperative evaluations.

Arresting the heart to perform a stationary surgery may have undesirable side effects due to the use of the heart–lung machine for the circulation of blood and the ventilation of lungs. Also, after this operation, the surgeon attempts to restart the heart which may cause irregular heartbeats. Some other disadvantages of the arrested heart surgery are increasing the stroke risk [19] and long-time cognitive decline [20]. On the other hand, physical interaction with the heart as a moving organ is challenging due to its

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beating velocity and acceleration that are more than 210 mm/sec and 3800 mm/sec^2, respectively [21]. Accordingly, in some surgeries such as catheter ablation and mitral valve repair, the heart is allowed to beat freely during the surgery operation to wipe out the mentioned risks and side effects.

However, during these beating-heart surgeries, the online monitoring of the catheter and/or the surgical instruments' position inside the heart is a vital requirement. A method for screening the position of an instrument inside a tissue would be online ultrasound imaging. Moreover, the imaging of moving organs such as the beating-heart and chest (during the normal breathing) is helpful and has important information for *intraoperative* evaluation of dynamic moving structures. This condition would be achieved via a telerobotic system in which a slave robot has a compliant interaction with the moving tissue, and the sonographer performs the US imaging via a master robot without the requirement of synchronizing with the oscillatory motions of the tissue.

In the past decade, some control methods have been proposed for linear and nonlinear telerobotic systems [22–26] with the purpose of position and force tracking; however, they cannot be used in the tele-echography of a moving organ (e.g. the heart) which requires a motion or force compensation strategy in addition to a stable bilateral teleoperation.

Some control strategies [27–31] have been suggested for the compensation of the heart's physiological motion and synchronization of the robot with the heart using visual information and the predictive algorithms. In [32], the robot was synchronized with the heart using a high speed camera detecting target points. The Model Predictive Control (MPC) method was employed in [27,29] to predict the heart motion (with a known constant heartbeat rate), and the Smith predictor and Kalman filter were suggested in [30] and [31], respectively. However, these position-based methods have some drawbacks such as: a) a vision device with artificial or natural landmarks inside the surgery environment is required, b) during the echography and/or surgery, the heart soft tissue deforms in physical interactions with the instrument that increases the error of the vision systems, c) the processing of some vision data is time-consuming and generate significant delays in addition to communication delays.

Some other control strategies [1,33,34] were presented based on the force data to overcome the above-mentioned disadvantages. In this context, the iterative learning control [35] and active observer (AOB) based force control [36] methods were used to compensate the physiological motion. The MPC method was also proposed as a linear predictive force controller [37] and its performance was compared with the AOB approach in [38]. Lastly, a cascade force controller [39] was presented via a combination of the MPC and AOB approaches to compensate physiological disturbances. Moreover, a force-based position tracking system [40,41] was developed to apply a constant force on the heart's mitral valve using a catheter robotic system.

It should be mentioned that none of the previous vision/position-based or the force-based controllers for the beating-heart interaction was used for the tele-echography. Also, these controllers used predictive and/or observer-based methods or a combination of them while the convergence and robustness as well as the stability were not proved analytically. Moreover, the rate of disturbance observation and/or prediction should be significantly faster than the heart beat rate which is challenging to achieve in practice.

In this paper, a novel impedance-controlled telerobotic system is proposed and tested for tele-echography (remote ultrasound imaging). For the first time, the robotic tele-echography is investigated for imaging of moving organs (e.g. beating-heart and chest). To this end, the proposed control method employs the measured robot-tissue interaction forces but does not require any prediction, observation and/or learning of the organ's motion. In this bilateral telerobotic system, a virtual impedance model is implemented for the slave robot in order to comply with the natural force and/or disturbance of the moving tissue during the tracking of the master robot's trajectory. Moreover, the sonographer senses the tissue interaction force through the haptic feedback by implementing another impedance model for the master robot end-effector. The master impedance model can be adjusted such that the non-oscillatory part of the tissue force is provided for the sonographer (similar to a stationary tissue), which is useful for the tele-echography of beating-heart that has high-frequency oscillatory interaction forces. Under this condition, the sonographer's fatigue will decrease as he does not feel the high-frequency haptic force of the moving tissue during the imaging operation.

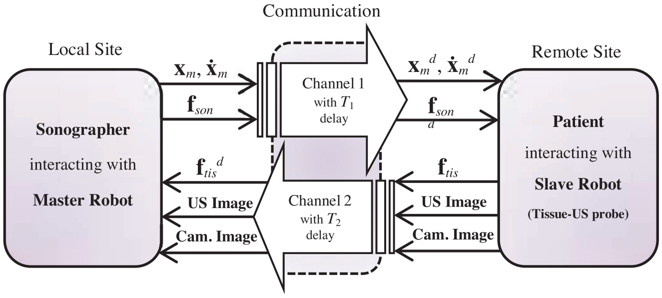

Fig. 1. The signals and imaging data transmitted via delayed communication channels.

For these purposes, the structure and parameters of the master and slave impedance models are designed appropriately such that they have desired responses with respect to the interaction forces of the sonographer and tissue. Also, the bounded time delays were taken into account in the communication channels between the local sonographer site and the remote patient site. The impedance models are realized on a multi-DOF master and slave robotic system with modeling uncertainties employing a new nonlinear bilateral adaptive controller. Using the Lyapunov stability theorem, the proposed telerobotic ultrasound imaging system is guaranteed to be stable and robust against communication delays and the modeling uncertainties..

2. Impedance-controlled telerobotic system with communication delays for tele-echography

2.1. Signals in delayed communication channels

The transmitted signals and imaging data with bounded time delays inside the communication channels are expressed in Fig. 1 for the presented robotic tele-echography system. As seen in this figure, the position $\mathbf{x}_m$, velocity $\dot{\mathbf{x}}_m$ and the sonographer-master interaction force $\mathbf{f}_{son}$ are transmitted from the local site to the remote slave-patient site via a communication channel with a time delay of T_1. On the other hand, the interaction force between the US probe (slave robot) and the moving tissue $\mathbf{f}_{tis}$ is transmitted back from the remote patient to the local sonographer. Also, the US data is transmitted from the US machine in the remote site to the sonographer. Moreover, the images of the patient's organ during the interaction with the US probe/slave robot are captured using a camera and provided online for the sonographer to perform the operation appropriately on the master robot. These signals and imaging data are transmitted from the remote to local site by the other communication channel that has a time delay of T_2.