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Adaptive fuzzy tracking control of robot manipulators actuated by permanent magnet synchronous motors[☆]

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A B S T R A C T

This paper presents a model-free controller for robot manipulators driven by permanent magnet synchronous motors (PMSM). The contribution of this paper is merging the electrical and mechanical equations of the robotic system to simplify the controller design procedure. In other words, due to the fact that the manipulator links are the load torques of the PMSMs, the uncertainties related to the manipulator dynamics have been transferred to the voltage equations of the PMSMs. Uncertainties including external disturbances and system dynamics are estimated and compensated in the control law using adaptive fuzzy systems. In contrast to most previous related works that ignore the PMSM electrical equations, both the electrical and mechanical equations are taken into consideration. Based on the Barbalat's lemma, the asymptotic convergence of the tracking error to zero is guaranteed. The case study is an articulated manipulator driven by PMSMs. In comparison with a robust controller for a single-link manipulator actuated by PMSM, the proposed method is superior due to faster and smoother responses.

1. Introduction

Permanent Magnet Synchronous Motors (PMSMs) have widespread applications in various industries due to their favorite features such as high torque to volume ratio, reliable operation, and high efficiency [1]. Many robotic systems and machine tool drives are actuated by PMSMs [2–4].

Position and speed control of PMSMs have been frequently studied in the literature. A neural controller for uncertain PMSM has been presented in [5]. Recurrent wavelet neural networks have been applied to intelligent control of PMSMs in [6]. An intelligent position controller for PMSM using recurrent fuzzy neural cerebellar model articulation network has been developed in [7]. The controllers presented in [5-7] fail to consider the electrical equations of PMSM and simplify the controller design by just considering the mechanical motion equation of the motor. Thus, the contribution of this paper is presenting a position controller for PMSMs considering both electrical and mechanical equations of the motors and robot manipulator.

A novel approach for optimal nonlinear speed control of PMSM has been presented in [8]. However, its design procedure is complicated and estimation of the external disturbance using an observer is required in this method. In [9], a PID position regulation controller for robotic systems actuated by PMSMs has been presented, nevertheless it simplifies the system

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to one-degree-of- freedom robot manipulators. A discrete-time variable structure controller for PMSMs has been proposed in [10], while the convergence of the tracking error to zero has not been guaranteed. In [11], a chattering-free nonsingular fast terminal sliding-mode controller for PMSMs has been developed where the upper bound of load torque and its time derivative are required. In [12], a controller for robotic systems driven by PMSMs has been presented. However, it requires the manipulator dynamics in the control law. Therefore, other contributions of this paper are presenting a model-free controller for robot manipulators driven by PMSMs and guaranteeing the asymptotic convergence of the tracking error to zero.

Model-based control of robot manipulators using PMSMs has been presented in [3] based on the assumption that the exact mathematic model of the system is available and can be used in the control law. However, model-based approaches such as feedback linearization are faced with some important difficulties in practical implementations [13]. The first reason is that establishing an exact mathematical model a difficult task, since robot manipulators are complex nonlinear multi-variable systems with structured and unstructured uncertainties. Sensing requirement is another challenge of model-based approaches [14]. Thus, in this paper, a model-free controller for robot manipulators driven by PMSMs is presented in which uncertainties are estimated using adaptive fuzzy systems [15]. We have witnessed widespread applications of various neural networks, fuzzy systems and machine learning approaches in adaptive and robust control of robot manipulators and other systems [16-21] due to their universal approximation property. Parallelism and excellent learning capabilities are other beneficial characteristics of fuzzy systems and neural networks [22-23]. Thus, in this paper uncertainties including manipulator dynamics and motor parameters are estimated and compensated using adaptive fuzzy systems. It should be noted that many previous approaches have excluded the electrical dynamics of PMSM in their design procedure that can deteriorate the system performance in high speed applications [24]. Therefore, the motivation of this paper is to improve the performance of these systems by considering PMSM electrical dynamics in the controller design.

The rest of this paper is organized as follows: Section 2 presents modeling of the robotic system and PMSM. Section 3 develops the control law. In Section 4, stability analysis is presented. Section 5 illustrates the simulation results. Finally Section 6 concludes the paper.

2. Modeling

The manipulator dynamics is described by

$$D(\theta)\ddot{\theta} + C(\theta,\dot{\theta})\dot{\theta} + g(\theta) = \tau_L. \tag{1}$$

in which $\theta \in R^n$ denote the vector of joint angular positions, $C(\theta,\dot{\theta})\dot{\theta} \in R^n$, $D(\theta)$ and $g(\theta) \in R^n$ are completely described in [3,25]. Also $\tau_L \in R^n$ is the vector of load torques on the electric motors as

$$J\ddot{\theta} + B\dot{\theta} + \tau_L = \tau_m. \tag{2}$$

where $\tau_m \in R^n$ is the torque vector produced by motors and J, and B, are the $n \times n$ diagonal matrices for inertia and damping of motors, respectively. By substituting (1) into (2), one can easily obtain

$$\bar{D}(\theta)\ddot{\theta} + \bar{C}(\theta,\dot{\theta})\dot{\theta} + g(\theta) = \tau_m. \tag{3}$$

where $\bar{D}(\theta) = D(\theta) + J, \quad \bar{C}(\theta,\dot{\theta}) = C(\theta,\dot{\theta}) + B.$

Now consider the electrical equation of the i$^{\text{th}}$ PMSM [3]

$$v_{qi} = R_i I_{qi} + L_{qi}\dot{I}_{qi} + P_i L_{di} I_{di}\dot{\theta}_i + P_i\lambda_i\dot{\theta}_i. \tag{4}$$

$$v_{di} = R_i I_{di} + L_{di}\dot{I}_{di} - \dot{\theta}_i P_i L_{qi} I_{qi}. \tag{5}$$

where v_{di} and v_{qi} are the voltages along the d and q axes. Motor currents along the d and q axes for the ith motor are respectively denoted by I_{di} and I_{qi}. In these equations, P_i denotes the number of pole pairs, R_i shows the resistance of stator windings, λ_i is the amplitude of the flux that the permanent magnets of the rotor induces in the stator phases. Also, the constant matrices L_{di} and L_{qi} are the d and q axis inductances. The input of dynamic Eq. (2) is the motor torque vector τ_{mi} which is calculated by

$$\tau_{mi} = 3P_i[\lambda_i I_{qi} + (L_{di} - L_{qi})I_{di}I_{qi}]/2. \tag{6}$$

According to [3], the Inverse Park Transformation (IPT) is used to obtain the stator voltages of each motor. In other words,

$$v_{abc,i} = T(\theta_i)v_{qd0,i}. \tag{7}$$

$$v_{abc} = \begin{bmatrix} v_{ai} \\ v_{bi} \\ v_{ci} \end{bmatrix}, v_{qd0} = \begin{bmatrix} v_{qi} \\ v_{di} \\ v_{0i} \end{bmatrix}, \mathbf{T}(\theta_i) = \begin{bmatrix} \cos(P_i\theta_i) & \sin(P_i\theta_i) & 1 \\ \cos(P_i\theta_i - 2\pi/3) & \sin(P_i\theta_i - 2\pi/3) & 1 \\ \cos(P_i\theta_i + 2\pi/3) & \sin(P_i\theta_i + 2\pi/3) & 1 \end{bmatrix}. \tag{8}$$

In a balanced system, the term v_{0i} is considered to be zero.

In order to have a compact representation of the system, (4)-(6) can be rewritten as

$$\dot{\mathbf{I}}_{\mathbf{q}} = \mathbf{L_q}^{-1}\mathbf{v_q} - \mathbf{L_q}^{-1}\mathbf{R}\mathbf{I_q} - \mathbf{P}\mathbf{L_q}^{-1}\lambda\dot{\theta} - \mathbf{P}\mathbf{L_q}^{-1}\mathbf{L_d}\eta. \tag{9}$$