Model-free control of manipulator in task space containing mismatched uncertainty

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Abstract In this paper, a novel trajectory tracking control method for manipulator task space containing mismatched uncertainty is proposed. This paper considers the mismatched uncertainty that exists in the signal conversion between joint space and task space in the robotic arm system. The time delay estimation is employed to approximate the dynamic and kinematic parameters of the system to achieve model-free control. The time delay estimation errors is treated as part of the system disturbances and a disturbance observer based on an auxiliary control system capable of estimating both matched and mismatched disturbances is designed, which does not require additional design of adaptive laws to compensate for disturbances or upper bounds on the derivatives of disturbances. We transform the control error by a prescribed performance function to accomplish transient control of the error, and design a fast terminal sliding surface for the virtual control variables based on the backstepping design method to improve the convergence speed of the controller. Based on the Lyapunov criterion, the closed-loop stability of the whole system is demonstrated. The

feasibility and superiority of the method in this paper is demonstrated by numerical simulation compared with other control methods.

Keywords Prescribed performance control · Backstepping design method · Mismatched uncertainty · Fast terminal sliding surface · Model-free control

1 Introduction

In recent years, as robotic manipulators are more and more widely applied in daily life and industry [1, 2, 3, 4, 5], the control accuracy of robots is required to be higher and higher. However, because of the complex dynamics and uncertainties of robotic arm systems, it is still challenging to achieve high precision trajectory tracking of robots. Researchers have developed many control methods to address this problem, such as PID control [6, 7] for practical applications and many advanced control techniques designed to enhance control performance, such as model predictive control(MPC) [8, 9], sliding mode control(SMC) [10, 11], adaptive control [12, 13].

Since it is difficult to obtain an accurate system model of a manipulator during operation, the estimation of dynamic and kinematic parameters in the manipulator system and the estimation and compensation of external disturbances is considered one of the main problems to be solved by researchers. Many researchers have focused on the study of adaptive or robust controllers to achieve the required performance. [14] proposed an adaptive backstepping nonsingular fast terminal sliding mode controller, which employs adaptive technology to approach the upper bound of disturbances and uncertainties. In [15], an adaptive motion controller is designed that requires neither complicated

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gain constraints nor upper/lower bounds on model parameters in the dynamics for controller design and analysis. [16] proposed a model-independent adaptive fractional high-order terminal sliding mode controller and utilized an adaptive tuning control to evaluate the uncertain dynamics of the system without relying on the prior knowledge of the upper bounds. The main disadvantage of these methods is the inability to accurately estimate uncertainties and disturbances, resulting in a slightly conservative controller design. [17] developed an adaptive bias RBF neural network control for a robotic manipulator, which improves the approximation accuracy and the robustness of the RBFNN controller for the dynamics with significant bias. In [18], an adaptive fuzzy integral sliding-mode control is developed for robust fault-tolerant control of robot manipulators, and a fuzzy logic system is introduced to approximate the unknown nonlinear terms that include the model uncertainty and fault components. Similar to the above methods [19,20], techniques that employ fuzzy logic or neural networks to estimate uncertainty can provide accurate estimations of unknown variables. However, they take a long time for the estimates to converge to the actual state in weight training by approximation rules, which is not conducive to real-time applications. The lumped uncertainty can also be estimated and compensated by designing disturbance observers or extended state observers [21,22,23], and these methods also enable to obtain accurate estimates of the unknowns. But traditional observers require upper bounds on the uncertainty or uncertainty time derivatives, which are difficult to obtain. Therefore researchers have proposed many methods that combine adaptive with observers. [24] designed an adaptive super-twisting disturbance observer with an adaptive law to update the gain parameters, which can estimate the system disturbances in fixed time. In [25], an adaptive sliding mode disturbance observer is proposed to estimate and compensate the system uncertainty, and similarly, an adaptive update law is proposed to estimate the upper bound of the first-order derivative value of the uncertainty. As shown in the above study, the design of the observer adaptive gain is often complex in order to make the overall closed-loop system stabilized. In addition, time-delay estimation (TDE) is also an efficient way to deal with uncertainty [26,27,28]. It can achieve accurate estimation of uncertainty by a simple structure, but when the uncertainty changes drastically in a short period of time, significant errors are generated, so the time-delay estimation error must be taken into consideration. To this end, one of the objectives of this paper is to propose a more feasible and less restrictive method for dealing with system uncertainty.

Moreover, all the above studies consider only matched uncertainties, while the manipulator system also has mismatched uncertainties. The mismatched uncertainties represent the case where the uncertainty terms impact the part of the system with no control input. Since there is no direct control signal in the influenced state, the matched part of the system should be changed to produce an indirect control effort to eliminate the effect of the mismatch uncertainties. And it is known that the backstepping control design has a unique superiority when the disturbances or uncertainties are not satisfied by the matched conditions [29,30]. Therefore, this paper is based on the backstepping design approach for the controller design. Meanwhile, almost all of the above studies only consider the stability and steady-state error of the system and do not study the transient performance. The prescribed performance control can limit the control error to the range of the prescribed function and effectively control the transient performance, which has been widely used in various systems since it was proposed [31,32].

According to the above discussion, this paper proposes a novel task space-based robotic arm trajectory tracking control method that involves mismatched uncertainties. Different from [33,34,18], which takes the joint angle variations on the joint space as the desired signal, this paper directly adopts the required trajectory of the manipulator in the task space as the desired trajectory and considers the uncertainties in the signal transformation between the joint space and the task space. The uncertainties are mismatched and not directly affected by the control inputs. This paper is based on the framework of backstepping design to facilitate the handling of mismatched uncertainty, first transforming the control error through a prescribed function to limit the transient error to a given range. Then a fast terminal sliding surface is designed for the following virtual control variables to enhance the controller convergence speed. In [35,36,37], they use the time-delay method to estimate the lumped uncertainty including disturbances. We consider that the disturbances may change drastically in a short period of time, causing large time-delay estimation errors, greatly reduced control accuracy and robustness. While the model parameters generally fluctuate less and can be effectively estimated by the time-delay method, so we estimate the dynamic and kinematic parameters with TDE. However, the time delay estimation error is still a problem that needs to be considered. In this paper, the time delay estimation error is combined into the disturbance term. And for system disturbances, unlike [14,18,24,38], due to the presence of mismatched disturbances, we adopt a less restrictive disturbance observer, which

does not require the design of complex adaptive gains to compensate for the upper bound of the disturbance or the derivative of the disturbance. In summary, the main characteristics of this paper are as follows:

(1): Considering the mismatched uncertainties in the signal transformation between joint space and task space in the robotic arm system, accurate tracking based on the desired trajectory in task space is achieved.

(2): The model-free control is achieved by approximating the kinematic and dynamic parameters in the system by time delay estimation. And a disturbance observer that can observe both matched and mismatched disturbances is designed for disturbances that combine the time delay estimation errors.

(3): Based on the framework of backstepping design, the prescribed performance function is combined with fast terminal sliding mode control to improve the controller convergence speed while regulating the transient performance of the system. The Lyapunov criterion demonstrates the closed-loop stability of the whole system.

The rest of this paper is organized as follows. In Section II, we describe the problem to be solved and introduce the controlled robotic arm system. In Section III, a model-free adaptive control method is designed for controlled systems containing mismatched disturbances, and its closed-loop stability is demonstrated. Our controller is applied to 3-degree-of-freedom robotic manipulators, and simulation results are presented in Section IV. The research conclusions are given in Section V.

2 Problem formulation

The controller designed in this paper is applied to a robotic arm system that contains disturbances in signaling between joint space and task space. According to [39, 40], the dynamic model of the n -links manipulator in the joint space can be expressed as:

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

where $q = [q_1, q_2, \dots, q_n]^T \in \mathbb{R}^n$ is a vector of joint angular position. $\dot{q}, \ddot{q} \in \mathbb{R}^n$ are the velocity and acceleration vectors of joints, respectively. $M(q) \in \mathbb{R}^{n \times n}$ is a positive definite inertia matrix. $C(q, \dot{q}) \in \mathbb{R}^{n \times n}$ denotes the centripetal and coriolis matrix, $G(q) \in \mathbb{R}^n$ is the vector of gravitational torques, $\tau_d \in \mathbb{R}^n$ expresses the external disturbance signal and $\tau \in \mathbb{R}^n$ is the vector of control torques.

The kinematic and differential mapping between the joint space and the task space can be described as:

$$p = f(q) + f_d, \quad \dot{p} = J\dot{q} + \dot{f}_d \quad (2)$$

where $f_d \in \mathbb{R}^m$ is the disturbance signal in the kinematic of the system. $m \leq n$, $p = [p_1, p_2, \dots, p_m]^T \in \mathbb{R}^m$ are the coordinates of the end-effector in the task space. $f : \mathbb{R}^n \rightarrow \mathbb{R}^m$ denotes the mapping of the joint space to the task space constituted by the kinematic equations. $J = \frac{\partial f}{\partial q}$ is the $m \times n$ Jacobian matrix. We assume that the end-effector is required to track the desired trajectory $p_d(t) \in \mathbb{R}^m$, which is at least triply continuously differentiable. Let the task tracking error $e(t) = p - p_d$, the objective of this paper is to design finite time control algorithm that accomplish the following equation:

$$\lim_{t \rightarrow \infty} e(t) = \lim_{t \rightarrow \infty} \dot{e}(t) = 0 \quad (3)$$

Since kinematic redundancy is not the focus of our discussion in this paper, it is assumed that $m = n$.

Assumption 1: The disturbances τ_d and f_d are bounded. f_d is at least first-order derivable.

And the following relevant properties are satisfied [40]:

Property 1: The inertia matrix $M(q)$ is positive definite symmetric. And $\forall q \in \mathbb{R}^n$ the following inequalities are satisfied:

$$k_m \leq \|M(q)\| \leq k_M, \|C(q, \dot{q})\| \leq k_C, \|G(q)\| \leq k_G$$

where k_m, k_M, k_C and k_G are positive constants.

Property 2: The inertia matrix $M(q)$ and the centripetal Coriolis matrix $C(q, \dot{q})$ satisfy that

$$x^T \left[\frac{1}{2} \dot{M}(q) - C(q, \dot{q}) \right] x = 0, \forall x \in \mathbb{R}^n$$

Property 3: In the kinematic model, there exist positive constants k_J such that the following inequalities hold true:

$$0 \leq \|J\| \leq k_J, \forall q \in \mathbb{R}^n$$

Introducing constant matrix $\bar{M} = \text{diag}(\bar{m}_1, \bar{m}_2, \dots, \bar{m}_n)$ and $\bar{J} = \text{diag}(\bar{j}_1, \bar{j}_2, \dots, \bar{j}_n)$, based on (1) and (2) we can rewrite the system as

$$\begin{cases} \dot{p} = \bar{J}\dot{q} + N_1 + \dot{f}_d \\ \bar{M}\ddot{q} + N_2 = \tau + \tau_d \end{cases} \quad (4)$$

where N_1, N_2 represent the kinematic and kinetic parameter terms of the system, respectively. $N_1 = [J(q) - \bar{J}] \dot{q}$, $N_2 = [M(q) - \bar{M}] \ddot{q} + C(q, \dot{q})\dot{q} + G(q)$. Based on the above properties, we can know that N_1 and N_2 are bounded.

3 Control of the robotic manipulator

In this section we develop an novel controller for a manipulator system containing mismatched disturbances based on sliding mode control and prescribed performance function with the backstepping design technique.

3.1 Model-based controller

In this part, based on the above kinematic and dynamical model of the robotic arm, we design a controller for the accurate model of the manipulator system to achieve the tracking of the desired trajectory in the framework of the backstepping method combined with sliding mode control and prescribed performance control. For uncertainties and disturbances, they will be estimated and compensated by time delay estimation and disturbance observer in the later section.

Let $x_1 = p$, $x_2 = \dot{q}$, $x_1, x_2 \in \mathbb{R}^n$, then system (4) can be rewritten as:

$$\begin{cases} \dot{x}_1 = \bar{J}x_2 + N_1 + d_1 \\ \dot{x}_2 = \bar{M}^{-1}\tau - \bar{M}^{-1}N_2 + d_2 \end{cases} \quad (5)$$

where $d_1 = \dot{f}_d$, $d_2 = \bar{M}^{-1}\tau_d$, d_1 and d_2 are the mismatched and matched disturbances of the system, respectively. And

$$\begin{aligned} \dot{e}(t) &= \dot{x}_1 - \dot{p}_d \\ &= \bar{J}x_2 + N_1 + d_1 - \dot{p}_d \end{aligned} \quad (6)$$

To improve the transient and steady-state performance of the system, the trajectory tracking errors are required to satisfy the following inequality

$$-\delta_i v(t) < e_i < \delta_i v(t) \quad (7)$$

where $e_i (i = 1, 2, \dots, n)$ denotes the i th element of $e(t)$, and $0 < \delta_i \leq 1$ is a designed constant.

Then we introduce the following finite-time prescribed performance function:

$$v(t) = \begin{cases} \left(v_0 - \frac{t}{T_f}\right) e^{\left(1 - \frac{T_f}{T_f - t}\right)} + v_{T_f}, & t \in [0, T_f) \\ v_{T_f}, & t \in [T_f, +\infty) \end{cases} \quad (8)$$

where $v_0 \geq 1$ and $v_{T_f} > 0$ are the design parameters. From(), performance function $v(t)$ is positive smooth exponential decreasing with $\lim_{t \rightarrow T_f} v(t) = v_{T_f} > 0$ and $v(t) = v_{T_f}$ for any $t \geq T_f$.

To achieve prescribed performance control, we introduce the following error transformation method to convert the constrained error in (6) into an equivalent unconstrained error $\varepsilon(t)$, abbreviated as ε .

$$Q(\varepsilon_i) = \delta_i \frac{e^{\varepsilon_i} - e^{-\varepsilon_i}}{e^{\varepsilon_i} + e^{-\varepsilon_i}} = \frac{e_i(t)}{v(t)} \quad (9)$$

Property 4: $Q(\varepsilon_i)$ is a smooth and strictly increasing function, $\lim_{\varepsilon_i \rightarrow -\infty} Q(\varepsilon_i) = -\delta_i$, $\lim_{\varepsilon_i \rightarrow +\infty} Q(\varepsilon_i) = \delta_i$.

From the definition of $Q(\varepsilon_i)$, we obtain

$$\varepsilon_i = Q^{-1}\left(\frac{e_i(t)}{v(t)}\right) = \frac{1}{2} \ln \frac{\delta_i v(t) + e_i(t)}{\delta_i v(t) - e_i(t)} \quad (10)$$

and

$$\frac{\partial Q(\varepsilon_i)}{\partial \varepsilon_i} = \delta_i - \delta_i \left(\frac{e^{\varepsilon_i} - e^{-\varepsilon_i}}{e^{\varepsilon_i} + e^{-\varepsilon_i}} \right)^2 \quad (11)$$

We can get $e_i(t) = v(t)Q(\varepsilon_i)$, then we know

$$\dot{e}_i(t) = \dot{v}(t)Q(\varepsilon_i) + v(t) \frac{\partial Q(\varepsilon_i)}{\partial \varepsilon_i} \dot{\varepsilon}_i \quad (12)$$

According to $e(t) = p - p_d$, we can derive

$$\begin{aligned} \dot{\varepsilon}_i &= \frac{\dot{e}_i(t) - \dot{v}(t)Q(\varepsilon_i)}{v(t) \frac{\partial Q(\varepsilon_i)}{\partial \varepsilon_i}} \\ &= \frac{\dot{e}_i(t)}{v(t) \frac{\partial Q(\varepsilon_i)}{\partial \varepsilon_i}} - \frac{\dot{v}(t)Q(\varepsilon_i)}{v(t) \frac{\partial Q(\varepsilon_i)}{\partial \varepsilon_i}} \\ &= \Psi(\varepsilon_i, t) \dot{e}_i(t) + \phi(\varepsilon_i, t) \end{aligned} \quad (13)$$

with

$$\begin{aligned} \Psi(\varepsilon_i, t) &= \frac{1}{v(t) \frac{\partial Q(\varepsilon_i)}{\partial \varepsilon_i}} \\ \phi(\varepsilon_i, t) &= -\frac{\dot{v}(t)Q(\varepsilon_i)}{v(t) \frac{\partial Q(\varepsilon_i)}{\partial \varepsilon_i}} \end{aligned}$$

Applying the backstepping design method, the trajectory tracking controller designed for the system in (5) is as follows.

Step 1 : To facilitate the subsequent derivation, we first define two auxiliary variables as $z_1 = \varepsilon$, $z_2 = x_2 - \alpha$, where α is a vector of virtual control input. We design α as

$$\alpha = \frac{1}{\bar{J}} \left[-N_1 + \dot{p}_d - \hat{d}_1 - k_1 z_1 - \frac{\phi(\varepsilon, t)}{\Psi(\varepsilon, t)} \right] \quad (14)$$

where $\hat{d}_1$ is the estimation of d_1 , obtained from the observer designed later.

Consider the Lyapunov function as $V_1 = \frac{1}{2} z_1^T z_1$, then according to (13) and (14), we can obtain the time derivative of V_1

$$\begin{aligned} \dot{V}_1 &= z_1^T [\Psi(\varepsilon, t)(\bar{J}x_2 + N_1 + d_1 - \dot{p}_d) + \phi(\varepsilon, t)] \\ &= z_1^T [\Psi(\varepsilon, t)(\bar{J}(z_2 + \alpha) + N_1 + d_1 - \dot{p}_d) + \phi(\varepsilon, t)] \\ &= -k_1 \Psi(\varepsilon, t) z_1^T z_1 + \Psi(\varepsilon, t) \bar{J} z_1^T z_2 + \Psi(\varepsilon, t) z_1^T \tilde{d}_1 \end{aligned} \quad (15)$$

where $\tilde{d}_1 = d_1 - \hat{d}_1$ is the vector of estimation errors. By the definition of $\Psi(\varepsilon_i, t)$ we know that $\Psi(\varepsilon_i, t) > 0$ and is bounded.

Step 2 : To enhance the robustness of the controller and improve the convergence speed, we introduce the sliding surface. Define a switching function as

$$s = z_2 + c_1 \text{sign}^{a_1}(z_1) + c_2 \text{sign}^{a_2}(z_1) \quad (16)$$

where $c_1 = \text{diag}(c_{11}, c_{12}, \dots, c_{1n})$, $c_2 = \text{diag}(c_{21}, c_{22}, \dots, c_{2n})$ are the gain coefficient matrices; $0 < a_1 < 1$, $1 < a_2 < 2$. Choose a Lyapunov candidate function as $V_2 = V_1 + \frac{1}{2}s^T s$. Applying (16) and according to the definitions of z_1 , z_2 , it leads to

$$\begin{aligned} \dot{V}_2 &= \dot{V}_1 + s^T (\dot{z}_2 + c_1 a_1 \text{sign}^{a_1-1} z_1 \dot{z}_1 + c_2 a_2 \text{sign}^{a_2-1} z_1 \dot{z}_1) \\ &= \dot{V}_1 + s^T [\Xi(z_1) (\Psi(\varepsilon, t) \dot{e}(t) + \phi(\varepsilon, t)) + \dot{x}_2 - \dot{\alpha}] \\ &= -k_1 \Psi(\varepsilon, t) z_1^T z_1 + \Psi(\varepsilon, t) \bar{J} z_1^T z_2 + \Psi(\varepsilon, t) z_1^T \bar{d}_1 \\ &\quad + s^T [\Xi(z_1) (\Psi(\varepsilon, t) \dot{e}(t) + \phi(\varepsilon, t)) \\ &\quad + \bar{M}^{-1} \tau - \bar{M}^{-1} N_2 + d_2 - \dot{\alpha}] \end{aligned} \quad (17)$$

where $\Xi(z_1) = c_1 a_1 \text{sign}^{a_1-1} z_1 + c_2 a_2 \text{sign}^{a_2-1} z_1$.

Then we can design the controller τ as

$$\begin{aligned} \tau &= \bar{M} [-\Xi(z_1) (\Psi(\varepsilon, t) \dot{e}(t) - \phi(\varepsilon, t)) + \bar{M}^{-1} N_2 \\ &\quad - \hat{d}_2 - \Psi(\varepsilon, t) \bar{J} z_1 + \dot{\alpha} - h(s + \beta \text{sign}(s))] \end{aligned} \quad (18)$$

where h , β are positive constant matrix and $\hat{d}_2$ is the estimation of disturbance term d_2 , it is designed in the later content.

Remark 1: The proposed controller requires the position and velocity signals of the end-effector and the angular velocity signals of the joints. However, the velocity of the end-effector and the angular velocity of the joints cannot be available directly, while the position of the end-effector is measurable and the joint position can be obtained directly from the encoder. Therefore, in order to estimate the joints angular velocities and end-effector velocities, we adopt first-order exact differential [41].

$$\begin{aligned} \dot{\omega}_0 &= \kappa_q, \dot{\zeta}_0 = \kappa_p \\ \kappa_q &= -\lambda_0 |\omega_0 - q|^{1/2} \text{sign}(\omega_0 - q) + \omega_1 \\ \kappa_p &= -\gamma_0 |\zeta_0 - q|^{1/2} \text{sign}(\zeta_0 - q) + \zeta_1 \\ \dot{\omega}_1 &= -\lambda_1 \text{sign}(\omega_1 - \kappa_q) \\ \dot{\zeta}_1 &= -\gamma_1 \text{sign}(\zeta_1 - \kappa_p) \end{aligned} \quad (19)$$

where $\lambda_0, \lambda_1, \gamma_0$ and γ_1 are positive constants. Then we can obtain $\omega_0 = q$, $\omega_1 = \dot{q} = x_2$, $\zeta_0 = p$, $\zeta_1 = \dot{p}$.

3.2 Time delay estimation

It is known that the accurate model of the manipulator is difficult to obtain, and there is uncertainty in the manipulator model, which means that N_1 and N_2 in (5) are unknown. To effectively solve this problem, we apply the TDE to estimate the unknown kinematic and dynamic parameters, $\hat{N}_1, \hat{N}_2$ are the estimation of N_1, N_2 . A simple struture as

$$\begin{aligned} \hat{N}_1(t) &\cong N_1(t - T) \\ \hat{N}_2(t) &\cong N_2(t - T) \end{aligned} \quad (20)$$

where T stands for a very short time delay constant and it is generally set to a sampling time.

Then the kinematic and dynamic equations at time $(t - T)$ can be rewritten as

$$\begin{cases} \dot{x}_1(t - T) = \bar{J} x_2(t - T) + N_1(t - T) + d_1(t - T) \\ \dot{x}_2(t - T) = \bar{M}^{-1} \tau(t - T) - \bar{M}^{-1} N_2(t - T) + d_2(t - T) \end{cases} \quad (21)$$

where d_1, d_2 are unknown disturbance term. We cannot directly obtain their exact values at the last sampling moment, so we design the disturbance observer to get their estimated values $\hat{d}_1, \hat{d}_2$.

Substituting $\hat{d}_1, \hat{d}_2$ and combining (20) with (21), we get

$$\begin{aligned} \hat{N}_1(t) &= \bar{J} x_2(t - T) - \dot{x}_1(t - T) + \hat{d}_1(t - T) \\ \hat{N}_2(t) &= \tau(t - T) - \bar{M} \dot{x}_2(t - T) + \hat{d}_2(t - T) \end{aligned} \quad (22)$$

From (22), we need the values of $\tau(t - T)$ and $\dot{x}_2(t - T)$, where $\tau(t - T)$ is the value of the control signal τ at the previous moment, which is available, and $\dot{x}_2(t - T)$ can be obtained by the exact differentiator in the previous section, so the TDE can effectively achieve model-free control.

The bounded TDE error vector is defined as follows:

$$\begin{aligned} \theta_1 &= (N_1 - \hat{N}_1) \\ \theta_2 &= (N_2 - \hat{N}_2) \end{aligned} \quad (23)$$

It is known that the TDE error θ_1 and θ_2 is bounded, determined by [42, 43].

To guarantee that the time delay estimation error is bounded, the following inequalities must be satisfied

$$\begin{aligned} \|I - J^{-1} \bar{J}\| &< 1 \\ \|I - M^{-1}(q) \bar{M}\| &< 1 \end{aligned} \quad (24)$$

Assume ϖ_i is the i th eigenvalue of $M(q)$, according to **Property 1**, ϖ_i is bounded. Let η_i is the i th eigenvalue of matrix $(I - M^{-1}(q) \bar{M})$, then $\eta_i = 1 - \bar{m}_i / \varpi_i$.

In order to satisfy the inequality $\|I - M^{-1}(q)\bar{M}\| < 1$, $-1 < \eta_i < 1$ is a sufficient condition, i.e., $-1 < 1 - \bar{m}_i/\varpi_i < 1$ allows the required inequality to hold. Then we only need to choose $0 < \bar{m}_i < 2\varpi_i$. And since ϖ_i is bounded, a reasonable matrix $\bar{M}$ can be found to make the above inequality hold. Similarly, inequality $\|I - M^{-1}(q)\bar{M}\| < 1$ can be accomplished by selecting appropriate $\bar{J}$.

To deal with the time delay estimation errors, we treat them as part of the system disturbances. Then d_1 and d_2 can be rewritten as

$$\begin{aligned} d_1 &= \theta_1 + \dot{f}_d \\ d_2 &= \bar{M}^{-1}(\tau_d - \theta_2) \end{aligned} \quad (25)$$

Then system (5) can be formulated as:

$$\begin{cases} \dot{x}_1 = \bar{J}x_2 + \hat{N}_1 + d_1 \\ \dot{x}_2 = \bar{M}^{-1}\tau - \bar{M}^{-1}\hat{N}_2 + d_2 \end{cases} \quad (26)$$

3.3 Disturbance estimation design

To facilitate the design of the estimator, we first convert the system (26) to the following form

$$\dot{X} = -HX + G(X) + B\tau + \Delta \quad (27)$$

where $X = [x_1, x_2]^T$, $H = \text{diag}(h_1, h_2)$, $h_1 = \text{diag}(h_{11}, h_{12}, \dots, h_{1n})$, $h_2 = \text{diag}(h_{21}, h_{22}, \dots, h_{2n})$, $G(X) = \begin{bmatrix} h_1x_1 + \bar{J}x_2 + \hat{N}_1 \\ h_2x_2 - \bar{M}^{-1}\hat{N}_2 \end{bmatrix}$, $B = [0, \bar{M}^{-1}]^T$, $\Delta = [d_1, d_2]^T$.

To construct an observer capable of estimating both matched and mismatched disturbances, we first design the following auxiliary control system

$$\dot{X}_a = -HX_a + G(X) + B\tau \quad (28)$$

As shown above, H , $G(X)$, B and τ are known variables, so the state X_a of the auxiliary system is measurable.

Define the errors between X and X_a as X_e , according to (27) and (28), we can obtain

$$\dot{X}_e = -HX_e + \Delta \quad (29)$$

We consider Δ as an unknown input, then (29) can be treated as a linear system.

Let $\hat{X}_e$ represent the estimated value of X_e and design the following structure for $\hat{X}_e$

$$\dot{\hat{X}}_e = -L\hat{X}_e + \dot{X}_e + LX_e \quad (30)$$

where $L \in \mathbb{R}^{2n \times 2n}$ is a positive-definite and diagonal matrix. $L = \text{diag}(L_1, L_2)$, $L_1 = \text{diag}(l_{11}, l_{12}, \dots, l_{1n})$, $L_2 = \text{diag}(l_{21}, l_{22}, \dots, l_{2n})$.

According to (29), we can obtain an estimation of the disturbance Δ of the following form

$$\hat{\Delta} = H\hat{X}_e + \dot{X}_e \quad (31)$$

Let the error between the estimation of $\hat{X}_e$ and X_e as $\tilde{X}_e = X_e - \hat{X}_e$. From (29) and (30) we can get

$$\begin{aligned} \dot{\tilde{X}}_e &= \Delta - HX_e - (-L\hat{X}_e + \dot{X}_e + LX_e) \\ &= -L\tilde{X}_e \end{aligned} \quad (32)$$

Subtracting $\hat{\Delta}$ from Δ , based on (31) we can derive the disturbance estimation error that satisfies

$$\begin{aligned} \tilde{\Delta} &= \Delta - \hat{\Delta} \\ &= \Delta - (H\hat{X}_e + \dot{X}_e) \\ &= \Delta - (H\hat{X}_e - HX_e + \Delta) \\ &= H\tilde{X}_e \end{aligned} \quad (33)$$

Remark 2: In contrast to existing ESO, DO, etc [18, 24, 38], the observer employed in this paper does not require any conditions or assumptions about disturbances. Although in **Assumption 1**, we assume that f_d and τ_d are bounded and f_d is derivable. However, the bounds of the disturbance are unknown, we don't need their upper bound values. And if the disturbance is infinite, the system is not controllable. The assumption that f_d is derivable is to transform the system into the equation of state, not a condition required by this disturbance observer. Moreover the closed-loop stability containing the observation error is demonstrated in the next section. Thus the disturbance observer in this paper can effectively handle both matched and mismatched disturbances.

3.4 Proof of closed-loop system

Substituting the estimation results of the above disturbance estimator into the virtual control variable α and control law τ .

$$\begin{aligned} \alpha &= \frac{1}{J} \left[-\hat{N}_1 + \dot{p}_d - \hat{d}_1 - k_1z_1 - \frac{\phi(\varepsilon, t)}{\Psi(\varepsilon, t)} \right] \\ \tau &= \bar{M} \left[-\Xi(z_1) (\Psi(\varepsilon, t)\dot{e}(t) - \phi(\varepsilon, t)) + \bar{M}^{-1}\hat{N}_2 \right. \\ &\quad \left. - \hat{d}_2 - \Psi(\varepsilon, t)\bar{J}z_1 + \dot{\alpha} - h(s + \beta \text{sign}(s)) \right] \end{aligned} \quad (34)$$

Fig. 1: Sketch of the proposed ABIFTSMC based on ESO

Choose a Lyapunov function as $V_3 = V_2 + \frac{1}{2} \tilde{\Delta}^T \tilde{\Delta}$. It can be deduced from (14) and (18) that

$$\begin{aligned} \dot{V}_3 &= \dot{V}_2 + \tilde{\Delta}^T \dot{\tilde{\Delta}} \\ \dot{V}_3 &= -k_1 \Psi(\varepsilon, t) z_1^T z_1 - h s^T s - h \beta \sum_{i=1}^n |s_i| \\ &\quad - \Psi(\varepsilon, t) \bar{J} \sum_{i=1}^n c_{1,i} |z_{1,i}|^{a_1+1} - \Psi(\varepsilon, t) \bar{J} \sum_{i=1}^n c_{2,i} |z_{1,i}|^{a_2+1} \\ &\quad + \Psi(\varepsilon, t) z_1^T \tilde{d}_1 + s^T \tilde{d}_2 + \tilde{\Delta}^T \dot{\tilde{\Delta}} \end{aligned} \quad (35)$$

Based on (32) and (33), we can obtain

$$\begin{aligned} \tilde{\Delta}^T \dot{\tilde{\Delta}} &= \tilde{\Delta}^T H \dot{\tilde{X}}_e \\ &= -\tilde{\Delta}^T H L \tilde{X}_e \\ &= -\tilde{\Delta}^T L \tilde{\Delta} \\ &= -\tilde{d}_1^T L_1 \tilde{d}_1 - \tilde{d}_2^T L_2 \tilde{d}_2 \end{aligned} \quad (36)$$

Then the following inequality can be given

$$\tilde{\Delta}^T \dot{\tilde{\Delta}} \leq -\lambda_{\min}(L_1) \|\tilde{d}_1\|^2 - \lambda_{\min}(L_2) \|\tilde{d}_2\|^2 \quad (37)$$

It is well known that the following inequalities hold

$$\begin{aligned} z_1^T \tilde{d}_1 &\leq \frac{1}{r_1} \|z_1\|^2 + r_1 \|\tilde{d}_1\|^2 \\ s^T \tilde{d}_2 &\leq \frac{1}{r_2} \|s\|^2 + r_2 \|\tilde{d}_2\|^2 \end{aligned} \quad (38)$$

Therefore, based on the above inequality, it is deduced that

$$\begin{aligned} \dot{V}_3 &\leq -k_1 \Psi(\varepsilon, t) z_1^T z_1 - h s^T s \\ &\quad + \frac{1}{r_1} \Psi(\varepsilon, t) \|z_1\|^2 + r_1 \Psi(\varepsilon, t) \|\tilde{d}_1\|^2 + \frac{1}{r_2} \|s\|^2 + r_2 \|\tilde{d}_2\|^2 \\ &\quad - \lambda_{\min}(L_1) \|\tilde{d}_1\|^2 - \lambda_{\min}(L_2) \|\tilde{d}_2\|^2 \\ &\leq -\Psi(\varepsilon, t) \left(k_1 - \frac{1}{r_1} \right) \|z_1\|^2 - \left(h - \frac{1}{r_2} \right) \|s\|^2 \\ &\quad - (\lambda_{\min}(L_1) - r_1 \Psi(\varepsilon, t)) \|\tilde{d}_1\|^2 \\ &\quad - (\lambda_{\min}(L_2) - r_2) \|\tilde{d}_2\|^2 \end{aligned} \quad (39)$$

To achieve closed-loop system stability, it is only necessary to choose k_1 , h , L_1 and L_2 to satisfy the following inequalities

$$\begin{aligned} k_1 - \frac{1}{r_1} &> 0, h - \frac{1}{r_2} > 0 \\ \lambda_{\min}(L_1) - r_1 \Psi(\varepsilon, t) &> 0, \lambda_{\min}(L_2) - r_2 > 0 \end{aligned} \quad (40)$$

where $r_1, r_2 \in \mathbb{R}$ are positive scalars and determined by the designer.

Remark 3: From the definition of $\Psi(\varepsilon, t)$, it is clear that $\Psi(\varepsilon, t) \in [0, 1]$ and bounded. And r_1 and r_2 are chosen by the designer, so the design parameters are feasible to satisfy the above inequalities. The stability of the closed-loop system can be achieved by designing the appropriate parameters.

4 Numerical simulation

In this section, the performance of the proposed approach is verified by numerical simulation of the three-link anthropomorphic robotic arm shown in Fig.2. q_1, q_2

Fig. 2: The architecture of two-link robotic manipulators

and q_3 represent the angle positions of joints, and $\dot{q}_1, \dot{q}_2$ and $\dot{q}_3$ are the angular velocities of joints. The kinematic equations of the three-joint manipulator are as follows

$$\begin{cases} x = \cos q_1 (l_2 \cos q_2) + l_3 \cos (q_2 + q_3) \\ y = \sin q_1 (l_2 \cos q_2) + l_3 \cos (q_2 + q_3) \\ z = l_2 \sin q_2 + l_3 \sin (q_2 + q_3) \end{cases}$$

where (x, y, z) is the end-effector position of the manipulator.

The dynamic of the manipulator in (1) by Lagrangian equation is represented as

$$M(q) = \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{bmatrix}, G(q) = \begin{bmatrix} g_1 \\ g_2 \\ g_3 \end{bmatrix},$$

$$C(q, \dot{q}) = \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix}.$$

$$\begin{aligned} m_{11} &= I_1 + a_1 \cos^2 q_2 + a_2 \cos (q_2 + q_3) + \\ &\quad 2a_3 \cos q_2 \cos (q_2 + q_3) \\ m_{12} &= m_{21} = m_{13} = m_{31} = 0, m_{33} = I_3 + a_2, \\ m_{22} &= I_2 + a_1 + a_2 + 2a_3 \cos q_3, \\ m_{23} &= m_{32} = a_2 + a_3 \cos q_3, \end{aligned}$$

Table 1: Physical parameters of the two-link robotic manipulator.

Symbol	Definition	Value
m_1	mass of link 1	10 kg
m_2	mass of link 2	8 kg
l_2	Length of link 2	0.5 m
r_2	Length of the center of mass of link 1	0.254 m
l_3	Length of link 3	0.4 m
r_3	Length of the center of mass of link 2	0.205 m
g	Gravitational constant	9.81 m/s

$$c_{11} = -\frac{1}{2} a_1 \dot{q}_2 \sin (2q_2) - a_3 \dot{q}_2 \sin (2q_2 + q_3) -$$

$$\frac{1}{2} a_2 (\dot{q}_2 + \dot{q}_3) \sin (2q_2 + 2q_3) -$$

$$a_3 \dot{q}_3 \cos q_2 \sin (q_2 + q_3)$$

$$c_{12} = -\frac{1}{2} a_1 \dot{q}_1 \sin (2q_2) - a_3 \dot{q}_1 \sin (2q_2 + q_3) -$$

$$\frac{1}{2} a_2 \dot{q}_1 \sin (2q_2 + 2q_3),$$

$$c_{13} = -a_3 \dot{q}_1 \cos q_2 \sin (q_2 + q_3) -$$

$$\frac{1}{2} a_1 \dot{q}_1 \sin (2q_2 + 2q_3),$$

$$c_{21} = -c_{12}, c_{31} = -c_{13}, c_{33} = 0$$

$$c_{23} = -a_3 (\dot{q}_2 + \dot{q}_3) \sin q_3,$$

$$c_{32} = -a_3 \dot{q}_2 \sin q_3, c_{22} = -a_3 \dot{q}_3 \sin q_3,$$

$$g_1 = 0, g_2 = b_1 \cos q_2 + b_2 \cos (q_2 + q_3),$$

$$g_3 = b_2 \cos (q_2 + q_3).$$

where $a_1 = m_2 r_2^2 + m_3 l_2^2$, $a_2 = m_3 r_3^2$, $a_3 = m_3 r_3 l_3$, $b_1 = (m_2 r_2 + m_3 l_2) g$, $b_2 = m_3 r_3 g$.

Table 1 lists the basic parameters of the robotic arm for numerical simulation

The initial values of the system are selected as $p_0 = [0.373, 0.384, 0.4987]^T$, $\dot{q}_0 = [0, 0, 0]^T$, respectively. The desired trajectories are selected as

$$\begin{cases} x = 0.3 + 0.1 \times \cos(t) \\ y = 0.3 + 0.1 \times \sin(t) \\ z = 0.2 - 0.033 \times t \end{cases} \quad (41)$$

To check the robustness of the system, we add the following disturbances to the system

$$d_1 = \begin{bmatrix} 0.5q_1 + \sin(3q_1) + \sin(t) \\ 1.3q_2 - 1.8\sin(2 * q_2) + 0.8\sin(t) \\ -1.8q_3 + 2\sin(3 * q_3) + 0.9\cos(t) \end{bmatrix}$$

$$d_2 = \begin{bmatrix} 1.5\dot{q}_1 + \cos(2q_1) + 2\cos(t) \\ -0.8\dot{q}_2 + 0.8\cos(3q_2) + 1.2\sin(t) \\ 1.5\dot{q}_3 - 3\sin(3q_3) + 1.4\sin(t) \end{bmatrix}$$

where d_1 represent the disturbances in the signal transformation from joint space to task space, which are mismatched disturbances. d_2 denote the disturbances when

Table 2: Controller parameters

Parameters	δ	v_0	T_f	v_{T_f}	k_1	c_1	c_2
Value	1	1	0.6	0.001	10	5	15
Parameters	a_1	a_2	h	β	L	J	M
Value	2	0.7	10	0.01	$40I^{3 \times 3}$	$5I^{3 \times 3}$	$8I^{3 \times 3}$

Desired position trajectory and actual position trajectory

the joints are rotated by the torques, which are matched disturbances.

Remark 4: There is no particular reason for the selection of the above disturbance functions, which represent unknown disturbance matrices and can be arbitrarily denoted by a time-varying function with a reasonable magnitude.

To verify the superior performance of the proposed control method in the fast convergence and tracking accuracy, it is compared with other recently proposed advanced control methods, including the adaptive NFTSMC approach indicated in [33], second order NFTSMC strategy presented in [34], adaptive fuzzy integral SMC [18], and adaptive backstepping NFTSMC in [14]. The parameters of our proposed controller are shown in Table 3.

Figure 1 shows the tracking results of the proposed control method for the spatial cylindrical helix. Figure 2 shows the variation of the components of the tracking error in the x, y, z directions in the three-dimensional task space, respectively. It can be seen from the figure 2 that the errors are all restricted to the prescribed performance function. From the above results, it can be seen that our proposed approach achieves accurate

Position trajectory tracking errors

model-free trajectory tracking for the robotic arm system in the presence of matched and mismatched disturbances. And the transient control of errors can be achieved by adjusting the parameters of the prescribed performance function.

Furthermore to demonstrate the superior performance of the proposed control method, it is compared with the recently proposed advanced control methods [33, 34, 14, 18]. Since none of the above comparison methods consider the mismatched disturbance, the mismatched disturbance d_1 in the controlled system is not considered in the simulation comparison of the above approaches, while the proposed control method in this paper still operates in the presence of the mismatched disturbance d_2 .

All comparative simulations are performed in the same initial states. Figures 3 to 5 show the position tracking error of each joint for different control methods. It can be seen from the figures that our controller converges the error to zero in a faster time compared to the other control methods. The speed of error convergence for all these methods, including the approach proposed in this paper, is quite significantly affected by parameters such as proportional gain, and generally the larger the gain value, the faster the system converges, but with greater oscillations. In this simulation, the parameters of each method are selected based on trial-and-error method or experience to obtain a balance between convergence speed and oscillation. The main advantage of the controller proposed in this paper is that the control error can be directly limited within a reasonable range by the prescribed performance function, which achieves the control of transient performance. As can be seen from the figure, our control method also obtains smaller steady-state errors. For a more intuitive

Fig. 3: Tracking error of X-axis

Fig. 5: Tracking error of Z-axis

Fig. 4: Tracking error of Y-axis

Table 3: Comparison of the performance indices

Controller \ AE	AE ₁	AE ₂	AE ₃
Proposed controller	0.0005	0.0011	0.0022
ABNFTSMC	0.0005	0.0025	0.0066
ANFTSMC	0.0008	0.0027	0.0084
SOFNTSMC	0.0004	0.0020	0.0070
AISMC	0.0024	0.0012	0.0039

illustration, we introduce the average value of the errors (AE) for quantitative analysis and comparison. The AE are defined as follows:

$$AE_j = \frac{1}{t_f - t_0} \int_{t_0}^{t_f} |e_j(t)| dt, \quad j = 1, 2, 3 \quad (42)$$

where t_0 and t_f are the initial time and the end time, respectively. Performance indicators of the comparative control strategies are reported in Table 3. From the above table, it can be seen that, compared to other methods, even though the controller in this paper operates with the included additional mismatched disturbances, it still obtains the smallest AE values.

Fig.6 exhibits the Control torque of each joint for different controllers. Because the same desired trajectory is tracked on the same robotic arm model, the torque of the methods used for comparison is basically similar. In contrast, the method proposed in this paper has a large difference in torques from the comparison

Fig. 6: Control torque of each joint for different control methods

method because of the inclusion of mismatched disturbances. As can be seen from the figure, our controller remains basically smooth, without singularity and with less chatter, even with the additional consideration of mismatched disturbances.

5 Conclusion

In this paper, we consider the mismatched uncertainty in the conversion of the robot arm joint space signal to the actual motion of the task space end-effector and design a model-free control method for this problem.

Firstly, the errors are transformed by a prescribed performance function to restrict the errors to a given range to achieve transient control. Then we designed a fast terminal sliding surface for the auxiliary control variables in the backstepping method to improve the convergence speed of the system. The dynamic and kinematic parameters of the robotic arm system are estimated utilizing time delay estimation to achieve model-free control. Considering the time delay estimation error as part of the external disturbance and designing an observer capable of estimating both matched and mismatched disturbances. The feasibility and superiority of the method in this paper are demonstrated by numerical simulation and theoretical derivation.

In the numerical simulation results, we can find that although we solve mismatched uncertainty, it also triggers the overshoot phenomenon. How to avoid overshoot on the basis of the method proposed in this paper is the focus of our future research.

Declarations

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Conflicts of interest

Authors have no conflict of interest to declare.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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