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Cooperative modalities in robotic tele-rehabilitation using nonlinear bilateral impedance control

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ABSTRACT

A nonlinear model reference adaptive bilateral impedance controller is proposed that can accommodate various cooperative tele-rehabilitation modes for patient–therapist interaction using a multi-DOF tele-robotic system. In this controller, two reference impedance models are implemented for the master and slave robots using new model reference adaptive control laws for the nonlinear bilateral teleoperation system. "Hand-over-hand" and "adjustable-flexibility" are two modes of patient–therapist cooperation that are realized using the proposed strategy. The Lyapunov-based stability proof guarantees the patient's and the therapist's safety during the cooperation and interaction with robots, even in the presence of modeling uncertainties of the multi-DOF teleoperation system. The performance of the proposed bilateral impedance controller is experimentally investigated for upper-limb tele-rehabilitation in the two mentioned cooperation modes.

1. Introduction

Stroke, cerebral palsy, multiple sclerosis, and Parkinson's disease are some of age-related disorders that cause various forms of disability. The proposed robotics-assisted framework for tele-rehabilitation will be useful for any pathology that impairs motion of a body extremity and necessitates retraining of a function. While the framework proposed in this paper has a wide range of applications, without loss of generality, the discussion in the following focuses on the rehabilitation after stroke as a particular example of such disabilities.

Since the required intensive rehabilitation of patients with disabilities is costly, robotic systems have been developed to provide consistent and reproducible rehabilitation services (Blank, French, Pehlivan, & O'Malley, 2014; Gupta & O'Malley, 2006; Krebs & Hogan, 2012). Different robotic rehabilitation systems have been developed and tested in the past two decades involving only one robot manipulator interacting with the patient's limb (Gupta, O'Malley, Patoglu, & Burgar, 2008; Hogan, Krebs, Sharon, & Charnnarong, 1995; Krebs, Volpe, Williams, Celestino, Charles, Lynch, & Hogan, 2007; Riener, Nef, & Colombo). However, to perform rehabilitation tasks with live (online) cooperation or assistance of a therapist, a second robot is needed to capture the therapist's input. A bilateral teleoperation system can provide a tele-rehabilitation environment that allows the therapist and the patient to interact with each other for various movements and functional therapies.

The concept of tele-rehabilitation using robotic systems has been presented in Atashzar, Shahbazi, Tavakoli, and Patel (2015), Basdogan, Ho, Srinivasan, and Slater (2000), Carignan and Krebs (2006), Jadhav and Krovi (2004), Johnson, Loureiro, and Harwin (2008), Kim et al. (2004), Popescu, Burdea, Bouzit, and Hentz (2000), Reinkensmeyer, Pang, Nessler, and Painter (2002), Shahbazi, Atashzar, Tavakoli, and Patel (2015) and Tao (2014). The unilateral (Jadhav & Krovi, 2004; Reinkensmeyer et al., 2002) and bilateral (Basdogan et al., 2000; Carignan & Olsson, 2004; Kim et al., 2004) systems for tele-rehabilitation rely on a shared virtual environment (SVE) visible to both the patient and the therapist. Most of these strategies (Basdogan et al., 2000; Jadhav & Krovi, 2004; Kim et al., 2004; Reinkensmeyer et al., 2002) have used the two robots positions in the SVE. The interaction force has been also measured in Tao (2014), Carignan and Olsson (2004) to achieve the force reflecting performance in tele-rehabilitation besides the position tracking performance.

A new trilateral architecture has been suggested in Shahbazi, Atashzar, and Patel (2014) and Shahbazi, Atashzar, Tavakoli, and Patel (2016) for mirror therapy of the patient's impaired limb using the Guidance Virtual Fixtures (GVFs) concept and incorporating the patient's functional (healthy) limb. In this architecture, the therapist supervised the cooperation of impaired and functional limbs of the patient by generating some corrective movements (Shahbazi et al.,

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2016). Moreover, different multi-agent strategies have been recently studied in Sharifi, Talebi, and Motaharifar (2016) for training some trainees by the therapist during the tele-rehabilitation of a patient. Different position and force objectives have been presented in Sharifi et al. (2016) for multilateral (multi-master–slave) systems; however, the impedance adjustment was not studied. In the above-mentioned recent works (Shahbazi et al., 2014, 2016; Sharifi et al., 2016), the system uncertainty has not been taken into account, and a nonlinear stability analysis (such as Lyapunov method) has not be employed for the multi-DOF telerobotic system.

Various control methods have been suggested for single-DOF (linear) teleoperation systems (Colgate, 1993; Dongjun & Li, 2003; Lawrence, 1993; Polushin, Liu, Lung, & On, 2010). However, to perform complex and dexterous therapy exercises, multi-DOF (nonlinear) teleoperation systems are required. Accordingly, some adaptive bilateral control strategies have been proposed to synchronize the positions of nonlinear master and slave robots (Chopra, Spong, & Lozano, 2008; Liu & Chopra, 2013; Nuño, Ortega, & Basañez, 2010). Also, to achieve both position tracking and force tracking, nonlinear adaptive control methods (Ryu & Kwon, 2001) have been developed. The controllers presented in Ryu and Kwon (2001), Sharifi, Behzadipour, and Salarieh (2016), Liu and Tavakoli (2011) require the acceleration signals of the robots, and force tracking is achieved only when the estimates of unknown model parameters converge to the real values; this only happens in the presence of persistent excitations.

Using the impedance/admittance control theory (Abdossalami & Sirouspour, 2009; Hogan, 1985; Sharifi, Behzadipour, & Vossoughi, 2014b), interactive rehabilitation tasks were realized for interaction of a patient with a robot (Krebs et al., 2003; Krebs et al., 2007); such tasks cannot be performed well by pure position or force control. The impedance control context has been employed for one-DOF linear bilateral teleoperation systems (Cho & Park, 2005; Dubey, Tan Fung, & Everett, 1997; Hashtrudi-Zaad & Salcudean, 2001; Rubio, Avello, & Florez, 1999). An impedance/admittance model with a damping element for both master and slave robots was defined in Abbott and Okamura (2007). What is still missing is a bilateral impedance control framework for multi-DOF nonlinear teleoperation systems with corresponding nonlinear stability analysis, which is the focus of this paper, aimed at dexterous movements.

In the present work, a new nonlinear adaptive bilateral impedance controller is developed. While the control framework is applicable to general teleoperation systems, in this paper we focus on facilitating two specific modes of patient–therapist cooperation in robotic tele-rehabilitation (item 2 in the list below).

The proposed control framework has the following characteristics:

(1) The impedance of the teleoperation system is controlled by enforcing two desired impedance models for the master and slave robots, interacting with the therapist and the patient. This is unlike the previous nonlinear bilateral controllers (Hashemzadeh & Tavakoli, 2015; Liu & Tavakoli, 2011, 2012; Ryu & Kwon, 2001) that have position and force tracking control objectives. In the proposed control strategy, by adjustment of the impedance models, the patient and the therapist are not forced to have the same position as is the objective of traditional PEB (Position Error Based) (Polushin et al., 2010) and DFR (Direct Force Reflection) (Liu, Tao, & Tavakoli, 2014) control strategies for teleoperation systems.

(2) Two multi-DOF robotic tele-rehabilitation strategies can be accommodated using the proposed bilateral impedance control framework. The cooperative “hand-over-hand” and “adjustable-flexibility” modes of patient–therapist interaction are achieved through appropriate selection of the two reference impedance models for the master and slave robots.

(3) Due to (a) the freedom provided for the patient and the therapist as a result of adjusting the impedance models, (b) the stability of these impedance models, and (c) the Lyapunov-based stability of the entire multi-DOF nonlinear tele-rehabilitation system in the presence of modeling uncertainties, the patient and therapist safety is guaranteed. Patient safety is a critically important issue in robotic tele-rehabilitation (Carignan & Krebs, 2006). Note that the stability of the multi-DOF nonlinear telerobotic system was not proven in most of previous studies focusing on tele-rehabilitation applications (Jadhav & Krovi, 2004; Johnson et al., 2008; Popescu et al., 2000; Reinkensmeyer et al., 2002).

(4) The force and position scaling factors are defined in the proposed impedance models to adjust the haptic force feedback level and to account for possible workspace asymmetries between the master and slave robots. Employing the force scaling, the therapist can sense a scaled-down version of the patient force. Also, using the position scaling, the therapist motion trajectory can be scaled-up for the patient such that the slave robot motion become larger than the master one. As a result of this feature, the therapist fatigue reduces using the proposed robotic tele-rehabilitation strategy in comparison with the direct physical interaction of the patient and the therapist (without employing robots).

(5) The proposed bilateral controller is robust against modeling uncertainties in the nonlinear teleoperation system using two adaptation laws for the master and the slave control systems. In addition, unlike the previous nonlinear bilateral adaptive controllers (such as Ryu and Kwon (2001), Liu and Tavakoli (2011), Liu and Tavakoli (2012)) in which force tracking was achieved only when the estimation of model parameters converged to the real values (persistent excitation condition), the position and force tracking can be obtained simultaneously in the current framework without any requirement on the precise identification of system parameters.

(6) The design of proposed control laws for the master and the slave is motivated by a new nonlinear Model Reference Adaptive Impedance Control (MRAIC) scheme presented recently for physical human–robot interaction (involving a single robot but not a teleoperation system) (Sharifi et al., 2014b). Since in the MRAIC method, the closed-loop dynamics of the robot is made similar to the reference impedance model which is a stable system, the scheme in Sharifi et al. (2014b) is more effective than simple adaptive impedance controllers in realizing the impedance model for a nonlinear manipulator.

The aforementioned characteristics and applications of the proposed bilateral impedance controller are novel in the context of robotic tele-rehabilitation systems.

2. Multi-DOF robotic tele-rehabilitation system

The nonlinear dynamics of an n-DOF tele-rehabilitation system (including the master and slave robot manipulators) is introduced in the joint space as Slotine and Li (1991):

$$\mathbf{M}_{\mathbf{q},m}(\mathbf{q}_m)\ddot{\mathbf{q}}_m + \mathbf{C}_{\mathbf{q},m}(\mathbf{q}_m, \dot{\mathbf{q}}_m)\dot{\mathbf{q}}_m + \mathbf{G}_{\mathbf{q},m}(\mathbf{q}_m) + \mathbf{F}_{\mathbf{q},m}(\dot{\mathbf{q}}_m) = \boldsymbol{\tau}_m + \boldsymbol{\tau}_{th} \quad (1)$$

$$\mathbf{M}_{\mathbf{q},s}(\mathbf{q}_s)\ddot{\mathbf{q}}_s + \mathbf{C}_{\mathbf{q},s}(\mathbf{q}_s, \dot{\mathbf{q}}_s)\dot{\mathbf{q}}_s + \mathbf{G}_{\mathbf{q},s}(\mathbf{q}_s) + \mathbf{F}_{\mathbf{q},s}(\dot{\mathbf{q}}_s) = \boldsymbol{\tau}_s - \boldsymbol{\tau}_{pa} \quad (2)$$

where $\mathbf{q}_m$ and $\mathbf{q}_s \in \mathbb{R}^{n\times 1}$ are the joint position vectors, $\mathbf{M}_{\mathbf{q},m}(\mathbf{q}_m)$ and $\mathbf{M}_{\mathbf{q},s}\left(\mathbf{q}_s\right) \in \mathbb{R}^{n\times n}$ are the inertia or mass matrices, $\mathbf{C}_{\mathbf{q},m}\left(\mathbf{q}_m, \dot{\mathbf{q}}_m\right)$ and $\mathbf{C}_{\mathbf{q},s}\left(\mathbf{q}_s, \dot{\mathbf{q}}_s\right) \in \mathbb{R}^{n\times n}$ include the centrifugal and Coriolis terms, $\mathbf{G}_{\mathbf{q},m}\left(\mathbf{q}_m\right)$ and $\mathbf{G}_{\mathbf{q},s}\left(\mathbf{q}_s\right) \in \mathbb{R}^{n\times 1}$ are the gravity terms, $\mathbf{F}_{\mathbf{q},m}\left(\dot{\mathbf{q}}_m\right)$ and $\mathbf{F}_{\mathbf{q},s}\left(\dot{\mathbf{q}}_s\right) \in \mathbb{R}^{n\times 1}$ are the friction torques, and $\boldsymbol{\tau}_m$ and $\boldsymbol{\tau}_s \in \mathbb{R}^{n\times 1}$ are the vectors of the control torques (from the joint actuators) of the master and the slave robots, respectively. Also, $\boldsymbol{\tau}_{th}$ and $\boldsymbol{\tau}_{pa} \in \mathbb{R}^{n\times 1}$ are the interaction torques that the therapist applies to the master robot and the slave robot applies to the patient, respectively. Then, the robots' end-effector dynamics in the Cartesian space is defined as:

$$\mathbf{M}_{\mathbf{x},m}\left(\mathbf{q}_m\right)\ddot{\mathbf{x}}_m + \mathbf{C}_{\mathbf{x},m}\left(\mathbf{q}_m, \dot{\mathbf{q}}_m\right)\dot{\mathbf{x}}_m + \mathbf{G}_{\mathbf{x},m}\left(\mathbf{q}_m\right) + \mathbf{F}_{\mathbf{x},m}\left(\dot{\mathbf{q}}_m\right) = \mathbf{f}_m + \mathbf{f}_{th} \quad (3)$$

$$\mathbf{M}_{\mathbf{x},s}\left(\mathbf{q}_s\right)\ddot{\mathbf{x}}_s + \mathbf{C}_{\mathbf{x},s}\left(\mathbf{q}_s, \dot{\mathbf{q}}_s\right)\dot{\mathbf{x}}_s + \mathbf{G}_{\mathbf{x},s}\left(\mathbf{q}_s\right) + \mathbf{F}_{\mathbf{x},s}\left(\dot{\mathbf{q}}_s\right) = \mathbf{f}_s - \mathbf{f}_{pa} \quad (4)$$

where $\mathbf{x}_m$ and $\mathbf{x}_s \in \mathbb{R}^{6\times 1}$ are the position vectors of master and slave robots' end-effectors, respectively, in the Cartesian coordinates. $\mathbf{f}_{th}$ and $\mathbf{f}_{pa} \in \mathbb{R}^{6\times 1}$ are the interaction forces that the therapist applies to the master end-effectors and the slave end-effector applies to the patient,