IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received May 18, 2020, accepted June 8, 2020, date of publication June 10, 2020, date of current version June 24, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3001391

A Novel Fault-Tolerant Control Method for Robot Manipulators Based on Non-Singular Fast Terminal Sliding Mode Control and Disturbance Observer

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This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (NRF-2019R1D1A3A03103528).

ABSTRACT In this study, a novel Fault-Tolerant Control Methodology (FTCM) is developed for robot manipulators. First, to overcome singularity glitch and to enhance convergence time of conventional Terminal Sliding Mode Control (TSMC), a new Fast Terminal Sliding Mode Surface (FTSMS) is constructed. Next, to reduce the computation complexity and to provide requirements about undefined nonlinear functions for the control system, a Disturbance Observer (DO) to estimate uncertain dynamics, external disturbances, or faults. Besides, a Super-Twisting Reaching Control Law (STRCL) is designed to compensate for the estimated error of disturbance observer with chattering rejection. Final, a novel, robust, FTCM was developed for robot manipulators to obtain the stability goal of the system, to reach the prescribed performance, and to overcome the effects of disturbances, nonlinearities, or faults. Accordingly, the proposed FTCM has remarkable features, such as fast convergence speeds, robust precision, high tracking performance, significant alleviation of chattering behavior, and finite-time convergence. The position tracking computer simulations were implemented to exhibit the effectiveness and feasibility of the suggested FTCM compared with other control algorithms.

INDEX TERMS Fault-tolerant control, Non-Singular Fast Terminal Sliding Mode Control, robotic manipulators, disturbance observer, Super-Twisting Control Law.

I. INTRODUCTION

RRobots are essential for manufacturing, human life, and performing complex tasks nowadays and in the future. With the need for high-quality products, the robot is more widely used. To achieve quality products with high productivity, the robot system must be operated smoothly, reliably, and safely. Unfortunately, Robotic manipulators unavoidably face many complicated uncertainties caused by unmodeled and unknown dynamic models, nonlinear frictional forces, exterior disturbances, or faults. Consequently, this leads to obstacles for the control design process and precise control of robot manipulators. The tracking control of robotic manipulators has concerned many scientists in studying its potential capability. The tracking control method of robotic systems that require a high degree of precision, safety, and stability during operation has been an important subject in both theoretical and practical applications [1], [2]. Developing solutions to enhance the tracking performance and fast response of robotic systems, specifically with respect to uncertainty, external disturbances, and possible faults, continues to present a challenge in robotics research. To enhance the reliability, tracking performance, and safety of robotic systems in all cases, Fault-Tolerant Control Methods (FTCMs) have been recommended [3]–[9], however, it is difficult to apply fault-tolerant controls in robotic systems due to high nonlinearities, external disturbances, and dynamic uncertainties. Furthermore, the time delay implicit in mechanical systems is also a concern for the performance of FTCM. FTCMs can be categorized as either passive FTCM or active FTCM [10].

In the passive FTCM, a control system is constructed without fault detection process for both standard and fault

The associate editor coordinating the review of this manuscript and approving it for publication was Ton Do.

conditions. Therefore, the performance of the control system is depended on the robust properties to handle external disturbances or uncertainties. As published in the literature, several FTCMs have been successfully adopted to control uncertain nonlinear systems. Noteworthy examples such as sliding mode FTCM [11]–[13] or adaptive FTCM [14]. The remarkable characteristics of the passive FTCM are fast response with external disturbances, uncertainties or fault occurrence. However, this method needs partial information about possible system faults and capability solves high magnitude faults. Consequently, it is limited in applying to the real robot system.

Different from the passive FTCM, In the active FTCM, the output signal of the controller is constantly adjusted according to a fault approximation response, which is estimated by a fault diagnosis observer (FDO) [14]–[17]. As a result, the control performance of the active FTCM depends on the fault information accuracy. The active FTCM with the exact fault information will provide performance better than that of a passive FTCM and therefore it is more suitable for real robot applications. On the other hand, wrong fault information leading to the robot system runs loss stability and damage. Therefore, designing an active FTCM based on the exact fault observation is really challenges for the researchers. In controlling robot manipulators, active FTCM offers a control performance better than passive FTCM due to compensation from online control reconfiguration.

In the literature, several control methods, which can be adapted for use in the FTCM design, have been successful in controlling robot systems in real-world applications with uncertainties, disturbances, or faults. The successful control methods employed in these studies include Computed Torque Controllers (CTC) [15], PID controllers [18], [19], Synchronization Controllers (SCs) [20], [21], intelligent controllers [22]–[25], a predictive controller [26], Adaptive Controllers (ACs) [27], [28], and Sliding Mode Controllers (SMCs) [29]–[33]. Among these mentioned control methods, SMC has a simple design, a robust control algorithm, and a proven ability to solve perturbations, uncertainties, or system faults. SMC has attracted a great deal of attention in control system as well as in FTCM [11]–[13]. Unfortunately, the classical SMC is not an optimal solution for all robot control problems because of its limitations, which include chattering behavior, singularity phenomena, and the requirement to know the upper limit values of disturbances, uncertainties, and faults in advance. Recently, several studies have proposed enhanced control algorithms to handle the SMC control obstacles [34]–[36]; these control schemes applied a nonlinear sliding variable for the improvement of the transient performance, called the Terminal Sliding Mode Control (TSMC).

Generally, the conventional TSMC can be used solve the problems associated with classical SMC, but issues persist with the singularity phenomenon, and convergence speeds can be slower for TSMC than for SMC. Hence, to remove the singularity phenomenon issue and improve convergence speed at the same time, Non-Singular Fast Terminal Sliding Mode Controllers (NFTSMCs) have been developed [37]–[40].

Despite their advantages, it is important to note that serious chattering phenomena will occur whenever using one of the above control schemes in real robotic systems (e.g., SMC, TSMC, and FNTSMC) with a large sliding gain value in the switching control law. Consequently, the chattering can compromise the robustness behavior of the control system and significantly weaken its performance. As such, researchers have focused a lot of effort to develop methods that eliminate chattering, including Boundary Layer (BL) [41]–[43], High-Order Sliding Mode Control (HOSMC) [43]–[45], Super-Twisting Algorithm (STA) [46], or Full-Order Sliding Mode Control (FOTSMC) [47]–[51]. However, these methods using BL to eliminate chattering come with tradeoffs and require selection between weakening the chattering phenomenon or the path tracking precision. On the contrary, HOSMC, STA, or FOTSMC offers both higher tracking precision and chattering dismissal. Therefore, in this study, we develop a novel, robust FTCM with STRCL to achieve the control target with smooth control input signals.

As mentioned, the active FTCM will provide control performance better than that of a passive FTCM when the exact fault information is used. Therefore, to precisely estimate the effects of the uncertainties, disturbances, or faults acting on the robot system, a simple resolution is to design observers. Researching this trend, numerous observers based on control schemes have been established [52]–[55]. With those control algorithms, firstly, a disturbance observer is constructed to estimate external disturbance and uncertainty terms. Then, these estimated values are supported for feedforward control technique to compensate for disturbances and uncertainties in the system. Noteworthy is that, according to the stable condition of the SMC, the sliding gain values must assign greater than the boundary values of disturbances and uncertainties in the system [33]. However, the large sliding gain values will cause serious chattering. For this reason, a simple resolution reduced the chattering in control input is that the effects of disturbances and uncertainties must cut down on the system. According to the mentioned solution, DO has been added into the SMC to compensate for the effects of disturbances and uncertainties to reject the chattering behavior [56], [57].

For all control methods based on SMC, TSMC, NFTSMC, or FOTSMC, the two greatest challenges are to achieve an exact value of the upper bounds for the lumped uncertain terms and an exact robot model in the design procedure of the control system. To overcome these challenges, many types of SMC and TSMC have been suggested based on ACs because they can automatically adapt the control parameters to reject the influences of environmental disturbances, uncertainties, or faults [42], [58]–[61]. And, to approximate unknown nonlinear functions, several computing attempts have been suggested, such as Neural Networks (NNs) [23], [39], [62], [63] and Fuzzy Logic Systems (FLSs) [22], [64], due to their approximation capabilities.

However, using NNs or FLSs to approximate unknown nonlinear functions lead to increases the complex calculations for the control system.

Purposed by the above analysis, the aim of this report is to design a novel FTCM for robot manipulators based on the combination of NFTSMC, DO, and STRCL that solves several important problems: 1) speedy transient performance; 2) convergence in a short time; 3) rejection of the chattering phenomenon; (4) highly effective for trajectory tracking control with the presence of exterior disturbances, uncertainties, component or actuator faults; 5) rejects the requirement for prior information about upper bound values of exterior disturbances, uncertainties, or faults.

The remainder of this report is outlined as follows: The problem statement is given in section 2. Section 3 describes the design process of the proposed FTCM. In section 4, the proposed FTCM is applied to a robotic system [65], and its simulation tracks the prescribed pathway and compares it to control schemes based on conventional SMC [33], [66] and TSMC [34] to inspect positional errors, fast transient performance, and chattering phenomenon rejection. Finally, section 5 summarizes the notable conclusions of this work.

Notations: Several symbols are utilized throughout this paper, $\|*\|$ and $|*|$ correspond to the Euclidean norm and modulus, while N and R correspond to the spaces of natural numbers and real numbers, respectively. $\{*\}^{-1}$ and $\{*\}^T$ correspond to inverse of and matrix transpose of, respectively.

II. STATEMENT OF THE PROBLEM

A. THE PROBLEM STATEMENT

Consider the robotic dynamic equation explained by:

$$\ddot{\theta} = M^{-1}(\theta)\left(\tau - V_m\left(\theta,\dot{\theta}\right)\dot{\theta} - F_r\left(\dot{\theta}\right) - G(\theta) - \tau_d\right) + \psi\left(t - T_f\right)\omega\left(\theta,\dot{\theta},\tau\right) \tag{1}$$

where $\theta(t), \dot{\theta}(t), \ddot{\theta}(t) \in R^n$ represent the position, velocity and acceleration at each joint of the robot system, respectively, $M(\theta) \in R^{n\times n}$ is the inertia matrix, $V_m\left(\theta,\dot{\theta}\right) \in R^{n\times 1}$ indicates the Coriolis and centrifugal forces, $G(\theta) \in R^{n\times 1}$ is the gravitational force term, $\tau(t) \in R^{n\times 1}$ represents the control input torque, $\tau_d(t) \in R^{n\times 1}$ indicates anonymous disturbances, $\psi\left(t - T_f\right)\omega\left(\theta,\dot{\theta},\tau\right)$ is the unexpected fault terms that affect the robotic system, T_f indicates the time instant that a fault occurs, the $\psi\left(t - T_f\right)$ function gives the time profile of a fault that occurs at some unknown time T_f, and $\omega\left(\theta,\dot{\theta},\tau\right)$ is the bounded but uncontrollable term of the controlled system output.

The following fundamental property satisfies the robot dynamic model (1):

Property 1: The inertia matrix is a positive definite matrix and limited as follows:

$$0 < \lambda_{\min}\{M(\theta)\} \leqslant \|M\| \leqslant \lambda_{\max}\{M(\theta)\} \leqslant \Upsilon, \quad \Upsilon > 0 \tag{2}$$

where $\lambda_{\min}\{M(\theta)\}$ and $\lambda_{\max}\{M(\theta)\}$ correspond to the minimum and maximum eigenvalues of the inertia matrix.

The $\psi\left(t - T_f\right)$ function is defined as a diagonal matrix with the following form:

$$\psi\left(t - T_f\right) = \operatorname{diag}\left\{\psi_1\left(t - T_f\right), \cdots, \psi_n\left(t - T_f\right)\right\} \tag{3}$$

In the literature, there are two types of faults that have been identified, including abrupt and incipient faults, according to the following formula:

$$\psi\left(t - T_f\right) = \begin{cases} 0, & t \leqslant T_f \\ 1 - e^{-\nu}\left(t - T_f\right), & t > T_f \end{cases} \tag{4}$$

where $\nu > 0$ indicates the unknown fault evolution rate.

When the value of ν is small, it characterizes incipient faults. While ν is large, the formula characterizes abrupt faults.

To simplify the analysis and design in the control system, the robot dynamic model (1) can be rearranged:

$$\ddot{\theta} = M^{-1}(\theta)\tau + M^{-1}(\theta)\left(V_m\left(\theta,\dot{\theta}\right)\dot{\theta} + G(\theta)\right) + M^{-1}(\theta)\left(F_r\left(\dot{\theta}\right) + \tau_d\right) + \psi\left(t - T_f\right)\omega\left(\theta,\dot{\theta},\tau\right) \tag{5}$$

Here, we assign $x_1 = \theta, x_2 = \dot{\theta}, x = [x_1, x_2]^T$ and $u = \tau$; thus, the dynamic mode (5) can be described according to the following expression:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = q(x)u - H(x) - \Delta \end{cases} \tag{6}$$

where $H(x) = M^{-1}(\theta)\left(V_m\left(\theta,\dot{\theta}\right)\dot{\theta} + G(\theta)\right)$ indicates the known element, $q(x) = M^{-1}(\theta)$ represents a smooth nonlinear function, and $\Delta = M^{-1}(\theta)\left(F_r\left(\dot{\theta}\right) + \tau_d\right) - \psi\left(t - T_f\right)\omega\left(\theta,\dot{\theta},\tau\right)$ gives the anonymous element in the system dynamics.

Our goal is to propose a robust, active FTCM such that this control algorithm can provide the prescribed performance regardless of disturbances, uncertainties, and faults.

The following constraint is assumed for the control design approach.

Assumption 1: The modelling uncertainty is bounded such that

$$\|\Delta\| \leqslant \Lambda \tag{7}$$

where Λ are arbitrary positive constants.

III. FTCM FOR ROBOT MANIPULATORS BASED ON NFTSMC, DO, AND STRCL

This section presents FTCM for robot manipulators based on the combination of NFTSMC, DO, and STRCL, which secures the stabilization of the system and obtains the prescribed tracking performance.

A. DESIGN OF THE NEW FTSMS

To overcome singularity glitch and to enhance convergence time of conventional TSMC, the new FTSMS is constructed as:

$$\sigma_i = \dot{e}_i + \frac{2\gamma_1}{1 + E^{-\mu_1(|e_i|-\phi)}}e_i + \frac{2\gamma_2}{1 + E^{\mu_2(|e_i|-\phi)}}|e_i|^{\alpha}sgn(e_i) \tag{8}$$

where $\sigma \in R^n$ is the FTSMS, E defines as exponential function. Likewise, $e_i = x_{1i} - x_{ri}$ represents the positional control error, and $\dot{e}_i = \dot{x}_{1i} - \dot{x}_{ri}$ represents the velocity control error $x_r \in R^n$ is the prescribed reference path. Furthermore, $\gamma_1, \gamma_2, \mu_1, \mu_2$ are the positive constants, $0 < \alpha < 1$, and $\phi = \left(\frac{\gamma_2}{\gamma_1}\right)^{1/(1-\alpha)}$.

Based on the SMC, the following terms must be satisfied when the control errors run in the sliding mode:

$$\sigma_i = 0; \quad \dot{\sigma}_i = 0 \tag{9}$$

Combining dynamic (8) with terms (9) gives:

$$\dot{e}_i = -\frac{2\gamma_1}{1+E^{-\mu_1(|e_i|-\phi)}}e_i - \frac{2\gamma_2}{1+E^{\mu_2(|e_i|-\phi)}}|e_i|^\alpha sgn(e_i) \tag{10}$$

To prove that $e_i = 0$ is an equilibrium point, and it will converge to zero in finite time, the following Lyapunov function is considered:

$$V_1 = 0.5e_i^2 \tag{11}$$

Calculating time derivation of Lyapunov function (11) and noting (10), we can yield as:

$$\begin{aligned}\dot{V}_1 &= e_i\dot{e}_i \\ &= -\frac{2\gamma_1}{1+E^{-\mu_1(|e_i|-\phi)}}e_i^2 - \frac{2\gamma_2}{1+E^{\mu_2(|e_i|-\phi)}}|e_i|^{\alpha+1} \\ &< 0\end{aligned} \tag{12}$$

The inequality (12) confirms $e_i = 0$ in finite-time according to Lyapunov criterion.

Once $|e_i(0)| > \phi$, the sliding motion includes two phases:

The first phase: $e_i(0) \to |e_i| = \phi$, the first part of Eq. (10) offers the role of providing a rapid convergence speed and the second part plays a secondary role.

$$\begin{aligned}\int_0^{t_1} dt &= \int_\phi^{e_i(0)} \frac{1}{\frac{2\gamma_1}{1+E^{-\mu_1(|e_i|-\phi)}}e_i + \frac{2\gamma_2}{1+E^{\mu_2(|e_i|-\phi)}}|e_i|^\alpha} d(|e_i|) \\ &< \int_\phi^{e_i(0)} \frac{1}{\gamma_1|e_i|}d(|e_i|) = \frac{\ln(|e_i(0)|) - \ln(\phi)}{\gamma_1}\end{aligned} \tag{13}$$

The second phase: $|e_i| = \phi \to e_i = 0$, the second component of Eq. (10) offers the role greater than the first one.

$$\begin{aligned}\int_0^{t_2} dt &= \int_0^{\phi} \frac{1}{\frac{2\gamma_1}{1+E^{-\mu_1(|e_i|-\phi)}}e_i + \frac{2\gamma_2}{1+E^{\mu_2(|e_i|-\phi)}}|e_i|^\alpha} d(|e_i|) \\ &< \int_0^{\phi} \frac{1}{\gamma_1|e_i|^\alpha}d(|e_i|) = \frac{1}{\gamma_2(1-\alpha)}|\phi|^{1-\alpha}\end{aligned} \tag{14}$$

The time total of the sliding motion phase is defined as:

$$\begin{aligned}T_s &= t_1 + t_2 \\ &< \frac{\ln(|e_i(0)|) - \ln(\phi)}{\gamma_1} + \frac{1}{\gamma_2(1-\alpha)}|\phi|^{1-\alpha}\end{aligned} \tag{15}$$

The state variable of the dynamic (10) converge to sliding manifold($\sigma(0) \to 0$) within the defined time T_r, which was point out in [67]. Therefore, the time total for stability on the sliding manifold is computed as: $T \le T_r + T_s$.

B. DESIGN OF NFTSMC

With system (6), $\ddot{e}$ is described as follows:

$$\ddot{e} = q(x)u - H(x) - \Delta - \ddot{x}_r \tag{16}$$

Let us take the time derivation of Eq. (8):

$$\begin{aligned}\dot{\sigma} &= \ddot{e} + \frac{2\gamma_1}{1+E^{-\mu_1(|e|-\phi)}}\dot{e} + \frac{2\gamma_1\mu_1\dot{e}sgn(e)E^{-\mu_1(|e|-\phi)}}{\left(1+E^{-\mu_1(|e|-\phi)}\right)^2}e \\ &+ \frac{2\gamma_2\alpha}{1+E^{\mu_2(|e|-\phi)}}|e|^{\alpha-1}\dot{e} - \frac{2\gamma_2\mu_2\dot{e}E^{\mu_2(|e|-\phi)}}{\left(1+E^{\mu_2(|e|-\phi)}\right)^2}|e|^\alpha\end{aligned} \tag{17}$$

Noting result (16), therefore, Eq. (17) becomes:

$$\begin{aligned}\dot{\sigma} &= q(x)u - H(x) - \Delta - \ddot{x}_r + \frac{2\gamma_1}{1+E^{-\mu_1(|e|-\phi)}}\dot{e} \\ &+ \frac{2\gamma_1\mu_1\dot{e}sgn(e)E^{-\mu_1(|e|-\phi)}}{\left(1+E^{-\mu_1(|e|-\phi)}\right)^2}e \\ &+ \frac{2\gamma_2\alpha}{1+E^{\mu_2(|e|-\phi)}}|e|^{\alpha-1}\dot{e} - \frac{2\gamma_2\mu_2\dot{e}E^{\mu_2(|e|-\phi)}}{\left(1+E^{\mu_2(|e|-\phi)}\right)^2}|e|^\alpha\end{aligned} \tag{18}$$

In order to reach the prescribed tracking performance, the following control method is designed for the robotic system (1):

$$u = -q^{-1}(x)(u_n + u_r) \tag{19}$$

where the term of the nominal control, u_n, holds the path of the control errors on the FTSMS (8). u_n is defined as follows:

$$\begin{aligned}u_n &= -H(x) - \ddot{x}_r + \frac{2\gamma_1}{1+E^{-\mu_1(|e|-\phi)}}\dot{e} \\ &+ \frac{2\gamma_1\mu_1\dot{e}sgn(e)E^{-\mu_1(|e|-\phi)}}{\left(1+E^{-\mu_1(|e|-\phi)}\right)^2}e \\ &+ \frac{2\gamma_2\alpha}{1+E^{\mu_2(|e|-\phi)}}|e|^{\alpha-1}\dot{e} - \frac{2\gamma_2\mu_2\dot{e}E^{\mu_2(|e|-\phi)}}{\left(1+E^{\mu_2(|e|-\phi)}\right)^2}|e|^\alpha\end{aligned} \tag{20}$$

In order to combat the influences of the lumped anonymous elements on dynamics of the robot manipulator, a reaching control law is proposed according to the following expression:

$$u_r = (\Lambda + \rho)sgn(\sigma) \tag{21}$$

where ρ is a minor positive constant.

Remark 1: The convergence condition of sliding mode only guarantees that the initial motion point at any position in the state space can approach the sliding surface within a defined time, and there is no limitation on the prescribed pathway of the reaching motion. The reaching law enhances faster convergence time of reaching motion.

C. STABILITY ANALYSIS OF NFTSMC

Applying control input signals (19)-(21) to Eq. (18) gives:

$$\dot{\sigma} = -u_r - \Delta \tag{22}$$

To confirm the correctness of the control commands (19)-(21), the Lyapunov function is defined as:

$$V_2 = 0.5\sigma^T \sigma \tag{23}$$

Therefore, the time derivative of Eq. (23) is given as:

$$\dot{V}_2 = \sigma^T \dot{\sigma} \tag{24}$$

Now, substituting Eq. (22) into Eq. (24), we can yield the following inequality:

$$\begin{aligned} \dot{V}_2 &= \sigma^T(-u_r - \Delta) \\ &= \sigma^T(-(\Lambda + \rho)\, sgn(\sigma) - \Delta) \\ &= (-\Lambda|\sigma| - \Delta\sigma) - \rho|\sigma| \\ &\le -\rho|\sigma| \end{aligned} \tag{25}$$

From inequality (25), it is apparent that the robotic system of Eq. (1) is globally stable under the control law (19)-(21), and the control errors will approach zero in a short time regardless of disturbances, uncertainties, and faults. However, the main challenge in scheming an FTCM based on SMC, TSMC, or NFTSMC is serious chattering. To overcome the above challenge, proposed FTCM for robot manipulators is developed and clearly stated below.

D. DESIGN OF DO

The lumped uncertain component can be described according to estimation, as follows:

$$\Delta = \hat{\Delta} + \tilde{\Delta} \tag{26}$$

where $\hat{\Delta}$ is the estimated value of the lumped uncertainty of Δ, it is used to compensate the effects of the lumped uncertain term, and $\tilde{\Delta}$ is the estimated error of disturbances, $\tilde{\Delta} = [\tilde{\Delta}_1, \ldots, \tilde{\Delta}_n]$, this estimated error is assumed to be bounded by an unknown positive constant, $\|\tilde{\Delta}_i\| \le \Pi_i|\sigma_i|^{0.5}$; $i = 1, \ldots, n$ with $\Pi_i > 0$.

We design an observer to estimate the lumped uncertain term for the system (6) with time-varying disturbance as:

$$\begin{aligned} \dot{\hat{\Delta}} &= k_1(\hat{\omega} - \dot{x}_1) \\ \dot{\hat{\omega}} &= q(x)\,u - H(x) - \hat{\Delta} - k_2(\hat{\omega} - \dot{x}_1) \end{aligned} \tag{27}$$

where $\hat{\Delta}$ is the estimated value of Δ, and $\hat{\omega}$ is the estimated value of x_2, $k_1 > 0$, $k_2 > 0$.

E. STABILITY ANALYSIS OF DO

Let us select the Lyapunov function for DO (27) as:

$$V_3 = 0.5\frac{1}{k_1}\tilde{\Delta}^2 + 0.5\tilde{\omega}^2 \tag{28}$$

where $\tilde{\Delta} = \Delta - \hat{\Delta}$ is the estimated error of disturbances, $\tilde{\omega} = x_2 - \hat{\omega}$ is the estimated error of the state variable x_2.

Taking time derivative of Eq. (28), we have:

$$\begin{aligned} \dot{V}_3 &= \frac{1}{k_1}\tilde{\Delta}\dot{\tilde{\Delta}} + \tilde{\omega}\dot{\tilde{\omega}} \\ &= \frac{1}{k_1}\tilde{\Delta}\left(\dot{\Delta} - \dot{\hat{\Delta}}\right) + \tilde{\omega}\left(\dot{x}_2 - \dot{\hat{\omega}}\right) \\ &= \frac{1}{k_1}\tilde{\Delta}\dot{\Delta} - \frac{1}{k_1}\tilde{\Delta}\dot{\hat{\Delta}} + \tilde{\omega}\left(\dot{x}_2 - \dot{\hat{\omega}}\right) \end{aligned} \tag{29}$$

Substituting Eqs. (26) and (27) into Eq. (29) gives:

$$\begin{aligned} \dot{V}_3 &= \frac{1}{k_1}\tilde{\Delta}\dot{\Delta} + \tilde{\Delta}\tilde{\omega} + \tilde{\omega}\left(-\Delta + \hat{\Delta} + k_2(\hat{\omega} - \dot{x}_1)\right) \\ &= \frac{1}{k_1}\tilde{\Delta}\dot{\Delta} - k_2\tilde{\omega}^2 \le 0 \end{aligned} \tag{30}$$

When k_1 is selected as a relative large value, we have $1/k_1\,\dot{\Delta} \approx 0$. Obviously, the lumper uncertainty can be estimated by this DO, and the compensation of the lumped uncertain term will be realized in the designed controller.

F. DESIGN OF THE PROPOSED FTCM

In this paper, the FTCM is proposed for robot manipulators to achieve high performance with no significant chattering as follow:

$$u = -q^{-1}(x)(u_n + u_r) \tag{31}$$

where, the u_n is designed based on novel FTSMS and DO as follows:

$$\begin{aligned} u_n = &-H(x) - \hat{\Delta} - \ddot{x}_r + \frac{2\gamma_1}{1 + E^{-\mu_1(|e| - \phi)}}\dot{e} \\ &+ \frac{2\gamma_1\mu_1\dot{e}\,sgn(e)\,E^{-\mu_1(|e|-\phi)}}{\left(1 + E^{-\mu_1(|e|-\phi)}\right)^2}e \\ &+ \frac{2\gamma_2\alpha}{1 + E^{\mu_2(|e|-\phi)}}|e|^{\alpha-1}\dot{e} - \frac{2\gamma_2\mu_2\dot{e}E^{\mu_2(|e|-\phi)}}{\left(1 + E^{\mu_2(|e|-\phi)}\right)^2}|e|^{\alpha} \end{aligned} \tag{32}$$

and STRCL of u_r is designed as

$$\begin{aligned} u_r &= \Upsilon_1|\sigma|^{0.5}sgn(\sigma) + \eta \\ \dot{\eta} &= -\Upsilon_2 sgn(\sigma) \end{aligned} \tag{33}$$

where $\Upsilon_1 = diag(\Upsilon_{11}, \ldots, \Upsilon_{1n})$ and $\Upsilon_2 = diag(\Upsilon_{21}, \ldots, \Upsilon_{2n})$. Υ_{1i} and Υ_{2i} are assigned to satisfy the following relationship[63]:

$$\begin{cases} \Upsilon_{1i} > 2\Pi_i \\ \Upsilon_{2i} > \Upsilon_{1i}\dfrac{5\Pi_i\Upsilon_{1i} + 4\Pi_i^2}{2(\Upsilon_{1i} - 2\Pi_i)}; \end{cases} \quad i = 1, 2, \ldots, n \tag{34}$$

Block Diagram of the designed control system is illustrated in Fig. 1.

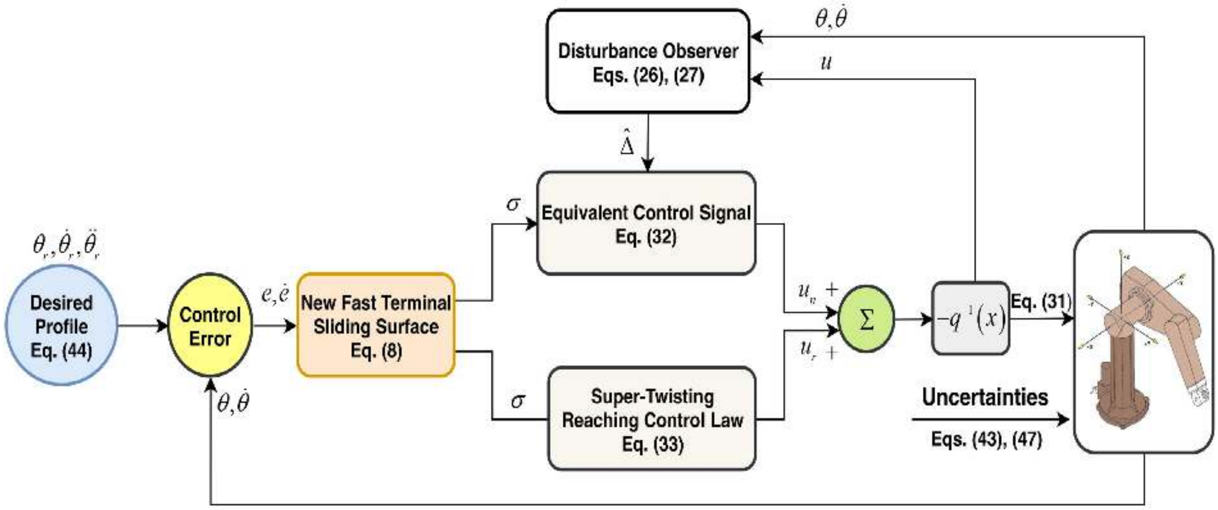

FIGURE 1. Diagram of the proposed FTCM.

G. STABILITY ANALYSIS OF THE PROPOSED FTCM

To verify correctness of the proposed system (31)-(33), the following procedure:

Applying control commands (31)-(33) to Eq. (18) gains:

$$\begin{cases} \dot{\sigma} = \tilde{\Delta} - \Upsilon_1 |\sigma|^{0.5} sgn(\sigma) - K \\ \dot{K} = -\Upsilon_2 sgn(\sigma) \end{cases} \tag{35}$$

Now, using one of the elements in Eq. (35) as follows:

$$\begin{cases} \dot{\sigma}_i = \tilde{\Delta}_i - \Upsilon_{1i} |\sigma_i|^{0.5} sgn(\sigma_i) - K_i \\ \dot{K}_i = -\Upsilon_{2i} sgn(\sigma_i) \end{cases} \tag{36}$$

Let us consider the following Lyapunov function for dynamic (36):

$$V_4 = \kappa^T Q \kappa \tag{37}$$

Here, $\kappa = \left[\sigma_i^{0.5}, \lambda_i\right]^T$, $Q = \frac{1}{2}\begin{bmatrix} 4\Upsilon_{2i} + \Upsilon_{1i}^2 & -\Upsilon_{1i} \\ -\Upsilon_{1i} & 2 \end{bmatrix}$.

If $\Upsilon_{2i} > 0$, so, according to Rayleigh's inequality:

$$\lambda_{\min}(Q) \|\kappa\|^2 \leq V_4 \leq \lambda_{\max}(Q) \|\kappa\|^2 \tag{38}$$

with $\|\kappa\|^2 = |\sigma_i| + \eta_i^2$.

Taking the time derivation of Eq. (37), we can yield:

$$\dot{V}_4 = -\frac{1}{|\sigma_i|^{0.5}} \kappa^T P \kappa + \frac{1}{|\sigma_i|^{0.5}} \left[\tilde{\Delta}_i, 0\right] Q \kappa \tag{39}$$

with $P = \frac{\Upsilon_{1i}}{2}\begin{bmatrix} 2\Upsilon_{2i} + \Upsilon_{1i}^2 & -\Upsilon_{1i} \\ -\Upsilon_{1i} & 1 \end{bmatrix}$.

With Assumption $\left\|\tilde{\Delta}_i\right\| \leq \Pi_i |\sigma_i|^{0.5}; i = 1, \ldots, n$, it can gain:

$$\begin{aligned} \dot{V}_4 &\leq -\frac{1}{|\sigma_i|^{0.5}} \kappa^T \tilde{P} \kappa \\ &\leq -\frac{1}{|\sigma_i|^{0.5}} \lambda_{\min}\left(\tilde{P}\right) \|\kappa\|^2 \end{aligned} \tag{40}$$

where

$$\tilde{P} = \frac{\Upsilon_{1i}}{2}\begin{bmatrix} \begin{pmatrix} 2\Upsilon_{2i} + \Upsilon_{1i}^2 \\ -(4\Upsilon_{2i} + \Upsilon_{1i})\Pi_i \end{pmatrix} & -(\Upsilon_{1i} + 2\Pi_i) \\ -(\Upsilon_{1i} + 2\Pi_i) & 1 \end{bmatrix}.$$

We select $\tilde{P} > 0$. So, $\dot{V}_4 < 0$.

Employing inequality (38) obtains:

$$|\sigma_i|^{0.5} \leq \|\kappa\| \tag{41}$$

It follows that

$$\dot{V}_4 \leq \upsilon V_4^{0.5} \tag{42}$$

with $\upsilon = \frac{\lambda_{\min}\left(\tilde{P}\right)}{\lambda_{\max}^{0.5}(Q)}$.

Refer to [67], $\sigma_i = 0$ and $\dot{\sigma}_i = 0$ in finite-time ($t_{ri} = 2V_4^{0.5}(t = 0)/\upsilon$). Therefore, $\sigma = 0$ and $\dot{\sigma} = 0$ in finite-time ($T_r = \max_{i=1,\ldots,n}\{t_{ri}\}$) and e_i,$\dot{e}_i$ also stabilize to zero in finite-time ($T \leq T_r + T_s$) under the control commands (31)-(33).

IV. SIMULATION RESULTS AND DISCUSSION

To exhibit the tracking performance of the suggested control method, position tracking computer simulations were performed for a PUMA 560 robot [65]. For convenience in the analysis, in this work, we only consider a robot manipulator with the first three joints (the remainder three joints were locked). The kinematic and dynamic model with the crucial parameters found in a 3-DOF PUMA560 robot manipulator has been previously described in detail [65].

The friction and disturbance term at each joint are modelled as follows:

$$F_r(\theta, \dot{\theta}) + \tau_d = \begin{cases} 1.5\sin\left((t-2)\dot{\theta}_1\right) + 1.2\theta_1^3 \\ 1.3\sin\left((t-2)\dot{\theta}_2\right) + 1.1\theta_2^3 \\ 2.5\sin\left((t-2)\dot{\theta}_3\right) + 1.3\theta_1^3 \end{cases} \tag{43}$$

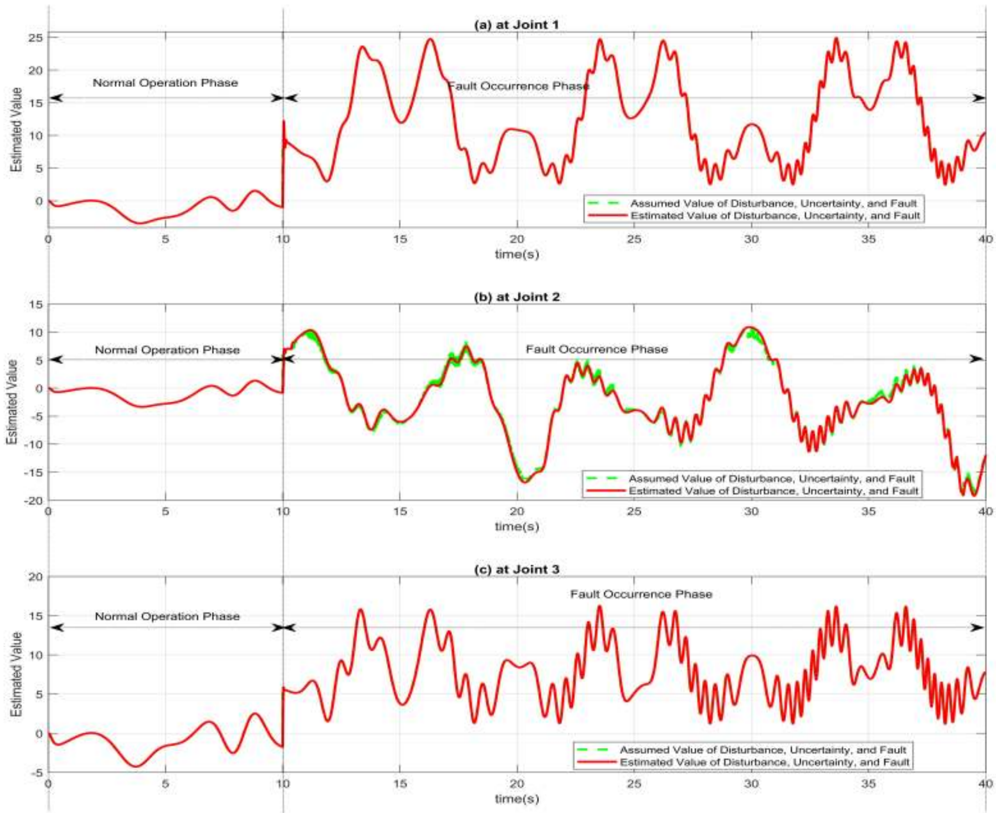

FIGURE 2. **Assumed and estimated value of disturbance, uncertainty, and fault: (a) at the first Joint, (b) at the second Joint, and (c) at the third Joint.**

The reference joint paths for the position tracking at each joint are designed according to the following expression:

$$x_r = \begin{bmatrix} 0.5 + \cos\left(\dfrac{t}{5\pi}\right) - 1 \\ -0.5 + \sin\left(\dfrac{t}{5\pi} + \dfrac{\pi}{2}\right) \\ 0.5 + \sin\left(\dfrac{t}{5\pi} + \dfrac{\pi}{2}\right) - 1 \end{bmatrix} \tag{44}$$

The initial position trajectories for the robotic system were indicated as $\theta_1(0) = 0$, $\theta_2(0) = 0$, $\theta_3(0) = 0$, $\dot{\theta}_1(0) = 0$, $\dot{\theta}_2(0) = 0$, and $\dot{\theta}_3(0) = 0$.

MATLAB/Simulink software was used to perform all simulations with a fixed-step size of $10^{-3}s$.

In order to exhibit the improvements in the tracking performance gained by using the suggested control algorithm, its reference path performances were compared with other control algorithms, including the normal SMC [33] and NFTSMC [37], [68], [69]. The details of SMC and NFTSMC design are briefly described as follow:

The normal SMC [33] has the following control torque:

$$u = -q^{-1}(x)\begin{bmatrix} H(x) + c(x_2 - \dot{x}_r) - \ddot{x}_r \\ +(\Sigma + \xi)\, sgn(\sigma) \end{bmatrix} \tag{45}$$

where $\sigma = \dot{e} + ce$ is the linear sliding manifold, c is a positive constant.

Further, the NFTSMC [69] has the following control torque:

$$u = -q^{-1}(x)\begin{bmatrix} H(x) + \varpi \frac{q}{l} \dot{e}^{2-l/q} - \ddot{x}_r \\ +(\Sigma + \xi)\, sgn(\sigma) \end{bmatrix} \tag{46}$$

where $\sigma = e + \varpi^{-1}\dot{e}^{l/q}$ is a nonlinear sliding manifold.

TABLE 1. **Control parameter selection of control algorithms.**

Control Algorithm	Control Parameters	Control Parameter Values
SMC	c, ξ, Σ	$2, 0.01, 20$
NFTSMC	$l, q, \varpi, \xi, \Sigma$	$5, 3, 2, 0.01, 20$
Proposed Control Algorithm	$\gamma_1, \gamma_2, \mu_1, \mu_2$	$2.0, 2.0, 1.2, 1.4$
	$\phi, \alpha, \Upsilon_1, \Upsilon_2$	$1, 0.6, 16, 20$
DO	k_1, k_2	$20000, 200$

The control parameters that were selected for use in the algorithms are depicted in Table 1. The performance simulations were carried out in cases of both normal and fault operations to compare the controllers under expressions of positional accuracy, transient response, steady-state error, and the resulting chattering phenomenon in their control inputs. For situation 1, the system was controlled in normal operating condition with the assumed disturbances and uncertainties. For situation 2, the system was controlled in fault operating conditions with the assumed disturbances, uncertainties, and faults.

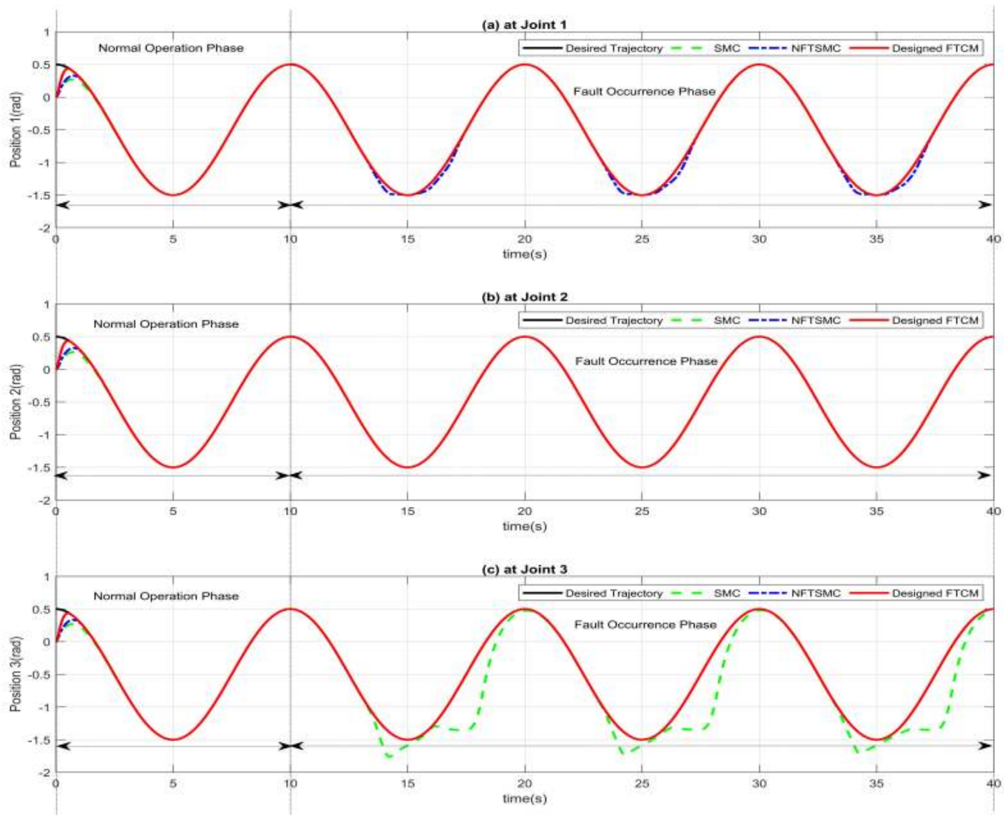

FIGURE 3. Tracking positions are provided by SMC, NFTSMC, and proposed controller: (a) at the first Joint, (b) at the second Joint, and (c) at the third Joint.

TABLE 2. The average control errors are provided by control systems.

	E_1	E_2	E_3
SMC	0.008021	0.007490	0.154244
NFTSMC	0.019966	0.005121	0.004845
Proposed Controller	0.002819	0.002807	0.002785

In Situation 1 at times where $0s < t < 10s$, we first consider the robot working in normal operation. The effectiveness of DO is analyzed. The target of DO in this condition is to precisely approximate the assumed value of disturbances and uncertainties. The time history of the assumed disturbances and uncertainties, and the outputs of DO are illustrated in Fig. 2. From Fig. 2, it is seen that DO has estimated the assumed value of disturbances and uncertainties with high precision, thus, DO provides exact information for the control loop in this phase. The tracking positions, positional control errors, and velocity control errors of the three joints for all three of the tested control algorithms are shown in Figs. 3, 4, and 5, respectively. Table 2 states the average control errors which are provided by SMC, NFTSMC, and proposed controller. From the simulation results in Figs. 3, 4, and 5, we observed that each control algorithm offered good tracking performance when the assumed disturbances and uncertainties were applied to the robotic dynamic system. SMC, NFTSMC, and proposed controller are based on the SMC to design a control approach. Therefore, those controllers preserve the robust ability of SMC in mitigating disturbances and uncertainties, as well as the ability to obtain high position tracking accuracy. It is noteworthy that the controller suggested in this study has the best performance compared to the other tested control algorithms because it preserves the low steady-state error and the fast-transient response properties of the NFTSMC, exact information from DO, and STRCL. The reader can see the results reported in Table 2.

Fig. 6 shows response time of the sliding mode manifolds at the first three joints of the robot manipulator. It is seen that the novel FTSMS has a fast-transient response.

In Situation 2 at times where $10s \leqslant t \leqslant 40s$, the fault-tolerant ability of all tested control methods was considered to inspect the influences of the faults to the robot manipulator, and a fault function was assumed in the robotic system according to the following expression:

$$\begin{aligned} &\omega\left(\theta, \dot{\theta}, \tau\right) \\ &= \begin{bmatrix} \begin{pmatrix} 25\sin\left(\theta_1\theta_2\right) + 1.5\cos\left(\dot{\theta}_1\theta_2\right) \\ +2.5\cos\left(\dot{\theta}_1\dot{\theta}_2\right) \end{pmatrix} \\ 0.3\sin\left(t\right)u_2 \\ \begin{pmatrix} 15\sin\left(\theta_3\theta_1\right) + 1.2\cos\left(\dot{\theta}_2\theta_2\right) \\ +2.5\cos\left(\dot{\theta}_2\dot{\theta}_3\right) \end{pmatrix} \end{bmatrix} \\ &T_f \geqslant 10s \end{aligned} \tag{47}$$

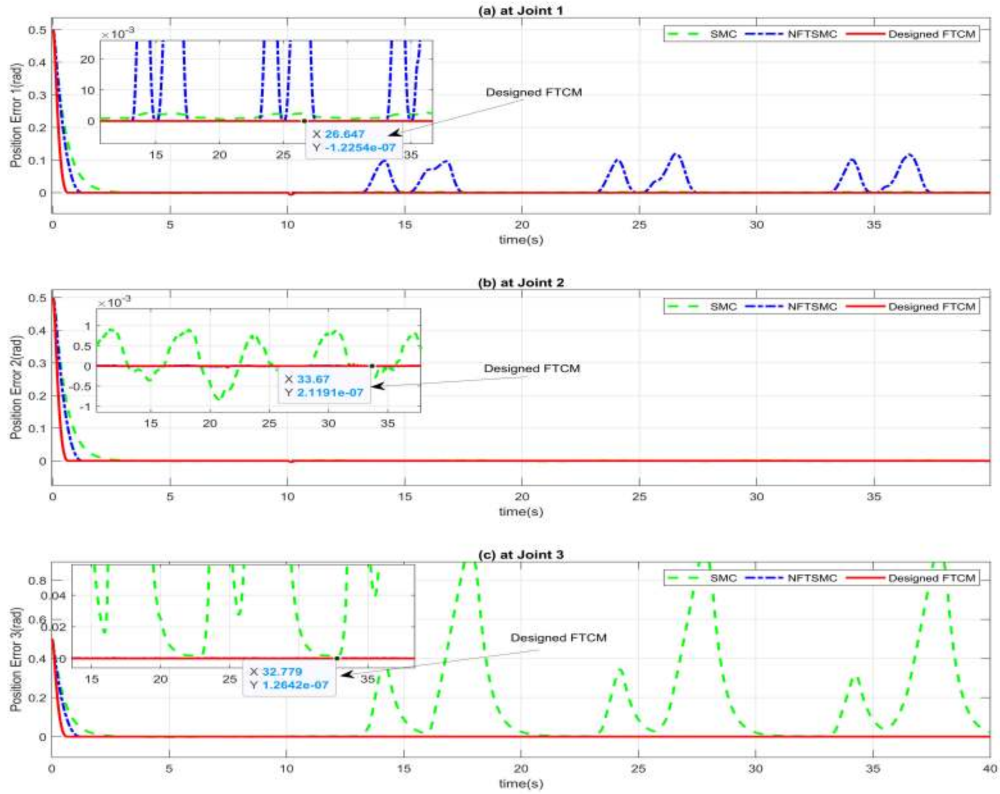

FIGURE 4. Positional control errors are provided by SMC, NFTSMC, and proposed controller: (a) at the first Joint, (b) at the second Joint, and (c) at the third Joint.

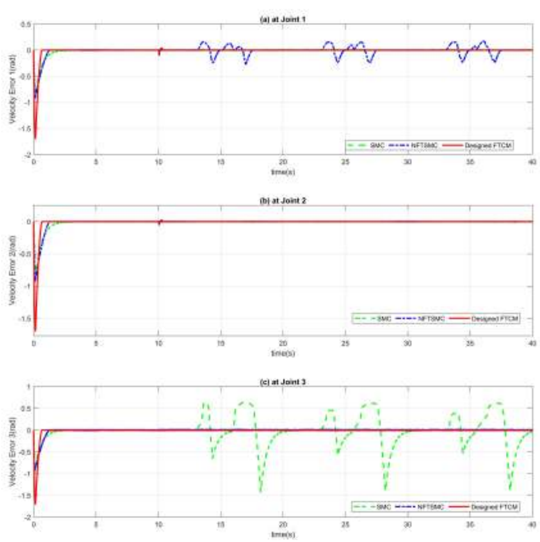

FIGURE 5. Velocity control errors are provided by SMC, NFTSMC, and proposed controller: (a) at the first Joint, (b) at the second Joint, and (c) at the third Joint.

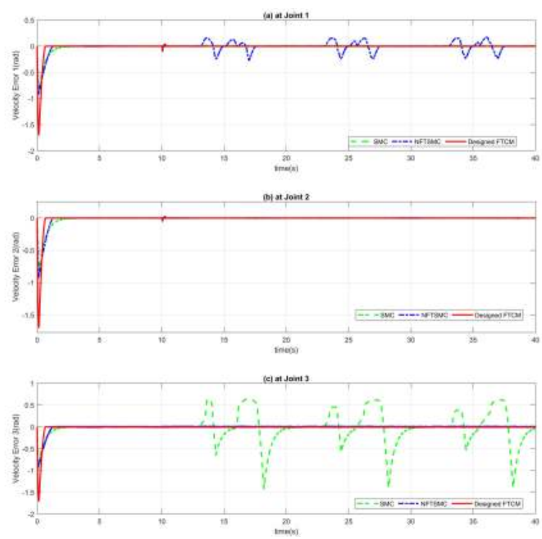

FIGURE 6. Response time of the sliding mode manifolds: (a) at the first Joint, (b) at the second Joint, and (c) at the third Joint.

From Eq. (47), an abrupt fault, $25\sin(\theta_1\theta_2) + 1.5\cos\left(\dot{\theta}_1\theta_2\right) + 2.5\cos\left(\dot{\theta}_1\dot{\theta}_2\right)$, was assumed to appear in the first joint at times where $t \geqslant 10s$, the effectiveness of the control input at the second joint was assumed to be damaged by $0.3\sin(t)\,u_2$ once the time reached $t \geqslant 10s$, and an abrupt fault, $25\sin(\theta_1\theta_2) + 1.5\cos\left(\dot{\theta}_1\theta_2\right) + 2.5\cos\left(\dot{\theta}_1\dot{\theta}_2\right)$, was assumed appear in the third joint at times where $t \geqslant 10s$, during the simulation. The effectiveness of DO is also investigated. The goal of DO in the second phase is to precisely approximate the assumed disturbances, uncertainties, faults.

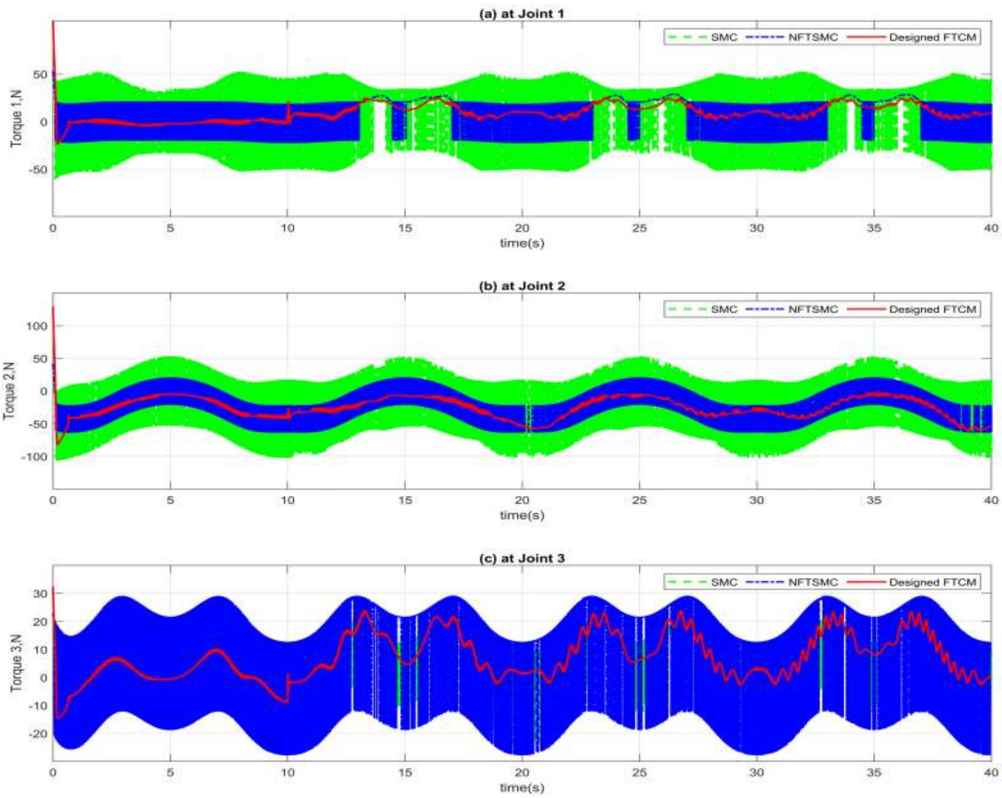

FIGURE 7. Control input signals are provided by SMC, NFTSMC, and proposed controller: (a) at the first Joint, (b) at the second Joint, and (c) at the third Joint.

From Fig. 2, it is observed that DO also has the ability to estimate the assumed value of disturbances, uncertainties, and faults with high accuracy, thus, DO exactly provides information of these lumped uncertain components for designed control loop in fault occurrence phase.

From Figs. 3, 4, 5, and Table 2, we observed that SMC offers the poorest path tracking performance, where the operation of the robotic manipulator becomes unstable, especially, at the third joint, during the presence of a fault. Although SMC gives good tracking performance for the robotic system in cases of disturbances and uncertainties, once faults appear, the system loses stability instantaneously. NFTSMC has better tracking performance than SMC, but its accuracy is low, especially, at the first joint. While the proposed control algorithm provides a faster transient response and smaller trajectory tracking error compared to SMC and NFTSMC. The proposed control algorithm offered the best performance with respect to tracking errors among the compared control algorithms because of the combination of NFTSMC, DO, and STRCL.

Throughout the simulation process in both situations, the proposed control scheme improves the tracking position accuracy at the three joints, respectively in comparison with SMC, as follows: the first joint (64.85%), the second joint (62.52%), and third joint (98.11%). And. the proposed scheme also enhances the tracking position precision at the three joints, respectively in comparison with NFTSMC, as follows: the first joint (85.88%), the second joint (45.18%), and third joint (42.51%).

The control input signals of the controllers, including SMC, NFTSMC, and suggested control methodology, are depicted in Fig. 7. The results in Fig. 7 indicates that suggested control methodology seems to offer a continuous control signal with minor chattering. Because disturbances, uncertainties, faults were estimated by DO. Moreover, the remaining of the estimated errors also were handled by STRCL. While SMC and NFTSMC offer discontinuous control efforts when both methods applied a large gain in high-frequency control to combat the effects of those lumped uncertain components.

From trajectory tracking performance and its performance comparison, we observed that suggested control algorithm offers the best performance compared to the other control methods, including SMC and NFTSMC, under expressions of the pathway tracking precision, speedy transient response, small steady state error, and chattering removal.

Remark 2: The parameters for SMC, NFTSMC, and proposed sliding surface were experimentally selected and based on their convergence properties. For example, $\gamma_1, \gamma_2, \mu_1, \mu_2$ are the positive constants, $0 < \alpha < 1$, and $\phi = \left(\frac{\gamma_2}{\gamma_1}\right)^{1/(1-\alpha)}$. The parameters for the proposed control input with DO and

STRCL were experimentally chosen to make system stable, to obtain the desired performance with a fast convergence time, and to satisfy the conditions, which were mentioned in the study and have been explained in greater detail by previous researchers [37], [38], [58], [70]. The parameters of the controllers, including SMC and NFTSMC were chosen to guarantee stability and obtain the good performance (refer to SMC [33], and NFTSMC [37], [68]).

Remark 3: In this work, we only simulated abrupt faults, as their influences are larger than incipient faults in a robotic system. Therefore, since the suggested control scheme can effectively manage abrupt faults entirely, it is also able to resolve the influences from incipient faults.

Remark 4: In order to confirm the effectiveness of the suggested control system from a technical viewpoint, it would be more convincing to demonstrate experimental results on real systems. Nonetheless, experimenting with various fault types in a real system is difficult and presents dangerous challenges and possible damage to the robotic system. Accordingly, in literature related to fault-tolerant control systems, almost every strategy, including this report, has adopted simulation performance to prove the usefulness of controllers [71]–[73]. However, verifying the effectiveness of the suggested control methodology in experimental patterns by implementing suitable methods without destroying a robotic system is an important goal and will be considered in future study.

Remark 5: It should be noted that the control parameters are chosen by performing repetitive testing and control error checking. In this condition how to choose these parameters is a remarkable issue. Future research is to select the optimal control parameters by applying optimization algorithms.

V. CONCLUSION

In this study, a novel FTCM is developed for robot manipulators. First, to overcome singularity glitch and to enhance convergence time of conventional TSMC, a new FTSMS is constructed. Next, to reduce the computation complexity and to provide requirement about undefined nonlinear functions for the control system, a DO to estimate uncertain dynamics, external disturbances, or faults. Besides, a STRCL is designed to compensate the estimated error of disturbance observer with chattering rejection. Final, a novel, robust, FTCM was developed for robot manipulators to obtain the stability goal of the system, to reach the prescribed performance, and to overcome the effects of disturbances, nonlinearities, or faults. Accordingly, the proposed FTCM has remarkable features, including fast convergence speeds, robustness against uncertainty, high tracking performance, and convergence errors in finite-time. Furthermore, the control input signal has impressively small chattering behavior. Finally, position tracking computer simulations were used to confirm that the suggested FTCM offers better tracking performance when compared with other control algorithms.

According to theoretical proof, simulation performance, and a comparison with both SMC and NFTSMC, the proposed control strategy has some contributions, as follows: (1) the proposed strategy is easy in implementation, which provides finite-time convergence, and faster transient performance without singularity obstacle in controlling; (2) the proposed strategy inherits the advantages of the NFTSMC, STRCL, and estimation ability of DO in the features of robustness towards the existing uncertainties; (3) a new FTSMS was introduced, and evidence of finite-time convergence was sufficiently confirmed; (4) the accuracy of the proposed strategy was further enhanced in the trajectory tracking control; (5) the proposed strategy displayed the smoother control torque actions with lesser oscillation.

REFERENCES

[1] K. C. Lau, E. Y. Y. Leung, P. W. Y. Chiu, Y. Yam, J. Y. W. Lau, and C. C. Y. Poon, "A flexible surgical robotic system for removal of early-stage gastrointestinal cancers by endoscopic submucosal dissection," *IEEE Trans. Ind. Informat.*, vol. 12, no. 6, pp. 2365–2374, Dec. 2016.

[2] F. Lunardini, C. Casellato, A. d'Avella, T. D. Sanger, and A. Pedrocchi, "Robustness and reliability of synergy-based myocontrol of a multiple degree of freedom robotic arm," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 24, no. 9, pp. 940–950, Sep. 2016.

[3] K. M. Ben-Gharbia, A. A. Maciejewski, and R. G. Roberts, "A kinematic analysis and evaluation of planar robots designed from optimally fault-tolerant jacobians," *IEEE Trans. Robot.*, vol. 30, no. 2, pp. 516–524, Apr. 2014.

[4] R. C. Hoover, R. G. Roberts, A. A. Maciejewski, P. S. Naik, and K. M. Ben-Gharbia, "Designing a failure-tolerant workspace for kinematically redundant robots," *IEEE Trans. Autom. Sci. Eng.*, vol. 12, no. 4, pp. 1421–1432, Oct. 2015.

[5] G. Chen, Y. Song, and F. L. Lewis, "Distributed fault-tolerant control of networked uncertain Euler–Lagrange systems under actuator faults," *IEEE Trans. Cybern.*, vol. 47, no. 7, pp. 1706–1718, Jul. 2017.

[6] Y. Zhao, J. Wang, F. Yan, and Y. Shen, "Adaptive sliding mode fault-tolerant control for type-2 fuzzy systems with distributed delays," *Inf. Sci.*, vol. 473, pp. 227–238, Jan. 2019.

[7] Y. Su, C. Zheng, and P. Mercorelli, "Nonlinear PD fault-tolerant control for dynamic positioning of ships with actuator constraints," *IEEE/ASME Trans. Mechatronics*, vol. 22, no. 3, pp. 1132–1142, Jun. 2017.

[8] Y. Gao, G. Sun, J. Liu, Y. Shi, and L. Wu, "State estimation and self-triggered control of CPSs against joint sensor and actuator attacks," *Automatica*, vol. 113, Mar. 2020, Art. no. 108687.

[9] X. Liu, M. Zhang, Y. Wang, and E. Rogers, "Design and experimental validation of an adaptive sliding mode observer-based fault-tolerant control for underwater vehicles," *IEEE Trans. Control Syst. Technol.*, vol. 27, no. 6, pp. 2655–2662, Nov. 2019.

[10] J. Jiang and X. Yu, "Fault-tolerant control systems: A comparative study between active and passive approaches," *Annu. Rev. Control*, vol. 36, no. 1, pp. 60–72, Apr. 2012.

[11] Q. Meng, T. Zhang, J.-F. He, and J.-Y. Song, "Adaptive vector sliding mode fault-tolerant control of the uncertain stewart platform based on position measurements only," *Robotica*, vol. 34, no. 6, pp. 1297–1321, Jun. 2016.

[12] M. Van, X. P. Do, and M. Mavrovouniotis, "Self-tuning fuzzy PID-nonsingular fast terminal sliding mode control for robust fault tolerant control of robot manipulators," *ISA Trans.*, vol. 96, pp. 60–68, Jan. 2020.

[13] T. Wang, W. Xie, and Y. Zhang, "Sliding mode fault tolerant control dealing with modeling uncertainties and actuator faults," *ISA Trans.*, vol. 51, no. 3, pp. 386–392, May 2012.

[14] G. Tao, S. Chen, and S. M. Joshi, "An adaptive actuator failure compensation controller using output feedback," *IEEE Trans. Autom. Control*, vol. 47, no. 3, pp. 506–511, Mar. 2002.

[15] M. Van, H.-J. Kang, Y.-S. Suh, and K.-S. Shin, "A robust fault diagnosis and accommodation scheme for robot manipulators," *Int. J. Control, Autom. Syst.*, vol. 11, no. 2, pp. 377–388, Apr. 2013.

[16] B. Xiao, Q. Hu, and Y. Zhang, "Adaptive sliding mode fault tolerant attitude tracking control for flexible spacecraft under actuator saturation," *IEEE Trans. Control Syst. Technol.*, vol. 20, no. 6, pp. 1605–1612, Nov. 2012.

[17] Q. Song, W. J. Hu, L. Yin, and Y. C. Soh, "Robust adaptive dead zone technology for fault-tolerant control of robot manipulators using neural networks," *J. Intell. Robot. Syst.*, vol. 33, no. 2, pp. 113–137, 2002.

[18] Y. Su, P. C. Muller, and C. Zheng, "Global asymptotic saturated PID control for robot manipulators," *IEEE Trans. Control Syst. Technol.*, vol. 18, no. 6, pp. 1280–1288, Nov. 2010.

[19] W. Yu and J. Rosen, "Neural PID control of robot manipulators with application to an upper limb exoskeleton," *IEEE Trans. Cybern.*, vol. 43, no. 2, pp. 673–684, Apr. 2013.

[20] W. Shang, S. Cong, Y. Zhang, and Y. Liang, "Active joint synchronization control for a 2-DOF redundantly actuated parallel manipulator," *IEEE Trans. Control Syst. Technol.*, vol. 17, no. 2, pp. 416–423, Mar. 2009.

[21] Y. Su, D. Sun, L. Ren, and J. K. Mills, "Integration of saturated PI synchronous control and PD feedback for control of parallel manipulators," *IEEE Trans. Robot.*, vol. 22, no. 1, pp. 202–207, Feb. 2006.

[22] A. T. Vo, H.-J. Kang, and T. D. Le, "An adaptive fuzzy terminal sliding mode control methodology for uncertain nonlinear second-order systems," in *Proc. Int. Conf. Intell. Comput.*, 2018, pp. 123–135.

[23] A. T. Vo, H.-J. Kang, and V.-C. Nguyen, "An output feedback tracking control based on neural sliding mode and high order sliding mode observer," in *Proc. 10th Int. Conf. Hum. Syst. Interact. (HSI)*, Jul. 2017, pp. 161–165.

[24] A. Tayebi, S. Abdul, M. B. Zaremba, and Y. Ye, "Robust iterative learning control design: Application to a robot manipulator," *IEEE/ASME Trans. Mechatronics*, vol. 13, no. 5, pp. 608–613, Oct. 2008.

[25] M. Wang and A. Yang, "Dynamic learning from adaptive neural control of robot manipulators with prescribed performance," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 47, no. 8, pp. 2244–2255, Aug. 2017.

[26] P. Poignet and M. Gautier, "Nonlinear model predictive control of a robot manipulator," in *Proc. 6th Int. Workshop Adv. Motion Control Proc.*, 2000, pp. 401–406.

[27] F. Aghili, "Adaptive control of manipulators forming closed kinematic chain with inaccurate kinematic model," *IEEE/ASME Trans. Mechatronics*, vol. 18, no. 5, pp. 1544–1554, Oct. 2013.

[28] L. A. Castaneda, A. Luviano-Juarez, and I. Chairez, "Robust trajectory tracking of a delta robot through adaptive active disturbance rejection control," *IEEE Trans. Control Syst. Technol.*, vol. 23, no. 4, pp. 1387–1398, Jul. 2015.

[29] Q. Meng, T. Zhang, X. Gao, and J.-Y. Song, "Adaptive sliding mode fault-tolerant control of the uncertain stewart platform based on offline multibody dynamics," *IEEE/ASME Trans. Mechatronics*, vol. 19, no. 3, pp. 882–894, Jun. 2014.

[30] A. Ferrara and G. P. Incremona, "Design of an integral suboptimal second-order sliding mode controller for the robust motion control of robot manipulators," *IEEE Trans. Control Syst. Technol.*, vol. 23, no. 6, pp. 2316–2325, Nov. 2015.

[31] Y.-W. Liang, S.-D. Xu, D.-C. Liaw, and C.-C. Chen, "A study of T–S model-based SMC scheme with application to robot control," *IEEE Trans. Ind. Electron.*, vol. 55, no. 11, pp. 3964–3971, Nov. 2008.

[32] S. Islam and X. P. Liu, "Robust sliding mode control for robot manipulators," *IEEE Trans. Ind. Electron.*, vol. 58, no. 6, pp. 2444–2453, Jun. 2011.

[33] C. Edwards and S. Spurgeon, *Sliding Mode Control: Theory and Applications*. Boca Raton, FL, USA: CRC Press, 1998.

[34] S. Yu, X. Yu, B. Shirinzadeh, and Z. Man, "Continuous finite-time control for robotic manipulators with terminal sliding mode," *Automatica*, vol. 41, no. 11, pp. 1957–1964, Nov. 2005.

[35] Q. Xu, "Piezoelectric nanopositioning control using second-order discrete-time terminal sliding-mode strategy," *IEEE Trans. Ind. Electron.*, vol. 62, no. 12, pp. 7738–7748, Jun. 2015.

[36] M. Zhihong, A. P. Paplinski, and H. R. Wu, "A robust MIMO terminal sliding mode control scheme for rigid robotic manipulators," *IEEE Trans. Autom. Control*, vol. 39, no. 12, pp. 2464–2469, Dec. 1994.

[37] J. Zheng, H. Wang, Z. Man, J. Jin, and M. Fu, "Robust motion control of a linear motor positioner using fast nonsingular terminal sliding mode," *IEEE/ASME Trans. Mechatronics*, vol. 20, no. 4, pp. 1743–1752, Aug. 2015.

[38] L. Yang and J. Yang, "Nonsingular fast terminal sliding-mode control for nonlinear dynamical systems," *Int. J. Robust Nonlinear Control*, vol. 18, pp. 557–569, Oct. 2010.

[39] A. T. Vo and H.-J. Kang, "An adaptive neural non-singular fast-terminal sliding-mode control for industrial robotic manipulators," *Appl. Sci.*, vol. 8, no. 12, p. 2562, 2018.

[40] V. A. Tuan and H. Kang, "A new finite time control solution for robotic manipulators based on nonsingular fast terminal sliding variables and the adaptive super-twisting scheme," *ASME J. Comput. Nonlinear Dyn.*, vol. 14, no. 3, Mar. 2019, Art. no. 031002, doi: 10.1115/1.4042293.

[41] G. Edelbaher, K. Jezernik, and E. Urlep, "Low-speed sensorless control of induction machine," *IEEE Trans. Ind. Electron.*, vol. 53, no. 1, pp. 120–129, Feb. 2006.

[42] H. Li, L. Dou, and Z. Su, "Adaptive nonsingular fast terminal sliding mode control for electromechanical actuator," *Int. J. Syst. Sci.*, vol. 44, no. 3, pp. 401–415, 2013.

[43] V. Utkin, "Discussion aspects of high-order sliding mode control," *IEEE Trans. Autom. Control*, vol. 61, no. 3, pp. 829–833, Mar. 2016.

[44] J. Davila, L. Fridman, and A. Levant, "Second-order sliding-mode observer for mechanical systems," *IEEE Trans. Autom. Control*, vol. 50, no. 11, pp. 1785–1789, Nov. 2005.

[45] G. Rubio-Astorga, J. Diego Sánchez-Torres, J. Cañedo, and A. G. Loukianov, "High-order sliding mode block control of single-phase induction motor," *IEEE Trans. Control Syst. Technol.*, vol. 22, no. 5, pp. 1828–1836, Sep. 2014.

[46] J. A. Moreno and M. Osorio, "Strict Lyapunov functions for the super-twisting algorithm," *IEEE Trans. Autom. Control*, vol. 57, no. 4, pp. 1035–1040, Apr. 2012.

[47] A. T. Vo and H.-J. Kang, "Adaptive neural integral full-order terminal sliding mode control for an uncertain nonlinear system," *IEEE Access*, vol. 7, pp. 42238–42246, 2019.

[48] Z. Song, C. Duan, J. Wang, and Q. Wu, "Chattering-free full-order recursive sliding mode control for finite-time attitude synchronization of rigid spacecraft," *J. Franklin Inst.*, vol. 356, no. 2, pp. 998–1020, Mar. 2018.

[49] Y. Feng, F. Han, and X. Yu, "Chattering free full-order sliding-mode control," *Automatica*, vol. 50, no. 4, pp. 1310–1314, 2014.

[50] Y. Feng, M. Zhou, X. Zheng, F. Han, and X. Yu, "Full-order terminal sliding-mode control of MIMO systems with unmatched uncertainties," *J. Franklin Inst.*, vol. 355, no. 2, pp. 653–674, Jan. 2018.

[51] X. Xiang, C. Liu, H. Su, and Q. Zhang, "On decentralized adaptive full-order sliding mode control of multiple UAVs," *ISA Trans.*, vol. 71, pp. 196–205, Nov. 2017.

[52] W.-H. Chen, J. Yang, L. Guo, and S. Li, "Disturbance-observer-based control and related methods—An overview," *IEEE Trans. Ind. Electron.*, vol. 63, no. 2, pp. 1083–1095, Sep. 2015.

[53] B. Xiao, X. Yang, and X. Huo, "A novel disturbance estimation scheme for formation control of ocean surface vessels," *IEEE Trans. Ind. Electron.*, vol. 64, no. 6, pp. 4994–5003, Jun. 2017.

[54] J. Du, X. Hu, M. Krstić, and Y. Sun, "Robust dynamic positioning of ships with disturbances under input saturation," *Automatica*, vol. 73, pp. 207–214, Nov. 2016.

[55] W. He, Z. Yan, C. Sun, and Y. Chen, "Adaptive neural network control of a flapping wing micro aerial vehicle with disturbance observer," *IEEE Trans. Cybern.*, vol. 47, no. 10, pp. 3452–3465, Oct. 2017.

[56] J. Liu, Y. Gao, X. Su, M. Wack, and L. Wu, "Disturbance-observer-based control for air management of PEM fuel cell systems via sliding mode technique," *IEEE Trans. Control Syst. Technol.*, vol. 27, no. 3, pp. 1129–1138, May 2019.

[57] Y. Cao and X. B. Chen, "Disturbance-observer-based sliding-mode control for a 3-DOF nanopositioning stage," *IEEE/ASME Trans. Mechatronics*, vol. 19, no. 3, pp. 924–931, Jun. 2014.

[58] B. Liang, Y. Zhu, Y. Li, P. He, and W. Li, "Adaptive nonsingular fast terminal sliding mode control for braking systems with electro-mechanical," *Int. J. Syst. Sci.*, vol. 44, no. 3, pp. 401–415, 2017.

[59] J. Zhang, Y. Lin, and G. Feng, "Analysis and synthesis of memory-based fuzzy sliding mode controllers," *IEEE Trans. Cybern.*, vol. 45, no. 12, pp. 2880–2889, Dec. 2015.

[60] S. Mondal and C. Mahanta, "Adaptive second order terminal sliding mode controller for robotic manipulators," *J. Franklin Inst.*, vol. 351, no. 4, pp. 2356–2377, 2014.

[61] S. Mobayen and F. Tchier, "A novel robust adaptive second-order sliding mode tracking control technique for uncertain dynamical systems with matched and unmatched disturbances," *Int. J. Control, Autom. Syst.*, vol. 15, no. 3, pp. 1097–1106, Jun. 2017.

[62] R. Sun, J. Wang, D. Zhang, and X. Shao, "Neural network-based sliding mode control for atmospheric-actuated spacecraft formation using switching strategy," *Adv. Space Res.*, vol. 61, no. 3, pp. 914–926, Feb. 2018.

[63] J. Liu and X. Wang, *Advanced Sliding Mode Control for Mechanical Systems*. Beijing, China: Springer, 2012.

[64] Q. Shen, B. Jiang, and V. Cocquempot, "Adaptive fuzzy observer-based active fault-tolerant dynamic surface control for a class of nonlinear systems with actuator faults," *IEEE Trans. Fuzzy Syst.*, vol. 22, no. 2, pp. 338–349, Apr. 2014.

[65] B. Armstrong, O. Khatib, and J. Burdick, "The explicit dynamic model and inertial parameters of the PUMA 560 arm," in *Proc. IEEE Int. Conf. Robot. Autom.*, vol. 3, Apr. 1986, pp. 510–518.

[66] V. I. Utkin, *Sliding Modes in Control and Optimization*. Berlin, Germany: Springer-Verlag, 2013, doi: 10.1007/978-3-642-84379-2.

[67] J. A. Moreno and M. Osorio, "A Lyapunov approach to second-order sliding mode controllers and observers," in *Proc. 47th IEEE Conf. Decis. Control*, Dec. 2008, pp. 2856–2861.

[68] S. S.-D. Xu, C.-C. Chen, and Z.-L. Wu, "Study of nonsingular fast terminal sliding-mode fault-tolerant control," *IEEE Trans. Ind. Electron.*, vol. 62, no. 6, pp. 3906–3913, Jun. 2015.

[69] Y. Feng, X. Yu, and Z. Man, "Non-singular terminal sliding mode control of rigid manipulators," *Automatica*, vol. 38, no. 12, pp. 2159–2167, 2002.

[70] Z. He, C. Liu, Y. Zhan, H. Li, X. Huang, and Z. Zhang, "Nonsingular fast terminal sliding mode control with extended state observer and tracking differentiator for uncertain nonlinear systems," *Math. Probl. Eng.*, vol. 2014, Oct. 2014, Art. no. 639707.

[71] X.-J. Li and G.-H. Yang, "Neural-network-based adaptive decentralized fault-tolerant control for a class of interconnected nonlinear systems," *IEEE Trans. Neural Netw. Learn. Syst.*, vol. 29, no. 1, pp. 144–155, Jan. 2018.

[72] B. Huo, Y. Xia, L. Yin, and M. Fu, "Fuzzy adaptive fault-tolerant output feedback attitude-tracking control of rigid spacecraft," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 47, no. 8, pp. 1898–1908, Aug. 2017.

[73] L. Liu, Z. Wang, and H. Zhang, "Data-based adaptive fault estimation and fault-tolerant control for MIMO model-free systems using generalized fuzzy hyperbolic model," *IEEE Trans. Fuzzy Syst.*, vol. 26, no. 6, pp. 3191–3205, Dec. 2018.

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