Adaptive sliding mode disturbance observer-based composite trajectory tracking control for robot manipulator with prescribed performance

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Abstract In this paper, the problem of the composite trajectory tracking control for robot manipulator with lumped uncertainties including unmodeled dynamics and external disturbances is investigated. To achieve the active disturbance rejection, the adaptive sliding mode disturbance observer is proposed to estimate the unknown lumped uncertainties in the absence of the prior upper bound information on the lumped uncertainties. Then, by combining the non-singular terminal sliding mode control and prescribed performance control approaches, the composite trajectory tracking controller is designed, and not only the finite-time convergence of the trajectory tracking errors, but also the prescribed performances are guaranteed. Finally, by applying the proposed control scheme to a two-DOF manipulator system, the effectiveness and advantages are verified by numerical simulations.

Keywords Robot manipulators · Sliding mode disturbance observer · Adaptive law · Sliding mode control

1 Introduction

Although the applications of robot manipulators are more and more extensive in practice, the high-precision motion control of the robot manipulators is still an important problem worthy further study due to the internal uncertainties and external disturbances, such as coupling dynamics, unmodeled uncertainties, high nonlinearity, and the external disturbances from the environment or mission objectives. To deal with these problems, many effective control approaches have been researched, including PID control [1], model predictive control (MPC) [2], $H_{\infty}$ control [3], sliding mode control (SMC) [4]. It should be pointed out that due to the merits of quick response, strong robustness and invariability to the matched disturbances, SMC is widely used in robot manipulator system control. For example, to guarantee the quick convergence of the robot manipulator’s trajectory tracking errors, the terminal sliding mode control (TSMC) is employed in [5]. Considering the singularity problem existing in the TSMC approaches, a nonsingular fast TSMC combining with neural network is proposed in [6], which eliminates the singular point and effectively counteracts the actuator failures in robot manipulator systems. More extensive references about this topic are presented in [7–12], and the reference therein.

It is worth mentioning that the disturbance rejection ability of SMC attributes to the switching function incorporating in the controller, but it also results in undesired chattering. In addition, the system uncertainties also affect the transient performance, and even cause the instability of the system. In order to actively compensate the disturbances, the disturbance observer-
based control (DOBC) approaches have been proposed in recent years [4, 13, 14]. The point of DOBC approaches is first accurately estimating the disturbance and then incorporating the estimation value in the controller to compensate disturbance, and in this way, the active disturbance rejection is realized. In [15], the disturbance observer-based SMC approach is proposed to counteract the mismatched disturbance in the second-order nonlinear system. By introducing the estimation value in the sliding surface, the disturbance can be eliminated and the chattering problem is alleviated. In [16], a finite-time disturbance observer (FTDOB)-based nonsingular terminal sliding mode control (NTSMC) approach is established for the buck power DC-DC converter system which subjects to mismatched/matched disturbances. To eliminate the requirement of the disturbance’s upper bound, an adaptive sliding mode disturbance observer is proposed in [17], and the disturbances in the space manipulator systems are compensated. Considering to improve the transient performance of the system, a prescribed performance-based neural adaptive control scheme is proposed for robot manipulators in [18], which transforms the constrained tracking problem into an unconstrained model and makes the tracking and observation errors with a prescribed overshoot range, convergence rate and tracking accuracy. In [19], the prescribed performance control is combined with super-twisting sliding mode control algorithm to ensure the smoothly movement of surgical robots.

Motivated by the aforementioned results, in this paper, a finite-time adaptive sliding mode disturbance observer (ASMDO)-based composite trajectory tracking control scheme is proposed for robot manipulator system subjects to matched disturbances. The main contributions are summarized as follows:

(1) Based on the equivalent control approach, a novel adaptive sliding mode disturbance observer is designed to eliminate the requirement of the upper bound of the lumped uncertainties, and the finite-time convergence of the disturbance estimation error can be guaranteed.

(2) By introducing the arctangent function to dynamically adjust the gain of the switching function, a novel continuous time reaching law is designed, and the chattering phenomenon in controller and sliding surface is effectively eliminated.

(3) By combining with the prescribed performance control and the nonsingular terminal sliding mode control (NTSMC) schemes, the finite-time composite trajectory tracking control approach is established for robot manipulator, which improves the transient performances and avoids the singularity problem simultaneously.

Finally, by applying the proposed control approach to a two-DOF robot manipulator model, the effectiveness of the proposed control scheme is validated.

2 Preliminaries

2.1 N-joint Rigid manipulator dynamic model

Consider a class of rigid manipulators with $n$-joint, the dynamic equation can be described as:

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

where $q \in \mathbb{R}^n$, $\dot{q} \in \mathbb{R}^n$, $\ddot{q} \in \mathbb{R}^n$ are, respectively, the position, velocity and acceleration vectors, $M(q) \in \mathbb{R}^{n \times n}$ is the system inertia matrix, $C(q, \dot{q}) \in \mathbb{R}^{n \times n}$ is the centripetal-Coriolis matrix, $G(q) \in \mathbb{R}^n$ is the gravity torque vector, $\tau \in \mathbb{R}^n$ is the generalized force/torque vector, $h \in \mathbb{R}^n$ is the matched external disturbance.

Actually, there always exist uncertainties in the system, and we can assume that the system matrices are constituted by two parts:

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

where $M_0(q), C_0(q, \dot{q}), G_0(q)$ are the nominal parts, $M_\Delta(q), C_\Delta(q, \dot{q}), G_\Delta(q)$ are the model uncertainties, and $M_0(q)$ is a positive definite matrix.

Therefore, the system dynamic Eq. (1) can be transformed into:

$$M_0(q)\ddot{q} + C_0(q, \dot{q})\dot{q} + G_0(q) = \tau + \zeta, \quad (2)$$

where $\zeta = h - G_\Delta(q) - C_\Delta(q, \dot{q})\dot{q} - M_\Delta(q)\ddot{q}$ is the lumped uncertainty containing the external disturbances and the unmodeled dynamics.

Let $q_d \in \mathbb{R}^n$ be a twice differentiable desired trajectory. Define $x_1 \triangleq q - q_d$, and $x_2 \triangleq \dot{q} - \dot{q}_d$ as the tracking error and its first derivative, respectively.
Then, we can transform system (2) into the following form:

\[
\begin{align*}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= -M_0^{-1}(q)(G_0(q) + C_0(q, \dot{q})\dot{q} + M_0(q)\ddot{q}_d) + M_0^{-1}(q)\tau + \xi,
\end{align*}
\]

where \(\xi = M_0^{-1}(q)\zeta\) and we denote \(\xi = [\xi_1, \ldots, \xi_n]^T\).

In order to facilitate the theoretical analysis, the following useful assumption and lemmas are given.

**Assumption 1** Each component of \(x\) is supposed to be bounded and its derivative satisfies \(|\dot{x}_i(t)| \leq l, \quad (i = 1, \ldots, n)\), \(\forall t \geq 0\), where \(l\) is a positive constant.

Consider the following nonlinear system:

\[
\dot{y} = -\lambda_1 \arctan(|y|)\text{sign}(|y|) - \lambda_2 \arctan(|y|)\text{sign}(|y|),
\]

where \(\lambda_1 > 0\) and \(\lambda_2 > 0\) are positive constants, \(m_1 > 0, n_1 > 0, p_1 > 0, q_1 > 0\) are positive odd integers satisfying \(m_1 > n_1, p_1 < q_1\), and \(y(0) = y_0\) is the initial condition, \(\text{sign}(\sigma)\) is defined as \(|\sigma|^{m_1}\text{sign}(\sigma)\), where \(\text{sign}(\cdot)\) is the signum function. Then, we have the following lemma.

**Lemma 1** The solution of system (4) converges to the origin within fixed time and the settling time is bounded by \(T_s < T_{\text{max}} \triangleq T_1 + T_2\), where

\[
T_1 = \frac{n_1(q_1 - p_1)}{\arctan(1)\lambda_1 (m_1 - n_1)}, \quad T_2 = \frac{q_1}{\arctan(1) p_1 \lambda_2}.
\]

**Proof** Without loss generality, we assume that \(|y_0| > 1\), and we first consider the case that \(y \in \Theta_0 \triangleq \{y||y|| > 1\}\) and it is true that \(\arctan(|y|) \geq \arctan(1)\).

Consider the Lyapunov function \(V_l = y^2\), and the derivative of \(V_l\) with respect to time is calculated as:

\[
\begin{align*}
\dot{V}_l &= 2y(-\lambda_1 \arctan(|y|)\text{sign}(|y|) - \lambda_2 \arctan(|y|)\text{sign}(|y|)) \\
&= -2\lambda_1 \arctan(|y|)|y|^{m_1 + n_1 - 1} - 2\lambda_2 \arctan(|y|)|y|^{p_1 + q_1} \\
&\leq -2\arctan(1)\lambda_1 |y|^{m_1 + n_1 - 1} - 2\arctan(1)\lambda_2 |y|^{p_1 + q_1} \\
&= -2\arctan(1)(\lambda_1 V_l^{m_1 + n_1 - 1} + \lambda_2) V_l^{p_1 + q_1} < 0. (5)
\end{align*}
\]

Next, we will show that there exists finite-time \(T_1(y_0) > 0\) such that for \(t > T_1(y_0), \quad y \in \Theta_1 \triangleq \{y||y|| \leq 1\}\) always holds.

To this end, we define \(v_0(t) \triangleq \frac{q_1 - p_1}{v_0^{q_1 - q_1}}\), and it follows from (5) that

\[
\frac{1}{1 + \frac{q_1 - p_1}{v_0^{q_1 - q_1}}} \frac{dv_0}{dt} \leq -2\arctan(1)\frac{q_1 - p_1}{2q_1},
\]

and thus \(v_0(t)\) is a monotonically decreasing function of time.

Then, integrating both sides of (6) yields that

\[
\int_{v_0(0)}^{v_0(t)} \frac{1}{1 + \frac{q_1 - p_1}{v_0^{q_1 - q_1}}} dv_0 \leq -2\arctan(1)\frac{q_1 - p_1}{2q_1} t,
\]

Define \(h(v_0(t)) = \int_{v_0(0)}^{v_0(t)} \frac{1}{1 + \frac{q_1 - p_1}{v_0^{q_1 - q_1}}} dv_0 + \lambda_2\), and it is clear that \(h(v_0(t))\) is also a monotonically decreasing function of time, and \(h(v_0(t)) = 0\) if and only if \(v_0(t) = 1\) (also implying that \(V_l = 1\)).

According to (7), we have

\[
h(v_0(t)) = \int_{v_0(0)}^{v_0(t)} \frac{1}{1 + \frac{q_1 - p_1}{v_0^{q_1 - q_1}}} dv_0 + \lambda_2 \leq h(v_0(0)) - 2\arctan(1)\frac{q_1 - p_1}{2q_1} t,
\]

which implies that there exists \(T_1(y_0) \triangleq \frac{q_1}{\arctan(1)(q_1 - p_1)} h(v_0(0))\), such that for \(t > T_1(y_0), \quad y \in \Theta_1 \triangleq \{y||y|| \leq 1\}\) always holds. Moreover, it is obvious that \(T_1(y_0)\) is bounded by

\[
\lim_{y_0 \to \infty} T_1(y_0) \leq \lim_{v_0(0) \to \infty} \frac{q_1}{\arctan(1)(q_1 - p_1)} h(v_0(0)).
\]


Now, we consider the case that \( y \in \Theta_1 \). With the inequality \( \arctan(|y|) > \arctan(1)|y| \), it is easy to obtain that

\[
V_t = 2y(-\lambda_1 \arctan(|y|)\frac{m_1}{n_1} - \lambda_2 \arctan(|y|)\frac{p_1}{q_1} (y)) \\
\leq -2 \arctan(1)\lambda_1 |y| - 2 \arctan(1)\lambda_2 |y| \frac{m_1 + 2q_1}{n_1} \\
= -2 \arctan(1)(\lambda_1 V_t + \lambda_2) < 0.
\]

Define \( w_0 = \frac{p_1}{q_1} \) and it follows from (8) that

\[
\frac{1}{\lambda_1 w_0 + \lambda_2} \frac{dw_0}{dr} \geq \arctan(1) \frac{p_1}{q_1}.
\]

By following the similar line of the previous case, we can show that there exists \( T_2(y_0) = \frac{1}{\lambda_1 w_0 + \lambda_2} \int_0^{w_0(0)} dw_0 \) such that for \( t \geq T_2(y_0) \), \( w_0 = 0 \) (also implying that \( y = 0 \)) and \( T_2(y_0) \) is bounded by \( T_2 \) determined by

\[
\lim_{y_0 \rightarrow 1} T_2(y_0) \leq \lim_{w_0(0) \rightarrow 1} \frac{1}{\lambda_1 w_0 + \lambda_2} \int_0^{w_0(0)} \frac{1}{\lambda_1 w_0 + \lambda_2} dw_0 \\
\leq \frac{1}{\lambda_1 w_0 + \lambda_2} \int_0^1 \frac{1}{\lambda_1 w_0 + \lambda_2} dw_0 \\
\leq \frac{1}{\lambda_2} \int_0^1 \frac{1}{\lambda_2} dw_0 = \frac{1}{\lambda_2} = T_2.
\]

Therefore, the system state \( y \) converges to the equilibrium point from any initial state \( y_0 \) within fixed time and the settling time is bounded by \( T_{\text{max}} \). \( \square \)

**Remark 1** It is worth mentioning that, to eliminate the chattering effects, the bounded nonlinear function \( \arctan(|y|) \) is employed to dynamically adjust the gain of the nonsmooth functions \( \frac{m_1}{n_1} \) and \( \frac{p_1}{q_1} \) in system (4). Specifically, if \( |y| \) is large enough, \( \arctan(|y|) \approx \frac{\pi}{2} \), thus the appealing features of the fixed-time stability can be ensured. While if \( |y| \) is small enough, the nonsmooth functions \( \frac{m_1}{n_1} \) and \( \frac{p_1}{q_1} \) may lead to undesired chattering phenomenon, and considering the fact of \( \arctan(|y|) \approx |y| \), (4) can be approximated as \( \dot{y} = \lambda_1 |y| - \lambda_2 |y| y \), thus the chattering phenomenon is eliminated successively.

Based on system (4), we further consider the following disturbed system

\[
\dot{y} = -\lambda_1 \arctan(|y|)\frac{m_1}{n_1} (y) - \lambda_2 \arctan(|y|)\frac{p_1}{q_1} (y) + \epsilon_0,
\]

where \( \epsilon_0 \) is the constant disturbance. Similar to Lemma 1, we have the following lemma immediately, and the detailed proof is omitted.

**Lemma 2** If \( \lambda_2 \) and \( 0 < \theta < 1 \) are chosen to satisfy \( \frac{\epsilon_0}{\arctan(1)(1-\theta)\lambda_2} \leq 1 \), then the solution of system (9) converges to a region \( \Theta_2 = \{y|y| \leq \left( \frac{\epsilon_0}{\arctan(1)(1-\theta)\lambda_2} \right)\frac{\epsilon_1}{\arctan(1)(1-\theta)\lambda_2} \} \) within fixed time and the settling time is bounded by \( T_2 < T_{\text{max}} \).

### 3 Disturbance observer and composite controller design

#### 3.1 Adaptive sliding mode disturbance observer

Before presenting the main results, inspired by [20], a useful lemma is presented. Consider the following first-order system

\[
\dot{\sigma}_a = -(c(t) + \eta)\text{sign}(\sigma_a) + d(t),
\]

where \( \sigma_a \in \mathbb{R} \) represents the system state, \( d(t) \in \mathbb{R} \) is a bounded disturbance, i.e. there exists \( d_0 > 0 \) such that \( |d(t)| < d_0, \eta \in \mathbb{R}^+ \).

If \( c(t) > |d(t)| \), the system (10) is ensured to be convergence and the average value of \(-(c(t) + \eta)\text{sign}(\sigma_a)\)
equals to the equivalent control input. Because this control input is a virtual variable, a low-pass filter which refers to [20, 21] is constructed to approximate this control signal and the output is defined as \( \hat{u}_{eq} \), which sets as follows:

\[
\dot{\hat{u}}_{eq} = -\frac{1}{\varrho}(c(t) + \eta)\text{sign}(\sigma_{d}) + \tilde{u}_{eq},
\]

where \( \varrho > 0 \). \( c(t) \) is an adaptive parameter, and according to [22], the adaptive law can be designed as

\[
c(t) = -\int_{0}^{t} \left( \kappa_{1} \arctan(|\varphi(s)|)\text{sign} \frac{m_{1}}{n_{1}} \varphi(s) \right. \\
\left. + \kappa_{2} \arctan(|\varphi(s)|)\text{sign} \frac{p_{1}}{q_{1}} \varphi(s) \right) ds + c_{0}
\]

where \( \kappa_{1} > 0 \), \( \kappa_{2} > 0 \), \( m_{1} \), \( n_{1} \), \( p_{1} \), \( q_{1} \) are positive odd integers satisfying \( m_{1} > n_{1} \) and \( p_{1} < q_{1} \). \( c_{0} > 0 \) is the initial value of \( c(t) \), \( w \geq 2 \left( \frac{\varphi}{v(1-\eta_{1}k_{2}\arctan(1))} \right) \frac{p_{1}}{q_{1}} \), and \( 0 < v < 1, 0 < \theta_{1} < 1, \phi > 0 \) are the user-designed parameters.

**Lemma 3** If there exists \( \phi > 0 \) satisfying \( \dot{\hat{u}}_{eq} < \varphi \), \( \frac{1}{v}|\tilde{u}_{eq}| + w > |\hat{u}_{eq}| \) and \( \left( \frac{\varphi}{v(1-\eta_{1}k_{2}\arctan(1))} \right) \frac{p_{1}}{q_{1}} \leq 1 \), there always exists a fixed-time \( T_{f} > 0 \) such that, for \( t > T_{f} \), the inequality \( c(t) > |d(t)| \) holds.

**Proof** Taking the time derivative of \( \varphi(t) \) yields

\[
\dot{\varphi}(t) = -\kappa_{1} \arctan(|\varphi(t)|)\text{sign} \frac{m_{1}}{n_{1}} \varphi(t) \\
- \kappa_{2} \arctan(|\varphi(t)|)\text{sign} \frac{p_{1}}{q_{1}} \varphi(t) - \frac{1}{v} \frac{d|\tilde{u}_{eq}|}{dt}.
\]

Considering the Lyapunov candidate \( V_{s} = \frac{1}{2} \varphi^{2}(t) \), if \( |\varphi(t)| \geq 1 \), we have

\[
\dot{V}_{s} \leq -\kappa_{1} \arctan(1)|\varphi(t)| \frac{m_{1}}{n_{1}} - \kappa_{2} \arctan(1)|\varphi(t)| \frac{p_{1}}{q_{1}} \\
+ |\varphi(t)| \frac{\varphi d_{0}}{v} \\
= -\kappa_{1} \arctan(1)(2V_{s}) \frac{m_{1}}{n_{1}} - \theta_{1} k_{2} \arctan(1)(2V_{s}) \frac{p_{1}}{q_{1}} \\
- (1 - \theta_{1})k_{2} \arctan(1)|\varphi(t)| \frac{p_{1}}{q_{1}} + |\varphi(t)| \frac{\varphi d_{0}}{v},
\]

and it is clear that if \( |\varphi(t)| > \left( \frac{\varphi}{v(1-\eta_{1}k_{2}\arctan(1))} \right) \frac{q_{1}}{p_{1}} \), the inequality \( \dot{V}_{s} < 0 \) is guaranteed. Due to the parameters \( \theta_{1}, \kappa_{2}, \varphi \) are chosen to satisfy \( \left( \frac{\varphi}{v(1-\eta_{1}k_{2}\arctan(1))} \right) \frac{q_{1}}{p_{1}} \leq 1 \), thus \( \varphi(t) \) converges into the region \( \Delta_{0} \triangleq \{ \varphi(t) ||\varphi(t)| \leq 1 \} \). Thereafter, for \( \varphi(t) \in \Delta_{0} \), the following inequality holds

\[
\dot{V}_{s} \leq -\kappa_{1} \arctan(1)|\varphi(t)| \frac{m_{1} + 2q_{1}}{n_{1}} - \kappa_{2} \arctan(1) \\
|\varphi(t)| \frac{p_{1} + 2q_{1}}{q_{1}} + \frac{\varphi d_{0} |\varphi(t)|}{v} \\
= -\kappa_{1} \arctan(1)(2V_{s}) \frac{m_{1} + 2q_{1}}{n_{1}} - \theta_{1} k_{2} \arctan(1) \\
(2V_{s}) \frac{p_{1} + 2q_{1}}{q_{1}} - (1 - \theta_{1})k_{2} \arctan(1)|\varphi(t)| \frac{p_{1} + 2q_{1}}{q_{1}} + \frac{\varphi d_{0} |\varphi(t)|}{v},
\]

which implies that if \( |\varphi(t)| \geq \left( \frac{\varphi}{v(1-\eta_{1}k_{2}\arctan(1))} \right) \frac{q_{1}}{p_{1}} \), the inequality \( \dot{V}_{s} < 0 \) holds, thus according to Lemma 2, \( \varphi(t) \) will converge into the region \( \Delta_{1} \triangleq \{ \varphi(t) ||\varphi(t)| < \left( \frac{\varphi}{v(1-\eta_{1}k_{2}\arctan(1))} \right) \frac{q_{1}}{p_{1}} \} \) in fixed time. Due to \( w \) is chosen to satisfy \( w \geq 2 \left( \frac{\varphi}{v(1-\eta_{1}k_{2}\arctan(1))} \right) \frac{q_{1}}{p_{1}} \), it is clear that, for any \( \varphi(t) \in \Delta_{1} \), the inequality \( |\varphi(t)| = |c(t) - \frac{1}{v} |\hat{u}_{eq}| - w| < \frac{w}{2} \) always holds. If \( c(t) - \frac{1}{v} |\hat{u}_{eq}| - w > 0 \), we have

\[
c(t) > \frac{1}{v} |\hat{u}_{eq}| + w > |\hat{u}_{eq}| + \frac{w}{2} > |u_{eq}| = |d(t)|,
\]

and if \( c(t) - \frac{1}{v} |\hat{u}_{eq}| - w < 0 \), we also have

\[
c(t) > \frac{1}{v} |\hat{u}_{eq}| + w > |u_{eq}| = |d(t)|.
\]

Therefore, according to Lemma 2, there always exists fixed-time \( T_{f} > 0 \) such that the inequality \( c(t) > |d(t)| \) holds for \( t > T_{f} \).

Based on Lemma 3, and motivated by [23], in what follows, a novel sliding mode disturbance observer is proposed to estimate the lumped uncertainty \( \xi \) in the robot manipulator system (3). To this end, we select the following sliding surface,

\[
\sigma = s + \lambda_{1} \arctan(|s|)\text{sign} \frac{m_{1}}{n_{1}}(s) + \lambda_{2} \arctan(|s|)\text{sign} \frac{p_{1}}{q_{1}}(s),
\]

(12)
where $\sigma = [\sigma_1, \ldots, \sigma_n]^T \in \mathbb{R}^n$, and $s \triangleq z - x_2$ is the auxiliary variable, in which $z \in \mathbb{R}^n$ is determined by

$$
\dot{z} = -M_0^{-1}(q)(G_0(q) + C_0(q, \dot{q}) + M_0(q)\ddot{q}, -\lambda_1 \arctan(|s|)\sigma_1 \sin \frac{\pi}{2n1}(s) - \lambda_2 \arctan(|s|)\sin \frac{\pi}{2n2}(s) + v_{eq},
$$

where $\arctan(|s|) = \text{diag}(|\arctan(s_1)|, \ldots, |\arctan(s_n)|)$, $\sin(|s|) = [\sin(s_1), \ldots, \sin(s_n)]^T$, $o = \frac{n_1}{n_2}$, $m_1 > 0$, $\lambda_2 > 0$ are positive constants, $m_1 > 0$, $n_1 > 0$, $p_1 > 0$, $q_1 > 0$ are positive odd integers and satisfying $m_1 > n_1$, $p_1 < q_1$, and $v_{eq} \in \mathbb{R}^n$ is determined by

$$
v_{eq} = -\Psi\text{sign}(\sigma), \quad v_{eq}(0) = 0,
$$

with $\Psi = \text{diag}((c_1(t) + \eta), \ldots, (c_n(t) + \eta))$, and $\eta > 0$, the adaptive parameter $c_i(t)$ is updated by (11), $\text{sign}(\sigma) = [\text{sign}(\sigma_1), \ldots, \text{sign}(\sigma_n)]^T$.

Define the disturbance estimation error as $\hat{\xi} = \xi - v_{eq}$, and we have the following theorem.

**Theorem 1** With the sliding surface (12), and auxiliary systems (13)–(14), the disturbance estimation error $\hat{\xi}$ will converge to its equilibrium point in finite time.

**Proof** Taking the time derivative of $s$, it obtains

$$
\dot{s} = \dot{z} - \dot{x}_2
= -\lambda_1 \arctan(|s|)\sin \frac{\pi}{2n1}(s) - \lambda_2 \arctan(|s|)\sin \frac{\pi}{2n2}(s) + v_{eq} - \dot{\xi},
$$

and substituting (15) into (12) yields $\sigma = v_{eq} - \dot{\xi}$, and thus we have

$$
\dot{\sigma} = -\Psi\text{sign}(\sigma) - \dot{\xi}.
$$

Similar to the proof of Lemma 3, here comes the similar conclusion that there exists $T_{\xi} > 0$ such that, for $t > T_{\xi}$, the inequality $c_i(t) > |\hat{\xi}|$ always holds.

Then, by selecting the Lyapunov candidate as $V_1 = \frac{1}{2}\sigma^T \sigma$ and taking the derivative of $V_1$, we have

$$
\dot{V}_1 = -\sum_{i=0}^n \sigma_i((c_i(t) + \eta)\text{sign}(\sigma_i) + \dot{\xi}_i) \leq -\sum_{i=0}^n ((c_i(t) - |\hat{\xi}|)|\sigma_i| + \eta|\sigma_i|)
\leq -\sqrt{2}\eta V_1^{\frac{1}{2}}
$$

which implies that $\sigma$ converges to the equilibrium point in finite time. Referring to the upper conclusion $\sigma = v_{eq} - \dot{\xi}$ and the definition of the uncertainty estimation error, it can be concluded that the estimation error converges in finite time and $v_{eq} - \dot{\xi} = 0$.

Then, substituting $\sigma = 0$ into (12), we obtain $\dot{s} = -\lambda_1 \arctan(|s|)\sin \frac{\pi}{2n1}(s) - \lambda_2 \arctan(|s|)\sin \frac{\pi}{2n2}(s)$, and according to Lemma 1, $s$ will converge to the equilibrium point in finite time.

**Remark 2** It should be pointed that the sliding surface (12) relies on $\dot{s}$, and a nonlinear tracking differentiator [24] can be applied to obtain $\dot{s}$.

### 3.2 Composite trajectory tracking control strategy

In order to obtain the desired transient performances of trajectory tracking system, a composite control approach is proposed by combining a novel nonsingular terminal sliding mode control with the prescribed performance control approaches. According to [25], we define $\mu_i(t) = (\mu_i0 - \mu_i\infty)e^{-kt} + \mu_i\infty$, where $\mu_i0 > \mu_i\infty > 0$ and $k$ are user-defined parameters. In this subsection, a novel composite controller is designed to guarantee $|x_{1i}| < \epsilon_i\mu_i(t)$, where $0 \leq \epsilon_i \leq 1$, and $x_{1i}$ is the $i$th component of $x_1$.

Define $x_{1i}$’s transformation as $R(\epsilon_i) = \frac{e\epsilon_{x_{1i}} - e\epsilon_{x_{1i}}}{x_{1i} + \epsilon_{x_{1i}}}$, where $e_i$ is the component of $e$ and it is the state constrained by prescribed performance control. It is easy to verify $-\epsilon_i < R(\epsilon_i) < \epsilon_i$, and $e_i$ can be determined as $e_i = \frac{1}{2}\ln(\frac{\epsilon_i + \mu_i(t)}{\epsilon_i - \mu_i(t)})$. Then taking the first and second derivatives of $e_i$

$$
\dot{\epsilon}_i = \frac{\epsilon_i}{\epsilon_i^2 - \epsilon_i^2} (\dot{x}_{1i}\mu_i - \dot{\mu}_i x_{1i}),
$$

and

$$
\ddot{\epsilon}_i = -\frac{2\epsilon_i^3\mu_i\dot{\mu}_i + 2e_i x_{1i}\dot{x}_{1i}}{(\epsilon_i^2 - \epsilon_i^2)^2} (\dot{x}_{1i}\mu_i - \dot{\mu}_i x_{1i})
$$
Adaptive sliding mode disturbance observer-based composite trajectory

\[ \tau_i = G_0(q) + C_0(q, \dot{q}) \dot{q} + M_0(q) \ddot{q}_d + M_0 \Gamma^{-1} \dot{\chi}_x \]
\[ - M_0 \Pi^{-1} \dot{\Pi}_1 + M_0 \Gamma^{-1} \Pi^{-1} \dot{\Pi} \dot{\chi}_x \]
\[ - M_0 \Gamma^{-1} \Pi^{-1} \phi \dot{e}_i \]
\[ - M_0 \Gamma^{-1} \Pi^{-1} \arctan(|e|) \frac{\dot{q}_i}{\Pi} - M_0 \dot{\xi}_x, \]
\[ \tau_2 = - \frac{p_1}{q_1} M_0(q) \dot{\gamma}^{-1} \Gamma^{-1} |e| \frac{\dot{q}_i}{\Pi} - M_0 \dot{\xi}_x, \]
\[ (h_1 \arctan(|\sigma|) |\sigma| + h_2 \arctan(|\sigma|) |\sigma|), \]

where \( h_1 > 0 \) and \( h_2 > 0 \) are the controller gains, \( \Sigma_i (\dot{e}_i^{-1}) = diag \{ \Sigma_1 (\dot{e}_i^{-1}) \} \).

Theorem 2 Consider the trajectory tracking error system (3) subjects to lumped uncertainties, basing on the adaptive sliding mode disturbance observer (12)–(14), if the non-singular sliding mode controller is designed as (21), then the system states are finite-time stable and the prescribed performance is guaranteed.

Proof Consider the following Lyapunov candidate \( V_2 = \frac{1}{2} \Sigma_i^T \sigma_i \) and the derivative of \( V_2 \) along time is

\[ \dot{V}_2 \leq - \sum_{i=1}^{n} \sigma_i \Sigma_i (\dot{e}_i^{-1}) \left( h_1 \arctan(|\sigma_i|) |\sigma_i| + h_2 \arctan(|\sigma_i|) |\sigma_i| \right) \]
\[ + \Sigma_i (\dot{e}_i^{-1}) - \frac{q_1}{p_1} \xi_i \dot{\xi}_i^{-1} \Pi_i \mu_i \xi_i \]
\[ - \frac{q_1}{p_1} \xi_i \dot{\xi}_i^{-1} \Pi_i \mu_i \xi_i \]
\[ \leq - \sum_{i=1}^{n} \sigma_i \Sigma_i (\dot{e}_i^{-1}) \left( h_1 \arctan(|\sigma_i|) |\sigma_i| + h_2 \arctan(|\sigma_i|) |\sigma_i| \right) \]
\[ + \Sigma_i (\dot{e}_i^{-1}) - \frac{q_1}{p_1} \xi_i \dot{\xi}_i^{-1} \Pi_i \mu_i \xi_i \]
\[ \leq - \sum_{i=1}^{n} \sigma_i \Sigma_i (\dot{e}_i^{-1}) \left( h_1 \arctan(|\sigma_i|) |\sigma_i| + h_2 \arctan(|\sigma_i|) |\sigma_i| \right) \]
\[ + \Sigma_i (\dot{e}_i^{-1}) - \frac{q_1}{p_1} \xi_i \dot{\xi}_i^{-1} \Pi_i \mu_i \xi_i \]
\[ \leq - \sum_{i=1}^{n} \sigma_i \Sigma_i (\dot{e}_i^{-1}) \left( h_1 \arctan(|\sigma_i|) |\sigma_i| + h_2 \arctan(|\sigma_i|) |\sigma_i| \right) \]
\[ + \Sigma_i (\dot{e}_i^{-1}) - \frac{q_1}{p_1} \xi_i \dot{\xi}_i^{-1} \Pi_i \mu_i \xi_i \]
\[ \leq - \sum_{i=1}^{n} \sigma_i \Sigma_i (\dot{e}_i^{-1}) \left( h_1 \arctan(|\sigma_i|) |\sigma_i| + h_2 \arctan(|\sigma_i|) |\sigma_i| \right) \]
\[ + \Sigma_i (\dot{e}_i^{-1}) - \frac{q_1}{p_1} \xi_i \dot{\xi}_i^{-1} \Pi_i \mu_i \xi_i \]
\[ \leq - \sum_{i=1}^{n} \sigma_i \Sigma_i (\dot{e}_i^{-1}) \left( h_1 \arctan(|\sigma_i|) |\sigma_i| + h_2 \arctan(|\sigma_i|) |\sigma_i| \right) \]
\[ + \Sigma_i (\dot{e}_i^{-1}) - \frac{q_1}{p_1} \xi_i \dot{\xi}_i^{-1} \Pi_i \mu_i \xi_i \]
\[ \leq - \sum_{i=1}^{n} \sigma_i \Sigma_i (\dot{e}_i^{-1}) \left( h_1 \arctan(|\sigma_i|) |\sigma_i| + h_2 \arctan(|\sigma_i|) |\sigma_i| \right) \]
\[ + \Sigma_i (\dot{e}_i^{-1}) - \frac{q_1}{p_1} \xi_i \dot{\xi}_i^{-1} \Pi_i \mu_i \xi_i \]
\[ \leq - \sum_{i=1}^{n} \sigma_i \Sigma_i (\dot{e}_i^{-1}) \left( h_1 \arctan(|\sigma_i|) |\sigma_i| + h_2 \arctan(|\sigma_i|) |\sigma_i| \right) \]

The designed observer ensures that the disturbance estimation error converges to zero in finite time, which means that the estimation error is bounded in the convergence process. In (22), \( \arctan(\cdot), \Sigma_i (\dot{e}_i^{-1}) \) are bounded functions, and according to \( |x_{1i}| < \varepsilon_i \mu_i (t) \), it guarantees that the functions \( \sigma_i, \dot{\sigma}_i, \dot{\sigma}_i, \Pi_i, \mu_i \) are continuous and bounded in finite time. These conditions guarantee the boundedness of \( V_2 \) in the estimation error convergence process, which means that the
sliding variable won’t go to infinity. When the estimation error converges to the equilibrium point, it means \( \dot{\xi}_i = 0 \) and (22) is transformed to

\[
\dot{V}_2 \leq -\sum_{i=1}^{n} \zeta_i \left( \dot{e}_i^{\|}\right)^{1/2} \left( h_1 \arctan(|\sigma_{si}|) |\sigma_{si}|^{m_1+q_1}/n_1 \right)
+ h_2 \arctan(|\sigma_{si}|) |\sigma_{si}|^{p_1+q_1}/q_1 \right).
\]

For \(|\sigma_{si}(0)| \geq 1\) and combining the conclusion in Lemma 1, there exists \( \zeta_{i_{1}} \left( \dot{e}_i^{\|}\right)^{1/2} \). Thus (23) is \( \dot{V}_2 \leq -\sum_{i=1}^{n} \left( \arctan(1) h_1 |\sigma_{si}|^{m_1+q_1}/n_1 \right. + h_2 \arctan(1) h_2 |\sigma_{si}|^{p_1+q_1}/q_1 \right). \) Following Lemma 1, \( \sigma_{si} \) converges to the region \( \Delta \equiv \{ \sigma_{si}| |\sigma_{si}| \leq 1\} \) in fixed time and (23) is written as

\[
\dot{V}_2 \leq -\sum_{i=1}^{n} \zeta_i \left( \dot{e}_i^{\|}\right)^{1/2} \left( h_1 \arctan(1) |\sigma_{si}|^{m_1+2q_1}/n_1 \right)
+ h_2 \arctan(1) |\sigma_{si}|^{p_1+2q_1}/q_1 \right),
\]

if there still holds \( \zeta_{i_{1}} \left( \dot{e}_i^{\|}\right)^{1/2} > \epsilon \), then \( \sigma_{si} \) will continue converge to a region which we define as \( \Delta_3 \). Until \( \dot{\sigma}_{si}^{\|} \leq \epsilon \) establishes, there exists \( \zeta_{i_{1}} \left( \dot{e}_i^{\|}\right)^{1/2} > 0 \) with \( q_1, p_1 \) being odd integers, and then \( \sigma_{si} \) will converge to the equilibrium point.

In the convergence process, a special case need to be considered. When \( e_i \neq 0, \dot{e}_i = 0 \), it should be discussed whether this point is an attractor.

If \( \dot{e}_i \rightarrow 0 \), with the fact of \( \sin(x) \approx x \), \( x \approx 1/x \), it follows from (18) and (21) that

\[
\ddot{e}_i = \Pi_1 \sum_{i \neq j} \dot{\xi}_i - \frac{P_1 q_1}{q_1} \left( h_1 \arctan(|\sigma_{si}|) \sin^{n_1}/q_1 |\sigma_{si}| \right)
+ h_2 \arctan(|\sigma_{si}|) |\sigma_{si}|^{p_1+q_1}/q_1 \right),
\]

because of \(|\sigma_{si}| \geq 1\), it is obvious that \( \dot{e}_i \neq 0 \). Thus \( \dot{e} = 0 \) won’t obstruct the convergence of \( \sigma_{si} \) and it is not an attractor.

After reaching the region of the sliding surface, according to (19) and Lemma 2, the sliding motion is

\[
\dot{e}_i = -\rho_1 \arctan(|e_i|) \sin^{n_1}/q_1 \left( e_i \right) - \rho_2 \arctan(|e_i|) \sin^{p_1+q_1}/q_1 \left( e_i \right) + \Delta_3,
\]

then \( e \) and \( \dot{e} \) converge to the region of the equilibrium point in finite time. Then considering that \( e_i, \dot{e}_i \) are transformed from \( R(e_i) = \frac{e_i - e_i^\Delta}{x_i + x_i^\Delta} \) and the original system states satisfy \( x_i = R(e_i) \mu_i(t) \). Then it is obvious that with the convergence of \( e_i, x_i \) also converges in finite time.

This completes the proof. \( \square \)

Remark 3 The term \( \zeta_{i_{1}}(\cdot) \) in controller \( \tau \) is designed for solving the singularity problem. The bound \( \epsilon \) is supposed to be small so that when \(|\sigma_{si}(0)| \geq 1\), \( \zeta_{i_{1}} \left( \dot{e}_i^{\|}\right)^{1/2} = 1 \) always holds until it converges to \( \Delta_2 \). After that, the convergence process still continues until \( \dot{\sigma}_{si}^{\|} \leq \epsilon \) and at this time, \( \sigma_{si} \) converges into \( \Delta_3 \), which is the finite-time convergence region.

4 Simulation

In this section, to validate the effectiveness of the proposed control strategy, numerical simulations based on a two-DOF robot manipulator are derived. Detailed model variables of the robot manipulator system reference to [26] and the parameters are given in Table 1.

| Parameter | Value |
|-----------|-------|
| \( m_1 \) (kg) | 0.5 |
| \( m_2 \) (kg) | 1.5 |
| \( m_{10} \) (kg) | 0.4 |
| \( l_1 \) (m) | 1 |
| \( J_1 \) (kg m) | 5 |
| \( J_2 \) (kg m) | 5 |

where \( m_{10}, m_{20} \) are the nominal values. The predefined trajectory is set as: \( q_{d1} = 1.25 - 7/5 \exp(-t) + 7/20 \exp(-4t) \); \( q_{d2} = 1.25 + \exp(-t) - 1/4 \exp(-4t) \) and the initial conditions of the system states are given as: \( q_1 = 0.5, q_2 = 1.5 \). To verify the robustness of
the control method, a sinusoidal signal disturbance is presented: \( d = [10 \sin(t) + \sin(2\pi t); 8 \cos(2t) + \sin(2\pi t)] \). The parameters of the proposed control strategy are given in Table 2.

To validate the advantages of fast convergence and robustness, the finite-time terminal sliding mode control scheme given in [26] and the integral sliding mode control proposed in [27] are employed to compare with the proposed control strategy. To ensure the accuracy of the comparison simulation, the initial value and the external disturbance are selected as the same one. The finite-time terminal sliding mode control scheme is set as follows:

\[
\begin{align*}
\sigma_c &= e + \beta \text{sign}^{d}(\dot{e}) \\
\tau_c &= G_0 + C_0 \dot{q} + M_0 \dot{q} - M_0 \dot{\dot{\xi}} - \frac{1}{\beta \alpha} |\dot{e}|^{1-\alpha} \Pi^{-1} \gamma^{-1} M_0 \dot{\dot{\xi}} \\
&- \frac{M_0}{\Pi \gamma} (\Pi x_2 \gamma - \Pi \hat{r} x_1 - \Pi \hat{y} x_1) \\
&+ \frac{1}{\beta \alpha} |\dot{e}|^{1-\alpha} \Pi^{-1} \gamma^{-1} M_0 (-h_1 \sigma_c - h_2 \text{sign}^{0.5}(\sigma_c)),
\end{align*}
\]

(24)

where \( \beta = 2, \alpha = 0.9 \) and the controllers gains are: \( h_1 = 10, h_2 = 10 \). The integral sliding mode controller is set as follows:

\[
\begin{align*}
\dot{s} &= \dot{e} + \int_0^t (K_2 \text{sign}^{d_2}(\dot{e}(\sigma)) + K_1 \text{sign}^{d_1}(e(\sigma)))d\sigma \\
\tau &= \tau_0 + \tau_{eq} + \tau_r \\
\tau_0 &= M_0 \dot{q} + C_0 (q, \dot{q}) \dot{q} + g_0(q) \\
\tau_{eq} &= -M_0 (K_2 \text{sign}^{d_2}(\dot{e}) + K_1 \text{sign}^{d_1}(e)) \\
\tau_r &= \frac{s}{\|s\|}
\end{align*}
\]

The sliding surface is depicted in Fig. 4 from which we can see that the designed chattering-reduced reaching law is reacted and the system states reach the sliding surface quickly, and the reaching time can be reduced by adjusting the parameters. Figure 5 describes the variation trend of adaptive parameters. Considering the given sinusoidal external disturbance and the presence

![Fig. 1](image1.png)  
![Table 2](image2.png)
of unmodeled dynamics of the system, the designed adaptive law can accurately estimate the first derivative of the lumped uncertainties and compensate in the observer under the condition that the exact information of the uncertainties is unknown, thus ensuring the estimation accuracy of the observer.

In order to verify the effectiveness and the estimation accuracy, the sliding mode disturbance observer in [17] is used to compare with the proposed observer.

\[
\begin{align*}
    s &= \dot{q} - \eta \\
    \dot{\eta} &= M_0^{-1}(q)(\tau + \dot{d} + \lambda_0 s + \lambda_1 \text{sgn}(s) \\
    &- G_0(q) - C_0(q, \dot{q})\dot{q}) \\
    \dot{d} &= \dot{\xi} + \lambda_2 M_0(q)\dot{q} \\
    \dot{\xi} &= \lambda_2(G_0(q) + C_0(q, \dot{q})\dot{q} - \dot{M}_0(q)\dot{q} - \tau - \dot{d}) \\
    &+ (\dot{\beta} + \lambda_3)\text{sgn}(s) \\
    \dot{\beta} &= -\delta_0\dot{\beta} + 2\|\lambda_1 \text{sgn}(s)\| \\
    \dot{\xi}_1 &= M_0^{-1}\dot{d}
\end{align*}
\]

where $\dot{\xi}_1$ is the estimation value, and to ensure fairness, the same observer gains are selected, i.e. $\lambda_2 = 20, \lambda_3 = 20$. 
The comparison estimation values curves of ASMDO in reference [17] and the proposed ASMDO.

Figure 6 shows the comparison curves of the two different kinds of adaptive sliding mode observers. From the zoomed part of Fig. 6, it is obvious to see that aiming at the fast time-varying disturbance, the proposed observer has a better estimate performance which can quickly track the changing uncertainty and the estimation precision is higher.

5 Conclusion

In this paper, a novel adaptive sliding mode disturbance observer-based composite control is addressed to solve the trajectory tracking problem for robot manipulator system subjects to lumped uncertainties. Firstly, the finite-time adaptive sliding mode disturbance observer is designed without the uncertainty’s prior information and the uncertainty is accurately estimated. After that, the composite control strategy guarantees the finite-time convergence of the system trajectory tracking errors and the transient and steady-state performance are constrained by prescribed performance. Finally, simulations validated the effectiveness of the proposed composite control scheme.

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Data availability The authors declare that the data supporting the results of this study are available within the article.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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