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Neural network-based robust finite-time control for robotic manipulators considering actuator dynamics

Haitao Liu [a,b,*], Tie Zhang [a]

[a] South China University of Technology, Guangzhou 510640, Guangdong, China
[b] Guangdong Ocean University, Zhanjiang 524088, Guangdong, China

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ABSTRACT

A novel neural network-based robust finite-time control strategy is proposed for the trajectory tracking of robotic manipulators with structured and unstructured uncertainties, in which the actuator dynamics is fully considered. The controller, which possesses finite-time convergence and strong robustness, consists of two parts, namely a neural network for approximating the nonlinear uncertainty function and a modified variable structure term for eliminating the approximate error and guaranteeing the finite-time convergence. According to the analysis based on the Lyapunov theory and the relative finite-time stability theory, the neural network is asymptotically convergent and the controlled robotic system is finite time stable. The proposed controller is then verified on a two-link robotic manipulator by simulations and experiments, with satisfactory control performance being obtained even in the presence of various uncertainties and external disturbances.

1. Introduction

As a kind of highly automatic equipment, robotic manipulators are more and more widely applied due to their capability of increasing the production efficiency and improving the product quality. Robotic manipulators are of high nonlinearity, strong time variation and highly coupled dynamic characteristics, so that a high-performance controller is necessary. However, the conventional controllers, such as proportional-integral-derivative (PID) controllers, are of poor performance and low robustness due to unknown nonlinearities and external disturbances. In order to solve this problem, a controller that can implement exact trajectory tracking with fast error convergence and strong robustness under the action of various disturbances should be developed.

In recent years, the continuous finite-time control has been paid more and more attention by researchers because it can effectively improve the tracking precision and the transient performance of robotic manipulators. Different from the asymptotic stability, finite-time stability [1] implies that a system may stabilize to equilibrium in finite time and may give rise to fast transient and high-precision performances, which are very useful for the high-quality industrial robot control system. Until now, the researchers have proposed several finite-time control approaches, such as the finite-time stability approach of homogeneous systems [2,3], the finite-time Lyapunov stability approach [4–6] and the terminal sliding mode approach [7–9]. Moreover, for the regulation of robotic manipulators, many approaches were developed in the past few years, among which the nonsingular terminal sliding mode control is more popular [7,10–12]. Tang [7] first adopted the terminal sliding mode controller to control robotic manipulators. Feng [10] proposed a nonsingular terminal sliding manifold to overcome the singularity around the equilibrium. However, the discontinuous terms of the sliding mode controller may cause “chattering” phenomenon, which may excite un-modeled high-frequency dynamics. To eliminate the chattering, a boundary-layer method was put forward, but a trade-off between the performance and the chattering was required in this method. Hong [11] proposed a finite-time controller with PD plus gravity compensation through the state feedback and the dynamic output feedback control. To achieve the global finite-time control, Su [12] proposed a nonlinear PD plus (NPD+) controller by replacing linear errors with non-smooth continuous exponential ones. Furthermore, Su [13] proposed another global finite-time controller with stronger convergence based on the inverse dynamics of robot manipulators. In the above-mentioned controllers, the dynamic parameters of robotic manipulators are assumed to be exactly known, and various uncertainties are ignored. However, in practice, accurate dynamic parameters are quite difficult to obtain, especially for the 6-DOF industrial robot with complex dynamic model. In order to avoid the performance degradation of robotic manipulators due to uncertainties, Zhao et al. [6] proposed a new robust finite-time control approach based on the backstepping method, but the

* Corresponding author at: South China University of Technology, Guangzhou 510640, Guangdong, China.
E-mail address: gdliuht@126.com (H. Liu).

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approach only took into consideration the set-point control of robot systems. In the existing researches, the dynamic characteristics of the actuator are commonly ignored for the purpose of simplifying the design of the controller, even though they play an important role in the complete robotic dynamics, especially under the conditions of high-velocity moment, variable load, joint friction and actuator moment saturation. In order to improve the tracking precision of robotic manipulators, the actuator dynamics should be considered in the design of robot controllers.

It is well known that multi-layer neural networks can approximate any continuous functions as accurate as possible [14]. Based on the universal approximation property of multi-layer neural networks, many adaptive neural network control schemes have been developed to overcome the high nonlinearity of the tracking control of robotic manipulators [15–18]. In this paper, we propose a novel neural network-based robust finite-time control (NNFTC) strategy for robotic manipulators with uncertainties, in which the actuator dynamics is fully considered. The controller consists of a modified variable structure term and a neural network, which are, respectively, used to guarantee fast response and precise tracking and to compensate uncertainties and external disturbances.

The remainder of this paper is organized as follows; Section 2 presents the dynamic model of robotic manipulators considering actuator dynamics; Section 3 puts forward a robust finite-time control strategy based on the neural network for the trajectory tracking and verifies the global finite-time stability of the proposed controller; Section 4 presents the simulation and experiment results conducted on a two-link robotic manipulators; and, in Section 5 some conclusions are drawn.

2. Problem formulation

2.1. Dynamic model of robotic manipulator considering actuator dynamics

According to the Lagrange theory, the dynamic model of a robotic manipulator with n serial links incorporating external disturbances can be expressed as

$$M(q)\ddot{q}+C(q,\dot{q})\dot{q}+D\dot{q}+G(q)=\tau \tag{1}$$

where $q,\dot{q}$, and $\ddot{q}\in\mathbf{R}^n$ are the vectors of joint position, velocity and accelerations, respectively. $M(q)\in\mathbf{R}^{n\times n}$ is a symmetric positive-definite inertia matrix, $C(q,\dot{q})\in\mathbf{R}^{n\times n}$ is the centrifugal Coriolis matrix, $D\in\mathbf{R}^{n\times n}$ is the diagonal positive-definite matrix composed of damping friction coefficients for each joint, $G(q)\in\mathbf{R}^n$ is the gravity term, and $\tau\in\mathbf{R}^n$ denotes the torque input vector on joints.

In general, the dynamic model of the armature-controlled AC servo motors on an n-link robot manipulator can be generally expressed as follows:

$$\tau_m=J_m\ddot{q}_m+D_m\dot{q}_m+\tau_L \tag{2}$$

$$\tau_m=K_\tau u \tag{3}$$

where $\tau_m\in\mathbf{R}^n$ is the vector of electromagnetic torque, $q_m\in\mathbf{R}^n$ is the angular position vector of the motors, $\tau_L\in\mathbf{R}^n$ is the vector of load torque at the motor shaft, $J_m\in\mathbf{R}^{n\times n}$ is the diagonal matrix of the moment inertia, $D_m\in\mathbf{R}^{n\times n}$ is the diagonal matrix of torsional damping coefficients, and $u\in\mathbf{R}^n$ denotes the vector of armature input voltages. Ignoring the electromagnetic properties, the torques is proportional to the voltage (see (3)), $K_\tau=\mathrm{diag}(K_{\tau1}, K_{\tau2},\ldots, K_{\tau n})$ is a diagonal matrix of the torque constants.

In addition, the relationship between the joint position q and the motor-shaft position q_m can be described as

$$N=\frac{q_m}{q}=\frac{\tau}{\tau_L} \tag{4}$$

where $N\in\mathbf{R}^{n\times n}$ is a diagonal matrix of the gear ratios for the n joints.

According to (1)–(4), the dynamic model of robotic manipulators considering actuator dynamics can be written as

$$M_H(q)\ddot{q}+C_H(q,\dot{q})\dot{q}+D_H\dot{q}+G_H(q)=u \tag{5}$$

where $M_H=K_\tau^{-1}(N^{-1}M+NJ_m), C_H=K_\tau^{-1}N^{-1}C, D_H=K_\tau^{-1}(N^{-1}D+ND_m)$ and $G_H=K_\tau^{-1}N^{-1}G$.

The parameters in dynamic model (5) are the functions of such physical parameters as link mass, link length and inertial moment. In fact, precise values of these parameters are difficult and even impossible to acquire due to the existence of measurement errors, payloads variation and external disturbances. Therefore, it is assumed that the actual system can be written as

$$\begin{aligned}
&M_H(q)=\hat{M}_H(q)+\Delta M_H(q)\\
&C_H(q,\dot{q})=\hat{C}_H(q,\dot{q})+\Delta C_H(q,\dot{q})\\
&D_H=\hat{D}_H+\Delta D_H\\
&G_H(q)=\hat{G}_H(q)+\Delta G_H(q)
\end{aligned} \tag{6}$$

where the estimation values $\hat{M}_H(q),\hat{C}_H(q,\dot{q}),\hat{D}_H$ and $\hat{G}_H(q)$ are nominal parts; $\Delta M_H(q),\Delta C_H(q,\dot{q}),\Delta D_H$ and $\Delta G_H(q)$ are defined as uncertain parts.

2.2. Relative lemmas

Lemma 1. Bhat et al.[19]. *Supposing that there exists a continuously differentiable function $V(x)$ defined on a neighborhood $U\subset\mathbf{R}^n$ of the origin, and that real numbers $c>0$ and $0<\alpha<1$, such that*

(1) $V(x)$ *is positive definite on* U;
(2) $\dot{V}(x)+cV^\alpha(x)\le 0,\ \forall x\in U$.

Then, there exists an area $U_0\subset\mathbf{R}^n$ such that any $V(x)$, which stars from U_0, can reach $V(x)=0$ in finite time. The settling time T_{reach}, which is the time interval for reaching $V(x)=0$, satisfies

$$T_{\mathrm{reach}}(x_0)\le\frac{V(x_0)^{1-\alpha}}{c(1-\alpha)} \tag{7}$$

where $V(x_0)$ is the initial value of $V(x)$.

Lemma 2. Yu et al. [20] *For any real numbers l_i, $i=1, 2,\ldots, n$ and $0<\lambda<2$, the following inequality holds*:

$$(|l_1|^2+\cdots+|l_n|^2)^{\lambda/2}\le|l_1|^\lambda+\cdots+|l_n|^\lambda \tag{8}$$

2.3. Problem statement

The finite-time control problem for trajectory tracking is to design a control law u to achieve the tracking error $e=0$ in finite time. Here, tracking errors $e(t)$ and $\dot{e}(t)$ are defined as follows:

$$e=q_d-q,\ \ \dot{e}=\dot{q}_d-\dot{q} \tag{9}$$

3. Control strategy design

In this section, a neural network-based robust finite-time control strategy is proposed to improve the tracking performance of robotic manipulators.