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Adaptive estimator-based nonsingular fast terminal sliding mode control of robotic manipulator systems under FDI attacks and actuator failure

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ABSTRACT

This paper is focused on the adaptive estimator-based super-twisting nonsingular fast terminal sliding mode control of manipulator systems with false data injection (FDI) attacks and actuator failure. First, a novel mathematical model is established for the robotic manipulator systems with parameter perturbation, FDI attacks, actuator failure, external disturbance, and joint friction. As the dynamics of FDI attacks are often unknown or unpredictable, a novel adaptive fixed-time estimator-based defense method is designed to actively eliminate the negative effects induced by the FDI attacks. Meanwhile, an adaptive super-twisting nonsingular fast terminal sliding mode controller (NFTSMC) is designed to realize rapid convergence and desirable tracking precision. After that, the fixed-time stability of the manipulator systems are proved using the Lyapunov function. Finally, the comparative simulation verifies the superiority of the proposed control strategy over the current control methods.

1. Introduction

With the progress of technology and social development, high-precision robotic manipulators have become an indispensable part of industrial production and they are widely used to perform complex and dangerous industrial tasks, see, e.g., spacecraft manipulators [1] industrial welding robots [2,3], shipboard manipulators [4,5], medical puncture [6]. However, robotic manipulators are prone to encounter some unfavorable factors, resulting in performance degradation of the manipulator systems. In recent decades, various control methods have been designed to address the impact of such problems, see, e.g., PID control method [7], adaptive control method [8,9] and sliding mode control (SMC) method [10–13]. It is worth noting that the SMC has the advantage of dealing with nonlinearity and uncertainty of robotic manipulators, which has been extensively adopted for the control of robotic systems. However, the traditional SMC method in [11,12] has defects of slow convergence speed, serious chattering, etc. To address these drawbacks, a terminal sliding mode surface (TSMS) was constructed in [14,15], which can ensure the finite-time stability of robotic manipulator systems. Nevertheless, its TSMS is prone to the phenomenon of singularity. To overcome singularity, the nonsingular fast TSMS (NFTSMS) was designed in [16–18], which can make the system finite-time stable.

On the other hand, the robotic manipulator systems are easily affected by various uncertain factors. Examples include unmodeled manipulator dynamics, parameter ingestion, external interference, actuator failure. In the past few years, many intelligent algorithms

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have been devised to solve the robust control of robotic manipulator systems subject to those uncertain factors, such as neural network algorithms [19,20], fuzzy algorithms [21], and adaptive algorithms [22–24]. In [20], a new fuzzy wavelet neural network was devised to address these uncertainties. In [23], assuming that the state of the robotic system is not measurable, an adaptive state observer was constructed to improve the control performance of nonlinear systems. In [25], a descriptor sliding-mode observer method was presented to address the problem of actuator failure in systems over digital communication channels. It follows from the above results that various intelligent algorithms have been introduced to deal with the uncertainty factors in the robotic manipulator systems to improve the accuracy of trajectory tracking and speed of the robotic manipulator systems.

With the increasing complexity of control requirements, the traditional point-to-point control of robotic manipulator cannot provide satisfactory performance. The networked control technology is gradually occupying a dominant position in industry. However, the network-based control systems are vulnerable to malicious cyber-attacks [26]. Malicious adversaries can hack into intelligent devices and communication networks of robotic manipulator systems, which may lead to severe outcomes. In [27], a malicious attacker performs cyber-attacks to compromise the integrity of the robotic systems and then degrade the control performance. In [28], details on how to attack industrial robots were discussed and an illustration on the industrial robot was demonstrated. Therefore, it is of great significance to study the cyber-security defense strategies for robotic manipulators. There are many attack strategies reported in reality, see, e.g., replay attacks, false data injection (FDI) attacks, DoS attacks. In particular, FDI attacks, which can compromise the integrity and availability of data, have attracted much attention from researchers. In [29], an adaptive SMC scheme was proposed to actively eliminate the FDI attacks on actuator. In [30], an extended observer was constructed to defend against the cyber-attacks, and the tracking errors were introduced to design the terminal integral SMC method. In [31], the problem of optimal FDI attacks scheduling and countermeasure design for car-like robots was investigated. Using the advanced deep reinforcement learning methods, the strategy for optimizing FDI attacks was devised.

In many engineering applications of robotic manipulator systems, real-time performance is extremely important. In [32], a new adaptive super-twisting global integral TSMC was designed to ensure that the manipulator systems are finite-time stable. In the study of [33], the effects of nonlinear factors were considered, where a novel nonsingular fixed-time SMC method was proposed. In [34], the fixed-time stability issue of nonlinear systems with parametric uncertainties was studied, and a new adaptive fixed-time stability analysis criterion was established. Nevertheless, the FDI attacks were not addressed in the above results. The main challenging issue is how to establish a unified model for robotic manipulator systems subject to FDI attacks and design suitable adaptive estimator and controller to achieve the fixed-time security control of manipulator systems. This is also the motivation behind this study.

In this paper, we are committed to studying the problem of adaptive estimator-based super-twisting nonsingular fast terminal SMC of manipulator systems with FDI attacks and actuator failure. A malicious adversary intends to interfere with the control signals by FDI attacks. Then, we develop a mathematical model for the dynamics of FDI attacks and subsequently design a new adaptive fixed-time estimator-based defense method to actively mitigate the effects of FDI attacks. More importantly, a novel adaptive estimator-based super-twisting NFTSMC is designed to guarantee that the robotic manipulator systems are fixed-time stable and achieve desirable tracking precision under FDI attacks and actuator failure. The main contributions of the paper are presented as follows:

(1) The security control of manipulators under FDI attacks is studied. Different from the robotic manipulator models in [35–37], this paper considers the cyber-attacks case and establishes a novel mathematical model of manipulators containing FDI attacks. Meanwhile, the proposed model includes actuator failure, parameter perturbation, external disturbance, and joint friction, which is more general than the current ones.

(2) A novel adaptive super-twisting nonsingular fast terminal SMC method is developed. Compared with the finite-time SMC methods introduced in [32,38], our SMC method ensures that the manipulator systems are fixed-time stable. In addition, compared with the fixed-time methods in [33,39,40], the devised control method directly deals with the security control problem of fixed-time tracking of n-link manipulator systems with FDI attacks and actuator failure.

(3) A new adaptive fixed-time estimator is constructed to actively eliminate the adverse effects of FDI attacks on manipulator systems. In comparison with the observers in [41,42], which can only provide asymptotic or finite-time convergence, the devised estimator can realize fixed-time convergence of estimation error dynamics. Meanwhile, the designed estimator does not require prior knowledge of FDI attacks and it can dynamically adjust the parameters based on the information of tracking error changes due to unknown FDI attacks.

Notation. For simplicity and convenience, some symbols are adopted in this paper. More specifically, for a real vector $W = [w_1, \ldots, w_n]^T \in \Re^n$, $\|W\|$ represents the 2-norm of a vector, $\mathrm{sgn}^k(W)$ is specified as $\mathrm{sgn}^k(W) = [|w_1|^k \mathrm{sign}(w_1), \ldots, |w_n|^k \mathrm{sign}(w_n)]^T$, $\mathrm{sign}(\cdot)$ is the sign function.

2. Problem formulation and preliminaries

The control structure of manipulator systems is presented in Fig. 1, where sensors, controllers, and actuators are connected through a communication network, and the adversary may launch FDI attacks on the communication network. Considering the influence of parameter perturbation, FDI attacks, actuator failure, external disturbance, and joint friction, the mathematical model of the n-link rigid manipulators is calculated as follows

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) + F_v\dot{q} + F_s(\dot{q}) = \tau + \tau_d + u_a(t), \tag{1}$$

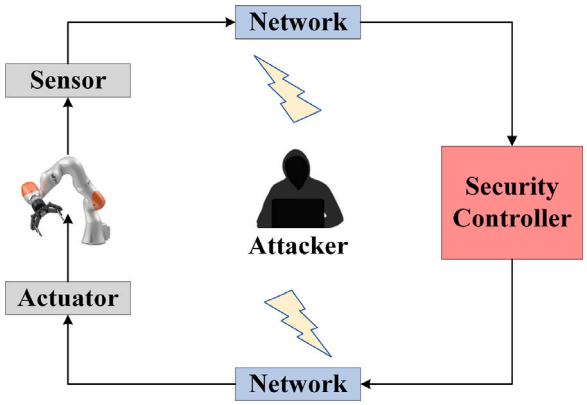


Fig. 1. Manipulator systems with FDI attacks.

where $q \in \Re^n, \dot{q} \in \Re^n$, and $\ddot{q} \in \Re^n$ are the position, velocity and acceleration vectors of the manipulator, respectively, $M(q) \in \Re^{n\times n}$ denotes the inertia matrix of the manipulator, $C(q,\dot{q}) \in \Re^{n\times n}$ denotes the centrifugal force and the Coriolis matrix, $G(q) \in \Re^n$ denotes the gravity vector, $F_v \in \Re^{n\times n}$ denotes the matrix of viscous friction coefficients, $F_s(\dot{q}) \in \Re^n$ denotes the static friction vector, $\tau_d \in \Re^n$ denotes external disturbance, $u_a(t) \in \Re^n$ denotes malicious FDI attacks, $\tau \in \Re^n$ denotes the control torque constrained by actuator failure. Recall that the manipulator system may have parameter perturbation, thus, $M(q)$, $C(q,\dot{q})$ and $G(q)$ are described in the form of Eq. (2):

$$\begin{cases} M(q) = M_0 + \Delta M(q), \\ C(q,\dot{q}) = C_0 + \Delta C(q,\dot{q}), \\ G(q) = G_0 + \Delta G(q), \end{cases} \tag{2}$$

where M_0, C_0 and G_0 denote the nominal part of the robotic manipulator, $\Delta M(q)$, $\Delta C(q,\dot{q})$ and $\Delta G(q)$ are the unknown perturbations of M_0, C_0 and G_0.

Motivated by the FDI attack model in [43], the FDI attack signal is described as

$$u_a(t) = \begin{cases} \Delta(t)\Theta(q,\dot{q},t), t \in [\underline{\varpi}, \overline{\varpi}], \\ 0 \qquad\quad , t \notin [\underline{\varpi}, \overline{\varpi}], \end{cases} \tag{3}$$

where $\Delta(t)\Theta(q,\dot{q},t)$ is information about position and velocity stolen by a malicious attacker. The attack duration range is $t \in [\underline{\varpi}, \overline{\varpi}]$. Two important assumptions on the FDI attacks are made in this work as follows:

Assumption 1 (*[43]*)**.** The FDI attack signal $u_a(t)$ is bounded and it satisfies

$$\begin{cases} \|\Delta(t)\| \le \lambda_1, \\ \|\Theta(q,\dot{q},t)\| \le \psi(q,\dot{q},t), \end{cases} \tag{4}$$

where λ_1 is an unknown positive constant, $\psi(q,\dot{q},t)$ is a known positive function.

Assumption 2 (*[30]*)**.** The derivatives of the FDI attack signal $u_a(t)$ is bounded and it satisfies

$$\|\dot{u}_a(t)\| \le \lambda_2, \tag{5}$$

where λ_2 is an unknown positive constant.

Remark 1. As the dynamics of FDI attacks are often unknown or unpredictable, it is difficult to describe FDI attacks with a precise mathematical model. In this paper, we consider that FDI attacks occur in the communication network between sensor and controller, as well as between controller and actuator. For convenience, we have simplified to use $u_a(t)$ to represent FDI attacks that occur on both channels above.

Considering the actuator failure of [32], the control torque can be characterized as follows

$$\tau = \tau_u + \varphi_a\left(t - T_f\right)\Phi(q,\dot{q},\tau) = \tau_u + \tau_a, \tag{6}$$

where τ_u is the input signal of the nominal actuator, $\tau_a = \varphi_a\left(t - T_f\right)\Phi(q,\dot{q},\tau)$ is the uncertain actuator failure, and T_f is the time constant at which the actuator fails. $\varphi_a\left(t - T_f\right) = \mathrm{diag}\left\{\varphi_{a1}\left(t - T_f\right), \ldots, \varphi_{an}\left(t - T_f\right)\right\}$ and $\varphi_{ai}\left(t - T_f\right)$ is

$$\varphi_{ai}\left(t - T_f\right) = \begin{cases} 1 - e^{-l_{ti}\left(t - T_f\right)}, \text{if } t \ge T_f, \\ 0 \qquad\qquad\quad , \text{if } t < T_f, \end{cases} \tag{7}$$

where $l_{ti} > 0$, $i = 1, \ldots, n$. $\Phi(q, \dot{q}, \tau)$ is a nonlinear function of link displacement, velocity, and actuator failure.

From Eqs. (1)–(3) and Eq. (6), the dynamic model of the robotic manipulator is calculated as

$$M_0\ddot{q} + C_0\dot{q} + G_0 = \tau_u + D_d + u_a(t), \tag{8}$$

where $D_d = \tau_a + \tau_d - \Delta M(q)\ddot{q} - \Delta C(q, \dot{q})\dot{q} - \Delta G(q) - F_v\dot{q} - F_s(\dot{q})$ is the lumped uncertainty, which contains parameter perturbation, external disturbance, actuator failure and joint friction.

The purpose of the paper is to design an adaptive super-twisting NFTSMC for the robotic manipulator system with FDI attacks, external disturbance, parameter perturbation, actuator failure and joint friction. The devised controller has the advantages of more accurate tracking trajectory and faster convergence speed. In addition, it can ensure that the robotic manipulator system is fixed-time stable. To achieve this goal, some assumptions and lemmas are necessary.

Assumption 3 ([44]). The nonlinear function D_d is bounded and it satisfies

$$\|D_d\| \le n_0 + n_1\|q\| + n_2\|\dot{q}\|^2, \tag{9}$$

where n_0, n_1 and n_2 are unknown positive constants.

Assumption 4 ([45]). The inertia matrix $M(q)$ of the manipulator system is bounded, i.e., satisfies

$$0 < \varpi_m^* \le \|M(q)\| \le \varpi_M^* \le \xi, \tag{10}$$

where $\|M(q)\|$ is the 2-norm of the matrix, ξ is a positive constant, ϖ_m^* and ϖ_M^* are the minimum and maximum eigenvalues of $M(q)$, respectively.

Lemma 1 ([46]). *For any vector $W = [w_1, \ldots, w_n]^T \in \Re^n$, it satisfies*

$$\left(\sum_{i=1}^{n}|w_i|\right)^{\zeta_1} \le \sum_{i=1}^{n}|w_i|^{\zeta_1}, \tag{11}$$

$$\left(\sum_{i=1}^{n}|w_i|\right)^{\zeta_2} \le n^{\zeta_2-1}\sum_{i=1}^{n}|w_i|^{\zeta_2}, \tag{12}$$

where $i = 1, \ldots, n$, $0 < \zeta_1 < 1$ and $\zeta_2 > 1$.

Lemma 2 ([47]). *For robotic manipulator system (1), if there is a Lyapunov function V, it satisfies*

$$\dot{V} \le -\left(\kappa_1 V^{p_3} + \kappa_2 V^{p_4}\right)^{\gamma}, \tag{13}$$

where κ_1, κ_2, p_3, p_4 and γ are all positive constants, $p_3\gamma < 1$, $p_4\gamma > 1$. Thus, the origin of the robotic manipulator system (1) is fixed-time convergent. The setting time of the system satisfies

$$T_1 \le T_{1\max} = \frac{1}{{\kappa_1}^{\gamma}\left(1 - p_3\gamma\right)} + \frac{1}{{\kappa_2}^{\gamma}\left(p_4\gamma - 1\right)}. \tag{14}$$

Lemma 3 ([48]). *For robotic manipulator system (1), if there is a Lyapunov function V, it satisfies*

$$\dot{V} \le -\kappa_4 V^{p_5} - \kappa_5 V^{p_6} + \rho_r, \tag{15}$$

where $\kappa_4 > 0$, $\kappa_5 > 0$, $p_5 > 1$, $0 < p_6 < 1$ and $\rho_r > 0$. Then the origin of the manipulator system (1) is fixed-time convergent and the set of residuals of the solution is expressed as

$$\left\{\lim_{t\to T_2} x \middle| V \le \min\left\{\left(\frac{l_r}{\kappa_4}\right)^{\frac{1}{p_5}}, \left(\frac{l_r}{\kappa_5}\right)^{\frac{1}{p_6}}\right\}\right\}, \tag{16}$$

where $l_r = \frac{\rho_r}{1-\mu_r}$, $0 < \mu_r < 1$ is a scalar. Meanwhile, the convergence time of the system is bounded and satisfies

$$T_2 \le T_{2\max} = \frac{1}{\kappa_4\left(p_5 - 1\right)} + \frac{1}{\kappa_5\left(1 - p_6\right)}. \tag{17}$$

Lemma 4 ([49]). *For $\gamma' > 1$, $a > 0$ and $b \le a$, we have*

$$(a - b)^{\gamma'} \ge b^{\gamma'} - a^{\gamma'}. \tag{18}$$

Lemma 5 ([49]). *For $\gamma'' > 0$, $c \ge 0$ and $y > 0$, we have*

$$c^{\gamma''}(y - c) \le \frac{1}{1 + \gamma''}\left(y^{1+\gamma''} - c^{1+\gamma''}\right). \tag{19}$$

Proof. If $c = 0$, clearly, the inequality (19) holds. If $c > 0$, defining $f(c) = c^{\gamma''}(y-c) - \frac{1}{1+\gamma''}\left(y^{1+\gamma''} - c^{1+\gamma''}\right)$, and taking the derivative of $f(c)$ with respect to c, we have

$$\frac{df(c)}{dc} = \gamma'' c^{\gamma''-1}(y-c). \tag{20}$$

From Eq. (20), when $c = y$, $f(c)$ is taken as the maximum value, i.e., $f(c) \le f(y) = 0$. Thus, the inequality (19) holds. The proof is completed.

A trajectory tracking error system shall be first constructed before designing the controller. Defining q_d as the desired displacement vector, the displacement tracking error of the manipulator and its derivatives are denoted as $\varepsilon_1 = q - q_d$ and $\varepsilon_2 = \dot{\varepsilon}_1 = \dot{q} - \dot{q}_d$, respectively, it is not difficult to obtain the Eq. (21):

$$\begin{aligned}\dot{\varepsilon}_2 &= \ddot{q} - \ddot{q}_d \\ &= M_0^{-1}\left(\tau_u + D_d + u_a(t) - C_0\dot{q} - G_0\right) - \ddot{q}_d \\ &= F + B\tau_u + \rho + Bu_a(t),\end{aligned} \tag{21}$$

where $F = -M_0^{-1}\left(C_0\dot{q} + G_0\right) - \ddot{q}_d$, $\rho = M_0^{-1}\cdot D_d$ denotes the uncertainty in the practical application of the manipulator and $B = M_0^{-1}$. According to Assumptions 3 and 4, the lumped uncertainty ρ is bounded and its upper bound is described as

$$\|\rho\| \le n_3 + n_4\|q\| + n_5\|\dot{q}\|^2 \le \iota\varphi, \tag{22}$$

where n_3, n_4 and n_5 are positive constants, $\iota = \max\left\{n_3, n_4, n_5\right\}$, $\varphi = 1 + \|q\| + \|\dot{q}\|^2$. Combining the above analysis, the error system is given as

$$\begin{cases} \dot{\varepsilon}_1 = \varepsilon_2, \\ \dot{\varepsilon}_2 = F + B\tau_u + \rho + Bu_a(t), \end{cases} \tag{23}$$

Subsequently, the SMC is designed based on the above obtained error system.

3. Main results

The main results of this work are showed in this section, which include the design of the NFTSMS, the devise of the adaptive fixed-time estimator and controller, and the stability analysis.

3.1. NFTSMS

To reach the transient response quickly, avoid singularity, and guarantee that the tracking error of the robotic manipulator systems converges to zero in a fixed time, the NFTSMS is developed as

$$\begin{aligned}s &= (1+\varepsilon_1^2)^{\frac{p_1}{p_2}}\arctan(\varepsilon_1) + \left(\frac{1}{\alpha_1(\arctan(\varepsilon_1))^{\frac{n_1}{n_2}-\frac{p_2}{p_1}} + \beta_1}\dot{\varepsilon}_1\right)^{\frac{p_1}{p_2}} \\ &= \sigma + (l\dot{\varepsilon}_1)^{\frac{p_1}{p_2}},\end{aligned} \tag{24}$$

where $s = \left[s_1, \ldots, s_n\right]^T$, s_i is the ith element of the SMS, $\sigma = \left[\sigma_1, \sigma_2, \ldots, \sigma_n\right]^T$, $\sigma_i = (1+\varepsilon_{1i}^2)^{\frac{p_1}{p_2}}\arctan(\varepsilon_{1i})$, $l_i = \frac{1}{\alpha_1(\arctan(\varepsilon_{1i}))^{\frac{n_1}{n_2}-\frac{p_2}{p_1}} + \beta_1} > 0$, $i = 1, 2, \ldots, n$, $\alpha_1 > 0$ and $\beta_1 > 0$ are scalars, $l = \mathrm{diag}\left\{l_1, l_2, \ldots, l_n\right\}$, n_1, n_2, p_1 and p_2 are all positive odd numbers, and $n_1 > n_2, p_1 > p_2$.

The NFTSMS (24) is differentiated as

$$\dot{s} = \gamma + \varphi + \Gamma\Lambda\left(\dot{\varepsilon}_2(\alpha_1(\arctan(\varepsilon_1))^{\frac{n_1}{n_2}-\frac{p_2}{p_1}} + \beta_1) - \omega\right), \tag{25}$$

where $\gamma = \left[\gamma_1, \gamma_2, \ldots, \gamma_n\right]^T$, $\gamma_i = 2\frac{p_1}{p_2}(1+\varepsilon_{1i}^2)^{\frac{p_1}{p_2}-1}\varepsilon_{1i}\dot{\varepsilon}_{1i}\arctan(\varepsilon_{1i})$, $\varphi = \left[\varphi_1, \ldots, \varphi_n\right]^T$, $\varphi_i = \frac{(1+\varepsilon_{1i}^2)^{\frac{p_1}{p_2}}\dot{\varepsilon}_{1i}}{1+\varepsilon_{1i}^2}$, $\omega_i = \frac{\alpha_1(\frac{n_1}{n_2}-\frac{p_2}{p_1})(\arctan(\varepsilon_{1i}))^{\frac{n_1}{n_2}-\frac{p_2}{p_1}-1}\dot{\varepsilon}_{1i}^2}{1+\varepsilon_{1i}^2}$, $i = 1, \ldots, n$, $\omega = \left[\omega_1, \ldots, \omega_n\right]^T$, $\Gamma = \mathrm{diag}\left\{\Gamma_1, \ldots, \Gamma_n\right\}$, $\Gamma_i = \frac{p_1}{p_2}\left(\frac{\dot{\varepsilon}_{1i}}{\alpha_1(\arctan(\varepsilon_{1i}))^{\frac{n_1}{n_2}-\frac{p_2}{p_1}} + \beta_1}\right)^{\frac{p_1}{p_2}-1}$, $\Lambda = \mathrm{diag}\left\{\Lambda_1, \ldots, \Lambda_n\right\}$, $\Lambda_i = (\alpha_1(\arctan(\varepsilon_{1i}))^{\frac{n_1}{n_2}-\frac{p_2}{p_1}} + \beta_1)^{-2}$.

From Eq. (23), Eq. (25) is calculated as

$$\dot{s} = \gamma + \varphi + \Gamma\Lambda\left((F + B\tau_u + \rho + Bu_a(t))(\alpha_1(\arctan(\varepsilon_1))^{\frac{n_1}{n_2}-\frac{p_2}{p_1}} + \beta_1) - \omega\right). \tag{26}$$

Let $\dot{s} = 0$ and ignore $u_a(t)$ and ρ for the moment. Then the SMC is devised as follows

$$\tau_{eq} = -B^{-1}\left(\frac{\Gamma^{-1}\Lambda^{-1}(\gamma+\varphi) - \omega}{\alpha_1(\arctan(\varepsilon_1))^{\frac{n_1}{n_2}-\frac{p_2}{p_1}} + \beta_1} + F\right). \tag{27}$$

Due to the existence of FDI attacks $u_a(t)$ and lumped uncertainty ρ, it is not easy to realize accurate tracking control only by the equivalent controller. For this reason, the FDI attacks and lumped uncertainty will be addressed in the next subsection.

Remark 2. Singularity has always been a challenging issue in SMC. In this paper, The NFTSMS is designed by referring to the arctan function. It solves the singularity problem of traditional TSMS. This SMS not only bypasses the singularity problem directly, but also ensures that the stabilization time is independent of the initial conditions of the system state.

3.2. A novel adaptive fixed-time estimator-based defense method

To defend against malicious FDI attacks, a novel fixed-time estimator-based defense method is devised as

$$\begin{cases} \dot{\hat{\upsilon}}_e = {M_0}^{-1}\tau - {M_0}^{-1}\left(C_0\dot{q} + G_0\right) - \ddot{q}_d + \dot{\hat{u}}_a(t), \\ \eta = \dot{\partial} + \ell_1\boldsymbol{\Phi}_1, \\ \dot{\hat{u}}_a(t) = \dot{J}_w + \ell_1\dot{\boldsymbol{\Phi}}_1, \\ \dot{J}_w = \kappa_1\boldsymbol{\Phi}_2 + \kappa_3\mathrm{sign}\left(\eta\right), \end{cases} \tag{28}$$

where $\upsilon_e = \dot{q} - \dot{q}_d$, $\hat{\upsilon}_e$ is the estimation of υ_e, $\hat{u}_a(t)$ is the estimation of the FDI attacks $u_a(t)$, $\partial = \upsilon_e - \hat{\upsilon}_e = \left[\partial_1, \partial_2, \ldots, \partial_n\right]^T$, $\boldsymbol{\Phi}_{1i} = \left(\partial_i + \ell_2{\partial_i}^{\xi_1}\right)^{\frac{1}{\xi_2}}$, $\eta = \left[\eta_1, \eta_2, \ldots, \eta_n\right]^T$, $\mathrm{sign}\left(\eta\right) = \left[\mathrm{sign}\left(\eta_1\right), \mathrm{sign}\left(\eta_2\right), \ldots, \mathrm{sign}\left(\eta_n\right)\right]^T$, $\boldsymbol{\Phi}_1 = \left[\boldsymbol{\Phi}_{11}, \boldsymbol{\Phi}_{12}, \ldots, \boldsymbol{\Phi}_{1n}\right]^T$, $\boldsymbol{\Phi}_{2i} = \left(\eta_i + \kappa_2{\eta_i}^{\xi_3}\right)^{\frac{1}{\xi_4}}$, $\boldsymbol{\Phi}_2 = \left[\boldsymbol{\Phi}_{21}, \boldsymbol{\Phi}_{22}, \ldots, \boldsymbol{\Phi}_{2n}\right]^T$, ℓ_1, ℓ_2, κ_1, κ_2, κ_3, ξ_1, ξ_2, ξ_3 and ξ_4 are all positive constants, $i = 1, 2, \ldots, n$, $\xi_1 > \xi_2 > 1$, $\xi_3 > \xi_4 > 1$. Furthermore, ∂ is differentiated as

$$\begin{aligned} \dot{\partial} = &\ \dot{\upsilon}_e - \dot{\hat{\upsilon}}_e \\ = &\ {M_0}^{-1}\tau - {M_0}^{-1}\left(C_0\dot{q} + G_0\right) - \ddot{q}_d + u_a(t) - {M_0}^{-1}\tau \\ &+ {M_0}^{-1}\left(C_0\dot{q} + G_0\right) + \ddot{q}_d - \hat{u}_a(t) \\ = &\ u_a(t) - \hat{u}_a(t). \end{aligned} \tag{29}$$

Then the analysis result of system (1) under FDI attacks is given as follows:

Theorem 1. *For system (1), the fixed-time estimator-based defense method (28) can effectively defend against the FDI attacks $u_a(t)$. The estimation error can converge in a fixed time T_d. The setting time satisfies*

$$\begin{aligned} T_d \le &\ \frac{1}{{\varpi_1}^{1/\xi_4}\left(1 - \frac{\xi_4+1}{2\xi_4}\right)} + \frac{1}{{\varpi_2}^{1/\xi_4}\left(\frac{\xi_3+\xi_4}{2\xi_4} - 1\right)} \\ &+ \frac{1}{{\varpi_3}^{1/\xi_2}\left(1 - \frac{\xi_2+1}{2\xi_2}\right)} + \frac{1}{{\varpi_4}^{1/\xi_2}\left(\frac{\xi_1+\xi_2}{2\xi_2} - 1\right)}. \end{aligned} \tag{30}$$

Proof. Defining the Lyapunov function as $V_d = \frac{1}{2}\eta^T\eta$. The time derivative of V_d is

$$\begin{aligned} \dot{V}_d &= \eta^T\dot{\eta} \\ &= \eta^T\left(\ddot{\partial} + \ell_1\dot{\boldsymbol{\Phi}}_1\right) \\ &= \eta^T\left(\dot{u}_a(t) - \dot{J}_w - \ell_1\dot{\boldsymbol{\Phi}}_1 + \ell_1\dot{\boldsymbol{\Phi}}_1\right) \\ &= \eta^T\left(\dot{u}_a(t) - \kappa_1\boldsymbol{\Phi}_2 - \kappa_3\mathrm{sgn}\left(\eta\right)\right) \\ &\le -\kappa_1\eta^T\boldsymbol{\Phi}_2 - \kappa_3\left\|\eta\right\| + \left\|\eta\right\|\left\|\dot{u}_a(t)\right\| \\ &\le -\left(\kappa_1{}^{\xi_4}\sum_{i=1}^{n}\left({\eta_i}^2\right)^{\frac{\xi_4+1}{2}} + \kappa_2\kappa_1{}^{\xi_4}\sum_{i=1}^{n}\left({\eta_i}^2\right)^{\frac{\xi_3+\xi_4}{2}}\right)^{\frac{1}{\xi_4}}. \end{aligned} \tag{31}$$

According to Lemma 1, inequality (31) satisfies

$$\begin{aligned} \dot{V}_d &\le -\left(\varpi_1\left(\sum_{i=1}^{n}\left({\eta_i}^2\right)\right)^{\frac{\xi_4+1}{2}} + \varpi_2\left(\sum_{i=1}^{n}\left({\eta_i}^2\right)\right)^{\frac{\xi_3+\xi_4}{2}}\right)^{\frac{1}{\xi_4}} \\ &\le -\left(\varpi_1{V_d}^{\frac{\xi_4+1}{2}} + \varpi_2{V_d}^{\frac{\xi_3+\xi_4}{2}}\right)^{\frac{1}{\xi_4}}, \end{aligned} \tag{32}$$

where $\varpi_1 = \kappa_1{}^{\xi_4}n^{\frac{1-\xi_4}{2}}$, $\varpi_2 = \kappa_2\kappa_1{}^{\xi_4}n^{1-\frac{\xi_3+\xi_4}{2}}$, since $\xi_3 > \xi_4 > 1$, it yields $\frac{\xi_4+1}{2\xi_4} < 1$ and $\frac{\xi_3+\xi_4}{2\xi_4} > 1$. According to Lemma 2, it can be analyzed that η converges to zero in a fixed time, and the setting time T_1 satisfies

$$T_1 \le \frac{1}{{\varpi_1}^{1/\xi_4}\left(1 - \frac{\xi_4+1}{2\xi_4}\right)} + \frac{1}{{\varpi_2}^{1/\xi_4}\left(\frac{\xi_3+\xi_4}{2\xi_4} - 1\right)}. \tag{33}$$

Once $\eta_i = 0$ is satisfied, we have $\dot{\partial}_i = -\ell_1\left(\partial_i + \ell_2 \partial_i^{\xi_1}\right)^{\frac{1}{\xi_2}}$. Then, redefining a new Lyapunov function as $V_\partial = \frac{1}{2}\partial^T\partial$. Differentiating V_∂, it yields

$$\begin{aligned}\dot{V}_\partial &= \partial^T\dot{\partial} \\ &= -\left(\ell_1{}^{\xi_2}\sum_{i=1}^{n}\left(\partial_i{}^2\right)^{\frac{\xi_2+1}{2}} + \ell_2\ell_1{}^{\xi_2}\sum_{i=1}^{n}\left(\partial_i{}^2\right)^{\frac{\xi_1+\xi_2}{2}}\right)^{\frac{1}{\xi_2}}.\end{aligned} \tag{34}$$

According to Lemma 1, the Eq. (34) satisfies

$$\begin{aligned}\dot{V}_\partial &\le -\left(\varpi_3\left(\sum_{i=1}^{n}\left(\partial_i{}^2\right)\right)^{\frac{\xi_2+1}{2}} + \varpi_4\left(\sum_{i=1}^{n}\left(\partial_i{}^2\right)\right)^{\frac{\xi_1+\xi_2}{2}}\right)^{\frac{1}{\xi_2}} \\ &\le -\left(\varpi_3 V_\partial{}^{\frac{\xi_2+1}{2}} + \varpi_4 V_\partial{}^{\frac{\xi_1+\xi_2}{2}}\right)^{\frac{1}{\xi_2}},\end{aligned} \tag{35}$$

where $\varpi_3 = \ell_1{}^{\xi_2} n^{\frac{1-\xi_2}{2}}$ and $\varpi_4 = \ell_2\ell_1{}^{\xi_2} n^{1-\frac{\xi_1+\xi_2}{2}}$, since $\xi_1 > \xi_2 > 1$, it yields $\frac{\xi_2+1}{2\xi_2} < 1$ and $\frac{\xi_1+\xi_2}{2\xi_2} > 1$. According to Lemma 2, we can get that ∂ and $\dot{\partial}$ converge to zero in a fixed time. Meanwhile, the convergence time T_2 satisfies

$$T_2 \le \frac{1}{\varpi_3{}^{1/\xi_2}\left(1-\frac{\xi_2+1}{2\xi_2}\right)} + \frac{1}{\varpi_4{}^{1/\xi_2}\left(\frac{\xi_1+\xi_2}{2\xi_2}-1\right)}. \tag{36}$$

Therefore, the state of the estimator designed in Eq. (28) will converge in a fixed time, and the setting time of estimation error satisfies the inequality (30).

In the devised fixed-time estimator (28), κ_3 is designed based on the prior knowledge of FDI attacks. However, it may not be an easy task to obtain prior knowledge of FDI attacks in the actual environment. To overcome this problem, an adaptive method is introduced to estimate κ_3, and the adaptive algorithm is devised as follows

$$\begin{cases}\kappa_{3i}(t) = Y_0 + Y_i(t), \\ \dot{Y}_i(t) = -r_1\left(\varsigma_i(t) + r_2\varsigma_i(t)^{r_3}\right)^{\frac{1}{r_4}}, \\ \varsigma_i(t) = \kappa_{3i}(t) - \dfrac{1}{\beta_a}\left|\bar{u}_{eqi}\right| - \upsilon_a, \\ \dot{u}_{eqi} = \dfrac{1}{\iota_a}\left(l_{a1}\left(e_{Yi} + l_{a2}e_{Yi}{}^{r_3}\right)^{\frac{1}{r_4}}\right),\end{cases} \tag{37}$$

where $\kappa_{3i}(t)$ is an estimate of κ_3. u_{eqi} is the equivalent control input signal. $u_{eq} = \left[u_{eq1}, u_{eq2}, \ldots, u_{eqn}\right]^T$, $\kappa_3(t) = \mathrm{diag}\left\{\kappa_{31}(t), \kappa_{32}(t), \ldots, \kappa_{3n}(t)\right\}$, $e_{Yi} = \kappa_{3i}(t) - \bar{u}_{eqi}$, $e_Y = \left[e_{Y1}, e_{Y2}, \ldots, e_{Yn}\right]^T$, $Y(t) = \left[Y_1(t), \ldots, Y_n(t)\right]^T$, l_{a1}, l_{a2}, r_1, r_2, r_3, r_4, and β_a are positive constants, $r_3 > r_4 > 1$, $0 < \beta_a < 1$, $\iota_a > 0$ and $Y_0 > 0$ are time constants, $\varsigma(t) = \left[\varsigma_1(t), \varsigma_2(t), \ldots, \varsigma_n(t)\right]^T$, $i = 1, 2, \ldots, n$.

Combining Eqs. (28) and (37), a new adaptive fixed-time estimator-based defense method is obtained. It can actively mitigate the impact of FDI attacks on the manipulator system.

Remark 3. In Eq. (28), the sliding component $\kappa_3\mathrm{sign}(\eta)$ is applied to defend against for the FDI attacks $\dot{u}_a(t)$. Thereinto, the sliding gain κ_3 is designed based on Assumption 2. It is noted that the boundary of FDI attack λ_2 is unknown in the actual working environment. Therefore, an equivalent control u_{eq} is designed to precisely counteract the derivatives of the FDI attacks.

3.3. Controller design

To overcome the effects of lumped uncertainty ρ, the auxiliary controller is devised as

$$\tau_{au} = -B^{-1}\left(k_1 s + k_2\mathrm{sgn}^{\gamma_3}(s) + k_3\mathrm{sgn}^{\gamma_4}(s) + \iota\varphi\mathrm{sign}\left(\Lambda^{\frac{1}{2}}s\right)\right), \tag{38}$$

where $\mathrm{sgn}^{\gamma_3}(s) = \left[|s_1|^{\gamma_3}\mathrm{sign}(s_1), \ldots, |s_n|^{\gamma_3}\mathrm{sign}(s_n)\right]^T$, $\gamma_3 > 1$, k_1, k_2, and k_3 are all positive constants, $\mathrm{sgn}^{\gamma_4}(s) = \left[|s_1|^{\gamma_4}\mathrm{sign}(s_1), \ldots, |s_n|^{\gamma_4}\mathrm{sign}(s_n)\right]^T$, $0 < \gamma_4 < 1$, $\mathrm{sign}\left(\Lambda^{\frac{1}{2}}s\right) = \left[\mathrm{sign}\left(\Lambda_1^{\frac{1}{2}}s_1\right), \ldots, \mathrm{sign}\left(\Lambda_n^{\frac{1}{2}}s_n\right)\right]^T$.

As mentioned above, the entire NFTSMC is designed as

$$\begin{aligned}\tau_u = &\ \tau_{eq} + \tau_{au} - \hat{u}_a(t) \\ = &-B^{-1}\left(\frac{\Gamma^{-1}\Lambda^{-1}(\gamma+\varphi)-\omega}{\alpha_1(\arctan(\varepsilon_1))^{\frac{n_1}{n_2}-\frac{p_2}{p_1}}+\beta_1} + F\right) \\ &- B^{-1}\left(k_1 s + k_2\mathrm{sgn}^{\gamma_3}(s) + k_3\mathrm{sgn}^{\gamma_4}(s) + \iota\varphi\mathrm{sign}\left(\Lambda^{\frac{1}{2}}s\right)\right) \\ &- \hat{u}_a(t).\end{aligned} \tag{39}$$

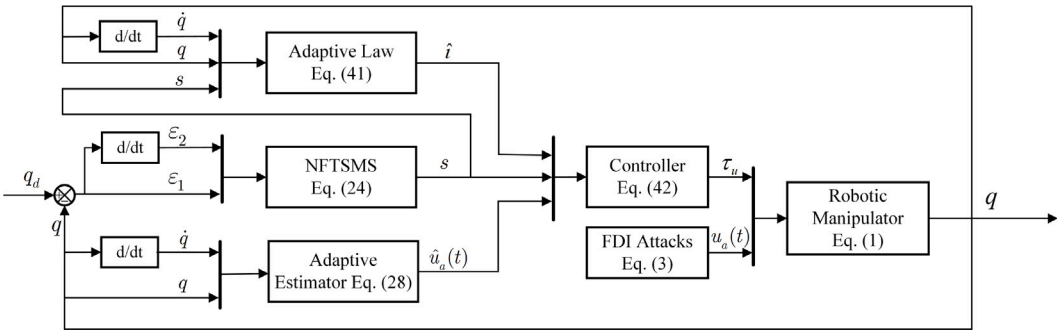


Fig. 2. The structure diagram of the adaptive estimator-based NFTSM control scheme.

It is noted that the control law (39) requires a priori knowledge about the lumped uncertainty ρ in advance, which however may not be fully known in reality. To solve this problem, the controller is optimized using an adaptive approach. After refinement, the adaptive estimator-based NFTSMC is given as

$$\begin{aligned}\tau_u =& -B^{-1}\left(\frac{\Gamma^{-1}\Lambda^{-1}(\gamma+\varphi)-\omega}{\alpha_1(\arctan(\varepsilon_1))^{\frac{n_1}{n_2}-\frac{p_2}{p_1}}+\beta_1}+F\right)\\ &-B^{-1}\left(k_1 s+k_2\mathrm{sgn}^{\gamma_3}(s)+k_3\mathrm{sgn}^{\gamma_4}(s)+\hat{\iota}\varphi\mathrm{sign}\left(\Lambda^{\frac{1}{2}}s\right)\right)\\ &-\hat{u}_a(t),\end{aligned} \tag{40}$$

where $\hat{\iota}$ is the estimation of ι, it is calculated by the following adaptive law (41).

$$\dot{\hat{\iota}}=\eta_1\varphi\left\|\Lambda^{\frac{1}{2}}s\right\|-\eta_2\hat{\iota}^{\gamma_3}-\eta_3\hat{\iota}^{\gamma_4}, \tag{41}$$

where η_1, η_2, and η_3 are all positive constants, $\hat{\iota}(0)>0$.

Remark 4. The lumped uncertainty will affect the control performance of the robotic manipulator system, and the robot may not be able to fully and accurately obtain environmental information and respond to environmental changes when performing tasks. In addition, the existence of lumped uncertainty makes the design of controller more complex and difficult. In the paper, the adaptive law is designed to effectively solve the adverse effects of lumped uncertainty, and the designed adaptive algorithm does not need the detailed dynamic parameters of the robotic manipulator system and the prior knowledge of the lumped uncertainty.

The chattering phenomenon is a common problem in SMC, which is solved by utilizing an adaptive super-twisting algorithm. Finally, a novel adaptive estimator-based super-twisting NFTSMC is devised as follows:

$$\begin{aligned}\tau_u =& -B^{-1}\left(\frac{\Gamma^{-1}\Lambda^{-1}(\gamma+\varphi)-\omega}{\alpha_1(\arctan(\varepsilon_1))^{\frac{n_1}{n_2}-\frac{p_2}{p_1}}+\beta_1}+F\right)\\ &-B^{-1}\left(k_1 s+k_2\mathrm{sgn}^{\gamma_3}(s)+k_3\mathrm{sgn}^{\gamma_4}(s)+\hat{k}_4\mathrm{sgn}^{\frac{1}{2}}\left(\Lambda^{\frac{1}{2}}s\right)+u_1\right)\\ &-\hat{u}_a(t),\end{aligned} \tag{42}$$

$$\dot{u}_1=\hat{k}_5\hat{\iota}\varphi\mathrm{sign}\left(\Lambda^{\frac{1}{2}}s\right), \tag{43}$$

$$\dot{\hat{k}}_4=\begin{cases}l\eta_4\mathrm{sign}\left(\|s\|-\zeta_1\right), & \hat{k}_4\geq\varpi_k,\\ \eta_5, & \hat{k}_4<\varpi_k,\end{cases} \tag{44}$$

$$\hat{k}_5=2\zeta_2\hat{k}_4, \tag{45}$$

where $\mathrm{sign}^{\frac{1}{2}}\left(\Lambda^{\frac{1}{2}}s\right)=\left[\left|\Lambda_1^{\frac{1}{2}}s_1\right|^{\frac{1}{2}}\mathrm{sign}\left(\Lambda^{\frac{1}{2}}s_1\right),\ldots,\left|\Lambda_n^{\frac{1}{2}}s_n\right|^{\frac{1}{2}}\mathrm{sign}\left(\Lambda^{\frac{1}{2}}s_n\right)\right]^T$, η_4 and η_5 are all positive constants, $\zeta_1>0$, $\zeta_2>0$, $\varpi_k>0$ are very small numbers.

The entire control scheme is exhibited in Fig. 2.

Remark 5. In the paper, a novel adaptive fixed-time estimator-based defense method is designed to defend against malicious FDI attacks, and an adaptive algorithm is used to solve the effect of lumped uncertainty. Then, a new adaptive estimator-based super-twisting NFTSMC is devised to achieve fixed-time stable and desirable tracking performance under FDI attacks and actuator

failure. Compared with [33,39,40], the NFTSMC has the advantages of more accurate tracking trajectory and faster convergence speed.

Remark 6. The saturation function method and the higher-order sliding mode algorithm are common methods to solve the chattering problem in SMC. However, it is difficult to choose the boundary layer width of the saturation function, and the design structure of the higher-order sliding mode algorithm is more complicated. Compared with the above two methods, the super-twisting algorithm is more suitable to address the chattering problem. But, the control gain of the traditional super-twisting algorithm is fixed, which leads to its limited ability of dealing with the chattering problem. Therefore, the adaptive technique is used to overcome this shortcoming.

3.4. Stability analysis

The adaptive estimator-based NFTSMC analysis result under FDI attacks and actuator failure is given as follows:

Theorem 2. *For the robotic manipulator system (1) with parameter perturbation, joint friction, external disturbance, malicious FDI attacks and actuator failure, under the action of the adaptive estimator-based NFTSMC (40), the error system of the manipulator (23) is fixed-time stable.*

Proof.

The stability analysis results of the arrival phase is described as follows.

At first, the estimation error of $\imath$ as $\tilde{\imath} = \imath - \hat{\imath}$ is defined and a Lyapunov function is developed as

$$V_1 = \frac{1}{2}s^T s + \frac{1}{2\eta_1}\tilde{\imath}^2. \tag{46}$$

Differentiating V_1, it yields

$$\begin{aligned}\dot{V}_1 =& \ s^T\dot{s} + \frac{1}{\eta_1}\tilde{\imath}\dot{\tilde{\imath}}\\ =& \ s^T\left(\gamma + \varphi + \Gamma\Lambda(F + B\tau_u + \rho + Bu_a(t))\left(\alpha_1(\arctan(\varepsilon_1))^{\frac{n_1}{n_2}\frac{p_2}{p_1}} + \beta_1\right)\right)\\ &- s^T\Gamma\Lambda\omega - \frac{1}{\eta_1}\tilde{\imath}\dot{\hat{\imath}}.\end{aligned} \tag{47}$$

Substituting Eqs. (40) and (41) into Eq. (47), we obtain

$$\begin{aligned}\dot{V}_1 =& \ s^T\Gamma\Lambda^{\frac{1}{2}}\left(-k_1 s - k_2\mathrm{sgn}^{\gamma_3}(s) - k_3\mathrm{sgn}^{\gamma_4}(s) - \hat{\imath}\varphi\mathrm{sign}\left(\Gamma\Lambda^{\frac{1}{2}}s\right) + \rho\right)\\ &- \frac{1}{\eta_1}\tilde{\imath}\left(\eta_1\varphi\left\|\Gamma\Lambda^{\frac{1}{2}}s\right\| - \eta_2\hat{\imath}^{\gamma_3} - \eta_3\hat{\imath}^{\gamma_4}\right),\\ =& \ s^T\Gamma\Lambda^{\frac{1}{2}}\left(-k_1 s - k_2\mathrm{sgn}^{\gamma_3}(s) - k_3\mathrm{sgn}^{\gamma_4}(s) - \hat{\imath}\varphi\mathrm{sign}\left(\Gamma\Lambda^{\frac{1}{2}}s\right) + \rho\right)\\ &- (\imath - \hat{\imath})\varphi\left\|\Gamma\Lambda^{\frac{1}{2}}s\right\| + \frac{\eta_2}{\eta_1}\tilde{\imath}^{\gamma_3} + \frac{\eta_3}{\eta_1}\tilde{\imath}^{\gamma_4},\\ \le& \ s^T\Gamma\Lambda^{\frac{1}{2}}\left(-k_1 s - k_2\mathrm{sgn}^{\gamma_3}(s) - k_3\mathrm{sgn}^{\gamma_4}(s)\right) - \hat{\imath}\varphi\left\|\Gamma\Lambda^{\frac{1}{2}}s\right\|\\ &+ \rho\left\|\Gamma\Lambda^{\frac{1}{2}}s\right\| - (\imath - \hat{\imath})\varphi\left\|\Gamma\Lambda^{\frac{1}{2}}s\right\| + \frac{\eta_2}{\eta_1}\tilde{\imath}^{\gamma_3} + \frac{\eta_3}{\eta_1}\tilde{\imath}^{\gamma_4}.\end{aligned} \tag{48}$$

From inequality (48), we have

$$\begin{aligned}\dot{V}_1 \le& -\lambda_{\min}\left\{\Gamma\Lambda^{\frac{1}{2}}\right\}k_1\|s\|^2 + s^T\Gamma\Lambda^{\frac{1}{2}}\left(-k_2\mathrm{sgn}^{\gamma_3}(s) - k_3\mathrm{sgn}^{\gamma_4}(s)\right)\\ &+ \frac{\eta_2}{\eta_1}\tilde{\imath}^{\gamma_3} + \frac{\eta_3}{\eta_1}\tilde{\imath}^{\gamma_4},\\ \le& \ s^T\Gamma\Lambda^{\frac{1}{2}}\left(-k_2\mathrm{sgn}^{\gamma_3}(s) - k_3\mathrm{sgn}^{\gamma_4}(s)\right) + \frac{\eta_2}{\eta_1}\tilde{\imath}^{\gamma_3} + \frac{\eta_3}{\eta_1}\tilde{\imath}^{\gamma_4},\end{aligned} \tag{49}$$

where $\lambda_{\min}\left\{\Gamma\Lambda^{\frac{1}{2}}\right\}$ is the minimum eigenvalue of $\Gamma\Lambda^{\frac{1}{2}}$.

According to Lemma 4 and Lemma 5, $\frac{\eta_2}{\eta_1}\tilde{\imath}^{\gamma_3} = \frac{\eta_2}{\eta_1}(\imath - \hat{\imath})\tilde{\imath}^{\gamma_3}$ satisfies

$$\begin{aligned}\frac{\eta_2}{\eta_1}\tilde{\imath}^{\gamma_3} \le& \frac{\eta_2}{\eta_1(1+\gamma_3)}\left(\imath^{1+\gamma_3} - (\imath - \tilde{\imath})^{1+\gamma_3}\right),\\ \le& \frac{\eta_2}{\eta_1(1+\gamma_3)}\left(2\imath^{1+\gamma_3} - \tilde{\imath}^{1+\gamma_3}\right).\end{aligned} \tag{50}$$

Similarly, $\frac{\eta_3}{\eta_1}\tilde{\imath}^{\gamma_4} = \frac{\eta_3}{\eta_1}(\imath - \hat{\imath})\hat{\imath}^{\gamma_4}$ satisfies

$$\begin{aligned}\frac{\eta_3}{\eta_1}\tilde{\imath}^{\gamma_4} &\le \frac{\eta_3}{\eta_1(1+\gamma_4)}\left(\imath^{1+\gamma_4} - (\imath-\tilde{\imath})^{1+\gamma_4}\right),\\ &\le \frac{\eta_3}{\eta_1(1+\gamma_4)}\left(2\imath^{1+\gamma_4} - \tilde{\imath}^{1+\gamma_4}\right).\end{aligned} \tag{51}$$

Replacing Eqs. (50) and (51) into Eq. (49), we have

$$\begin{aligned}\dot{V}_1 \le\ & s^T\Gamma\Lambda^{\frac{1}{2}}\left(-k_2\mathrm{sgn}^{\gamma_3}(s) - k_3\mathrm{sgn}^{\gamma_4}(s)\right) + \frac{\eta_2}{\eta_1(1+\gamma_3)}\left(2\imath^{1+\gamma_3} - \tilde{\imath}^{1+\gamma_3}\right)\\ &+ \frac{\eta_3}{\eta_1(1+\gamma_4)}\left(2\imath^{1+\gamma_4} - \tilde{\imath}^{1+\gamma_4}\right),\\ \le& -\lambda_{\min}\left\{\Gamma\Lambda^{\frac{1}{2}}\right\}k_2 2^{\frac{\gamma_3+1}{2}}\left(\frac{1}{2}s^Ts\right)^{\frac{\gamma_3+1}{2}} - \lambda_{\min}\left\{\Gamma\Lambda^{\frac{1}{2}}\right\}k_3 2^{\frac{\gamma_4+1}{2}}\left(\frac{1}{2}s^Ts\right)^{\frac{\gamma_4+1}{2}}\\ &+ \frac{2\eta_2}{\eta_1(1+\gamma_3)}\imath^{1+\gamma_3} - \frac{\eta_2(2\eta_1)^{\frac{1+\gamma_3}{2}}}{\eta_1(1+\gamma_3)}\left(\frac{1}{2\eta_1}\tilde{\imath}^2\right)^{\frac{1+\gamma_3}{2}}\\ &- \frac{\eta_3(2\eta_1)^{\frac{1+\gamma_4}{2}}}{\eta_1(1+\gamma_4)}\left(\frac{1}{2\eta_1}\tilde{\imath}^2\right)^{\frac{1+\gamma_4}{2}} + \frac{2\eta_3}{\eta_1(1+\gamma_4)}\imath^{1+\gamma_4},\\ \le& -\varpi_{k1}V_1^{\frac{1+\gamma_3}{2}} - \varpi_{k2}V_1^{\frac{1+\gamma_4}{2}} + \xi_k,\end{aligned} \tag{52}$$

where $\varpi_{k1} = \min\left\{\lambda_{\min}\left\{\Gamma\Lambda^{\frac{1}{2}}\right\}k_2 2^{\frac{\gamma_3+1}{2}}, \frac{\eta_2(2\eta_1)^{\frac{1+\gamma_3}{2}}}{\eta_1(1+\gamma_3)}\right\}$, $\xi_k = \frac{2\eta_2}{\eta_1(1+\gamma_3)}\imath^{1+\gamma_3} + \frac{2\eta_3}{\eta_1(1+\gamma_4)}\imath^{1+\gamma_4} > 0$, $\varpi_{k2} = \min\left\{\lambda_{\min}\left\{\Gamma\Lambda^{\frac{1}{2}}\right\}k_3 2^{\frac{\gamma_4+1}{2}}, \frac{\eta_3(2\eta_1)^{\frac{1+\gamma_4}{2}}}{\eta_1(1+\gamma_4)}\right\}$. Since $\frac{1+\gamma_3}{2} > 1$ and $0 < \frac{1+\gamma_4}{2} < 1$, it can be analyzed by Lemma 3 that s and $\tilde{\imath}$ can converge to zero in a fixed time. The setting time T_s satisfies

$$T_s \le \frac{1}{\varpi_{k1}}\frac{1}{\frac{1+\gamma_3}{2}-1} + \frac{1}{\varpi_{k2}}\frac{1}{1-\frac{1+\gamma_4}{2}}. \tag{53}$$

As mentioned above, s can reach and remain at the SMS in a fixed time, i.e., $s = \dot{s} = 0$. Combined with Eq. (25), we obtain

$$s = \dot{s} = \gamma + \varphi + \Gamma\Lambda\left(\dot{\varepsilon}_2(\alpha_1(\arctan(\varepsilon_1))^{\frac{n_1}{n_2}-\frac{p_2}{p_1}} + \beta_1) - \omega\right) = 0. \tag{54}$$

Now we are on the stage of showing the stability analysis of the sliding phase, and the main results are as follows. From Eq. (54), we have

$$(1+\varepsilon_1^2)^{\frac{p_1}{p_2}}\arctan(\varepsilon_1) + (l\dot{\varepsilon}_1)^{\frac{p_1}{p_2}} = 0. \tag{55}$$

By means of an equivalent transformation, we can obtain

$$(1+\varepsilon_1^2)(\arctan(\varepsilon_1))^{\frac{p_2}{p_1}} + l\dot{\varepsilon}_1 = 0. \tag{56}$$

Defining $z = \arctan(\varepsilon_1)$, we have

$$\alpha_1 z^{\frac{n_1}{n_2}} + \beta_1 z^{\frac{p_2}{p_1}} + \dot{z} = 0. \tag{57}$$

Then a new Lyapunov function is developed as

$$V_2 = \frac{1}{2}z^2. \tag{58}$$

The time derivative of V_2 is

$$\begin{aligned}\dot{V}_2 &= z\dot{z}\\ &= -\alpha_1 z^{\frac{n_1}{n_2}+1} - \beta_1 z^{\frac{p_2}{p_1}+1}\\ &= -\mu_1 V_1^{\frac{n_1+n_2}{2n_2}} - \mu_2 V_1^{\frac{p_1+p_2}{2p_1}},\end{aligned} \tag{59}$$

where $\mu_1 = 2^{\frac{n_1+n_2}{2n_2}}\alpha_1$, $\mu_2 = 2^{\frac{p_1+p_2}{2p_1}}\beta_1$, $n_1 > n_2$, $p_1 > p_2$, $\frac{n_1+n_2}{2n_2} > 1$, $0 < \frac{p_1+p_2}{2p_1} < 1$, Based on Lemma 3, the state z can converge to zero in a fixed time. Since $z = \arctan(\varepsilon_1)$, the tracking error ε can also converge to zero in a fixed time. The setting time satisfies

$$T_z \le \frac{2n_2}{\mu_1(n_1-n_2)} + \frac{2p_1}{\mu_2(p_2-p_1)}. \tag{60}$$

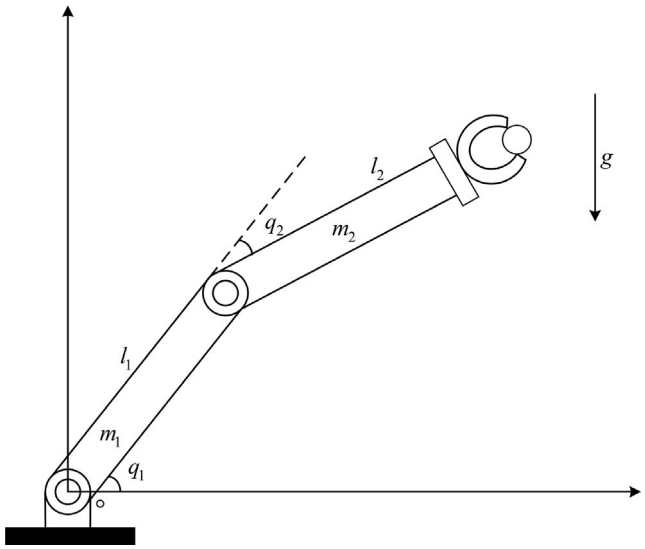


Fig. 3. An illustrative example of 2-link manipulators.

Therefore, the error system of the robotic manipulator (23) is fixed-time stable by using adaptive estimator-based NFTSMC. The overall setting time is bounded by

$$T \leq T_d + T_s + T_z. \tag{61}$$

4. Simulation results

In order to verify the superiority of the control method developed in the paper, trajectory tracking are carried out on the Matlab/Simulink software platform for the 2-link rigid manipulator plant. The specific comments are described below.

The structural diagram of the 2-link rigid manipulators is shown in Fig. 3, its dynamic model is given by:

$$\begin{aligned}&\begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix}\begin{bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \end{bmatrix} + \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix}\begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \end{bmatrix} + \begin{bmatrix} g_{11} \\ g_{21} \end{bmatrix} + \begin{bmatrix} f_{v11} & f_{v12} \\ f_{v21} & f_{v22} \end{bmatrix}\begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \end{bmatrix} \\ &+ \begin{bmatrix} f_{s11}(\dot{q}_1) \\ f_{s21}(\dot{q}_2) \end{bmatrix} = \begin{bmatrix} \tau_{u1} \\ \tau_{u2} \end{bmatrix} + \begin{bmatrix} \tau_{d1} \\ \tau_{d2} \end{bmatrix} + \begin{bmatrix} u_{a1}(t) \\ u_{a2}(t) \end{bmatrix},\end{aligned} \tag{62}$$

where $m_{11} = (m_1 + m_2) l_1^2 + m_2 l_2^2 + 2m_2 l_1 l_2 \cos(q_2) + J_1$, $m_{12} = m_2 l_2^2 + m_2 l_1 l_2 \cos(q_2)$, $m_{21} = m_2 {l_2}^2 + m_2 l_1 l_2 \cos(q_2)$, $m_{22} = m_2 l_2^2 + J_2$, $c_{22} = 0$, $c_{11} = -2m_2 l_1 l_2 \sin(q_2)\dot{q}_2$, $c_{12} = -m_2 l_1 l_2 \sin(q_2)\dot{q}_2$, $c_{21} = m_2 l_1 l_2 \sin(q_2)\dot{q}_1$, $g_{11} = (m_1 + m_2) g l_1 \cos(q_1) + m_2 g l_2 \cos(q_1 + q_2)$, $g_{21} = m_2 g l_2 \cos(q_1 + q_2)$, $f_{s11} = f_{s1} sign(\dot{q}_1)$ and $f_{s21} = f_{s2} sign(\dot{q}_2)$. $q = [q_1, q_2]^T$ and $\dot{q} = [\dot{q}_1, \dot{q}_2]^T$ are the position vectors and the velocity vectors of the two links, respectively, and the initial states are set to $q(0) = [q_1(0), q_2(0)]^T = [0.25, 2.1]^T$ and $\dot{q}(0) = [\dot{q}_1(0), \dot{q}_2(0)]^T = [0, 0]^T$, respectively. The coefficients of viscous friction are $f_{v11} = 0.5$, $f_{v12} = f_{v12} = 0$ and $f_{v22} = 0.5$. The coefficients of static friction are $f_{s1} = 2.5$ and $f_{s2} = 2.5$. m_1 and m_2 are the masses of links 1 and 2, respectively. l_1 and l_2 are the lengths of links 1 and 2, respectively. g is the acceleration of gravity. In addition, the physical parameters of the 2-link rigid manipulators are shown in Table 1.

The desired trajectory is given by

$$q_d = \begin{bmatrix} 1.45 - 1.4e^{-t} + 0.6e^{-4t} \\ 1.25 + e^{-t} - 0.5e^{-4t} \end{bmatrix}. \tag{63}$$

The FDI attack signal is set to

$$\Delta(t)\Theta(q, \dot{q}, t) = \begin{bmatrix} 2\sin(t) + 0.5\sin(200\pi t) \\ \cos(2t) + 0.5\sin(200\pi t) \end{bmatrix}. \tag{64}$$

The parameters of actuator faults are set to $l_{t1} = l_{t2} = 10000$, and the fault function is chosen as

$$\Phi = \begin{bmatrix} -0.4\tau_1, & t \geq 4 \\ -0.5\tau_2, & t \geq 5 \end{bmatrix}. \tag{65}$$

In addition, the external disturbance signal is selected as

$$\tau_d = \begin{bmatrix} \cos(100t) \\ 2\sin(50t) \end{bmatrix}. \tag{66}$$

Table 1
Physical parameters of the 2-link manipulators [45].

Symbol	Definition	Value
m_1^0	nominal mass of link 1	0.4 kg
m_2^0	nominal mass of link 2	1.2 kg
m_1	mass of link 1	0.5 kg
m_2	mass of link 2	1.5 kg
l_1	length of link 1	1 m
l_2	length of link 2	0.85 m
J_1	moment of inertia of link 1	5 kg m^2
J_2	moment of inertia of link 2	5 kg m^2
g	gravitational constant	9.81 m/s^2

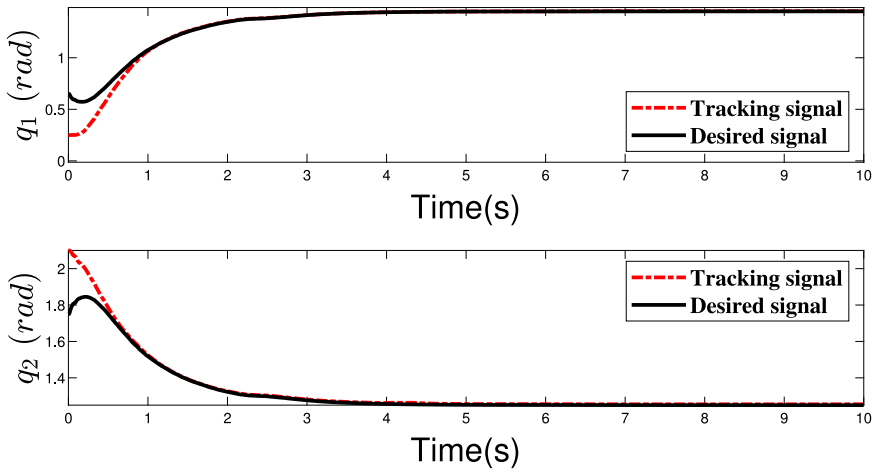


Fig. 4. Tracking response of joint position.

The parameters of the adaptive super-twisting NFTSMC are set to $\alpha_1 = 2$, $\alpha_2 = 2$, $n_1 = 13$, $n_2 = 11$, $p_1 = 11$, $p_2 = 9$, $\beta_1 = 2$, $\beta_2 = 2$, $k_2 = 2$, $k_3 = 1.5$, $\gamma_3 = 5/3$, $\gamma_4 = 3/5$, $\eta_1 = 15$, $\eta_2 = 5$, $\eta_3 = 3$, $\eta_4 = 25$, $\eta_5 = 0.8$, $\zeta_1 = 0.005$, $\zeta_2 = 1$, $\varpi_k = 0.5$, $\hat{k}_4(0) = 3$ and $\hat{\imath}(0) = 5$, respectively. The parameters of the adaptive estimator-based defense method are selected as $\ell_1 = 8$, $\ell_2 = 5$, $\kappa_1 = 2$, $\kappa_2 = 1.5$, $\xi_1 = 18/5$, $\xi_2 = 9/5$, $\xi_3 = 11/5$, $\xi_4 = 9/5$, $l_{a1} = 0.1$, $l_{a2} = 0.1$, $r_1 = 3$, $r_2 = 2$, $r_3 = 7/3$, $r_4 = 5/3$, $\Upsilon_0 = 38$, $\beta_a = 0.999$, $\upsilon_a = 0.1$ and $\iota_a = 0.05$, respectively.

In industrial production, the rigid robotic manipulator will suddenly change the load when grasping and releasing objects, it will directly affect the control performance of the manipulator systems. In this paper, in addition to considering the lumped uncertainty and FDI attacks, load mutation is also addressed in the trajectory tracking simulation. When $t \geq 3$ s, the mass of link 2 will increase by 0.3 kg. The specific simulation results are shown in Figs. 4–14. The tracking results of link 1 and link 2 for the desired position signal and velocity signal are shown in Figs. 4 and 5, respectively. The corresponding tracking error of the position vector is exhibited in Fig. 6. From the results in Figs. 4–6, it can be seen that the manipulator achieves satisfactory trajectory tracking performance under the action of adaptive estimator-based super-twisting NFTSMC. The sliding surfaces are presented in Fig. 7. It illustrates that the sliding mode variable s described in Eq. (24) can quickly converge and remain in NFTSMS, which also confirms the feasibility of the proposed control scheme. Fig. 8 shows the control torque response of link 1 and link 2. It can be seen that the chattering problem has been effectively solved. In addition, the continuous smooth control torque can ensure that the manipulator has a good control performance. Fig. 9 depicts the estimated value of the unknown FDI attacks, it can be observed that the designed defense method is effective. Fig. 10 illustrates the variation curve of the adaptive estimate $\hat{I}$. It can be seen that the adaptive estimate eventually converges to a constant. Based on the results in Figs. 4–10, we can see that the load mutation causes change in the sliding surface, control torque, and estimated value of FDI attacks when $t = 3$ s. It is worth noting that these response trajectories can quickly converge to the equilibrium state under the action of the adaptive estimator-based super-twisting NFTSMC algorithm. Fig. 11 depicts the evolution curves of the control gains, which shows that the results of the adaptive adjustment of the gains $\hat{k}_4$ and $\hat{k}_5$ are satisfactory. From Fig. 8, it can be seen that the response curve fluctuates due to the sudden failure of the actuator when $t = 4$ s and $t = 5$ s, it can quickly returns to the equilibrium state. Similar results can be obtained in Figs. 9–11. Meanwhile, the tracking performance exhibited in Figs. 4–6 is not deteriorated. It also confirms that the proposed control algorithm is robust and capable of providing satisfactory control performance for the manipulator system.

To better demonstrate the superiority of the adaptive fixed-time estimator (AFTE) proposed in this paper, it is simulated in comparison with two other observers, i.e., the finite-time extended state observer (FTESO) [41] and the adaptive extended state observer (AESO) [42]. The comparison of joint position and joint velocity tracking performance is shown in Figs. 12 and 13,

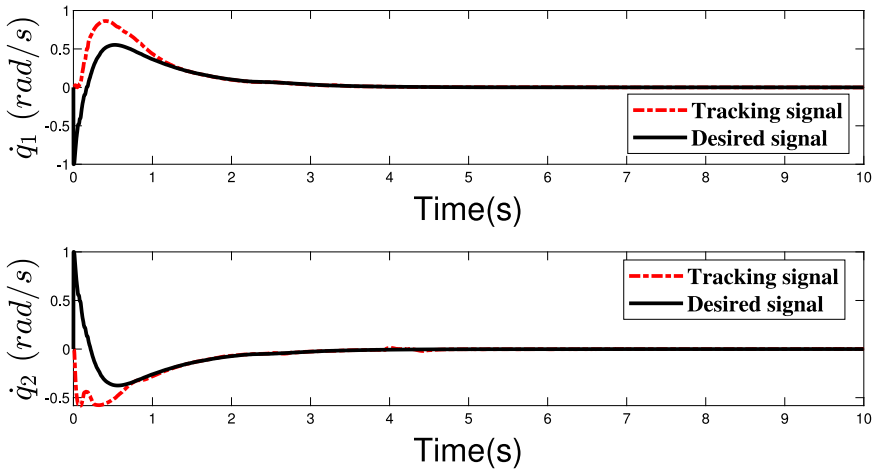


Fig. 5. Tracking response of joint velocity.

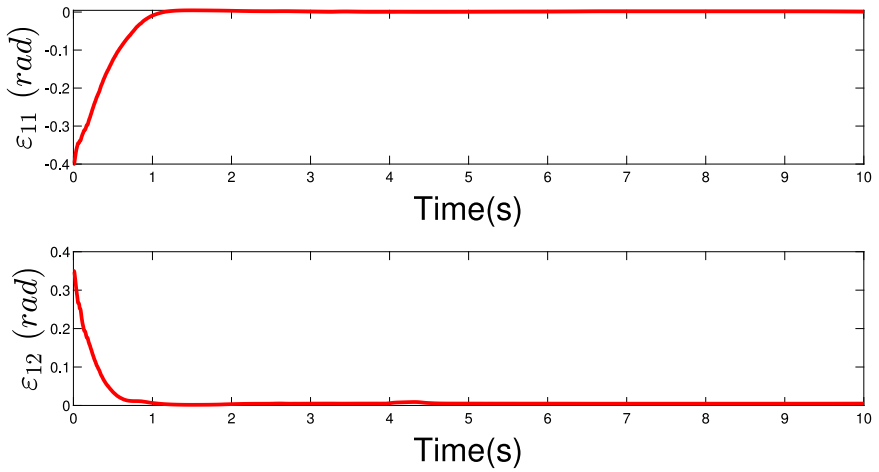


Fig. 6. The response of the tracking error.

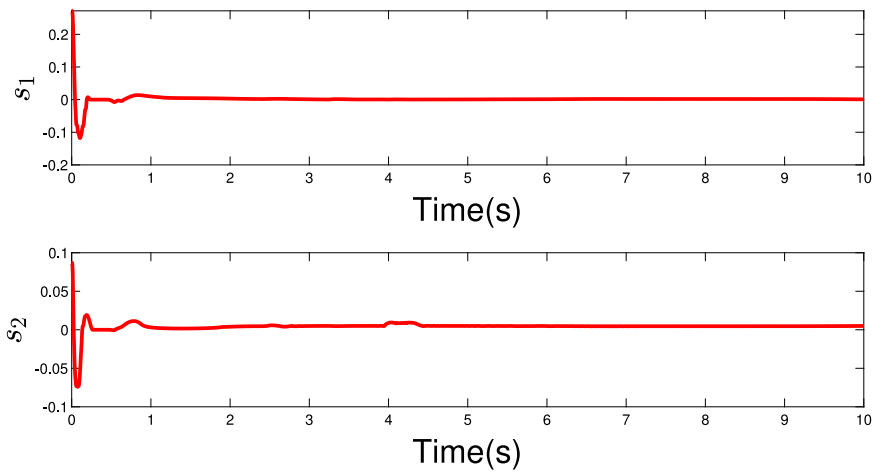


Fig. 7. The response of the sliding mode variable.

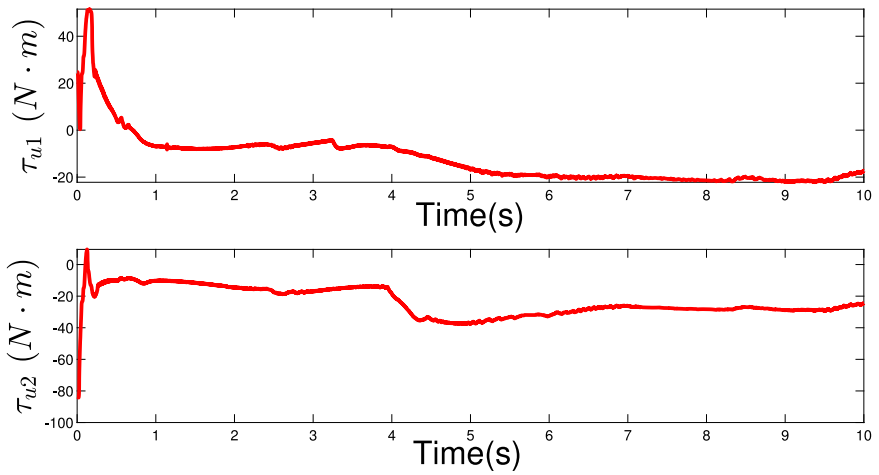


Fig. 8. The response of the control torque.

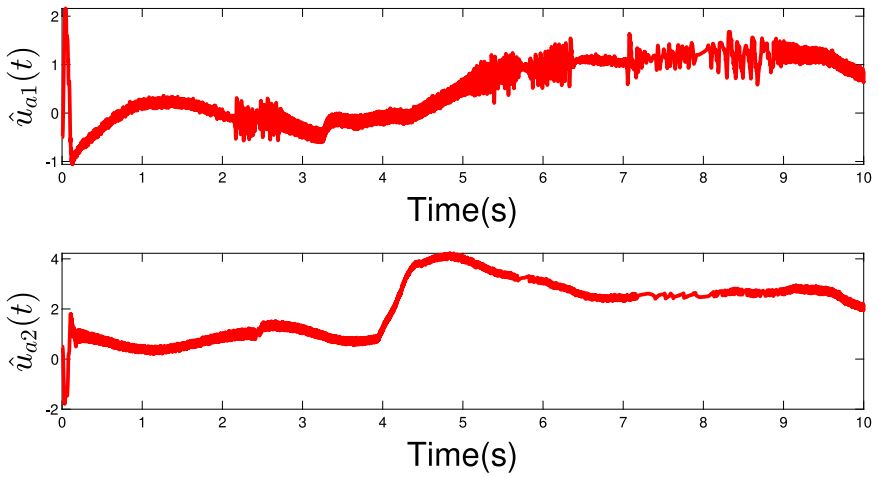


Fig. 9. The estimated value of unknown FDI attacks $u_a(t)$.

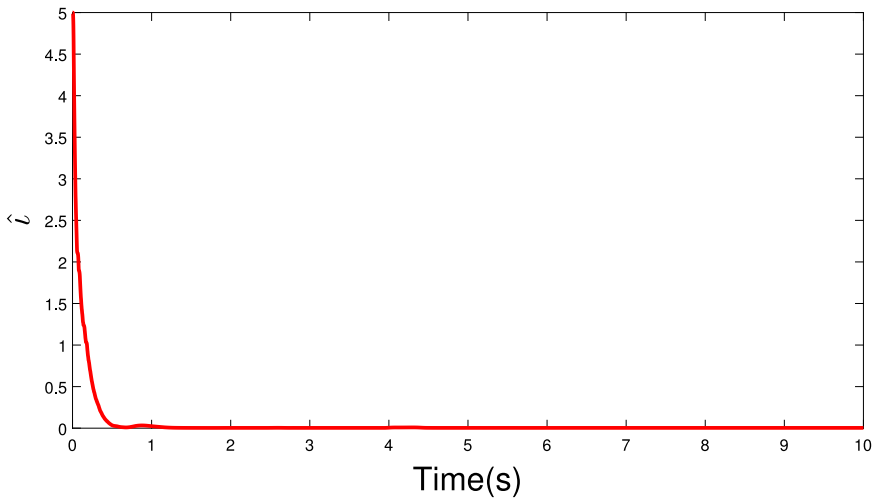


Fig. 10. The estimated of the unknown parameter l.

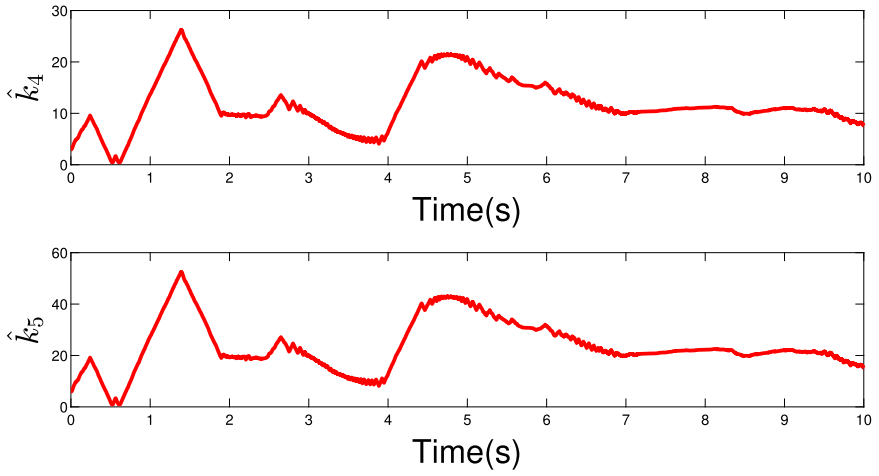


Fig. 11. Adaptive adjustment curve of the control gain.

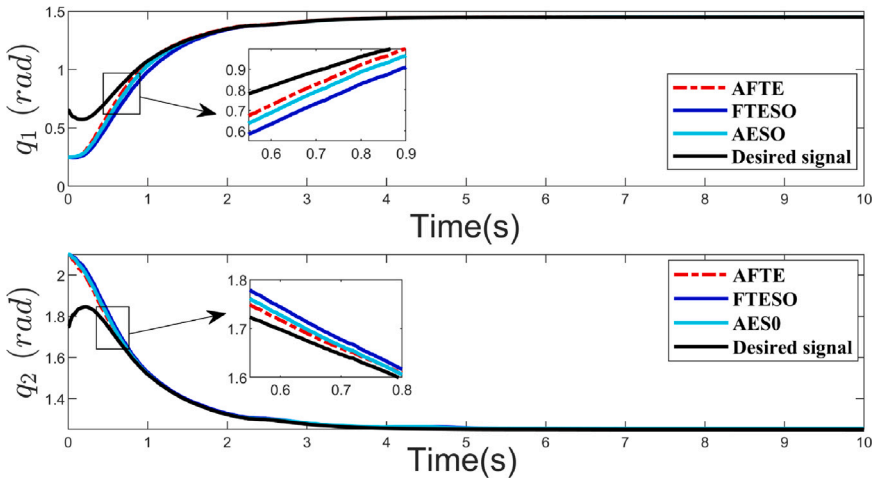


Fig. 12. The comparison of joint position.

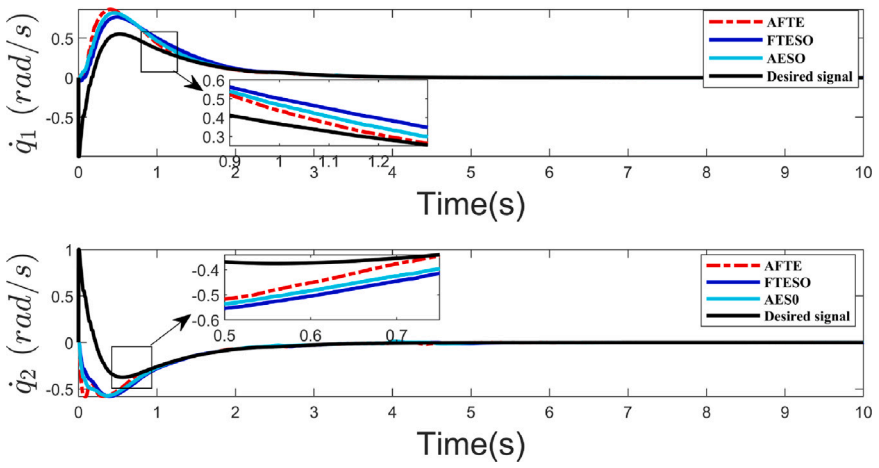


Fig. 13. The comparison of joint velocity.

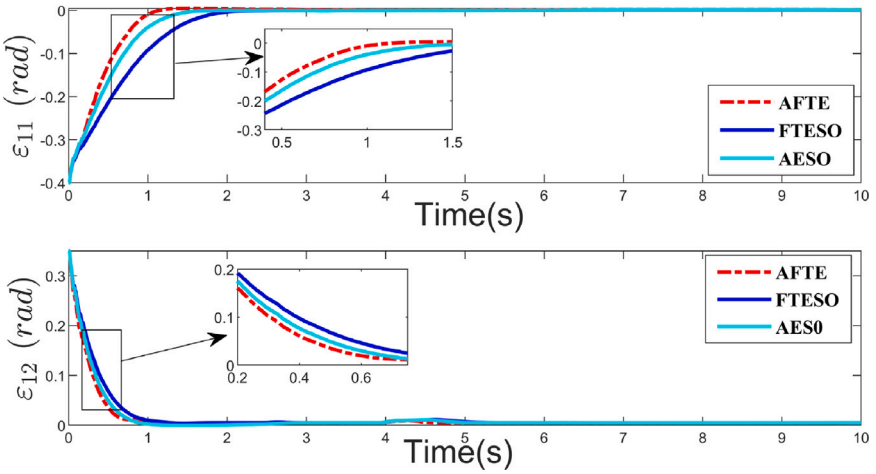


Fig. 14. The comparison of joint position errors.

respectively. The comparison of joint position error response is shown in Fig. 14. From those results, one can see that the tracking error of the system can converge to zero faster when the AFTE is applied in the system. It also shows that the defense strategy proposed in this paper is more effective. Therefore, the scheme proposed in this paper provides better control performance compared with the above two observers.

5. Conclusion

In the paper, we have studied the security control problem of FDI attacks and defense strategy design for robotic manipulators. A novel adaptive estimator-based super-twisting NFTSMC is proposed for robotic manipulator systems in the presence of parameter perturbation, joint friction, external disturbance, FDI attacks, and actuator failure. At first, a novel mathematical model of manipulator systems under FDI attacks and actuator failure is developed. Then, a novel adaptive fixed-time estimator-based defense method is proposed to actively mitigate the effects of FDI attacks. Next, a novel adaptive estimator-based super-twisting NFTSMC is designed to achieve fixed-time stable and desirable tracking precision under FDI attacks and actuator failure. After that, the fixed-time stability of the manipulator systems are proved by utilizing the Lyapunov function. Finally, the proposed control method is applied to trajectory tracking of a 2-link manipulator. The results demonstrate that the proposed method is effective when the robotic manipulator system is subject to FDI attacks and actuator failure.

CRediT authorship contribution statement

Wenqi Liu: Investigation, Writing – original draft. **Zehua Ye:** Formal analysis. **Dan Zhang:** Project administration, Resources, Supervision. **Jun Cheng:** Writing – review & editing. **Huaicheng Yan:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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