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Research article

Direct adaptive robust tracking control for 6 DOF industrial robot with enhanced accuracy

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ABSTRACT

A direct adaptive robust tracking control is proposed for trajectory tracking of 6 DOF industrial robot in the presence of parametric uncertainties, external disturbances and uncertain nonlinearities. The controller is designed based on the dynamic characteristics in the working space of the end-effector of the 6 DOF robot. The controller includes robust control term and model compensation term that is developed directly based on the input reference or desired motion trajectory. A projection-type parametric adaptation law is also designed to compensate for parametric estimation errors for the adaptive robust control. The feasibility and effectiveness of the proposed direct adaptive robust control law and the associated projection-type parametric adaptation law have been comparatively evaluated based on two 6 DOF industrial robots. The test results demonstrate that the proposed control can be employed to better maintain the desired trajectory tracking even in the presence of large parametric uncertainties and external disturbances as compared with PD controller and nonlinear controller. The parametric estimates also eventually converge to the real values along with the convergence of tracking errors, which further validate the effectiveness of the proposed parametric adaption law.

1. Introduction

Industrial robots have been extensively employed in modern industry. Typical applications mainly include spot welding, spray painting, assembly, pick and place for electronics, palletizing, packaging and labeling, product inspection, and testing [1]. One fundamental and challenging functionality or prerequisite of industrial robots in these applications is the accurate planned trajectory tracking, i.e. the industrial robots should follow and track the target paths with high precision over a large measurement range [2]. As such, the trajectory tracking control is of paramount importance to guarantee accurate operations for industrial robots, especially in the presence of parametric uncertainties and external disturbances.

At present, the design of trajectory tracking control has been a mainstream area of focus for industrial robots. A fuzzy logic controller was designed in [3,4] to track the given trajectory for a 2 DOF industrial robot. The controller parameters were optimized by using the particle swarm optimization with three different cost functions. The effectiveness of the designed controller was verified against a traditional proportional integral derivative (PID) robot controller through simulations. However, the fuzzy logic controller was not experimentally validated and its tuning process will become more difficult and very time consuming when implemented in real time. An adaptive back-stepping controller was developed in [5,6] for an n-DOF robotic manipulator by augmenting a new state to the state equations of the robot system. The effects of external disturbances on the robot tracking performance were explored and an exact comparison between the tracking efficiency of the state augmented adaptive back-stepping controller and four of the recently revealed control methods was made through different experiments to validate the efficiency of the designed back-stepping controller. However, the designed controller inevitably suffers from the inherent problem of “explosion of complexity”, which is caused by repeated differentiations of some nonlinear functions and cannot be avoided in the back-stepping method. A high-gain observer based output feedback tracking control was proposed in [7,8] for mobile robots in the presence of parametric uncertainties. The proposed controller could achieve adaptive state feedback control and asymptotic tracking. Although the stability of the robotic system was analyzed and established by using Lyapunov approach, the proposed approach can only guarantee asymptotic stability or exponential stability in the presence of parametric uncertainties and hence the steady state tracking error can only stay within an unknown ball whose size depends on the disturbances. In [9,10], a data-driven model-free adaptive sliding

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mode control approach was proposed to control the robotic exoskeleton dynamics by using an exponential reaching law. The controller design of the robotic exoskeleton depends only on the exactly measured input torque and output velocity of each joint of the exoskeleton. Even though the controller could guarantee the desired velocity tracking under time-varying uncertainties based on extensive simulations, exact knowledge of the robot dynamics was still required for the controller design, which would eventually lead to control chattering involving high frequency control activity and hence may excite neglected high frequency dynamics. In [11,12], an H∞ adaptive fuzzy integral sliding mode controller was proposed for controlling parallel robots with nonlinear uncertainties and external disturbances through the use of two online estimations. The enhancement of robust tracking performance and the elimination of reaching phase were guaranteed from a more theoretical design perspective. Although all states of the robotic system could be verified through simulation results to be uniformly ultimately bounded and the effects of the external disturbances on the tracking error could be attenuated to a prescribed level based on Lyapunov stability theorem and Riccati-inequality, the performance of designed controller could be highly restricted by some challenges such as complexity, slow transient performance, and unmolded dynamics, which were also not validated through experiments. In [13], neural network control strategies were designed to achieve balancing and posture control based on radial basis functions for biped robots. The neural networks were used to approximate the unknown model of the robot while both full state feedback control and output feedback control were considered. Simulations were carried out to illustrate the effectiveness of the control strategies. A neural network controller was designed in [14] to suppress the vibration of a flexible robotic manipulator system with input deadzone by approximating the unknown robotic manipulator dynamics and eliminating the effects of input deadzone in the actuators. The Lyapunov's direct method was used to ensure uniform ultimate boundedness of the closed-loop system. Simulations and experiments were conducted to prove the feasibility and control performance of the neural network controller. The adaptive fuzzy neural network control using impedance learning was designed in [15] for a constrained robot subject to unknown system dynamics and state constraints etc. The stability and tracking performance of the closed-loop control system were achieved via barrier Lyapunov's stability theory, and some simulation studies were carried out to illustrate the effectiveness of the control scheme.

This paper introduces a direct adaptive robust control for trajectory tracking of 6 DOF industrial robot in the presence of modelling uncertainties and uncertain nonlinearities. Unlike the existing robotic controllers in the literature, the proposed controller is designed in the working space of the end effector of the 6 DOF industrial robot and directly employs the information of the input reference or desired motion trajectory, which significantly facilitate the design process of the controller. The proposed controller has also been validated based on 6 DOF robotic platform, which demonstrates that the proposed controller can achieve a guaranteed transient and steady-state performance regardless of the un-modelled dynamics and external disturbances. The free trajectory tracking error can be better reduced by using the proposed controller over a wide range of time period as compared with the widely used PD control.

The paper mainly contributes to the following aspects: (a) The proposed control is designed in the working space of the end effector of the 6 DOF industrial robot with relatively high adjustable model compensation and disturbance robustness and actually provides a general framework and perspective for the tracking control design of industrial robots. (b) The proposed control and parametric adaption law are directly synthesized by using the input reference trajectory information, which significantly reduce the algorithm complexity and leads to the simple and easy control design and implementation. (c) The challenges of excellent trajectory tracking, high robustness against disturbances and parametric adaptation capability can be simultaneously satisfied by using the proposed controller in practice.

2. Robotic dynamics modelling

The dynamics of the rigid-linked 6 DOF industrial robot can be generally formulated in the working space of the end-effector as follows [16].

$$\mathbf{M}(\mathbf{x})\ddot{\mathbf{x}} + \mathbf{C}(\mathbf{x}, \dot{\mathbf{x}})\dot{\mathbf{x}} + \mathbf{G}(\mathbf{x}) + \mathbf{d} = \mathbf{F} \tag{1}$$

where $\mathbf{M}(\mathbf{x})$ and $\mathbf{C}(\mathbf{x}, \dot{\mathbf{x}})$ represent the inertial properties of the industrial robot, $\mathbf{C}(\mathbf{x}, \dot{\mathbf{x}})\dot{\mathbf{x}}$ represents the Coriolis and centrifugal force, $\mathbf{G}(\mathbf{x})$ is the gravitational force, $\mathbf{d}$ is the vector of unknown nonlinear functions such as external disturbances and un-modeled dynamics, $\mathbf{F}$ is the applied end-effector force vector, $\mathbf{x}$ is the end-effector position vector in the working space with three translational and three rotational positions.

The above Eq. (1) represents the dynamics in terms of the workspace coordinate of the end-effector where $\mathbf{M}(\mathbf{x})$, $\mathbf{C}(\mathbf{x}, \dot{\mathbf{x}})and\mathbf{G}(\mathbf{x})$ are effective parameters of the robot system. The dynamics (1) can be directly derived from the joint space coordinates through forward kinematics since the joint angles of the industrial robot can be directly measured or computed.

Eq. (1) has the following structural properties [16] which will facilitate the controller design.

Property 1. $\mathbf{M}(\mathbf{x})$ is a symmetric and positive definite matrix.

Property 2. $\dot{\mathbf{M}}(\mathbf{x}) - 2\mathbf{C}(\mathbf{x}, \dot{\mathbf{x}})$ is a skew-symmetric matrix, i. e. $\mathbf{x}^{\mathbf{T}}\left[\dot{\mathbf{M}}(\mathbf{x}) - 2\mathbf{C}(\mathbf{x}, \dot{\mathbf{x}})\right]\mathbf{x} = \mathbf{0}$.

In practice, the parameters of the robot dynamics cannot be known exactly in advance and will be uncertain in nature since the payloads of the robot may change and working conditions may vary with time. However, the parametric uncertainties are generally bounded and the boundaries can be predicted in advance.

The control objective is to synthesize a control force input $\mathbf{F}$ for the end-effector such that $\mathbf{x}$ tracks the desired trajectory $\mathbf{x_d}(t)$ as closely as possible. $\mathbf{x_d}(t)$ is assumed to be of at least second-order differentiable. The designed control force can then be transformed into the joint torques for controlling each joint to track the respective joint angle displacement based on the Jacobin matrix [16].

3. Direct adaptive robust control

In this section, a robust adaptive tracking controller is synthesized to adaptively and accurately track the desired trajectory of the end-effector with sufficient robustness in the presence of parametric variations and external uncertain disturbances [17].

Define the trajectory tracking error $\mathbf{e}$ of the end-effector as

$$\mathbf{e} = \mathbf{x_d} - \mathbf{x} \tag{2}$$

Define a switching manifold $\mathbf{s}$ based on the tracking error for the industrial robot as

$$\mathbf{s} = \dot{\mathbf{e}} + \mathbf{\Lambda e} = \left(\dot{\mathbf{x}}_\mathbf{d} + \mathbf{\Lambda e}\right) - \dot{\mathbf{x}} = \dot{\mathbf{x}}_\mathbf{eq} - \dot{\mathbf{x}} \tag{3}$$

where $\mathbf{\Lambda}$ is a constant positive definite diagonal matrix, $\mathbf{x_{eq}}$ is the equivalent position and orientation of the end-effector with respect to the workspace coordinate for specifying an assembly task, $\mathbf{x_d}$ is the input reference or desired motion trajectory.

As observed in Eq. (3), the equivalent position of the end-effector can be defined as

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