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Data-driven model-free adaptive sliding mode control for the multi degree-of-freedom robotic exoskeleton

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ABSTRACT

In this paper, a data-driven model-free adaptive sliding mode control (MFASMC) approach is proposed based on a novel transformation and linearization of the robotic exoskeleton dynamics and a discrete time sliding mode with exponential reaching law. The main feature of the approach is that the dynamics of the multi degree-of-freedom (DOF) robotic exoskeleton are transformed and linearized properly for MFASMC, the controller designing depends only on the measured input torque and output velocity of each joint of the exoskeleton and the sliding mode reaching law guarantees the convergence of MFASMC schemes. The proposed control strategy can maneuver the robotic exoskeleton tracking on its desired velocity tightly even when the dynamic parameter of the exoskeleton is time-varying irregularly and uncertainly. Extensive simulation experiments are conducted by a SimMechanics model of the robotic exoskeleton to illustrate the effectiveness of the proposed approaches.

1. Introduction

It has been proved that when the duration/intensity of conventional therapy (CT) is matched with that of robot-assisted therapy (RT), there is no difference between RT and CT groups in terms of motor recovery for the patients with stroke [21]. And robots deliver highly repetitive therapeutic tasks with minimal supervision of a therapist. Exoskeleton robots mentioned in this paper are designed to be worn to provide rehabilitation therapy for the stroke patients [13,15]. They all have a structure which resembles the human upper limb, **and have** robot joint axes that match the upper limb joint axes, so as to be worn expediently. The structure allows the exoskeleton to fully determine the upper limb posture and the controlled torques to be applied to each joint separately. It may be possible for exoskeletons to target specific muscles for training by generating a calculated combination of torques at certain joints [18].

Effective control strategies are necessary for the exoskeleton to operate coordinately with the human upper limb. Common strategies including position control and impedance control [2,7] are usually used in the control of manipulators. Many devices have reduced the negative effects of gravitational and frictional forces with gravity and friction compensation controllers [19,26,27]. Recently, researchers have begun to use more advanced control methods. The nonlinear computed torque control [23] is based on the dynamic model with position and velocity errors. The sliding PD control [3] guarantees the properties of convergence of error, limiting minimum time and maximum forces generated by the impedance control. The force-position control [22] is based on the users input force signal and a non-linear sliding mode control with exponential reaching law. The adaptive

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learning control [24] incorporating learning control approaches learns the impedance parameters of both robot and human. A model referenced adaptive impedance device has been used in the human–machine interaction force control [29]. The adaptive robust control [13] uses an adaptive observer to estimate the dynamic parameters. Fuzzy approximation-based adaptive backstepping control [16] makes it possible for human forearm to track any continuous desired trajectory in the presence of parametric/functional uncertainties, unmodeled dynamics, actuator dynamics, and/or disturbances from environments. In the control scheme, adaptive fuzzy approximators are used to estimate the dynamical uncertainties and an iterative learning scheme is utilized to compensate for unknown time-varying periodic disturbances.

As mentioned above, most of the control methods are model-based. The dynamic model of the exoskeleton has been already known before the controller design or the model structure is known and parameters can be estimated. That paves the way for more and more complicated controllers. Since the exoskeleton would be interacted with human upper limb, the interacting model is time-varying irregularly and uncertainly; the model based controller cannot be able to deal with these conditions.

The model-based schemes require a priori physical and mathematical knowledge of the process. As the development of modern industry has raised the model complexity of plants and computing burdens of conventional solutions, the data-driven schemes serve as an efficient alternative way, through which the necessary process information can be extracted directly from huge amounts of the recorded process data [30].

Data-driven control [12] means that the controller designing depends only on the input/output (I/O) measurement data of the controlled plant, without any explicitly using the system model, but it could be designed by using implicit information of the system dynamics or system structure. The PID related methods can be regarded as the earliest and the most successful long-lasting industrial application based on the process data. The core of data-based techniques is to take full advantages of the huge amounts of available process data, aiming to acquire the useful information within [32]. A data-based state feedback control method [28] has been developed for a class of nonlinear systems. It requires little prior knowledge about the system dynamics, and does not need to know or to build the mathematical model of the system. The multivariate statistical analysis methods, which utilize input and output information of the process, are very popular nowadays for the purpose of process monitoring and fault diagnosis. Based on principal component analysis (PCA), fuzzy positivistic C-means clustering [31] has been used on fault detection and isolation for vehicle suspension systems. The improved partial least squares (IPLS) [33] approach is presented to decompose the measurable process variables into the KPI-related and unrelated parts, respectively. In addition to the industry process monitoring and fault diagnosis, the data driven control method also has been applied on the robot control. The adaptive sliding mode controller [25] design is accompanied with some or all the manipulator parameters being unknown, derives a simple globally stable adaptive control law for the actuator torques and an estimation law for the unknown parameters such that the manipulator output tracks the desired trajectories after an initial adaptation process. The asymptotic convergence of the estimating is guaranteed by restricting the residual tracking errors to lie on a sliding surface. A local kernel-based learning approach [20] has been formulated for online model learning for task-space tracking control of redundant robots. The parametrization made the data-driven model learning methods possible in task-space tracking control of redundant robots. A sEMG-based joint force control method is developed in [5], this control strategy estimates the percentage of the muscle's force and no longer requires the precise modeling of the exoskeleton system. A data driven adaptive predictive control [17] has been proposed for the biped robots. The control mechanisms use the advantage of data-driven technique combined with online parameters estimation strategy in order to achieve an efficient approximation. The dynamics of the biped robots are rewritten in the MIMO nonlinear non-affine forms so that the controller can be designed by data-driven technique. The non-affine form of dynamics is set up by utilizing SVM-based optimization.

The data-driven technique that has been applied in robot control seems like to be used for estimating the unknown parameters or learning the plant model. Deep knowledge of the dynamics model and stronger mathematical muscle are necessary for the controller designing.

The data-driven model-free adaptive control (MFAC) method [8,9] implies that the controller designing is merely based on the I/O measurement data of the controlled plant, without explicitly or implicitly using the plant structure or dynamics information of the controlled plant, and whatever the plant is linear or nonlinear. MFAC has a systematic dynamic linearization framework, and a series of controller designing strategies with compact-mapping-like stability analysis for SISO and MIMO nonlinear systems [11]. Since the data-based MFAC method does not require a model of a plant in the controller designing, the modeling process, the unmodeled dynamics, the time-varying parameters and the theoretical assumptions on the dynamics of the plant do not exist. Instead of identifying the nonlinear model of the plant, a series of equivalent local dynamic linearization data models are built along the dynamic operation points of the closed-loop system using a new dynamic linearization technique (DLT) with a novel concept called pseudo-partial derivative (PPD) [10]. The time-varying PPD could be estimated merely using the I/O measurement data of a controlled plant. MFAC approach guarantees the bounded-input bounded-output stability and the tracking error convergence. But if the convergence speed of the tracking error is slow, a reset algorithm is needed to make parameter estimation algorithm having a stronger ability in tracking time-varying parameter. And MFAC cannot be directly used to control the robotics since the robot system is a MIMO affine nonlinear system.

In order to achieve the best control performances [1], a data-driven model-free adaptive sliding mode control (MFASMC) approach is proposed in this paper based on MFAC method. A novel transformation and linearization of the robotic exoskeleton dynamics enables the robotic exoskeleton under the control of the data-based controller. And a discrete time sliding mode with exponential reaching law guarantees the convergence of MFASMC schemes. The main feature of the approach is that the dynamics of the multi DOF robotic exoskeleton has been transformed and linearized properly for MFASMC, the controller design depends only on the measured input torque and output velocity of each joint of the exoskeleton and the sliding mode