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Brief paper

Iterative learning impedance control for rehabilitation robots driven by series elastic actuators[☆]

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ABSTRACT

Existing control techniques for rehabilitation robots commonly ignore robot dynamics by assuming a perfect inner control loop or are limited to rigid-joint robots. The dynamic stability of compliantly-actuated rehabilitation robots, consisting of the dynamics of both robot and compliant actuator, is not theoretically grounded. This paper presents an iterative learning impedance controller for rehabilitation robots driven by series elastic actuators (SEAs), where the control objective is specified as a desired impedance model. The desired impedance model is achieved in an iterative manner, which suits the repeating nature of patients' task through therapeutic process and also guarantees the transient performance of robot. The stability of the overall system is rigorously proved with Lyapunov methods by taking into account both the robot and actuator dynamics. Experimental results are presented to illustrate the performance of the proposed iterative control scheme.

1. Introduction

Stroke has become one of the leading causes of adult disability with the growing aging population in developed countries. Rehabilitation through physical therapy is the main treatment for such patients to regain maximum function (Hallett, 1999), and it has been shown that repeated and concurrent happening of human intentions to move is the key to recovery (Jenkins & Merzenich, 1987). The conventional manually assisted training is labor-intensive and physically demanding (Krebs, Hogan, Aisen, & Volpe, 1998). This motivates the development of rehabilitation robots, which have the advantages of low labor intensity and high repetition. Various rehabilitation robots have been developed over these years, including the Lower Extremity Powered Exoskeleton (LOPES) for gait rehabilitation (Veneman, Kruidhof, Hekman, Ekkelenkamp, Van Asseldonk, & Van Der Kooij, 2007), the treadmill-based exoskeleton (Lokomat) (Colombo, Joerg, Schreier, & Dietz, 2000) and the assistive device (EXPOS) (Kong & Jeon, 2006) for lower-limb rehabilitation, the finger rehabilitation robot (Agarwal, Fox, Yun, O'Malley, & Deshpande, 2015), and also the upper-limb rehabilitation robot (Li, Pan, Chen, & Yu, 2017b). Using series elastic actuators (SEAs) (Pratt & Williamson, 1995) is a popular solution and has become a mainstream in rehabilitation robots (Agarwal et al., 2015; Li et al., 2017b; Veneman et al., 2007), because of its several attractive features such as high force control accuracy, low output impedance, and tolerance to shocks (Paine, Oh, & Sentis, 2014).

While the use of SEA makes the hardware relatively safe, a safe control strategy is also required for the software of rehabilitation robots. Several robotic control strategies have been reported in the literature to realize the paradigm of "Assist-As-Need (AAN)" for rehabilitation (Duschau-Wicke, Zitzewitz, Caprez, Lunenburger, & Riener, 2000; Veneman et al., 2007). That is, the robot supplies the appropriate assistive force that a patient needs to accomplish tasks by assessing the performance of patients in real-time. These results commonly ignore the robot dynamics, by assuming a perfect inner control loop. Therefore, the stability of the closed-loop system is not theoretically grounded. In parallel, a class of control schemes (Hogan, 1985), known as impedance control, has been proposed for interaction control of different robotic systems (Albu-Schaffer, Ott, & Hirzinger, 2007; Cheah & Wang, 1998), which regulates a dynamic relationship between the desired trajectory and the interaction force and thus guarantees the stability of the closed-loop system. Among them, the iterative learning impedance controllers (Cheah & Wang, 1998) were proposed to achieve the

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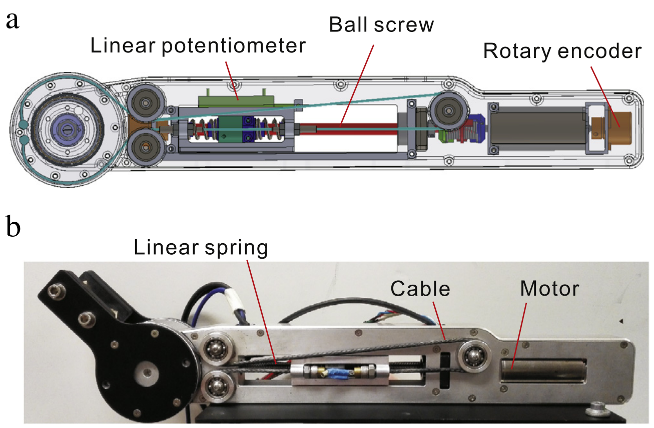

Fig. 1. Mechanical structure of SEA: (a) Principle of the actuator design (CAD model); (b) Prototype.

desired impedance model as actions are repeated, but they are applicable to rigid-joint robots without the coupling dynamics between robot and actuator. The iterative control explores and utilizes the information contained in repetitive actions, which is capable of achieving better transient tracking performance and attenuating repetitive disturbance (Arimoto, Kawamura, & Miyazaki, 1984). The iterative learning controller was proposed for rehabilitation robots in Freeman, Rogers, Hughes, Burridge, and Meadmore (2012), with the integration of functional electrical stimulation (FES) and robotics, but it does not consider the robot dynamics either.

In general, a rehabilitation robot driven by SEAs can be modeled as a high-order system (Petit, Dietrich, & Albu-Schaffer, 2015) consisting of both the rigid-link subsystem and the actuator subsystem. Finding a solution to stabilize both subsystems is not trivial. While several multi-modal controllers have been reported for SEA-driven robots in our previous works (Li, Pan, Chen, & Yu, 2017a; Li et al., 2017b), this paper considers the problem of iterative impedance control for rehabilitation robots. In particular, a desired impedance model (instead of stiffness only in Li et al. (2017a, 2017b)) is designed in the proposed controller such that more parameters can be specified (e.g. inertia, damping, stiffness) to suit stroked patients with different background during rehabilitation. The proposed controller also takes advantages of repetitive tasks through therapeutic process and iteratively achieves the desired impedance model with better transient performance. In addition, the proposed controller is able to stabilize both the rigid-link subsystem and the actuator subsystem, and the stability of the closed-loop system is rigorously proved with Lyapunov methods. Experimental results on the setup of an upper-limb rehabilitation robot are presented to demonstrate the performance of the proposed controller.

2. Background

2.1. Dynamic model of SEA-driven robot

A SEA is developed by placing an elastic element between motor and external load in the actuator (Pratt & Williamson, 1995). Fig. 1 illustrates a compact SEA (Li et al., 2017a), which is of high fidelity of force control, low output impedance, and large force range and bandwidth.

Consider a rehabilitation robot driven by SEAs. Let $\boldsymbol{q} \in \Re^{\bar{n}}$ denote the joint configurations, the dynamic model of SEA-driven rehabilitation robots can be described as (Albu-Schaffer et al., 2007; Li et al., 2017a; 2017b; Petit et al., 2015)

$$\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{C}(\boldsymbol{q}, \dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{g}(\boldsymbol{q}) = \boldsymbol{K}(\boldsymbol{\theta} - \boldsymbol{q}) + \boldsymbol{d}_r + \boldsymbol{\tau}_e, \quad (1)$$

$$\boldsymbol{B}\ddot{\boldsymbol{\theta}} + \boldsymbol{K}(\boldsymbol{\theta} - \boldsymbol{q}) = \boldsymbol{d}_a + \boldsymbol{\tau}, \quad (2)$$

where $\boldsymbol{\theta} \in \Re^{\bar{n}}$ is the vector of motor rotor shaft positions, $\boldsymbol{M}(\boldsymbol{q}) \in \Re^{\bar{n}\times\bar{n}}$, $\boldsymbol{C}(\boldsymbol{q}, \dot{\boldsymbol{q}})\dot{\boldsymbol{q}} \in \Re^{\bar{n}}$, and $\boldsymbol{g}(\boldsymbol{q}) \in \Re^{\bar{n}}$ denote the inertia matrix, the centripetal and Coriolis torque, and the gravitational torque of the robot respectively, $\boldsymbol{K} \in \Re^{\bar{n}\times\bar{n}}$ denotes the stiffness of the SEA, $\boldsymbol{\tau}_e \in \Re^{\bar{n}}$ represents the interaction torque, $\boldsymbol{B} \in \Re^{\bar{n}\times\bar{n}}$ is the inertia matrix of actuator, $\boldsymbol{\tau} \in \Re^{\bar{n}}$ denotes the input torque exerted on the actuator, and $\boldsymbol{d}_r, \boldsymbol{d}_a \in \Re^{\bar{n}}$ represent unmodeled disturbances at the rigid-link side and the actuator side respectively. Note that $\boldsymbol{\tau}_e = \boldsymbol{J}^T(\boldsymbol{q})\boldsymbol{f}_e$, where $\boldsymbol{f}_e \in \Re^{\bar{m}}$ denotes the interaction force between human and robot, and $\boldsymbol{J}(\boldsymbol{q}) \in \Re^{\bar{m}\times\bar{n}}$ is the Jacobian matrix from joint space to task space (e.g. Cartesian space).

It is assumed in this paper that the dynamic model is well defined or can be identified with sufficient accuracy such that $\boldsymbol{M}(\boldsymbol{q}), \boldsymbol{C}(\boldsymbol{q}, \dot{\boldsymbol{q}}), \boldsymbol{g}(\boldsymbol{q}), \boldsymbol{K}$ and $\boldsymbol{B}$ are known. Some important properties of the dynamic model include (Arimoto, 1996; Cheah & Li, 2015): (i) The matrices $\boldsymbol{M}(\boldsymbol{q}), \boldsymbol{C}(\boldsymbol{q}, \dot{\boldsymbol{q}})$, and $\boldsymbol{g}(\boldsymbol{q})$ are bounded; (ii) The matrix $\boldsymbol{M}(\boldsymbol{q})$ is symmetric and positive definite; (iii) The matrices $\boldsymbol{B}$ and $\boldsymbol{K}$ are diagonal and positive definite; (iv) The matrix $\dot{\boldsymbol{M}}(\boldsymbol{q}) - 2\boldsymbol{C}(\boldsymbol{q}, \dot{\boldsymbol{q}})$ is skew-symmetric.

2.2. Impedance control

The impedance control problem is formulated in terms of a reference trajectory and a desired dynamic relationship between the position error and the interaction force (Hogan, 1985). In this paper, the desired impedance model is defined in joint space as $\boldsymbol{M}_d(\ddot{\boldsymbol{q}} - \ddot{\boldsymbol{q}}_d) + \boldsymbol{C}_d(\dot{\boldsymbol{q}} - \dot{\boldsymbol{q}}_d) + \boldsymbol{K}_d(\boldsymbol{q} - \boldsymbol{q}_d) = \boldsymbol{\tau}_e$, where $\boldsymbol{q}_d \in \Re^{\bar{n}}$ is the vector of the desired joint angles which are time-varying, $\boldsymbol{M}_d, \boldsymbol{C}_d, \boldsymbol{K}_d \in \Re^{\bar{n}\times\bar{n}}$ denote the desired inertia, the desired damping, the desired stiffness matrices respectively, which are diagonal and positive definite. Note that the interaction torque $\boldsymbol{\tau}_e$ is taken into account in the desired impedance model, and hence the interaction force $\boldsymbol{f}_e$ is also considered in the subsequent development.

Let $\Delta\boldsymbol{q} = \boldsymbol{q} - \boldsymbol{q}_d$ represent the joint-space position error. Then, two matrices $\boldsymbol{\Gamma} \in \Re^{\bar{n}\times\bar{n}}$ and $\boldsymbol{\Lambda} \in \Re^{\bar{n}\times\bar{n}}$ and a vector $\boldsymbol{\tau}_l \in \Re^{\bar{n}}$ are defined as

$$\boldsymbol{\Lambda} + \boldsymbol{\Gamma} = \boldsymbol{M}_d^{-1}\boldsymbol{C}_d, \quad (3)$$

$$\boldsymbol{\Gamma}\boldsymbol{\Lambda} = \boldsymbol{M}_d^{-1}\boldsymbol{K}_d, \quad (4)$$

$$\dot{\boldsymbol{\tau}}_l + \boldsymbol{\Gamma}\boldsymbol{\tau}_l = \boldsymbol{M}_d^{-1}\boldsymbol{\tau}_e, \quad (5)$$

where both $\boldsymbol{\Lambda}$ and $\boldsymbol{\Gamma}$ are diagonal and positive definite. Eq. (5) describes a low-pass filter where $\boldsymbol{\tau}_e$ is the input signal and $\boldsymbol{\tau}_l$ is the output signal. Using (3)–(5), an augmented impedance error can be rewritten as

$$\begin{aligned}\bar{\boldsymbol{w}} &= \Delta\ddot{\boldsymbol{q}} + (\boldsymbol{\Lambda} + \boldsymbol{\Gamma})\Delta\dot{\boldsymbol{q}} + \boldsymbol{\Gamma}\boldsymbol{\Lambda}\Delta\boldsymbol{q} - \dot{\boldsymbol{\tau}}_l - \boldsymbol{\Gamma}\boldsymbol{\tau}_l \\ &= \dot{\boldsymbol{z}} + \boldsymbol{\Gamma}\boldsymbol{z}.\end{aligned} \quad (6)$$

where $\boldsymbol{z} = \Delta\dot{\boldsymbol{q}} + \boldsymbol{\Lambda}\Delta\boldsymbol{q} - \boldsymbol{\tau}_l$ is the impedance vector. It can be derived that the convergence of $\bar{\boldsymbol{w}} \to \boldsymbol{0}$ leads to the realization of the desired impedance model. From (6), the impedance vector $\boldsymbol{z}$ can be treated as the low-pass-filtered signal of $\bar{\boldsymbol{w}}$. In this paper, the control objective is formulated as $\boldsymbol{z} \to \boldsymbol{0}$, indicating the realization of the desired impedance model in the low-frequency range. This is reasonable for rehabilitation, as the frequency of patients' movement is usually low (e.g. $<$2 Hz). The formulation of $\boldsymbol{z} \to \boldsymbol{0}$ has been extensively used in Cheah and Wang (1998) and Wang and Cheah (1998), but those results are limited to rigid-joint robots. The overall SEA-driven robot, consisting of both the rigid-link subsystem and the actuator subsystem, is a high-order system, and finding a solution to stabilize both subsystems is not trivial, and neglecting the coupling dynamics is exposed to stability issues (Petit et al., 2015).