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UDE-based trajectory tracking control for flexible-joint manipulators with model uncertainties and backlash-like hysteresis

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Against the backdrop of technological iteration, robots have been applied in industrial manufacturing, logistics, deep space exploration and other fields [1]. As a core technology, trajectory tracking control guides robots to track preset paths accurately, which is the key to ensuring operational accuracy and efficiency [2]. Flexible-joint robotic manipulators (FJMs) improve their flexibility and adaptability via compliant joints and can compensate for assembly errors; however, their strong nonlinear and coupling characteristics greatly increase the difficulty of controller design [3]. Sliding mode control (SMC) and its variants provide an effective solution for such nonlinear systems and have been recently applied in various engineering fields: adaptive SMC is used in microgrids, plant-wide decentralized SMC is implemented in industrial processes such as the Tennessee Eastman benchmark problem, and fuzzy logic-enhanced SMC achieves chattering suppression and robustness improvement for nonlinear dynamic systems [4]. Therefore, the development of high-precision control algorithms for flexible-joint robotic manipulators holds important theoretical and engineering significance for the advancement of next-generation intelligent robots [5].

Methodology. The dynamic system model of n-link FJMs is

$$D(\rho)\ddot{\rho} + R(\rho,\dot{\rho})\dot{\rho} + O(\rho) = F(\tau), \tag{1}$$

where $\rho \in \mathbb{R}^n$ denotes the generalized coordinate vector of link positions, with its time derivatives $\dot{\rho} \in \mathbb{R}^n$ and $\ddot{\rho} \in \mathbb{R}^n$ representing the corresponding velocity and acceleration vectors. The symmetric positive-definite inertia matrix is denoted by $D(\rho) \in \mathbb{R}^{n\times n}$, whereas $R(\rho,\dot{\rho}) \in \mathbb{R}^{n\times n}$ characterizes the Coriolis and centrifugal force coupling effects. $O(\rho) \in \mathbb{R}^n$ represents the gravitational potential gradient vector, and $F(\tau) \in \mathbb{R}^n$ denotes the backlash hysteresis input vector. The backlash-like hysteretic nonlinearity can be characterized as

$$F(\tau) = B\tau + H(\tau), \tag{2}$$

where $B = \operatorname{diag}\{\sigma_1,\sigma_2,\ldots,\sigma_n\} > 0$, $|d_i(\tau_i)| \leqslant d_i^*$, $H(\tau) = [d_1(\tau_1), d_2(\tau_2), \ldots, d_n(\tau_n)]^{\mathrm{T}}$, $H^* = \sqrt{{d_1^*}^2 + {d_2^*}^2 + \cdots + d_n^{*2}}$.

Assumption 1. The desired trajectory is deterministic, continuous, and its magnitude remains within a finite interval.

Assumption 2. The slope $\bar{B}^*$ is unknown but bounded, with $|B|$ satisfying $\sigma^* \leqslant |B| \leqslant \bar{\sigma}^*$ for positive constants $\bar{\sigma}^*$ and σ^*.

Lemma 1. If a Lyapunov function candidate $V(x)$ is positive definite, continuous, and satisfies

$$\dot{V}(x) \leqslant -aV(x) + c. \tag{3}$$

To address nonlinear issues such as model uncertainties and backlash-like hysteresis, this section develops a control algorithm based on uncertainty and disturbance estimation (UDE), which enables high-precision tracking of the desired trajectory. The tracking error e is defined as

$$e = \rho - \rho_d, \tag{4}$$

where ρ_d represents the desired trajectory. The filtered error can be defined as

$$z = \dot{e} + \chi e, \tag{5}$$

where $\chi = \chi^{\mathrm{T}} > 0$. The desired error dynamics with respect to z are characterized by

$$\dot{z} = -kz, \tag{6}$$

where $k = k^{\mathrm{T}}$ is the positive definite gain matrix for error feedback. These uncertain terms can be reformulated into the following dynamic equation:

$$-(k+\chi)\dot{e} - k\chi e = \ddot{\rho}_d + v + g\tau, \tag{7}$$

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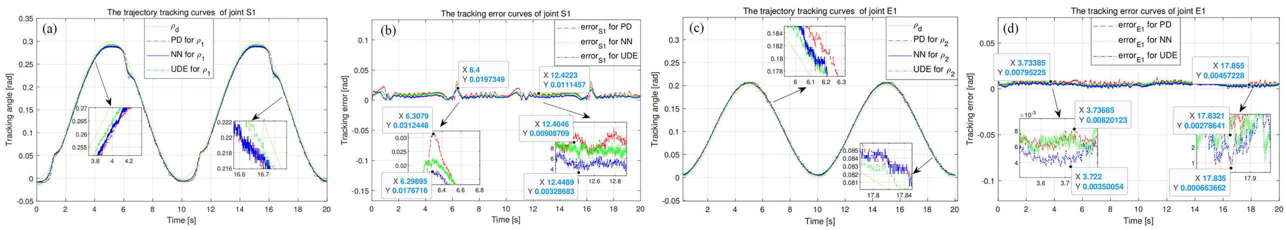

Figure 1 (Color online) Comparative experimental results of trajectory tracking performance and tracking errors. (a) and (b) show the trajectory tracking curves and tracking error curves of joint S1, respectively; (c) and (d) correspondingly present those of joint E1. The experimental results fully highlight the superior performance of the proposed UDE-based controller.

where $v = D^{-1}[(B\tau + H(\tau)) - R(\rho,\dot{\rho})\dot{\rho} - O(\rho)] - g\tau$.

If the filter $G_f(s)$ maintains unit gain and zero phase shift within v's main frequency band while having zero gain elsewhere, the uncertain term v can be approximated as follows:

$$\hat{v} = L^{-1}\left\{G_f(s)\right\} * v = L^{-1}\left\{G_f(s)\right\} * (\ddot{\rho} - g\tau), \tag{8}$$

where $\hat{v}$ represents the estimate of v, $*$ denotes the convolution operation, and $L^{-1}\{\cdot\}$ indicates the inverse Laplace transform. Thus, the UDE-based controller can be formulated as

$$\tau = \frac{1}{g}\left\{L^{-1}\left\{\frac{1}{1-G_f(s)}\right\} * (-(k+\chi)\dot{e} - k\chi e + \ddot{\rho}_d) - L^{-1}\left\{\frac{sG_f(s)}{1-G_f(s)}\right\} * \dot{\rho}\right\}. \tag{9}$$

The stability of the entire closed-loop system is rigorously proven, as formally stated in Lemma 1. The proof is based on the Lyapunov direct method, utilizing the following candidate function:

$$V = \frac{1}{2}z^{\mathrm{T}}z. \tag{10}$$

Results. The proposed UDE-based controller is experimentally validated on the Baxter robot. To evaluate the controller's trajectory tracking performance, its performance is benchmarked against a standard neural network (NN) controller and PD controller.

As shown in Figure 1, for joint S1, the error metrics of root mean square error (RMSE), mean absolute error (MAE), and steady-state error (SSE, calculated as the mean value of the last 0.5-second data as the steady-state response) under PD control are 0.0105, 0.0313, and 0.0080 rad, respectively. Under NN control, these metrics are 0.0086, 0.0234, and 0.0058 rad, respectively. In comparison, UDE-based control optimizes RMSE to 0.0069 rad, representing a 34.3% reduction compared with PD control and a 19.8% reduction compared with NN control. It also reduces MAE to 0.0108 rad, a 65.5% reduction compared with PD control and a 53.8% reduction compared with NN control. Additionally, UDE-based control reduces SSE to 0.0046 rad, a 42.5% reduction compared with PD control and a 20.7% reduction compared with NN control. For joint E1, RMSE, MAE, and SSE under PD control are 0.0068, 0.0131, and 0.0060 rad, respectively. Under NN control, these metrics are 0.0054, 0.0103, and 0.0048 rad, respectively. UDE-based control reduces RMSE to 0.0046 rad, a reduction of 32.4% compared with PD control and 14.8% compared with NN control. It also reduces MAE to 0.0084 rad, which is a reduction of 36.0% compared with PD control and 18.5% compared with NN control. SSE is optimized to 0.0041 rad, representing a reduction of 31.7% compared with PD control and 14.6% compared with NN control.

Conclusion. This study proposes a UDE-based control algorithm that successfully addresses the high-precision trajectory tracking problem. The core advantage of this algorithm lies in its extremely low dependence on prior information. The proposed method does not require a precise characterization of model uncertainties or hysteresis parameters for its implementation. Instead, only appropriate bandwidth parameters need to be set according to the system's fundamental dynamics to estimate model uncertainties and compensate for unknown hysteresis effects simultaneously, thus stably maintaining good control performance in complex dynamic environments. Quantitative analysis of the experimental data reveals that the proposed UDE-based control algorithm achieves optimal performance in terms of three core indicators commonly used to evaluate control accuracy: RMSE, MAE, and SSE. This result clearly demonstrates the algorithm's significant advantages in compensating for model parameter uncertainties and backlash-like hysteresis characteristics, and fully verifies its feasibility for practical application in flexible-joint robot systems.

The current control method still has the following limitations: the accuracy of the UDE-based control depends on the matching between the filter parameters and the disturbance frequency, and using a fixed time constant when the load frequency changes abruptly will lead to a degradation in system tracking performance.

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