Tracking control of a robotic system with deferred constraints and actuator faults

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Abstract
This paper proposes an adaptive sliding mode tracking control for a robotic manipulator to guarantee a deferred performance under input non-linearities and external perturbations. Control inputs of the robotic manipulator are entrapped into saturation and failures simultaneously. A common method to deal with output constraints is based on the barrier Lyapunov function, which requires the system states to be within the prescribed bounds initially; an error-shifting transformation is utilized and barrier functions are integrated into sliding model control to remove the unreasonable requirement and to realize a finite time convergence result collectively. Furthermore, the actuator faults are accommodated without any prior knowledge. Simulation examples are provided to verify the effectiveness of the proposed scheme.

1 INTRODUCTION

In real engineering applications, devices inevitably undergo input saturation and failures due to physical limitation, aging and abrasion of actuators. These input non-linearities will reduce the control performance heavily and are deserved to be compensated with appropriate control algorithms.

Fault-tolerant control has been constantly used to compensate for the adverse effect of actuator faults. According to the redundancy, there are two types of fault-tolerant policies (e.g. the active fault-tolerant control strategies [1–3] and the passive fault-tolerant control strategies [4]). Active fault-tolerant control employs a subsystem for fault diagnosis to adjust the controller parameters or structure when the fault occurs. Active fault-tolerant control can estimate and adjust the faults of the controller adaptively. Compared with active fault-tolerant control, passive fault-tolerant control needs some prior knowledge of the failures and is not sensitive to the actuator faults. Integrated

input non-linearities encounter more difficult control design and some pioneering works have been developed to solve input saturation and faults collectively [5–7]. In [5], a fault detection observer and an auxiliary term were proposed to detect the fault and establish the relation between angular velocity and total actuator faults. Then, the backstepping controller with the fault detection observer was presented to maintain that the space attitude maneuvers were stable, in spite of actuator saturations. In [6], an auxiliary system was proposed to compensate the input saturation. According to the action of the compensation term, the saturated input signal will be pulled back into the unsaturated region. Furthermore, disturbance observer techniques were utilized to compensate input saturation and estimate the lumped uncertainties of external disturbances and actuators. In[7], a finite-time fault estimator was designed to address the exact tracking problem of surface vehicle, and the saturated input signal was compensated by converting it into unknown-gain control signals. However, the aforementioned methods and

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other researches seldom consider the actuator faults, input saturation, and output constraint at the same time. When the initial states violate the prescribed constraint, the state constraint is hard to be achieved due to the actuator limitation. In synthetic control, it has practical application to consider input saturation, actuator fault and delay constraint simultaneously. A transient and steady performance should be met even under unexpected failures and saturation.

Barrier Lyapunov function (BLF) is an effective technique to ensure the constrained system within a pre-defined region because of the nature of this function [8–18]. BLF approaches infinity whenever its argument is close to the prescribed constraint. In order to obtain different performance constraints, BLF has been developed in many forms, including integral-type BLF [19], fractional-type BLF [20], tan-type BLF [21], and log-type BLF [22]. In [23], the BLF was presented to address multiple state constraints for a class of feedback linearizable systems in Brunovsky form. Integrated control methods have been proposed for non-linear systems with constant output/state constraint [24], time-varying output/state constraint [25], partial state constraint [26] and full state constraint [27] by combining BLF technique with adaptive methods, backstepping control and other control schemes. However, the above mentioned BLF requires initial states of the considered systems to satisfy the prescribed constraint, which is unreasonable in some certain situations. The proposed method cannot be implemented when initial tracking errors violate the constraints. Thus, in this paper, a novel control algorithm is designed to guarantee that the tracking error constraint can be satisfied within the finite setting time under any initial conditions.

Compared with existing control methods such as fuzzy neural control [28], optimization control [29], impedance control [30], adaptive control [31, 32], and admittance control [33], sliding mode control (SMC) conceives fast convergence, insensitivity to external disturbance and plenty parameter variation [34]. Thus, SMC is widely utilized in the field of tracking control of some non-linear systems for satisfying control performance. However, there are many drawbacks in the traditional SMC schemes such as uncertain setting time and singular problems. In order to compensate the limitations and preserve the benefits of traditional SMC methods, many effective solutions have been proposed. Terminal sliding mode control schemes were proposed in [35]. Compared with the traditional SMC, a non-linear term is added to the sliding surface constructed in terminal sliding mode control schemes to guarantee a finite-time convergence instead of asymptotic convergence. Along with terminal sliding mode surfaces, the system state can reach the ideal position in finite time. However, the singular problem exists in the terminal sliding mode control scheme, which is in the sense that the control magnitude may become unbounded when system state reaches zero. Recently, the non-singular terminal sliding mode control (NTSMC) [36, 37] and non-singular fast terminal sliding mode control (NFTSMC) [38, 39] have been proposed to address the aforementioned potential drawback. In comparison to NTSMC, the NFTSMC scheme is introduced to ensure a fast convergence rate to the ideal position in the whole process instead of another one only when the tracking error greatly exceeds the requirement. Because the actuator faults, input saturation, and output constraint are all considered, we only need to design an adaptive method to reach the control objective in finite time under any initial conditions and avoid the singular problems; a novel adaptive NFTSMC scheme for a robotic manipulator system has been proposed to compensate failed and saturated control input and to ensure error constraints under any initial conditions and bounded external disturbances.

There is an example to describe the aforementioned situation: a robot moves from a no restriction place at the beginning, and then heads for a bridge. Actuators may partially break in this period, but the objective action can be still accomplished. The unique contributions of this work are summarized as follows:

1) Compared with previous works [5–7, 40], which only handled the problem of actuator faults and input saturation without considering tracking error constraints, this paper proposes a solution to address the input saturation, tracking error constraints, actuator faults and external disturbances simultaneously. Even if some unknown actuator breaks down partially, some pre-defined control performance is still satisfied. Due to coupled situations, special emphases are made to the computational complexity.

2) The existing methods based on the traditional BLF cannot be implemented whenever the limited state violates the prescribed constraints initially [41–43]. In this paper, the restriction is removed by introducing a novel sliding mode surface. Furthermore, compared with [44], the prescribed constraints are satisfied within finite time under any initial conditions instead of only asymptotic stability. Thus, the setting time is compulsorily bounded to be smaller than the pre-assigned time. Otherwise, the prescribed constraint would be violated after the pre-assign time, but the aforementioned concern is removed.

3) To the best of our knowledge, the novel sliding surface is first proposed to address the tracking error constraint under any initial conditions. Besides, compared with [45], which designed a BLF-based approach in a reaching phase, a BLF-based sliding surface approach is proposed in a sliding phase in this paper. The BLF-based approach designed in the reaching phase cannot guarantee the transition from the reaching phase to sliding phase because the sliding surface converges to a smaller region instead of origin. Furthermore, the deferred constraint cannot be satisfied whenever constraint is violated initially, but the aforementioned problems are addressed by the novel sliding surface.

The rest of this paper is organized as follows: Section 2 states the problem formulates and main preliminaries of this paper. Section 3 introduces detailely the design of novel NFTSMC. In Section 4, we give some simulation examples to verify the effectiveness of the proposed method. Section 5 draws some remarkable conclusions.

Notations: \( I_n \) and \( \mathbb{R} \) denote the identity matrix in the space \( \mathbb{R}^{n \times n} \) and the set of real number, respectively. \(|\cdot|\) denotes the absolute value for scalars, \((\cdot)^{T}\) is the transpose vector, and \(|x|\)
implies the Euclidean norm for vectors and induced norm for matrices. Specifically, we use \( \dot{v} \) as the first order time derivative of \( v \).

## 2 PROBLEM FORMULATION

### 2.1 Preliminaries

There is an \( n \)-link robotic system described by [46]

\[
M(q)\ddot{q} + C(q, \dot{q})\dot{q} + G(q) = u + d(t),
\]

where \( q, \dot{q}, \ddot{q} \in \mathbb{R}^n \) represents the position, velocity and acceleration vectors; \( G(q) \in \mathbb{R}^n \) denotes the gravitational forces; \( C(q, \dot{q}) \in \mathbb{R}^{n \times n} \) denotes the coriolis and centrifugal matrix; \( M(q) \in \mathbb{R}^{n \times n} \) denotes the positive definite quality inertia matrix; the external disturbances are denoted by \( d(t) \in \mathbb{R}^n \) respectively. Moreover, the control input is \( u \in \mathbb{R}^n \).

**Assumption 1** [47]. The matrices \( G(q) \), and \( C(q, \dot{q}) \) and the vector \( M(q) \) are upper bounded, that is,

\[
0 < \left\| M(q) \right\| \leq M_{\text{max}},
\]

\[
0 < \left\| C(q, \dot{q}) \right\| \leq C_{\text{max}} \left\| \dot{q} \right\|
\]

\[
0 < \left\| G(q) \right\| \leq G_{\text{max}}
\]

\[
Y_1 \leq \left\| M^{-1}(q) \right\| \leq Y_2
\]

\[
Y_3 \leq \left\| G^{-1}(q) \right\| \leq Y_4,
\]

where \( M_{\text{max}}, C_{\text{max}}, G_{\text{max}}, Y_1, Y_2, Y_3, \) and \( Y_4 \) are positive constants.

Actuator faults are classified into four categories: (C1) loss of effectiveness, (C2) locked-in-place, (C3) floating around trim and (C4) hard-cover. Then, we simplify it as

\[
F_i = l_i(t)u_i, \quad i = 1, 2, ..., n,
\]

where \( F_i \) represents the actual control torque produced by the actuator, and \( u_i \) denotes the desired control torque. Moreover, \( l_i(t) = 1 \) implies that the \( i \)th actuator is healthy. When \( 0 < l_i(t) < 1 \), the \( i \)th actuator suffers from a partial loss of effectiveness, but it still works all the time. \( F \) can be written as

\[
F = D(t)u,
\]

where \( F = [F_1, ..., F_n]^T \) represents the applied control, \( D(t) = \text{diag}(l_1(t), ..., l_n(t)) \) denotes the actuator effectiveness, and \( u = [u_1, ..., u_n]^T \) denotes the control input of the robotic systems.

Because of the physical limitation on the actuator, the control signal \( F \) is constrained by a saturation value. The \( \text{sat}(F) = [\text{sat}(F_1), ..., \text{sat}(F_n)]^T \) is the control input generated by actuators. The saturation function can be described by [46]

\[
\text{sat}(F) = F + \Delta F
\]

where \( \Delta F \) is given as

\[
\Delta F = \begin{cases} 
0, & |F| \leq F_{\text{max}} \\
F_{\text{max}} - F, & F > F_{\text{max}} \\
-F_{\text{max}} - F, & F < -F_{\text{max}}.
\end{cases}
\]

where \( F_{\text{max}} \) denotes the saturation value. The following assumptions are necessary for the control objectives:

**Assumption 2** [48]. We suppose that the disturbance \( d(t) \) is uniformly bounded. In other words, there exists a constant \( \tilde{d} \in \mathbb{R}^n \), such that \( \|d(t)\| < \tilde{d}, \forall t \in [0, \infty) \).

**Assumption 3** [49]. The desired trajectory \( x_d \) is known, bounded and continuous.

### 2.2 Technical Lemmas and Definitions

**Definition 1** [44]. (Error-Shifting Transformation) A error-shifting transformation \( b(t) \) is designed as

\[
b(t) = \begin{cases} 
1 - \left( \frac{T - t}{T} \right)^3, & 0 \leq t < T \\
1, & t \geq T,
\end{cases}
\]

where \( T > 0 \) is the pre-assigned time.

**Lemma 1** [50]. Assume that a continuous positive-definite function \( A(t) \) satisfies the inequality

\[
A(t) \leq -\alpha A(t)^0, \forall t \geq t_0, A(t_0) \geq 0.
\]

where \( \alpha > 0 \), and \( 0 < \eta < 1 \) are constants. Then, for any given \( t_0 \), \( A(t) \) satisfies the inequality

\[
A(t)^{1-\eta} \leq A(t_0)^{1-\eta} - \alpha(1-\eta)(t - t_0), t_0 \leq t \leq t_1
\]

\[
A(t) = 0, \forall t \geq t_1
\]

with \( t_1 \) given as

\[
t_1 = t_0 + \frac{A(t_0)^{1-\eta}}{\alpha(1-\eta)}.
\]
When the sliding surface \( s = 0 \), the moving point will reach a sliding phase. Thus, the system changes from motion mode to sliding mode. The convergence time \( t_m \) of the sliding mode is determined by the equation: \( 0 = e + \chi \dot{e} + |e| \). Then the finite time \( t_m \) for obtaining \( e = 0 \) is given as follows:

\[
t_m = \max_{t \leq t_0} \left\{ \frac{a}{(\dot{e} + \chi t)(a - b)} \right\}, \tag{12}
\]

where \( t_0 \) is the initial time, and \( t \) is the time horizon of the reaching phase. \( \chi \) is a positive constant, and \( a \) and \( b \) are positive constraints satisfying \( 1 < \frac{a}{\chi} < 2 \).

Lemma 3 [52]. For \( U_i \), \( i = 1, 2, \ldots, n \), if \( 0 < \gamma < 1 \), then the following inequality holds:

\[
|U_1| + |U_2| + \cdots + |U_n| = |U_1| \gamma + |U_2| \gamma + \cdots + |U_n| \gamma. \tag{13}
\]

Lemma 4 [44]. The error-shifting transformation \( b(t) \) satisfies:

1) \( b(0) = 0 \). When \( t \in [0, T) \), \( b(t) \) is smoothly increasing.
2) \( b(T) = 1 \) is its maximum value. When \( \forall t \geq T \), \( b(t) \) remains at such a value thereafter.
3) \( b(t) \) has continuous derivatives up to two-order. \( b(t) \) and \( \dot{b}(t) \) are known and bounded for \( t \in [0, \infty) \).

3 | CONTROL DESIGN

In this part, the two adaptive control schemes based on novel NTSMC finite-time-convergence strategies are proposed, respectively. The control objectives are summarized in the following three aspects:

1) When the actuator faults and input saturation are considered in the robotic systems, the tracking error constraint is satisfied within finite time.
2) When unknown actuator breaks down partially, the tracking error constraint is still satisfied.
3) When initial errors violated the constraints, the adaptive method can still be implemented by utilizing the novel adaptive scheme. In the other words, the novel adaptive scheme can be implemented under any initial conditions.

3.1 | Design without actuator faults and input saturation

We firstly consider the robotic system without actuator faults and input saturation. We assume the unknown external disturbance exists. Let \( x_1 = q \), \( x_2 = \dot{q} \), the robotic dynamics (1) is rewritten as

\[
\begin{align*}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= f(x_1, x_2) + u
\end{align*}
\]

where \( f(x_1, x_2) = -C(x_1, x_2)x_2 - G(x_1) \). Define a position error \( e \) as

\[
e = x_1 - x_2,
\]

where \( x_d = [x_{d1}, \ldots, x_{dn}]^T \) represents the desired trajectory. By introducing the error-shifting transformation (7), the position error is transformed into

\[
\zeta = b(t)e.
\]

Considering (14), for making the non-linear system track the desired position in finite time and preventing the occurrence of singular points, we use the NTSMC technique to design the control law. According to the NTSMC, we have [53].

\[
s_1 = e + k' \dot{e} + k |e|, \quad k \geq 0, 0 < b < 2,
\]

where \( \dot{e} = |e| \text{sign}(e) \), \( k' \) and \( b \) are known positive constants. Based on (17), another sliding surface is designed as

\[
s = \phi + k \dot{\phi}, \quad k > 0, 0 < a < 2,
\]

where \( \dot{\phi} = |\phi|^{\gamma} \text{sign}(\phi) \), \( k' \) and \( a \) are known positive constants.

When \( a \geq 1 \), it is easy to verify \( \frac{\partial}{\partial a} |\phi|^{-a} = a |\phi|^{-a-1} \phi \). In order to make the tracking errors satisfy the constraints, we consider the following barrier function

\[
\varphi = \frac{1}{2} \sum_{i=1}^{n} \ln \frac{k^{2}_i}{k^{2}_i - \xi^2_i}, \tag{19}
\]

Remark 1. In the above description, the signal \( e \) represents the original tracking error. By means of the error-shifting transformation \( b \), the large initial tracking error \( e \) is changed into the tracking error \( \zeta \) starting from origin. By transforming \( e \) into \( \zeta \), \( k^2_i - \xi^2_i < 0 \) becomes \( k^2_i - \xi^2_i > 0 \) in the beginning, and initial violation can be solved by utilizing this transformation. \( T \) is the pre-assigned time. When \( \forall t \geq T \), \( b(t) = 1 \) remains thereafter. Thus, the signal \( \zeta \) is transformed into the signal \( e \) to satisfy the prescribed constraint after the pre-assigned time, and \( \varphi \) ensures that the transformation tracking error \( \zeta \) satisfies the prescribed constraint condition under any initial conditions. Moreover, we can adjust the convergence rate by changing the parameter \( a \).

The derivative of \( \varphi \) is

\[
\dot{\varphi} = \sum_{i=1}^{n} \frac{\dot{\zeta}_i \zeta_i}{k^{2}_i - \xi^2_i}. \tag{20}
\]
The second derivative of \( \varphi \) is

\[
\dddot{\varphi} = \sum_{i=1}^{n} \frac{\partial^2 (\varphi_2)}{\partial t^2} (k_i - \varphi_2) - (\varphi_2)(\ddot{\varphi}_2)\frac{\partial^2 (\varphi_2)}{\partial t^2} (k_i - \varphi_2)^2
\]

where

\[
\ddot{\varphi} = \sum_{i=1}^{n} \frac{\varphi_2}{k_i - \varphi_2} + \sum_{i=1}^{n} \frac{2(\varphi_2)}{(k_i - \varphi_2)^2}
\]

and it is easy to obtain that

\[
\dot{\varphi} = \dot{\varphi} + k_d \ddot{\varphi},
\]

where \( k = k_{\varphi} \cdot \varphi \cdot |t - 1| \).

Substituting (20) and (21) into (22), we obtain

\[
\dot{\varphi} = \sum_{i=1}^{n} \frac{\varphi_2}{k_i - \varphi_2} + k \sum_{i=1}^{n} \frac{\varphi_2}{(k_i - \varphi_2)^2} + k \sum_{i=1}^{n} \frac{\varphi_2}{k_i - \varphi_2}
\]

Then calculating the derivative of (18), we have

\[
\ddot{\iota} = \dddot{\varphi} + k_d \ddot{\varphi},
\]

Substituting (20) and (21) into (22), we obtain

\[
\ddot{\iota} = \ddot{\iota} + k \ddot{\varphi} + k \ddot{\iota}
\]

and it is easy to obtain that

\[
\ddot{\iota} = 2b(t) + 2b(t)
\]

Substituting (14) into (23), we obtain

\[
\ddot{\iota} = A_1 + A_2 \left( h(t) + 2b(t) + b(M^{-1}(\chi_1)u \right.
\]

where

\[
A_1 = \sum_{i=1}^{n} \frac{\varphi_2}{k_i - \varphi_2} + k \sum_{i=1}^{n} \frac{\varphi_2}{(k_i - \varphi_2)^2} \in \mathbb{R}^n
\]

\[
A_2 = k \left[ \frac{\varphi_2}{k_1 - \varphi_2}, \frac{\varphi_2}{k_2 - \varphi_2}, \ldots, \frac{\varphi_2}{k_n - \varphi_2} \right] \in \mathbb{R}^n
\]

We design the model-based control as

\[
u_1 = M(\chi_1)(b(t) - \chi_1 - A_1) - b(t)e
\]

Remark 2. We use \( A_2^+ \) to represent the pseudo-inverse of \( A_2^+ \). According to the property of the Moore–Penrose pseudo-inverse, we have

\[
A_2^+(A_2) = \begin{cases} 
0, & \text{if } A_2 = [0, 0, \ldots, 0] \\
1, & \text{otherwise.}
\end{cases}
\]

Substituting (29) into (26), we have

\[
\dot{\iota} = -\varepsilon \text{sign}(\iota),
\]

but \( d(t) \) is an unknown matrix and we design another model-based control as

\[
u_2 = M(\chi_1)(b(t) - \chi_1 (A_2^+ \xi \text{sign}(\iota) - A_2^+ A_1
\]

In order to ensure the stability of the robotic system, \( d \in \mathbb{R}^n \)

Substituting (31) and (32) into (26), we obtain

\[
\ddot{\iota} = A_1 + A_2 \left( b(t) + 2b(t) + b(M^{-1}(\chi_1)u \right.
\]

where \( \xi = A_2 \text{sign}(A_2^+) \) is a positive constant.

Remark 3. In this paper, we conclude that \( \xi \in \mathbb{R}^+, \varepsilon \in \mathbb{R}^+, \eta \in \mathbb{R}, b \in \mathbb{R}^+, \zeta \in \mathbb{R}^+, \gamma \in \mathbb{R}^{\infty}, \varphi \in \mathbb{R}^{\infty}, \text{and } d \in \mathbb{R}^{\infty}.
\]

Thus, The dimensionality of the equation (34) is a mixed scalar. When \( d(t) \) is known, (29) is available. Otherwise, (32) is available.

\[

Theorem 1. For the non-linear system (14) with any initial conditions, under assumptions 2-3, and the controller (32), the closed-loop system is stable and the tracking errors converge to the origin in finite time \( \eta = \epsilon + \tau, \) where

\[
t_e = t_0 + \frac{V(\xi(\beta))^{1-\frac{1}{2}}}{\xi \varepsilon(1 - \frac{1}{2})},
\]

\[
t_p = \max_{1 \leq i \leq n} \left\{ \frac{d}{(k_i)^{i/(a - 1)}} \right\}
\]

(35)
The period \( t \in [t_0, t_f] \) is the reaching phase and the period \( t \in [t_f, t_p] \) is the sliding phase.

**Proof.** We can know that \( \xi > 0 \) because of \( \xi = A_2 \text{sign}(A_2^T \hat{s}) \). Then, through (34), we obtain
\[
\dot{s} = -\xi \epsilon |s| - b|s|A_2M^{-1}M \text{sign}(A_2^T) \hat{s} + b \epsilon A_2M^{-1}d,
\]
where \( \epsilon > 0 \) is a constant. Then we can get the following result by using the Property 1.
\[
\dot{V}_1 = \frac{1}{2} \epsilon^2.
\]
After further calculation, the derivative of \( V_1 \) is
\[
\dot{V}_1 = \dot{s}.
\]
According to (40) and (38), we obtain
\[
\dot{V}_1 \leq -\xi \epsilon |s| \leq -\xi \epsilon V_1^{1/2}.
\]
Then, based on Lemma 1 and Lemma 2, we can conclude that the sliding mode surface can be reached within the finite time \( t_p \), that is, \( V_1(t) = 0, s(t) = 0 \) for all \( t \geq t_p \). Moreover, \( t_p \) is the largest time to make \( \varphi(t) \) transform into \( \varphi(t_p + t) = 0 \).

**Remark 4.** When \( V_1(t) = 0, s(t) = 0 \), there are four situations discussed around \( \varphi \) and \( \dot{s} \) and proving the tacking errors along with the sliding surface (18) converge to the origin in finite time \( t_p \).

1) When \( \varphi = 0 \) and \( \dot{s} = 0 \), we have \( s = 0 \). Thus, errors \( \xi \) and \( e_i \) are in the origin.
2) When we obtain \( s = 0 \), it leads to \( \varphi > 0 \) and \( \dot{s} = 0 \). Then
\[
\frac{1}{2} \sum_{i=1}^{n} k_i^2 \left( \frac{k_i^2}{k_i^2 - \chi_i^2} \right) > 0 \Rightarrow k_i^2 - \chi_i^2 > 0,
\]
\[
\sum_{i=1}^{n} \frac{\chi_i \bar{\gamma}_i}{k_i^2 - \chi_i^2} < 0 \Rightarrow \chi_i \bar{\gamma}_i < 0.
\]
According to (42), the signs of \( \chi_i \) and \( \bar{\gamma}_i \) are opposite, and the states \( \chi_i \) will converge to the origin ultimately.

3) When \( s = 0 \), the other situation is \( \varphi < 0 \) and \( \dot{s} > 0 \), which is not obtained because of \( \frac{k_i^2}{k_i^2 - \chi_i^2} > 0 \).

4) Due to the definition of \( A_2 \), it and only if \( \chi_i = 0 \), we could obtain \( \xi = 0 \). Thus, the situation of both \( \xi = 0 \) and \( \chi_i \neq 0 \) do not exist at the same time. Therefore we have \( \xi > 0 \), and the proposed method satisfies the Lemma 1.

### 3.1.1 Design with actuator fault and input saturation

The above section demonstrates the feasibility of the novel NTSMC. When the robotic system is accompanied with actuator faults and input saturation, we have a novel discussion in the robotic system.

Based on \( x_1 = q_1, x_2 = \dot{q}_1 \) (4) and (5), the robotic dynamics (1) is rewritten as
\[
\dot{x}_1 = x_2
\]
\[
\dot{x}_2 = M^{-1}(x_1)u + M^{-1}(x_1)\omega + M^{-1}(x_1)f(x_1, x_2),
\]
where
\[
\omega = (D - I)u + \Delta F + d(t)
\]
\[
f(x_1, x_2) = -C(x_1, x_2)x_2 - G(x_1).
\]

**Assumption 4.** The function \( \omega = [\omega_1, ..., \omega_n]^T \) is supposed and bounded, that is,
\[
|\omega_i| \leq \omega_{\max}, i = 1, ..., n,
\]
where \( \omega_{\max} \) is a positive constant. If the control input is bounded, assumption 4 is reasonable [46].

Thus, the model control is designed as
\[
u_3 = M(x_1)(b(t)^{-1}(\text{sign}(A_2^T) \text{sign}(\epsilon)) - \text{sign}(\epsilon))
\]
\[
\text{sign}(A_2^T) \omega^T \hat{\omega} - A_2^T A_2 - b(t) \epsilon - 2b(t) \bar{\epsilon}
\]
\[
- M^{-1}(x_1) \omega - M^{-1}(x_1)f(x_1, x_2) + \xi_d,
\]
where \( \hat{\omega} \) is the estimate of \( \omega \).

The updating law is defined as
\[
\dot{\hat{\omega}}^T = \bar{\delta} \epsilon A_2 M^{-1},
\]
where \( \bar{\delta} \) is a positive constant. Substituting (48) into (26), we obtain
\[
\dot{s} = A_1 + A_2(b \hat{e} + 2\hat{e} + b(b^{-1}(\text{sign}(A_2^T) \text{sign}(\epsilon)))
\]
\[
- A_2^T A_1 - b \bar{e} - 2b \bar{e} \text{sign}(\epsilon) \text{sign}(A_2^T) \hat{\omega}^T \hat{\omega}
\]
After further calculation, the time derivative of \( V_2 \) is

\[
V_2 = \dot{s}^2 + \frac{1}{\delta} \dot{\omega}^T \dot{\omega}.
\]

Substituting (49) and (50) into (55), we have

\[
\dot{V}_2 \leq -\xi \varepsilon |s| - \xi |s| ||\dot{\omega}|| - hsA_2 M^{-1} \dot{\omega} + \frac{1}{\delta} \dot{\omega}^T \dot{\omega} - h A_2 M^{-1} \dot{\omega} + h M^{-1} \omega - \text{sign}(s) \text{sign}(A_2^T) \dot{\omega}^T \dot{\omega}
\]

\[
= -\xi \varepsilon |s| - \xi |s| ||\dot{\omega}|| + \xi |s| ||\dot{\omega}|| - \xi |s| ||\dot{\omega}|| + \xi |s| ||\dot{\omega}||
\]

\[
= -\xi \varepsilon |s| ||\dot{\omega}|| + \xi |s| ||\dot{\omega}|| - \xi |s| ||\dot{\omega}|| + \xi |s| ||\dot{\omega}||
\]

\[
= -\xi \varepsilon |s| ||\dot{\omega}|| + \xi |s| ||\dot{\omega}|| - \xi |s| ||\dot{\omega}|| + \xi |s| ||\dot{\omega}||
\]

\[
\leq -\alpha V_2^\frac{1}{2},
\]

**Theorem 2.** In the non-linear robotic system (44) with actuator faults and saturation under any initial conditions. Then, under assumptions 2-3, and the controller (48), the closed-loop system is stable and the tracking errors will tend to convergence to the origin in finite time \( t_z = t_l + t_q \), where

\[
t_l = t_h + \frac{V'(\bar{s}(t_h))^{1-\frac{1}{2}}}{\alpha (1 - \frac{1}{2})}, \quad t_q = \frac{V'(\bar{s}(t_h))^{1-\frac{1}{2}}}{\alpha (1 - \frac{1}{2})},
\]

\[
t_q = \max_{1 \leq j \leq q} \left\{ \frac{a}{(k_j^*)^2 (a - 1)} \left| \varphi_j(t_l) \right|^{\frac{a-1}{2}} \right\}.
\]

The period \( t \in [t_l, t_q] \) is the reaching phase and the period \( t \in [t_l, t_q] \) is the sliding phase.

**Proof.** We use the same NTSMC as (18). According to (48) and (49), new changes are reflected as

\[
is = -\xi \varepsilon |s| - \xi |s| ||\dot{\omega}|| - hsA_2 M^{-1} \dot{\omega} + h A_2 M^{-1} \omega
\]

where \( \ddot{\omega} = \ddot{\omega} - \omega \). The following Lyapunov function is constructed as

\[
V_2 = \frac{1}{2} \dot{s}^2 + \frac{1}{\delta} \ddot{\omega}^T \ddot{\omega}.
\]

After further calculation, the time derivative of \( V_2 \) is

\[
\dot{V}_2 = \dot{s} \ddot{s} + \frac{1}{\delta} \ddot{\omega}^T \ddot{\omega}.
\]

where \( \alpha = \min \{ \xi \varepsilon, \xi |s| \} \) and \( \varepsilon \geq ||\omega|| \). Furthermore, the relationship \( ||\dot{\omega}|| \geq ||\ddot{\omega}|| - ||\omega|| \) is obtained based on Lemma 2 because of \( ||\omega|| + ||\dot{\omega}|| \geq ||\ddot{\omega}|| \). It implies \(-||\ddot{\omega}|| - ||\ddot{\omega}|| + ||\omega|| \). Then, based on Lemma 1 and Lemma 2, we can conclude that the sliding mode is reached within finite time \( t_z \), that is, \( V_1(t) = 0, s(t) = 0 \) for all \( t \geq t_z \). Moreover, \( t_q \) is the largest time to make \( \varphi(t_l) \) transform into \( \varphi(t_l + t_q) = 0 \).

**Remark 5.** When we obtain \( V_2(t) = 0, \alpha = \min \{ \xi \varepsilon, \xi |s| \} \) \( \xi s = 0 \) should be discussed. If and only if \( V_2(t) \) is equal to zero, then \( s \) is equal to zero, which means \( 0 < \alpha < \xi \varepsilon \) and it still satisfies the Lemma 1. Thus, the conclusion still holds. The other interpretations are similar to remark 4.

**Remark 6.** In order to be as close as possible to the actual disturbance as possible, the bounded disturbance \( d(t) \) is chosen in this paper. The disturbance always supplies energy to the system, which makes the system unstable in this sense. In the procedure of control design, the energy generated by the disturbance is offset by the method of the reverse cancellation of the maximum disturbance. According to (33) and (47), it is known that the disturbance energy is offset. After the energy is offset, the system energy keep a balance. Since the Lyapunov function is also an energy function in some way, in this paper, it can be known from (56) that the system is asymptotic stability in finite time.

### 4.1 SIMULATION

\( l_i \) is the distance from the empennage of joint \( i - 1 \) to the centre of joint \( i \). Considering a robot with two revolute joints in the vertical plane as shown in Figure 1, simulation is carried out to verify the effectiveness of the proposed control method. We define [27]

\[
M(q) = \begin{bmatrix}
m_{11}(q) & m_{12}(q) \\
m_{21}(q) & m_{22}(q)
\end{bmatrix},
\]

**FIGURE 1** A robot with two revolute joints

where \( \alpha = \min \{ \xi \varepsilon, \xi |s| \} \) and \( \varepsilon \geq ||\omega|| \). Furthermore, the relationship \( ||\dot{\omega}|| \geq ||\ddot{\omega}|| - ||\omega|| \) is obtained based on Lemma 2 because of \( ||\omega|| + ||\dot{\omega}|| \geq ||\ddot{\omega}|| \). It implies \(-||\ddot{\omega}|| - ||\ddot{\omega}|| + ||\omega|| \). Then, based on Lemma 1 and Lemma 2, we can conclude that the sliding mode is reached within finite time \( t_z \), that is, \( V_1(t) = 0, s(t) = 0 \) for all \( t \geq t_z \). Moreover, \( t_q \) is the largest time to make \( \varphi(t_l) \) transform into \( \varphi(t_l + t_q) = 0 \).

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Parameters of the robot are listed in the Table 1.

| Parameter | Description           | Value       |
|-----------|-----------------------|-------------|
| $m_1$     | Mass of link 1        | 2.00 kg     |
| $m_2$     | Mass of link 2        | 0.85 kg     |
| $l_1$     | Length of link 1      | 0.35 m      |
| $l_2$     | Length of link 2      | 0.31 m      |
| $I_1$     | Moment of inertia 1   | $\frac{1}{4} m_1 l_1^2$ kg · m² |
| $I_2$     | Moment of inertia 2   | $\frac{1}{4} m_2 l_2^2$ kg · m² |

\[ m_{11}(q) = \frac{1}{2} m_1 l_1^2 + m_2 l_1^2 + \frac{1}{2} m_2 l_2^2 + m_2 l_2 \cos(q_2) \]

\[ m_{12}(q) = \frac{1}{2} m_2 l_2^2 + \frac{1}{2} m_2 l_1 \cos(q_2) \]

\[ m_{21}(q) = \frac{1}{2} m_2 l_2^2 + \frac{1}{2} m_2 l_1 \cos(q_2) \]

\[ m_{22}(q) = \frac{1}{2} m_2 l_2^2, \]

\[ C(q, \dot{q}) = \begin{bmatrix} c_{11}(q, \dot{q}) & c_{12}(q, \dot{q}) \\ c_{21}(q, \dot{q}) & c_{22}(q, \dot{q}) \end{bmatrix}, \]

\[ c_{11}(q, \dot{q}) = -\frac{1}{2} m_2 l_2 \ddot{q}_2 \sin(q_2) \]

\[ c_{12}(q, \dot{q}) = -\frac{1}{2} m_2 l_1 \dot{q}_1 \dot{q}_2 \sin(q_2) \]

\[ c_{21}(q, \dot{q}) = \frac{1}{2} m_2 l_1 \dot{q}_1 \sin(q_2) \]

\[ c_{22}(q, \dot{q}) = 0, \]

\[ C(q) = \begin{bmatrix} c_1(q) \\ c_2(q) \end{bmatrix}, \]

\[ g_1(q) = \left( \frac{1}{2} m_1 l_1 + m_2 l_1 \right) \cos(q_1) + \frac{1}{2} m_2 l_2 \cos(q_1 + q_2) \]

\[ g_2(q) = \frac{1}{2} m_2 l_2 \cos(q_1 + q_2), \]

\[ q = \begin{bmatrix} q_1 \\ q_2 \end{bmatrix}, \frac{\dot{q}}{\ddot{q}} = \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \end{bmatrix}, \dot{q} = \begin{bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \end{bmatrix}. \]

Parameters of the robot are listed in the Table 1.

### 4.1 Design without actuator faults and input saturation

In this section, we examine the tracking performance of robotic system without actuator faults and input saturation. The control law is (32). The initial positions of the robotic system are given as

\[ q_{11}(0) = -0.5 \text{ rad} \]
of the control inputs are large constants, which is the side effect of the error-shifting transformation.

4.2 Design with actuator faults and input saturation

Under the same circumstances in the section 4.1, we examine the model-based control with actuator faults and input saturation in this section. In order to verify the effectiveness of the proposed controller (48), the three adaptive methods are compared with each other:

1) The first proposed method is based on the novel non-singular terminal sliding mode surface. The issues (input saturation, output constraint, actuator faults, and external disturbance) are addressed simultaneously under any initial conditions. Furthermore, the prescribed constraint can be satisfied within a pre-assigned time. The controller is proposed in (48).

2) The second proposed method based on traditional barrier Lyapunov function and non-singular terminal sliding method surface addresses the problems of constraint, input saturation, and actuator faults. However, the prescribed constraint must be satisfied initially because of the traditional BLF.

3) The third case is the proposed method in [54], which addresses the problem of actuator faults by utilizing the non-singular fast terminal sliding surface. However, input saturation and output constraint are not considered.

1) The initial positions of robotic system in the first case are given as

\[
q_{21}(0) = -0.5 \text{ rad} \\
q_{22}(0) = \dot{q}_{21}(0) = \dot{q}_{22}(0) = 0 \text{ rad}.
\] (65)

2) The initial positions of robotic system in the second case are given as

\[
q_{31}(0) = 0.8, q_{32}(0) = 0.9 \text{ rad} \\
\dot{q}_{31}(0) = \dot{q}_{32}(0) = 0 \text{ rad}.
\] (66)

3) The initial positions of robotic system in the third case are given as

\[
q_{41}(0) = -0.5 \text{ rad} \\
q_{42}(0) = \dot{q}_{41}(0) = \dot{q}_{42}(0) = 0 \text{ rad}.
\] (67)

In the three cases, we select the desired trajectory as \(q_d = [\cos(\pi t), \cos(\pi t)]^T\text{rad}\), where \(t \in [0, t_f]\) and \(t_f = 20\text{s}\). The external disturbance is \(d\). The control parameters are selected as: \(k_i = 0.4, \varepsilon = 15, T = 2, T_{\text{max}} = 20, b = 0.01, a = 1.5\). The value of \(b\) is chosen more smaller. The other parameters are selected as: \(k = 0.05, \omega = [0, 0]^T, \theta = 0.01\). Furthermore, the actuator faults scenarios \(D = \text{diag}\{t_1, t_2\}\) is given as follows

\[
t_i(t) = \begin{cases} 
1, & 0 \leq t < 1 \\
0.5 + 0.4\sin(0.05t + \pi/3), & t \geq 1
\end{cases}
\] (68)

and the other parameters about the third case are defined in [54]. In this section, the objective is to verify that the
model-based finite time control methods for robotic system with actuator faults and input saturation can make output tracking error satisfy the prescribed constraint within the pre-specified time under any initial conditions. Simulation results are shown in Figures 8–13.

As we can see in Figure 8(a–f), tracking performances of the three cases are presented. All of the three cases track the desired trajectory successfully in finite time. In Figure 8(c,d), the setting time is smaller than the setting time in Figure 8(a,b) because of the different initial positions. Furthermore, the setting time in the Figure 8(e,f) is faster than other cases in Figure 8(a–d) because the NFTSMC has faster convergence rate than NTSMC. However, the controller consumes more system resources because of the NFTSMC scheme reflected in Figure 12(e,f). In Figures 9 and 10, the output tracking errors converge into a small region in finite time by utilizing the error-shifting transformation whenever the constraints are violated initially. The tracking error signal $e$ does not satisfy the prescribed constraint initially, but the transformed tracking errors $z$ satisfy it. Thus, the proposed method can be implemented under any initial conditions.

In Figure 11(a,b), the tracking error must be constrained initially because the traditional BLF would approach infinity whenever its arguments are approaching the prescribed constraint. Furthermore, the tracking performances with the prescribed constraint and input saturation in Figures 9 and 10 are similar to the performances without the prescribed constraint and input saturation in Figure 11(c,d). Thus, the proposed method is more flexible to utilizing in practical applications.

In Figure 12(a), the initial values of control input are large enough because of $1/b$, but the value of $b$ is monotonically
FIGURE 12 The control inputs of three adaptive methods: (a) The control input by utilizing the proposed method with the novel sliding mode surface. (b) The control input by utilizing the proposed method with the novel sliding mode surface. (c) The control input of joint 1 by utilizing the proposed method with traditional BLF. (d) The control input of joint 2 by utilizing the proposed method with traditional BLF. (e) The control input of joint 1 by utilizing the proposed method in [54]. (f) The control input of joint 2 by utilizing the proposed method in [54].

Increasing. The controller will be stabilized within a pre-assigned finite time, and in Figure 12(b), the design of input saturation addresses the problem in Figure 12(a). The control input is constrained in the value $[-F_{\text{max}}/F_{\text{max}}]$. Accordingly, the design of actuator saturation addresses the side effect of the error-shifting transformation. In Figure 12(c,d), the initial values are smaller than the values in Figure 12(a,b) because the design is without the term of $1/h$. However, the design based on NFTSMC scheme causes more resource consumption for the robotic system in Figure 12(e,f).

Finally, the phase planes are presented in Figure 13(a–f). Three groups of comparison have been reflected in the phase planes. In Figure 13(a,b), stable limit cycles have been shown, which represents the proposed method in [54]. The adaptive method in [54] has addressed the actuator fault problems by utilizing non-singular fast terminal sliding surface. Although the strategy has satisfied the stable goal, the chattering was caused by the actuators faults. In Figure 13(c,d), stable limit cycles have been shown, which represents the proposed method without considering deferred constraint for comparison. Compared with the strategy in [54], the output constraint and input saturation were considered. In Figure 13(e,f), stable limit cycles have been shown, which represents the proposed method considering deferred constraint. In conclusion, all the three groups of comparison have stable limit cycles in Figure 13.

5 CONCLUSION

In the paper, we have proposed a novel adaptive NTSUMC scheme with error-shifting transformation to address the tracking problems of actuator faults, input saturation, external disturbances, and deferred tracking error constraints in robotic manipulator. Simulation results have shown that tracking error can satisfy the prescribed constraint within finite time under any initial conditions. Even if some unknown actuators break down partially, the performance constraints are still satisfied. Furthermore, it is needless to obtain any prior knowledge of actuator faults. The design of input saturation addresses the side effect of the error-shifting transformation. There is a good tracking performance in simulation results. Further work includes reducing chatter generated by symbolic function in the proposed control law and compensating potential uncertainties in the system.
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