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RESEARCH ARTICLE

TDE-Based Adaptive Super-Twisting Multivariable Fast Terminal Slide Mode Control for Cable-Driven Manipulators With Safety Constraint of Error

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ABSTRACT An adaptive super-twisting multivariable fast terminal sliding mode control scheme based on time delay estimation (TDE) and asymmetric error constraints are proposed to guarantee high-precision trajectory tracking control of cable-driven manipulators under complicated unknown uncertainties. The control system is constrained by joint position errors, which are asymmetric and time-varying. First, the error range of the joints is designed to ensure that the deviation of the joint position from the desired profile is not too large while ensuring the safety performance of the manipulator, and the remaining set-total system dynamics are estimated and compensated using time-delay estimation. Secondly, the design analysis of the angular false expectation using safety constraint functions allows the constraints of different cross sections to be handled in a unified system architecture; the problem of robotic arm motion trajectories with output constraints and uncertainties is addressed through rigorous analysis. The super-twisting adaptive control effectively ensures fast, accurate and robust convergence of the algorithm in satisfying all constraints in operation, and the stability of the closed-loop control system is analyzed using the Lyapunov method. Finally, the effectiveness and superiority of the proposed adaptive hyper-torsional non-singular terminal sliding mode control scheme are verified by simulations and experiments in 2-DOF.

INDEX TERMS Cable-diven manipulator, asymmetric error constraint, TDE scheme, adaptive supertwisting control.

I. INTRODUCTION

In recent years, cable-driven manipulators have gradually become a hot research topic due to their unique advantages [1], [2], [3], [4], [5]. Compared with traditional manipulators, cabledriven manipulators move the drive motor from the joint tothe base and transmit the force through the cable, so the motion inertia is more negligible, more flexible, has a higherload factor, and has higher safety [6], [7], [8], [9]. However, achieving accurate control of cable-driven manipulators is more complex than conventional robot arms. The key challenges are the complex system dynamics and maintaining control accuracy in the presence of external disturbances and damage to the manipulator. Therefore, achieving high-performance control of cable-driven manipulators remains a challenging task.

Many scholars have conducted much research on the robotic arm control accuracy problem. In [10], a robust PID controller was designed by combining robust control and PID control to realize the trajectory tracking control of the robotic arm. Literature [11] proposed a prescribed performance controller based on linear extended state observer (LESO) to solve the problem of stabilization of complex transformation systems and improve control accuracy. Xu B et al. proposed

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an orthogonal fuzzy PID [12]. However, most of the works in the literature that consider the joint tracking problem do not address the error constraint during the operation. However, the error constraint requirement cannot be ignored to ensure cable-driven manipulators' accurate and safe operation. In general, the purpose of control is to enable the error of the system to be gradually reduced to a minimum value, meaning that the error is within the control range. Due to the limitations of the mechanical control structure, some position ranges are unsafe, and this range varies with time. Suppose we encounter an unexpected event that causes a considerable deviation. In that case, the error floats in an unpredictable range, and we cannot react in time. It may lead to excessive motion errors in the mechanical system and collision with the outside world, causing safety problems and economic losses.

To solve the error constraint problem, in [13], a new constrained error variable similar to the sliding mode surface was proposed to ensure the prescribed position tracking performance of the robot manipulator. Li Y et al. solved the output constraint problem due to physical and environmental constraints by constructing an integral barrier Lyapunov function [14]. In [15], a controller was designed using the traditional logarithmic Lyapunov function to achieve trajectory tracking control of a robot arm under full-state constraints. However, most of these methods focus on input or output safety constraints and do not satisfy the time-varying and asymmetric safety constraints on position errors. In this regard, we introduce a safety constraint on the joint position error in the control link to set a safe range for the error between the actual joint position and the desired joint position so that there is an upper and lower limit. This upper limit can be given by the actual situation and can be asymmetric or time-varying. The control purpose is to satisfy the safety constraint to ensure the accurate and proper operation of the cable-driven manipulator.

This paper introduces the barrier function by considering the above problem to satisfy the security constraint. The barrier function is a continuous function that can replace the inequality constraint with an easier-to-handle penalty term in the objective function of constraint optimization. Due to this advantage, the barrier function has been the subject of academic research. In [16], the asymmetric potential Lyapunov function is used to cope with the output constraint. In [17], the potential barrier Lyapunov function (BLF) is used to design a model-based controller to prevent the position tracking error from violating the predefined output constraint. Inspired by the above literature, this paper adopts the safety constraint term of the generic barrier function in the design and analysis of the controller, which is a unified structure to solve time-varying and asymmetric position error safety constraints in a single control structure.

There have been many results on control methods based on asymmetric constraints of manipulators. Kai Z et al. propose a neural adaptive tracking control method for uncertain robotic manipulators with asymmetric and time-varying holomorphic constraints without involving feasibility conditions [18]. The scheme adapts to asymmetric but time-varying motion constraints. In [19], a new iterative learning control (ILC) scheme was proposed for tracking the non-repetitive reference trajectory of a robot manipulator over an iterative domain with different attempt lengths under joint angle asymmetry constraints. In [20], an adaptive timing estimation algorithm for uncertain robots is proposed, and this estimation process avoids measuring acceleration signals.

However, the model parameters include residual linkage dynamics, motor dynamics and set-total uncertainty, which are difficult to obtain by using traditional methods. Time-delay estimation schemes have been proposed and investigated to improve control performance more straightforwardly [21], [22]. TDE is a method that uses the state of a time-delay system to estimate the residual dynamics, which allows TDE to provide an attractive model-free property. Thanks to these properties, the TDE technique has been widely used since its introduction [23], [24], [25]. In [23], a new adaptive fractional-order non-singular terminal sliding mode time delay control (TDC) scheme is proposed and investigated for the high-performance control of cable-driven robotic arms, using time-delay estimation (TDE) as the basic framework. In [24], an adaptive super-torsional non-singular fast terminal sliding mode control scheme based on time lag estimation (TDE) is proposed to ensure high-precision trajectory tracking control of cable-driven robotic arms under complex unknown uncertainty conditions where the TDE is used to estimate and compensate for the remaining centralised system dynamics. However, the application of TDE is subject to estimation errors, especially when the system contains fast time-varying dynamics. This is likely to result in a degradation of control performance.

Therefore, TDE is usually combined with other robust control schemes, and the resulting TDE-based robust control schemes have both model-free characteristics and high control performance. Benefiting from these advantages, scholars have proposed many schemes such as sliding mode control (SMC). In [26], some new SMC schemes for NCSs subject to time-delay, packet losses, quantisation and uncertainty/disturbance are summarised. and terminal sliding mode (TSM) control [27], adaptive methods [28], fuzzy logic control [29] and neural network control [30]. In [24], a new TDE-based adaptive super-twisting nonsingular fast terminal sliding mode (AST-NFTSM) control scheme is proposed for the tracking control of robotic manipulators. The method has achieved good results. However, its design only considers the tracking error, while this paper considers the tracking error and achieves accurate tracking while also considering the asymmetric error constraint and improves the super-twisting algorithm to achieve fast convergence and high precision control.

Inspired by the above work, we propose a new adaptive super-twisting multivariable fast terminal sliding mode for accurate trajectory tracking of cable-driven manipulators. The method uses the TDE as the basic framework for the technique, exploiting the model-free properties while taking into account asymmetric error constraints and improving the super-twisting algorithm to ensure fast convergence and high control accuracy. The control scheme is able to guarantee high control performance in a simple manner. Finally, the effectiveness and superiority of the method are verified through comparative experiments.

The main contributions of this article are summarized as follows:

(1) In order to improve the control accuracy and robustness of the, this paper proposes an adaptive super-twisting multivariable fast terminal sliding mode control scheme based on TDE.

(2) In order to avoid the large control error of the and ensure the stability of the during operation, this paper uses the barrier function to add an asymmetric constraint on its error.

(3) The error between the measured state and the actual state is reduced, by estimating and compensating the aggregate system dynamics using time delay estimation.

The rest of the paper is organised as follows: Section 2 gives a description of the problem. Section 3 presents the design and discussion of the control scheme. Section 4 presents the experimental results and finally Section 5 concludes the paper.

II. PROBLEM FORMULATION

A. SYSTEM MODEL

The dynamic model of a with n-DOFs is represented as [26]:

$$J\ddot{\theta} + d_m\dot{\theta} = \tau_m - \tau_s \tag{1}$$

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) + fr(q,\dot{q}) + \tau_d = \tau_s \tag{2}$$

$$\tau_s = d_s(\dot{\theta} - \dot{q}) + k_s(\theta - q) \tag{3}$$

where, J and d_m are motor inertia and damping matrices, q and θ are joint and motor position vectors, $M(q)$ is inertia matrix, $C(q,\dot{q})$ is coriolis/centrifugal matrix, $g(q)$ is gravitation, $fr(q,\dot{q})$ is friction vector, τ_m and τ_s are control torque given for the motor and joint flexure torque, d_s is damping matrix, k_s is a joint stiffness matrix. τ_d represents the lumped un-known uncertainties.

To make convenient use of the TDE scheme, substitute (2) into (1) and apply a constant parameter $\tilde{M}$ gives:

$$\tilde{M}\ddot{q} + f = \tau_m \tag{4}$$

where, the expression for f is:

$$f = (M - \tilde{M})\ddot{q} + C(q,\dot{q})\dot{q} + g(q) + fr(q,\dot{q}) + \tau_d + J\ddot{\theta} + d_m\dot{\theta} \tag{5}$$

Remark 1: The three main components of f, including residual linkage dynamics, motor dynamics and aggregate uncertainty, are difficult to obtain by using traditional methods, and this paper uses TED to estimate the value of f in the subsequent paper.

Remark 2: The original dynamics model is a mathematical model based entirely on the characteristics of the cable-diven manipulator. In order to simplify the model as well as to facilitate the use of the TDE method and to add an additional parameter to facilitate our control process, this paper changes the original model form into the final dynamics model by a simple transformation. The dynamics models of system (1)-(3) will not be used for the proposed control scheme, and only the final dynamics model will be used for the derivation of the control scheme in this paper.

B. SAFETY CONSTRAINTS

1) ERROR SAFETY CONTRAINT

Define the attitude tracking error of the as:

$$e_Q = [e_{q1}, e_{q2}] = Q - Q_{di} \tag{6}$$

where, $Q = [q_1, q_2]^T$, $Q_{di}(t) = [q_{d1}(t), q_{d2}(t)]^T$. Based on the starting and ending positions, the velocity, the acceleration and the trajectory time t, six equations can be constructed and the six coefficients of the fifth order polynomial can be solved, then we can get $Q_{di}(t)$.

The attitude tracking error must satisfy the following conditions:

$$-\Omega_{Li}(t) < e_{qi}(t) < \Omega_{Hi}(t) \tag{7}$$

where, for all $t \geq 0$, the constraint functions Ω_{Li} and Ω_{Hi} are second order derivable functions and

$$0 < \Omega_{Li}(t) \leq \frac{\pi}{2} + Q_{di}(t), 0 < \Omega_{Hi}(t) \leq \frac{\pi}{2} - Q_{di}(t) \tag{8}$$

Remark 3: Safety constraints (6)-(8) require that the attitude tracking error not exceed a user-defined range. Where the constraint functions on each degree of freedom profile can differ, the constraint functions mentioned above can also be time-varying and asymmetric. If the constraint requirement (8) is violated, the kinematic performance of the robot arm can be affected, making its dynamical system unstable and leading to system failure.

2) SAFETY CONSTRAINT FUNCTION

In this section we present the structure of the barrier function, a structure that solves the problem of time-varying and asymmetric constrained demands. The error variables are introduced as follows:

$$\eta_{ij} = \frac{\Omega_{Lij}\Omega_{Hij}e_{ij}}{(\Omega_{Hij} - e_{ij})(\Omega_{Lij} + e_{ij})} \tag{9}$$

It is clear that $\eta_{ij} = 0$ if and only if $e_{ij} = 0$. Besides, when $e_{ij} \to \Omega_{Hij}$, $\eta_{ij} \to +\infty$, Alternatively, when $e_{ij} \to -\Omega_{Lij}$, we have $\eta_{ij} \to -\infty$.

Remark 4: For the universal barrier function V_{ij}, if the constraint function is symmetric, namely when $\Omega_{Hij} = \Omega_{Lij} = \Omega_{ij}$, the barrier function η_{ij} is as follows:

$$\eta_{ij} = \frac{\Omega_{ij}^2 e_{ij}}{\Omega_{ij}^2 - e_{ij}^2} \tag{10}$$

When there are no constraints on d_{eij}, this can be equated to $\Omega_{Hij} = \Omega_{Lij} = \Omega_{ij} \to +\infty$, so we have:

$$\lim_{\Omega_{ij}\to\infty} \eta_{ij} = e_{ij} \tag{11}$$

This represents that we can consider systems with no output constraint requirements as a special case of the general case of asymmetric constraint requirements.

For the position tracking the error constraint of the, we first introduce the transformed error variables as follows:

$$\eta_{qi} = \frac{\Omega_{qH}\Omega_{qL}e_{qi}}{(\Omega_{qH} - e_{qi})(\Omega_{qL} + e_{qi})} \tag{12}$$

where, $\eta_Q \in \mathbb{R}^2$ and η_{qi} means the barrier function of the ith degree of freedom.

3) TED SCHEME

As shown in equation (5), $\hat{f}$ is particularly complex and difficult to find, and in this section we will use the TED scheme to find the estimated value $\hat{f}$ of f:

$$\hat{f} \cong f(t - \Delta t) \tag{13}$$

where, Δt represents the delay time, then substitute the integrated system dynamics (4) into (16) yields

$$\hat{f}(t) \cong \tau_m(t - \Delta t) - \tilde{M}\ddot{q}(t - \Delta t) \tag{14}$$

As can be seen from (13) and (14), the main aim of the TED scheme is to estimate the set total system dynamics using only the time lag values of the control and acceleration signals, which then gives a model-free scheme.

In engineering applications, $\tau_m(t - \Delta t)$ is achieved with directly time delay of τ_m. In [2], $\ddot{q}(t - \Delta t)$ is obtained by the numerical differentiation method.

$$\begin{cases} \ddot{q}(t - \Delta t) = \dfrac{q(t) - 2q(t - \Delta t) + q(t - 2\Delta t)}{(\Delta t)^2}, & t > T \\ \ddot{q}(t - \Delta t) = 0, & t \leq T \end{cases} \tag{15}$$

Δt is determined by the interval time of the system pulse. Equation (15) mainly solves the problem that when just starting up, the initial phase $t \leq 2\Delta t$, $q(t)$ has the actual measured value, but $q(t - 2\Delta t)$ will be manually set to zero, which will lead to strong fluctuations in the system. Using equation (15) to select the segmentation function, which is automatically set $\ddot{q}(t - \Delta t) = 0$, when $T \geq 2\Delta t$, $t \leq T$, can make it possible that in the initial phase, the system will not have strong fluctuations due to the strong fluctuations of the estimated system generate excessive false responses. Also focus on (15) and its original version, namely:

$$\ddot{q}(t - \Delta t) = \frac{[q(t) - 2q(t - \Delta t) + q(t - 2\Delta t)]}{(\Delta t)^2} \tag{16}$$

It is widely used in many TDE-based robust control schemes [5], [21], [24], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40], [41], [42], [43], [44], [45], [46], [47], [48]. The simulation part of this paper proves its validity. If the measures are not taken, numerical differentiation (16) can significantly amplify noise effects and thus reduce the control performance. However, it has been shown theoretically [44] that this problem can be solved by reducing the gain M or by using an additional low-pass filter.

Remark 5: As shown in (15) and (16), the current values of the lumped system dynamics are obtained by the TDE scheme using time lag system state estimation. Therefore, the estimation error of this method becomes larger when there are large perturbations. However, the newly proposed method can reduce the estimation error, and the simulations in this paper demonstrate the method's effectiveness.

III. CONTROL DESIGN

A. STEP 1

In this step we define the error e_Q in the joint angle Q of the, it satisfies the equation the $e_Q = Q - Q_{di}$, and q_d is the artificially given expectation for the joint position. The range of q_i is $-\pi < q_i < \pi$.

Define ω as the derivative of Q. Use the back-stepping method we have $e_\omega = \omega - \alpha_\omega$, $\omega = \dot{Q}$.

The derivative of e_ω gives as follows:

$$\dot{e}_\omega = \frac{1}{\tilde{M}}(\tau_m - f) - \ddot{Q}_{di} \tag{17}$$

B. STEP 2

In this step, we consider the safety constraints of joint position error. Design the barrier function as(13)(14)

The derivative of η_{qi} gives as follows:

$$\dot{\eta}_{qi} = \Delta_{Hq} + \Delta_{Lq} + \gamma_{qi}\dot{e}_{qi} \tag{18}$$

where, $\Delta_{Hq} = \frac{\partial \eta_{qi}}{\partial \Omega_{qH}}\dot{\Omega}_{qH}$, $\Delta_{Lq} = \frac{\partial \eta_{qi}}{\partial \Omega_{qL}}\dot{\Omega}_{qL}$

Define the asymmetric constraint function:

$$\begin{aligned} \frac{\partial \eta_{qi}}{\partial \Omega_{qH}} &= -\frac{\Omega_{qL}e_{qi}^2}{(\Omega_{qH} - e_{qi})^2, (\Omega_{qL} + e_{qi})}, \\ \frac{\partial \eta_{qi}}{\partial \Omega_{qL}} &= \frac{\Omega_{qH}e_{qi}^2}{(\Omega_{qH} - e_{qi})(\Omega_{qL} + e_{qi})^2} \end{aligned} \tag{19}$$

$$\gamma_{qi} = \frac{\partial \eta_{qi}}{\partial e_{qi}} = \frac{\Omega_{qH}\Omega_{qL}(e_{qi}^2 + \Omega_{qH}\Omega_{qL})}{(\Omega_{qH} - e_{qi})^2(\Omega_{qL} + e_{qi})^2} \tag{20}$$

C. STEP 3

In this step, we consider joint position kinematics of cable-driven s. Design the ASTMFTSM surface as:

$$S = \eta_Q + \varpi e_\omega \tag{21}$$

Deriving both sides of the equation(21)

$$\dot{S} = \eta_{\Omega Q} + \gamma_Q \circ e_\omega + \varpi \left[\frac{1}{\tilde{M}}(\tau_m - f) - \ddot{Q}_d\right] \tag{22}$$

Set:

$$\dot{S} = \alpha\tau_m + \beta_1 + \beta_2 \tag{23}$$

where,

$$\begin{aligned} \beta_1 &= \eta_{\Omega Q} + \gamma_Q \circ e_\omega - \frac{\varpi}{\tilde{M}}f - \frac{\varpi}{\tilde{M}}\ddot{Q}_d \\ \beta_2 &= \Delta\ddot{d}_w + \Delta\ddot{d}_{TDE}, \alpha = \frac{\varpi}{\tilde{M}} \end{aligned} \tag{24}$$

where $\Delta\ddot{d}_{TDE} = -\tilde{M}(\hat{f} - f)$ stands for the TDE error.

D. STEP 4

In this step, design of the overall controller will be carried out and we use the TED scheme (14) and (15) to obtain $\hat{f}$. The overall control scheme is as follows:

$$\begin{aligned} \tau_m &= -\frac{1}{\alpha}\beta_1 - \frac{1}{\alpha}(k_{q1}\xi_1(S) + z_\omega) \\ \dot{z}_\omega &= -k_{q2}\xi_2(S) \end{aligned} \tag{25}$$

$\xi_1(S)$ and $\xi_2(S)$ can be expressed as follows:

$$\begin{aligned} \xi_1(S) &= \frac{S}{\|S\|^{1/2}} + k_{q3}S, k_{q3} > 0 \\ \xi_2(S) &= \frac{d\xi_1(S)}{dS}\xi_1(S) = \frac{1}{2}\frac{S}{\|S\|^{1/2}} \\ &\quad + \frac{3}{2}k_{q3}\frac{S}{\|S\|^{1/2}} + k_{q3}^2 S \end{aligned} \tag{26}$$

k_{q1}, k_{q2} are adaptive gains and are all greater than zero.

$$\begin{aligned} \dot{k}_{q1} &= \begin{cases} \bar{k}_{q1}\|S\|\, sign(\|S\| - \varepsilon), & k_{q1} > \mu \\ \mu, & k_{q1} \le \mu \end{cases} \\ k_{q2} &= \eta_q k_{q1} \end{aligned} \tag{27}$$

In summary, (22) can be expressed as:

$$\begin{aligned} \dot{S} &= -k_{q1}\xi_1(S) + z_\omega \\ \dot{z}_\omega &= -k_{q2}\xi_2(S) + \beta_2 \end{aligned} \tag{28}$$

Theorem 1: In this system, with gain (27), the selection of a suitable parameter $\mu, \bar{k}_{q1}, \eta_q, \varepsilon, \varpi$ sliding surface S of the system can converge to 0 in finite time.

Remark 1: When the velocity error is greater than ε, the adaptive gain $\dot{k}_{q1}$ remains unchanged at a fixed value. When the velocity error is less than ε, the adaptive gain $\dot{k}_{q1}$ decreases with a small slope. To speed up the convergence rate, ε should be given a small value. The parameter $\bar{k}_{q1}$ determines how fast the adaptive gain decreases, which should depend on the control effect. In order to avoid singularities in the system, the parameterμ is as small as possible in the range of values. The parameter k_{q3} in the equation relate to the rate of growth of the adaptive gain. A larger k_{q3} results in faster growth of the adaptive gain and a more dramatic response to changes in error, but at the cost of introducing more measurement noise. The parameter η_q is the ratio between the respective adaptive gains k_{q1} and k_{q2}, which should depend on the control effect. The parameter determines the contribution of the velocity error e_w to the sliding surface.

Proof: For system (27), the Lyapunov method was used to analyse. The Lyapunov candidate functions were chosen as:

$$V_1 = \varsigma^T P\varsigma + \frac{1}{2\gamma_1}\left(k_{q1} - k_{q1}^*\right)^2 + \frac{1}{2\gamma_2}\left(k_{q2} - k_{q2}^*\right)^2 \tag{29}$$

where, k_{q1}, k_{q1}^* is a constant greater than zero: $\varsigma = \begin{bmatrix}\xi_1 & z_\omega\end{bmatrix}^T, P = \begin{bmatrix}\lambda^2 + 4\varepsilon & -\lambda \\ -\lambda & 1\end{bmatrix}$ is a symmetric positive definite matrix, where $\lambda > 0, \varepsilon > 0$.

Derive both sides of the equation(1)

$$\begin{aligned} \dot{V}_1 = \dot{\varsigma}^T P\varsigma + \varsigma^T P\dot{\varsigma} + \frac{1}{\gamma_1}\left(k_{q1} - k_{q1}^*\right)\dot{k}_{r1} \\ + \frac{1}{\gamma_2}\left(k_{q2} - k_{q2}^*\right)\dot{k}_{q2} \end{aligned} \tag{30}$$

make $k_2 = k_{q2} - \frac{\beta_2}{\xi_2}$, then $V_{10} = \varsigma^T P\varsigma$ can be transformed into:

$$\dot{V}_{10} = -2\xi_1'\varsigma^T Q\varsigma \tag{31}$$

where, Q is symmetric matrix,

$$\begin{aligned} Q &= \begin{bmatrix} c_1 & c_2 \\ c_2 & c_3 \end{bmatrix}, \\ c_1 &= k_{q1}\lambda^2 + 4k_{q1}\varepsilon - \lambda k_2 = a_1 k_{q1} - \lambda k_2 \\ c_2 &= \frac{1}{2}\left(-\lambda^2 - 4\varepsilon - \lambda k_{q1} + k_2\right) = \frac{1}{2}\left(-a_1 - \lambda k_{q1} + k_2\right) \\ c_3 &= \lambda. \end{aligned}$$

If $\dot{V}_{10}$ is negative definite, then the matrix Q is positive definite and their determinant is to be greater than zero. if $\det(Q) > 0$ is to be guaranteed, then the root discriminant $\lambda k_2(k_{q1} - \lambda) > 0$. Also because $|\beta_2| \le \bar{\delta}$, $\left\|\frac{1}{\xi_2}\right\| \le 2$, therefore, $k_2 > 0, k_{q2} > 2\bar{\delta}, k_{q1} > \lambda$

Where the value range of k_2 is

$$k_2 \in \left[\underline{k}_2, \bar{k}_2\right] = \left[k_{q2} - 2\bar{\delta}, k_{q2} + 2\bar{\delta}\right] \tag{32}$$

Make $k_{q1} = \lambda + \tau$, where $\tau > 0$, then the solution for $\det[Q] = 0$ is:

$$\begin{aligned} \rho_1^+ &= \lambda k_{q1} + k_2 + 2\sqrt{\lambda k_2\left(k_{q1} - \lambda\right)} \\ \rho_1^- &= \lambda k_{q1} + k_2 - 2\sqrt{\lambda k_2\left(k_{q1} - \lambda\right)} \end{aligned} \tag{33}$$

If the value range of ρ_1 is $\left(p_{1\max}^-, p_{1\min}^+\right)$, then $\det[Q] > 0$, when $\rho_{1\max}^- < P_{1\max}^-$, the presence of roots can be guaranteed. Male $\underline{k_2} = \kappa^2$, we have: $\bar{\delta}_2 < \lambda\tau\kappa^2$, then $\underline{k_2} > \frac{\bar{\delta}^2}{\lambda\tau}$, therefore $\underline{k_2} > \frac{\bar{\delta}^2}{\lambda\tau} + 2\bar{\delta}$.

Let $\lambda_{\max}\{P\}$ and $\lambda_{\min}\{P\}$ be the maximum and minimum eigenvalues of the matrixs, then (31) can be transformed into:

$$\dot{V}_{10} = -2\xi_1'\|\varsigma\|^2\lambda_{\min}\{Q\} \leqslant -\gamma_1 V_{10}^{1/2} - \gamma_2 V_{10} \tag{34}$$

where, $\gamma_1 = \frac{\lambda_{\min}\{Q\}\lambda\lambda_{\min}^{1/2}\{P\}}{\lambda_{\max}\{P\}}$, $\gamma_2 = 2k_{q3}\frac{\lambda_{\min}\{Q\}\lambda}{\lambda_{\max}\{P\}}$, therefore

$$\dot{V}_{10} \leqslant -\gamma_1 V_{10}^{1/2} \tag{35}$$

(30) can be transformed into:

$$\dot{V}_1 \le -\beta_\eta V_1^{1/2} + \phi_1 \cdot \left|k_{q1} - k_{q1}^*\right| + \phi_2 \cdot \left|k_{q2} - k_{q2}^*\right| \tag{36}$$

where, $\beta_\eta = \min\{\eta_1, \beta_1, \beta_2\}$, $\phi_1 = -\frac{1}{\gamma_1} \cdot k_{q1} \cdot |S| \cdot sign(|S| - \varepsilon) + \beta_1$, $\phi_2 = -\frac{1}{\gamma_2} \cdot \eta \cdot k_{q1} \cdot |S| \cdot sign(|S| - \varepsilon) + \beta_2$

In order to ensure k_{q1} and k_{q2} grow at slopes of $k_{q1} \cdot |S|$ and $\eta k_{q1} \cdot |S|$ respectively, then it has to meet $|S| > \varepsilon$, when the following conditions are satisfied:

$$\gamma_1 < \frac{k_{q1} \cdot \varepsilon}{\beta_1}, \quad \gamma_2 < \frac{\eta \cdot \bar{k}_{q1} \cdot \varepsilon}{\beta_2} \tag{37}$$

we have $\zeta_1 > 0$ and $\zeta_2 > 0$.

Therefore $\dot{V}_1 \leq -\beta_\eta V_1^{1/2} + \zeta_1 + \zeta_2 \leq -\beta_\eta V_1^{1/2}$, so $|S|$ can converge in finite time to the interval $|S| < \varepsilon_2$; If $|S| < \varepsilon_2$, then $\zeta_1 < 0$, $\zeta_2 < 0$. Positive and negative of $\dot{V}_1$ is unknown, the rate of change of the gain will become $-k_{q1} \cdot |S|$ and $-\eta \cdot k_{q1} \cdot |S|$, when the gain is reduced to the interval $|S| < \varepsilon_2$, the gain will increase at a slope of $k_{q1} \cdot |S|$ and $\eta \cdot k_{q1} \cdot |S|$

IV. SIMULATION

A. SET UP

In order to verify the effectiveness and superiority of the proposed method, a 2-DOF simulation is carried out and compared with that in [24]. At the same time, the convergence of certain degrees of freedom is compared with the existing methods. The system dynamics for the rigid part (2) are obtained directly from [24] with τ_d defined later. For the reference trajectory Q_{di}, it is achieved based on the quintuplet polynomial method, as shown in Fig. 2 (a) and (b).

Our upper and lower bounds for the security constraint are set as $\Omega_{qL} = 0.1e^{-0.04t} + 0.0001$, $\Omega_{qH} = 0.3e^{-0.08t} + 0.0001$.According to the design of the quintuple polynomial, after giving the starting and ending positions, velocity, acceleration and trajectory time T, the six coefficients of the quintuple polynomial can be solved according to six equations.The start and end constraint amounts are set to:

$$q(t_0) = q_0 = 0, q(t_1) = q_1 = 40$$
$$\dot{q}(t_0) = v_0 = 0, \dot{q}(t_1) = v_1 = 0$$
$$\ddot{q}(t_0) = a_0 = 0, \ddot{q}(t_1) = a_1 = 0$$

From the above equation, a system of 6 linear equations is obtained and the following solutions are obtained.

$$\begin{aligned}
T &= t_1 - t_0 \\
h &= q_1 - q_0 \\
k_0 &= q_0 \\
k_1 &= v_0 \\
k_2 &= \frac{a_0}{2} \\
k_3 &= \frac{1}{2T^3}[20h - (8v_1 + 12v_0)T - (3a_0 - a_1)T^2] \\
k_4 &= \frac{1}{2T^4}[-30h - (14v_1 + 16v_0)T + (3a_0 - 2a_1)T^2] \\
k_5 &= \frac{1}{2T^5}[12h - 6(v_1 + v_0)T + (a_1 - a_0)T^2]
\end{aligned}$$

From the above six parameters, the desired position can be set as

$$\begin{aligned}
q_d(t) &= k_0 + k_1(t - t_0) + k_2(t - t_0)^2 + k_3(t - t_0)^3 \\
&\quad + k_4(t - t_0)^4 + k_5(t - t_0)^5 \\
\dot{q}_d(t) &= k_1 + 2k_2(t - t_0) + 3k_3(t - t_0)^2 \\
&\quad + 4k_4(t - t_0)^3 + 5k_5(t - t_0)^4 \\
\ddot{q}_d(t) &= 2k_2 + 6k_3(t - t_0) + 12k_4(t - t_0)^2 \\
&\quad + 20k_5(t - t_0)^3
\end{aligned}$$

Since disturbances include TDE estimation errors and external environmental disturbances, we define the external disturbance as a cosine function $\Delta d_1 = 0.5\cos(5t)$to test and compare the response speed and immunity of the system to the disturbance. The parameters are set as shown in the table.2, and the parameters are selected by referring to Remark 1. One other robust control scheme is taken to

TABLE 1. Dynamical parameters.

parameter	numeric value
J	$[0.5,\ 0;\ 0,\ 0.2]\ kg \cdot m^2$
d_m	$[0.1,\ 0;\ 0,\ 0.02]\ N \cdot m \cdot s/rad$
d_s	$[50,\ 0;\ 0,\ 40]\ N \cdot m \cdot s/rad$
k_s	$[2,\ 0;\ 0,\ 1]\ 104N \cdot m/rad$

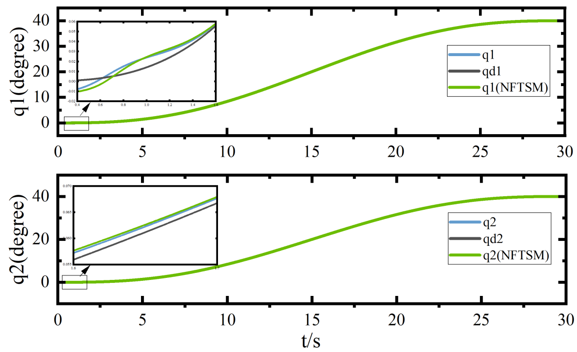

FIGURE 1. Trajectory tracking performance.

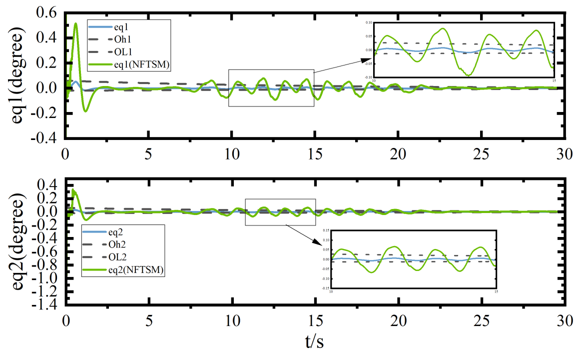

FIGURE 2. Control error.

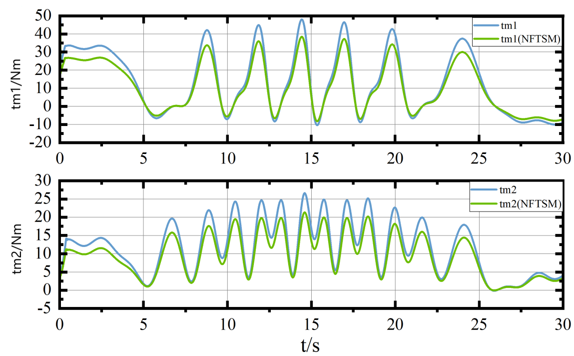

FIGURE 3. Control efforts.

TABLE 2. Parameter setting.

parameter	numeric value
$\tilde{M}$	0.12
k_{q3}	8
$\bar{k}_{q1}$	10
ε_2	0.01
η_q	1
ϖ	2
μ	0.2

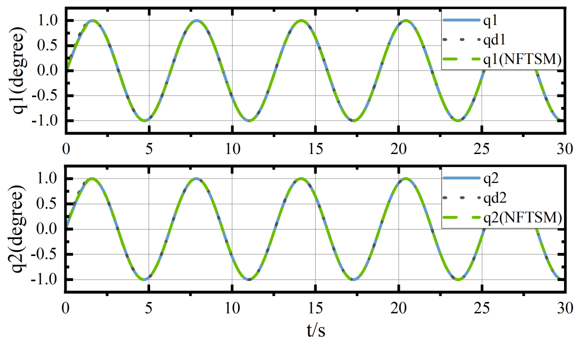

FIGURE 4. Trajectory tracking performance.

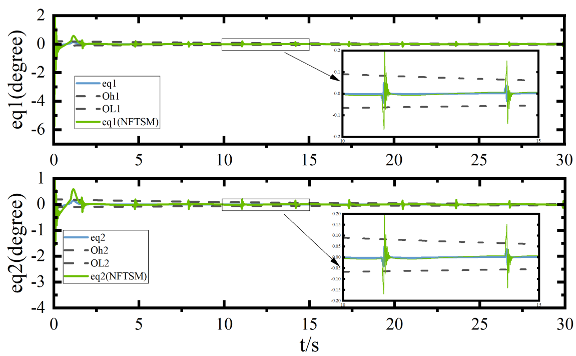

FIGURE 5. Control error.

simulate for comparisons with our proposed one, i.e., the TDE-based NFTSM (21) control scheme.

In the comparative simulation, the existing TDE-based NFTSM (21) control scheme uses the following parameters $k_1 = k_2 = 1.4$, $\alpha = 0.8$, $\Delta = 0.1$, $\eta = 0.2$, $\omega = 20$, $\mu = 0.003$, $\rho_{1\,\min} = 2$, $\rho_{1\,\max} = 30$, $\theta = 0.04$, $\tilde{M} = 0.12$. The delayed time Δt is selected as 1 ms with the sampling frequency of 1 kHz. The control parameters for NFTSM are selected the same as its original text.

B. SIMULATION RESULT

As shown in Fig. 1 and Fig. 4, both the control proposed in this paper and the control in the literature [24] can guarantee that the manipulator tracks the desired trajectory, thus effectively demonstrating the effectiveness of NFTSM and the method in this paper. Compared with the NFTSM method in the literature [24], the error between the actual trajectory

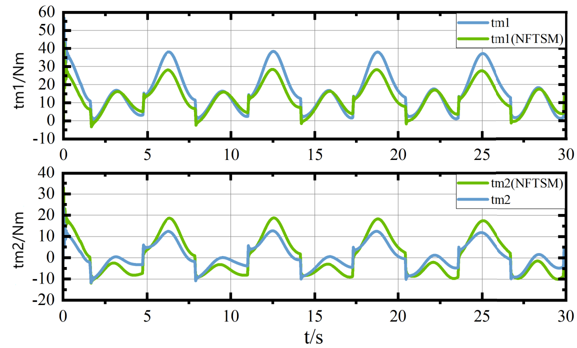

FIGURE 6. Control efforts.

of the manipulator and the desired trajectory of the method in this paper is smaller and the convergence time is shorter, indicating that the control of the method in this paper has better integrated control performance.

Figure 2 and Figure 5 show the joint position error of the manipulator. It can be seen that the error under the control of the method in this paper is smaller compared with NFTSM. Also, the error is within the safety constraint set in this paper; it satisfies the need of control and proves the effectiveness of the asymmetric constraint. Therefore, the method can provide greater control accuracy.

Figure 3 and Figure 6 show the control torque given by the motor. As can be seen in Figure 3, there is a large control torque that varies in real time to resist external disturbances as it completes the tracking of the desired trajectory. As can be seen in Fig. 6, the control torque forms a periodic variation under the influence of external disturbances, which can be changed in real time at any time according to the disturbances and the model errors generated by the TDE, and finally good control accuracy is maintained.

In general, the effectiveness and superiority of the method in this paper are proved by simulation. It is proved that the method in this paper has high control accuracy, good stability and superior performance.

V. CONCLUSION

A high-precision trajectory tracking controller based on asymmetric error constraints is designed for a cable-driven manipulator using a time-delay estimation method. Ensuring the asymmetric constraint for the joint position error of the cable-diven manipulator is a great challenge and makes the whole design process very difficult. In order to add the asymmetric constraint function to the original adaptive gain against external unknown disturbances, this paper designs a sliding film surface containing the safety constraint function and an effective adaptive super-twisting control method, which enables the controller to achieve two excellent functions. The method uses a safety constraint to keep the error within a safe range. The super-twisting design of the controller ensures that the manipulator satisfies the safety constraint in terms of control error. Meanwhile, the joint position error constraint is designed using the safety constraint function. Simulation results show that the method reduces the position error of the manipulator, so that the trajectory of the manipulator can be consistent with the desired trajectory to a large extent. Therefore, the method can make the manipulator work better in practical applications.

REFERENCES

[1] W. T. Townsend, "The effect of transmission design on force-controlled manipulator performance," Ph.D. thesis, Dept. Mech. Eng., MIT, Cambridge, MA, USA, 1988.

[2] W. B. Lim, S. H. Yeo, and G. Yang, "Optimization of tension distribution for cable-driven manipulators using tension-level index," *IEEE/ASME Trans. Mechatronics*, vol. 19, no. 2, pp. 676–683, Apr. 2014.

[3] X. Cui, W. Chen, X. Jin, and S. K. Agrawal, "Design of a 7-DOF cable-driven arm exoskeleton (CAREX-7) and a controller for dexterous motion training or assistance," *IEEE/ASME Trans. Mechatronics*, vol. 22, no. 1, pp. 161–172, Feb. 2016.

[4] W. Xu, Y. Wang, S. Jiang, J. Yao, and B. Chen, "Kinematic analysis of a newly designed cable-driven manipulator," *Trans. Can. Soc. Mech. Eng.*, vol. 42, no. 2, pp. 125–135, Jun. 2018.

[5] Y. Wang, S. Jiang, B. Chen, and H. Wu, "A new continuous fractional-order nonsingular terminal sliding mode control for cable-driven manipulators," *Adv. Eng. Softw.*, vol. 119, pp. 21–29, May 2018.

[6] X. Jin, "Adaptive fault-tolerant control for a class of output-constrained nonlinear systems," *Int. J. Robust Nonlinear Control*, vol. 25, no. 18, pp. 3732–3745, Dec. 2015.

[7] B. Niu, Y. J. Liu, G. D. Zong, Z. Y. Han, and J. Fu, "Command filter-based adaptive neural tracking controller design for uncertain switched nonlinear output-constrained systems," *IEEE Trans. Cybern.*, vol. 47, no. 10, pp. 3160–3171, Oct. 2017.

[8] Y. Li, Z. Ma, and S. Tong, "Adaptive fuzzy output-constrained fault-tolerant control of nonlinear stochastic large-scale systems with actuator faults," *IEEE Trans. Cybern.*, vol. 47, no. 9, pp. 2362–2376, Sep. 2017.

[9] Y.-D. Song and S. Zhou, "Tracking control of uncertain nonlinear systems with deferred asymmetric time-varying full state constraints," *Automatica*, vol. 98, pp. 314–322, Dec. 2018.

[10] S.-I. Han and J.-M. Lee, "Decentralized neural network control for guaranteed tracking error constraint of a robot manipulator," *Int. J. Control, Autom. Syst.*, vol. 13, no. 4, pp. 906–915, Aug. 2015.

[11] J. Xu and L. Qiao, "Robust adaptive PID control of robot manipulator with bounded disturbances," *Math. Problems Eng.*, vol. 2013, pp. 1–13, Jan. 2013.

[12] B. Xu, S. Ji, C. Zhang, C. Chen, H. Ni, and X. Wu, "Linear-extended-state-observer-based prescribed performance control for trajectory tracking of a robotic manipulator," *Industrial Robot, Int. J. Robot. Res. Appl.*, Jun. 2021.

[13] H. Zhou, R. Chen, S. Zhou, and Z. Liu, "Design and analysis of a drive system for a series manipulator based on orthogonal-fuzzy PID control," *Electronics*, vol. 8, no. 9, p. 1051, Sep. 2019.

[14] Y. Li, C. Yang, W. Yan, R. Cui, and A. Annamalai, "Admittance-based adaptive cooperative control for multiple manipulators with output constraints," *IEEE Trans. Neural Netw. Learn. Syst.*, vol. 30, no. 12, pp. 3621–3632, Dec. 2019.

[15] W. He, Y. Chen, and Z. Yin, "Adaptive neural network control of an uncertain robot with full-state constraints," *IEEE Trans. Cybern.*, vol. 46, no. 3, pp. 620–629, Apr. 2016.

[16] C. Yang, D. Huang, W. He, and L. Cheng, "Neural control of robot manipulators with trajectory tracking constraints and input saturation," *IEEE Trans. Neural Netw. Learn. Syst.*, vol. 32, no. 9, pp. 4231–4242, Sep. 2021.

[17] Q. Yao, "Adaptive fuzzy neural network control for a space manipulator in the presence of output constraints and input nonlinearities," *Adv. Space Res.*, vol. 67, no. 6, pp. 1830–1843, Mar. 2021.

[18] K. Zhao and Y. Song, "Neuroadaptive robotic control under time-varying asymmetric motion constraints: A feasibility-condition-free approach," *IEEE Trans. Cybern.*, vol. 50, no. 1, pp. 15–24, Jan. 2020.

[19] X. Jin, "Iterative learning control for robot manipulators with non-repetitive reference trajectory, iteration varying trial lengths, and asymmetric output constraints," in *Proc. Amer. Control Conf. (ACC)*, Jul. 2020, pp. 4804–4809.

[20] C. Zhu, Y. Jiang, and C. Yang, "Fixed-time parameter estimation and control design for unknown robot manipulators with asymmetric motion constraints," *Int. J. Control, Autom. Syst.*, vol. 20, no. 1, pp. 268–282, Jan. 2022.

[21] J. Lee, P. H. Chang, and M. Jin, "Adaptive integral sliding mode control with time-delay estimation for robot manipulators," *IEEE Trans. Ind. Electron.*, vol. 64, no. 8, pp. 6796–6804, Aug. 2017.

[22] S. Björklund, G. Le, and R. N. Ik, "A survey and comparison of time-delay estimation methods in linear systems," Linköping Univ., Linköping, Sweden, 2003.

[23] Y. Wang, F. Yan, S. Jiang, and B. Chen, "Time delay control of cable-driven manipulators with adaptive fractional-order nonsingular terminal sliding mode," *Adv. Eng. Softw.*, vol. 121, pp. 13–25, Jul. 2018.

[24] Y. Wang, K. Zhu, C. Bai, and F. Yan, "Adaptive super-twisting nonsingular fast terminal sliding mode control for cable-driven manipulators using time-delay estimation," *Adv. Eng. Softw.*, vol. 128, pp. 113–124, Feb. 2019.

[25] Y. Wang, F. Yan, K. Zhu, B. Chen, and H. Wu, "A new practical robust control of cable-driven manipulators using time-delay estimation," *Int. J. Robust Nonlinear Control*, vol. 29, no. 11, pp. 3405–3425, 2019.

[26] J. Hu, H. Zhang, H. Liu, and X. Yu, "A survey on sliding mode control for networked control systems," *Int. J. Syst. Sci.*, vol. 52, no. 6, pp. 1129–1147, Apr. 2021.

[27] W. Deng, J. Yao, and D. Ma, "Robust adaptive precision motion control of hydraulic actuators with valve dead-zone compensation," *ISA Trans.*, vol. 70, pp. 269–278, Sep. 2017.

[28] W. Deng, J. Yao, and D. Wei, "Time-varying input delay compensation for nonlinear systems with additive disturbance: An output feedback approach," *Int. J. Robust Nonlinear Control*, vol. 28, no. 1, pp. 31–52, Jan. 2018.

[29] Z. Lin, T. Zhang, Q. Xie, and Q. Wei, "Intelligent electro-pneumatic position tracking system using improved mode-switching sliding control with fuzzy nonlinear gain," *IEEE Access*, vol. 6, pp. 34462–34476, 2018.

[30] L. Sheng, G. Xiaojie, and Z. Lanyong, "Robust adaptive backstepping sliding mode control for six-phase permanent magnet synchronous motor using recurrent wavelet fuzzy neural network," *IEEE Access*, vol. 5, pp. 14502–14515, 2017.

[31] Y. Wang, B. Chen, and H. Wu, "Joint space tracking control of underwater vehicle-manipulator systems using continuous nonsingular fast terminal sliding mode," *Proc. Inst. Mech. Eng. M, J. Eng. Maritime Environ.*, vol. 232, no. 4, pp. 448–458, 2018.

[32] T. C. S. Hsia, "A new technique for robust control of servo systems," *IEEE Trans. Ind. Electron.*, vol. 36, no. 1, pp. 1–7, Feb. 1989.

[33] K. Youcef-Toumi and O. Ito, "A time delay controller for systems with unknown dynamics," *J. Dyn. Syst., Meas., Control*, vol. 112, no. 1, pp. 133–142, Mar. 1990.

[34] T. C. S. Hsia, T. A. Lasky, and Z. Guo, "Robust independent joint controller design for industrial robot manipulators," *IEEE Trans. Ind. Electron.*, vol. 38, no. 1, pp. 21–25, Feb. 1991.

[35] M. Jin, J. Lee, P. H. Chang, and C. Choi, "Practical nonsingular terminal sliding-mode control of robot manipulators for high-accuracy tracking control," *IEEE Trans. Ind. Electron.*, vol. 56, no. 9, pp. 3593–3601, Sep. 2009.

[36] Y. Wang, L. Gu, B. Chen, and H. Wu, "A new discrete time delay control of hydraulic manipulators," *Proc. Inst. Mech. Eng., I, J. Syst. Control Eng.*, vol. 231, no. 3, pp. 168–177, Mar. 2017.

[37] J. Kim, H. Joe, S.-C. Yu, J. S. Lee, and M. Kim, "Time-delay controller design for position control of autonomous underwater vehicle under disturbances," *IEEE Trans. Ind. Electron.*, vol. 63, no. 2, pp. 1052–1061, Feb. 2016.

[38] P. Cui, D. Zhang, S. Yang, and H. Li, "Friction compensation based on time-delay control and internal model control for a gimbal system in magnetically suspended CMG," *IEEE Trans. Ind. Electron.*, vol. 64, no. 5, pp. 3798–3807, May 2017.

[39] Y. Wang, F. Yan, J. Chen, F. Ju, and B. Chen, "A new adaptive time-delay control scheme for cable-driven manipulators," *IEEE Trans. Ind. Informat.*, vol. 15, no. 6, pp. 3469–3481, Jun. 2019.

[40] S. Roy, I. N. Kar, J. Lee, and M. Jin, "Adaptive-robust time-delay control for a class of uncertain Euler–Lagrange systems," *IEEE Trans. Ind. Electron.*, vol. 64, no. 9, pp. 7109–7119, Sep. 2017.

[41] M. Jin, S. H. Kang, P. H. Chang, and J. Lee, "Robust control of robot manipulators using inclusive and enhanced time delay control," *IEEE/ASME Trans. Mechatronics*, vol. 22, no. 5, pp. 2141–2152, Oct. 2017.

[42] J. Lee, M. Jin, and K. K. Ahn, "Precise tracking control of shape memory alloy actuator systems using hyperbolic tangential sliding mode control with time delay estimation," *Mechatronics*, vol. 23, no. 3, pp. 310–317, 2013.
[43] Y. Wang, J. Chen, L. Gu, and X. Li, "Time delay control of hydraulic manipulators with continuous nonsingular terminal sliding mode," *J. Central South Univ.*, vol. 22, no. 12, pp. 4616–4624, Dec. 2015.
[44] X. Cao, L. Gu, H. Qiu, C. Lai, and Y. Qin, "Continuous nonsingular terminal sliding mode contouring control of manipulator based on time delay estimation," *Proc. Inst. Mech. Eng., I, J. Syst. Control Eng.*, vol. 231, no. 10, pp. 836–848, Nov. 2017.
[45] M. Van, S. Ge, and H. Ren, "Finite time fault tolerant control for robot manipulators using time delay estimation and continuous nonsingular fast terminal sliding mode control," *IEEE Trans. Cybern.*, vol. 47, no. 7, pp. 1681–1693, Jul. 2017.
[46] H. Jing, R. Wang, J. Wang, and N. Chen, "Robust H_∞ dynamic output-feedback control for four-wheel independently actuated electric ground vehicles through integrated AFS/DYC," *J. Franklin Inst.*, vol. 355, no. 18, pp. 9321–9350, Dec. 2018.
[47] A. B. Farjadian, B. Thomsen, A. M. Annaswamy, and D. D. Woods, "Resilient flight control: An architecture for human supervision of automation," *IEEE Trans. Control Syst. Technol.*, vol. 29, no. 1, pp. 29–42, Jan. 2021.
[48] J. Kim, P.-H. Chang, and M. Jin, "Fuzzy PID controller design using time-delay estimation," *Trans. Inst. Meas. Control*, vol. 39, no. 9, pp. 1329–1338, Sep. 2017.
[49] X. Zhang, H. Wang, Y. Tian, L. Peyrodie, and X. Wang, "Model-free based neural network control with time-delay estimation for lower extremity exoskeleton," *Neurocomputing*, vol. 272, pp. 178–188, Jan. 2018.

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