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Optimal Joint Space Control of a Cable-Driven Aerial Manipulator

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ABSTRACT

This article proposes a novel method for maintaining the trajectory of an aerial manipulator by utilizing a fast nonsingular terminal sliding mode (FNTSM) manifold and a linear extended state observer (LESO). The developed control method applies an FNTSM to ensure the tracking performance's control accuracy, and an LESO to estimate the system's unmodeled dynamics and external disturbances. Additionally, an improved salp swarm algorithm (ISSA) is employed to parameter tune the suggested controller by integrating the salp swarm technique with a cloud model. This approach also uses a model-free scheme to reduce the complexity of controller design without relying on complex and precise dynamics models. The simulation results show that the proposed controller outperforms linear active rejection disturbance control and PID controllers in terms of transient performance and resilience against lumped disturbances, and the ISSA can help the proposed controller find optimal control parameters.

KEYWORDS

Aerial manipulator; cable-driven; robust control; linear extend state observer; salp swarm algorithm

Nomenclature

ξ	Generalized coordinates
χ	Position vector
Θ	Euler angles
m_A	Quadrotor's mass
I_A	Rotational inertia
U	Generalized forces and torques
τ_M	Moment produced by a propeller
k_m	Torque coefficient
q	Vector of the joint position
M	Inertia matrix of links
G	Gravitational term of links
J	Inertial matrix of motors
u	Output torques of motors
K_d	Joint stiffness matrix



N	Lumped disturbances
T_t	Translational energy
T_r	Rotational kinetic energy
P	Potential energy
Ω	Angular velocity
g	Gravitational acceleration
f_M	Force produced by a propeller
k_t	Thrust coefficient
$C(\Theta, \dot{\Theta})$	Coriolis term of the quadrotor
q_j	Vector of the motor position
C	Centrifugal and Coriolis forces term of links
τ_{ext}	Disturbance torque term of links
D	Damping matrix of motors
K_s	Joint damping matrix
\bar{M}	Diagonal gain matrix

1 Introduction

As special robot systems, unmanned aerial vehicles (UAVs) have the characteristics of simple structure, convenient operation and flexible manoeuvring, and are widely used in aerial work tasks, such as aerial photography mapping, power inspection, and battlefield reconnaissance [1,2]. Most existing UAVs can only perform passive monitoring tasks and cannot actively interact with their environment. To this end, the researchers added a multi-degree-of-freedom (multi-DOF) manipulator or gripper to the UAV to form a novel aerial robot system, which is the so-called aerial manipulator. Aerial manipulators obviously broaden mobile manipulations into three dimensions, allowing for novel applications, such as remote sampling [3], aerial grasp [4], bridge inspection [5], and cooperative aerial manipulation [6]. At present, most aerial manipulators currently use rigid manipulators, whose large moment of inertia will exacerbate the coupling effect between the manipulator and the UAV, making it difficult to maintain the pose of the system. To solve the above issues, cable-driven technique is implemented in the manipulator's physical structure, which rearranges the drive modules and utilizes cables to transmit torques and forces remotely. Due to their lower inertia, greater flexibility, and lighter mass, cable-driven mechanisms can enhance operational capabilities and increase flight time [7,8]. Aerial manipulator motion control is a well-studied but challenging topic. Robotic manipulators are closely coupled to UAVs, so controller design should take these into account. It is essential that the controller also be capable of handling the forces that result from interactions with the external environment. Furthermore, the flexible driving cable will also reduce the overall stiffness of the aerial manipulator, making it highly susceptible to external disturbances and its own internal vibrations. Therefore it is critical to develop a high-performance controller capable of controlling the cable-driven aerial manipulator's high-precision aerial operations.

At present, many approaches for motion control of aerial manipulators have been presented in the literatures, such as adaptive control strategy [9], backstepping control method [10], active disturbance rejection control [11], and proportion integration differentiation (PID) [12]. Kim et al. [13] proposed a robust control approach termed sliding mode control (SMC) for tracking the aerial manipulator's trajectories in joint space while taking uncertainties and disturbances into account. SMC is widely used in nonlinear systems due to its various advantages, including little sensitivity to changes in system parameters and no requirement for accurate modelling. The design of the sliding mode (SM) surface is critical in SMC since it affects the controller's convergence speed and tracking precision. Then,

terminal SMC (TSMC) and fast terminal SMC (FTSMC) approaches have been presented to assure the asymptotic convergence rate of SMC in a finite period [14]. However, FTSMC suffers from a singularity problem which may generate terms with a negative power index. In order to eliminate the singularity, a fast nonsingular terminal SMC (FNTSMC) has been developed [15]. Thanks to its superior properties, FNTSMC is becoming increasingly popular in engineering applications, such as industrial manipulator [16], permanent magnet synchronous motor servo system [17], and flexible spacecraft [18]. Unfortunately, the FNTSMC is not robust to parametric uncertainties as well as external disturbances, resulting in relatively poor dynamic features and lower control precision. In [19], a disturbance observer (DOB) technique has been combined with SMC, which achieves a good performance in quadrotor motion control. Chen et al. [20] designed a nonlinear DOB for unknown information based on Lyapunov theory and adopted it to a 2-DOF manipulator. DOB is characterized by the estimation of unknown disturbances at the system input. Therefore, it needs detailed information of the plant and cannot estimate the uncertainty within the system. Unlike DOB, ESO estimates the external disturbances and internal uncertainties of the system as an extended state and requires little model information. The ESO is available in two configurations, nonlinear ESO (NESO) and linear ESO (LESO). Chang et al. integrate a fuzzy sliding mode technique with NESO to develop a controller for an aerial manipulator subjected to lumped disturbances, which can hold the pose of system well [21]. However, NDOB has a lot of parameters to be determined, which will increase the difficulty of controller design. Compared to NESO, the performance of LESO is governed by only two parameters, observer bandwidth and controller bandwidth. LESO is often combined into existing control methods which can be found in previous works [22,23]. Inspired by these works, this article will combine FNTSMC with LESO (FNTSMC-LESO) to realize the trajectory tracking control in joint space for a cable-driven aerial manipulator.

As is widely known, controller parameters tuning is a challenging task [24], especially since the FNTSMC-LESO has four parameters to be tuned. This means that the suggested controller's parameters are regarded to be an optimized mathematical entity since the index is set to a minimum value. High-quality control effects are defined as minimizing the controller index. Our objective is to build a performance evaluation metric that accurately reflects the controller's performance. In general, the controller parameters are tuned in time domain by metaheuristic algorithms, such as particle swarm optimization (PSO) [25], artificial bee colony algorithm (ABC) [26], genetic algorithm (GA) [27], firefly algorithm (FA) [28], salp swarm algorithm (SSA) [29]. We focus exclusively on SSA in this paper due to its great robustness, simple parameters, and ease of implementation. SSA is an effective optimization algorithm developed in 2017 [30], which is fit for parameter tuning of the FNTSMC-LESO method. Unfortunately, standard SSA tends to fall into local optima, as well as most swarm intelligence algorithms, resulting in slower convergence in the later stages of the algorithm. Therefore, cloud model has been adopted in this article, which helps SSA achieve better performance. Furthermore, the improved SSA (ISSA) will be used to find appropriate control parameters for the proposed controller FNTSMC-LESO. The following summarizes the major contributions and aspects of this work:

- 1) A novel cable-driven aerial manipulator mounted on a quadrotor has been designed. Compared with existing works [31–34], the aerial manipulator system uses the cable-driven technique for transmitting forces and torques by rearrangement of drive modules. Due to lower inertia, greater flexibility, and lighter mass, cable-driven mechanisms can improve operational capabilities and increase flight time.
- 2) To achieve trajectory tracking accuracy in joint space, a fast nonsingular terminal sliding mode control is used to assure tracking accuracy and convergence speed. Additionally, the lumped

disturbances are estimated utilizing linear extended state observer. To our knowledge, there are no published reports on the FNFTSMC-LESO approach for cable-driven aerial manipulator.

- 3) A novel combination of SSA with cloud model, namely ISSA has been proposed for parameter tuning of the FNFTSMC-LESO. The performance of the optimized algorithm is compared with two other algorithms in terms of transient response analysis in time domain adopting the objective function of integral of time multiplied by absolute error (ITAE) performance index.

This article's outline is as follows. [Section 2](#) discusses the system modeling of aerial robots, including quadrotor dynamics and cable-driven manipulator dynamics. [Section 3](#) discusses the design process of the FNFTSMC-LESO method. Meanwhile, the suggested robust controller's stability study has been presented. Additionally, [Section 4](#) illustrates how to tune the proposed controller's settings using the enhance salp swarm method. [Section 5](#) contains the suggested controller's simulation findings and compares the alternative alternatives. Finally, [Section 6](#) summarizes some conclusions.

2 Mathematical Model

Consider the schematic view of a cable-driven aerial manipulator in [Fig. 1](#), where $\{I\}$ represents an inertial coordinate frame, $\{B\}$ denotes a body coordinate frame which is attached to the center of mass of the quadrotor, $\{1\}$ and $\{2\}$ are the frame attached to the joints of the manipulator, and $\{e\}$ denotes the end-effector's coordinate frame. The use of cable-driven technology, in particular, enables the drive unit to be located at the base of the manipulator, significantly simplifying the construction and lowering the quality of the robot arm's moving components.

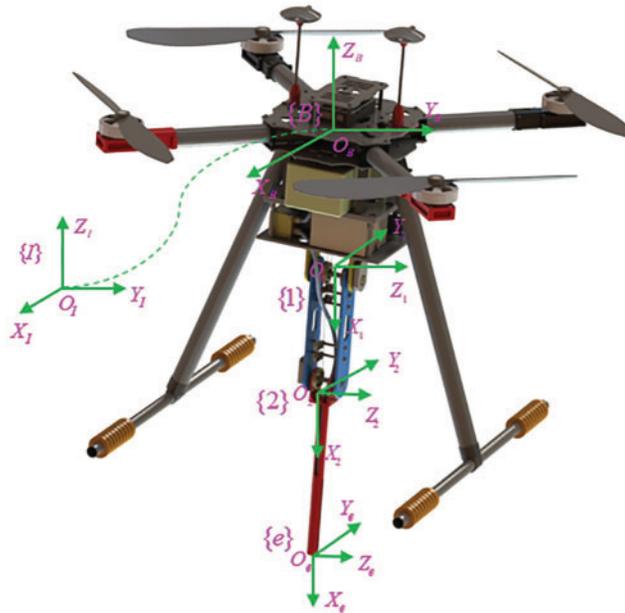


Figure 1: Schematic view of our prototype

Remark 1. In our work, the quadrotor and its manipulator are treated as two separate systems since the CAM works in hover [35]. In that case, the coupling effects between these two systems are considered as unmodeled features. As a result, the dynamics models for the quadrotor and the manipulator are independent, respectively.

2.1 Dynamics Model of a Quadrotor

The quadrotor model is constructed by describing the aircraft as a rigid body developing in three dimensions and subject to the main thrust and three torques. Its dynamics model can be deduced through Lagrangian approach [36]. Consider the generalized coordinates of the quadrotor stated by:

$$\xi = [x, y, z, \psi, \theta, \phi]^T \tag{1}$$

where $\chi = [x, y, z]^T$ is the position vector of the quadrotor relative to the frame $\{I\}$, $\Theta = [\psi, \theta, \phi]^T$ is the vector of Euler angles relative to the frame $\{B\}$. ψ , θ and ϕ are yaw angle of rotation about the axis Z_B , pitch angle of rotation about the axis Y_B , and roll angle of rotation about the axis X_B , respectively.

Let the Lagrangian formula [37] be expressed by:

$$L(\xi, \dot{\xi}) = T_t + T_r - P \tag{2}$$

where $T_t = \frac{1}{2}m_A\dot{\chi}^T\dot{\chi}$ and $T_r = \frac{1}{2}\Omega I_A \Omega$ denote the translational energy and rotational kinetic energy, respectively. $P = m_A g$ is the potential energy. m_A denotes the quadrotor’s mass, Ω denotes the vector of angular velocity, $I_A = \text{diag}(I_{xx}, I_{yy}, I_{zz})$ is the rotational inertia, g is the gravitational acceleration.

The relation between the angular speed Ω and the angular speed relative to the frame $\{B\}$ is expressed by a typical kinematic formula [38,39]:

$$\Omega = \begin{bmatrix} \dot{\phi} - \dot{\psi} \sin \theta \\ \dot{\theta} \cos \phi + \dot{\psi} \cos \theta \sin \phi \\ \dot{\psi} \cos \theta \cos \phi - \dot{\theta} \sin \phi \end{bmatrix} \tag{3}$$

The rotational kinetic energy T_r is expressed by:

$$T_r = \frac{1}{2}\dot{\Theta}^T J_A \dot{\Theta} \tag{4}$$

where $J_A = \Omega^T (\dot{\Theta}^{-1})^T I_A \dot{\Theta}^{-1} \Omega$ is the inertia matrix for the quadrotor’s full rotational kinetic energy described in generalized coordinates Θ . $\dot{\Theta}$ is the vector of the angular velocity of Euler angles.

Recalling Eq. (2), the quadrotor dynamics can be derived from Euler–Lagrange method with generalized forces, which is expressed as:

$$\frac{d}{dt} \left(\frac{\partial L}{\partial \dot{\xi}} \right) - \frac{\partial L}{\partial \xi} = U \tag{5}$$

where U are the generalized forces and torques. It can be expressed as:

$$U = \begin{bmatrix} \hat{F} \\ \tau_A \end{bmatrix} = \begin{bmatrix} \hat{F} \\ \sum_{i=1}^4 \tau_{M_i} \\ (f_{M2} - f_{M4})l \\ (f_{M3} - f_{M1})l \end{bmatrix} = \begin{bmatrix} U_{q1} \\ U_{q2} \\ U_{q3} \\ U_{q4} \end{bmatrix} \tag{6}$$

where f_{M_i} and τ_{M_i} ($i = 1, 2, 3, 4$) denote the force and moment generated by a propeller’s motor, l represents the distance between the center of gravity of the quadrotor and the propeller’s center, τ_A is generalized torques, U_{q_i} ($i = 1, 2, 3, 4$) denotes the control commands. \hat{F} is the main thrust relative to

the frame $\{B\}$ and described as:

$$\hat{\mathbf{F}} = R_{IB} \begin{bmatrix} 0 \\ 0 \\ U_{q1} \end{bmatrix} = \begin{bmatrix} \cos \theta \cos \psi & \sin \phi \sin \theta \cos \psi - \cos \phi \sin \psi & \cos \phi \sin \theta \cos \psi + \sin \phi \sin \psi \\ \cos \theta \sin \psi & \sin \phi \sin \theta \sin \psi + \cos \phi \cos \psi & \cos \phi \sin \theta \sin \psi - \sin \phi \cos \psi \\ -\sin \theta & \sin \phi \cos \theta & \cos \phi \cos \theta \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ U_{q1} \end{bmatrix} \quad (7)$$

where R_{IB} is the quadrotor's orientation relative to the frame $\{I\}$.

The control commands are relative to the rotational velocity of the propeller by means of the standard relationship [40–42]:

$$\begin{bmatrix} U_{q1} \\ U_{q2} \\ U_{q3} \\ U_{q4} \end{bmatrix} = \begin{bmatrix} k_t & k_t & k_t & k_t \\ \frac{\sqrt{2}}{2}k_t l & -\frac{\sqrt{2}}{2}k_t l & -\frac{\sqrt{2}}{2}k_t l & \frac{\sqrt{2}}{2}k_t l \\ \frac{\sqrt{2}}{2}k_t l & \frac{\sqrt{2}}{2}k_t l & -\frac{\sqrt{2}}{2}k_t l & -\frac{\sqrt{2}}{2}k_t l \\ -k_m & k_m & -k_m & k_m \end{bmatrix} \begin{bmatrix} \omega_1^2 \\ \omega_2^2 \\ \omega_3^2 \\ \omega_4^2 \end{bmatrix} \quad (8)$$

where k_t is thrust coefficient, k_m is torque coefficient, $\omega_i (i = 1, 2, 3, 4)$ represents the propeller's rotational speed.

Integrating Eqs. (5)–(7), the full quadrotor dynamics model is described as:

$$\begin{cases} m_A \ddot{\chi} + m_A g = \hat{\mathbf{F}} \\ \ddot{\Theta} = \tau_A - C(\Theta, \dot{\Theta})\dot{\Theta} \end{cases} \quad (9)$$

where $C(\Theta, \dot{\Theta})$ is the quadrotor's Coriolis and centrifugal term.

Considering the lumped disturbances, the system (9) is rearranged as:

$$\begin{cases} \ddot{x} = (\sin \theta \cos \psi \cos \phi + \sin \psi \sin \phi) U_1 / m_{A1} \\ \ddot{y} = (\sin \theta \sin \psi \cos \phi - \cos \psi \sin \phi) U_1 / m_A \\ \ddot{z} = \cos \theta \cos \phi U_1 / m_A - g \\ \ddot{\phi} = [(I_{yy} - I_{zz})\dot{\psi}\dot{\theta} + U_{q2}] / I_{xx} \\ \ddot{\theta} = [(I_{zz} - I_{xx})\dot{\psi}\dot{\phi} + U_{q3}] / I_{yy} \\ \ddot{\psi} = [(I_{xx} - I_{yy})\dot{\phi}\dot{\theta} + U_{q4}] / I_{zz} \end{cases} \quad (10)$$

Remark 2. An aerial manipulator's trajectory tracking control in joint space is the purpose of this study. The quadrotor just acts as an aerial platform, which can be controlled using the traditional PID method. Hence, the design process of the quadrotor controller is no longer discussed.

2.2 Dynamics Model of a Manipulator

Remark 3. Cable flexibility can be concentrated at the joints when ignoring the mass and rotational inertia of the cable. In that case, the force and moment of the joint are linearly related to the joint flexibility. The flexible joint is considered as a linear spring [43,44].

The rigid-flexible coupling dynamics model of the cable-driven manipulator is obtained by Lagrange-Euler formula [45]:

$$M\ddot{q} + C\dot{q} + G + \tau_{ext} = K_s(q_j - q) + K_d(\dot{q}_j - \dot{q}) \quad (11)$$

$$J\ddot{q}_j + D\dot{q}_j + K_s(q_j - q) + K_d(\dot{q}_j - \dot{q}) = u \quad (12)$$

where $q = [q_1, q_2]^T$ denotes joint position, $\dot{q} = [\dot{q}_1, \dot{q}_2]^T$ denotes joint speed, $\ddot{q} = [\ddot{q}_1, \ddot{q}_2]^T$ denotes joint acceleration. Similarly, q_j , \dot{q}_j , and \ddot{q}_j represent the position, speed and acceleration of the two motors, respectively. The inertia matrix, centrifugal and Coriolis forces terms, gravitational term, and disturbance torque term of links are denoted by the symbols M , C , G , and τ_{ext} , respectively. J , D , and u are inertial matrix, damping matrix, and output torque of motors, respectively. K_s and K_d denote joint's damping matrix and stiffness matrix, respectively.

Associating Eqs. (11) and (12), the dynamical model of the cable-driven aerial manipulator driven by motors is obtained by:

$$M\ddot{q} + C\dot{q} + G + J\ddot{q}_j + D\dot{q}_j + \tau_{ext} = u \quad (13)$$

In practice, accurate model information for the aerial manipulator is generally poorly available. Hence, a diagonal gain matrix \bar{M} is introduced to estimate the unknown nonlinear behavior [46], and Eq. (13) is rewritten as:

$$u = \bar{M}\ddot{q} + N \quad (14)$$

where $N = (M - \bar{M})\ddot{q} + C\dot{q} + G + J\ddot{q}_j + D\dot{q}_j + \tau_{ext}$ denotes the lumped disturbances consisting of unmodeled features and external disturbances.

3 Controller Design

Since the lumped disturbances in system (14) is strongly couplings and highly nonlinear, traditional techniques may be difficult for obtaining it. For solving this problem, a LESO technique is applied in the scheme of our proposed controller.

Remark 4. Despite the fact that the proposed controller requires little information of the dynamics model, the controller design process still needs to be described with the model.

The controller design is the same for each loop in that it needs no precise details of the numerical model and instead depends on the loop's input and output data. We use joint 1 q_1 as an example to determine the suggested controller's design procedure.

3.1 LESO Design

Recalling system (14), the dynamical model of joint 1 can be rewritten as:

$$\begin{cases} \ddot{q}_1 = \bar{M}_1^{-1}(u_1 - N_1) \\ y_1 = q_1 \end{cases} \quad (15)$$

where y_1 is the output.

The state-space form of Eq. (15) can be described as:

$$\begin{cases} \dot{x}_1 = A_1x_1 + B_1u_1 + E_1f_1 \\ y_1 = C_1x_1 \end{cases} \quad (16)$$

where $\mathbf{x}_1 = [q_1, \dot{q}_1]^T$, $\mathbf{u}_1 = u_1$, $\mathbf{y}_1 = y_1$, $\mathbf{f}_1 = -\bar{M}_1^{-1}N_1$, $\mathbf{A}_1 = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}$, $\mathbf{B}_1 = \begin{bmatrix} 0 \\ \bar{M}_1^{-1} \end{bmatrix}$, $\mathbf{E}_1 = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$, $\mathbf{C}_1 = \begin{bmatrix} 1 \\ 0 \end{bmatrix}^T$.

Remark 5. In practice, the lumped disturbances N_1 is differentiable and derivable. That means $\|N_1\| < \infty$, $\|\dot{N}_1\| < \infty$ with the bounds that $\sup_{t>0} \|N_1\| = N_b$, $\sup_{t>0} \|\dot{N}_1\| = n_b$.

With Remark 5, We use an extra extended state to express it. Furthermore, Eq. (16) is rewritten as:

$$\begin{cases} \dot{\bar{\mathbf{z}}}_1 = \bar{\mathbf{A}}_1 \bar{\mathbf{z}}_1 + \bar{\mathbf{B}}_1 \mathbf{u}_1 + \bar{\mathbf{E}}_1 \mathbf{h}_1 \\ \mathbf{y}_1 = \bar{\mathbf{C}}_1 \bar{\mathbf{z}}_1 \end{cases} \tag{17}$$

where $\bar{\mathbf{z}}_1 = [q_1, \dot{q}_1, x_3]^T$, $\mathbf{h}_1 = \dot{\mathbf{f}}_1$, $x_3 = -\bar{M}_1^{-1}N_1$, $\bar{\mathbf{A}}_1 = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}$, $\bar{\mathbf{B}}_1 = \begin{bmatrix} 0 \\ \bar{M}_1^{-1} \\ 0 \end{bmatrix}$,

$$\bar{\mathbf{E}}_1 = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}, \bar{\mathbf{C}}_1 = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}^T.$$

The LESO of system (17) is as follows:

$$\begin{cases} \dot{\hat{\mathbf{z}}}_1 = \mathbf{A}_1 \hat{\mathbf{z}}_1 + \mathbf{B}_1 \mathbf{u}_1 + \mathbf{L}_1 (\mathbf{y}_1 - \hat{\mathbf{y}}_1) \\ \hat{\mathbf{y}}_1 = \mathbf{C}_1 \hat{\mathbf{z}}_1 \end{cases} \tag{18}$$

where $\hat{\mathbf{z}}_1 = [\hat{q}_1, \hat{q}_1, \hat{x}_3]^T$, $\hat{\mathbf{z}}_1$ is the estimation of $\bar{\mathbf{z}}_1$, $\hat{q}_1, \hat{q}_1, \hat{x}_3$ are state variables, $\hat{\mathbf{y}}_1$ denotes the output, $\mathbf{L}_1 = [\beta_{11}, \beta_{12}, \beta_{13}]^T = [\xi_{11}\omega_{10}, \xi_{2}\omega_{10}, \xi_3\omega_{10}]^T$ is the observer gain vector. $\omega_{10} > 0$ denotes the observer bandwidth, $\varsigma_{1i} (i = 1, 2, 3)$ is selected such that $\lambda(s) = s^3 + \varsigma_{11}s^2 + \varsigma_{12}s + \varsigma_{13}$ is Hurwitz. The coefficient ς_{1i} satisfies:

$$\varsigma_{1i} = \frac{3!}{i!(3-i)!}, i = 1, 2, 3 \tag{19}$$

3.2 NTSM Design

Taking q_1 as an example to illustrate the design process of the NTSM. The tracking errors of the joint position, joint velocity and joint acceleration are defined as $e_1 = q_{1r} - q_1$, $\dot{e}_1 = \dot{q}_{1r} - \dot{q}_1$, and $\ddot{e}_1 = \ddot{q}_{1r} - \ddot{q}_1$, where q_{1r} , \dot{q}_{1r} , and \ddot{q}_{1r} are the referenced joint and its first-order derivative, second-order derivative. For q_1 , the following is the form of a NTSM surface [47]:

$$s_1 = e_1 + \beta_1 |\dot{e}_1|^{\gamma_1} \tanh(\dot{e}_1) = e_1 + \beta_1 \text{sig}(\dot{e}_1)^{\gamma_1} = 0 \tag{20}$$

where $\beta_1 > 0$, $1 < \gamma_1 < 2$ are constants. The symbol $\tanh(\cdot)$ represents the hyperbolic tangent function that effectively reduces chattering.

The first-order derivative of Eq. (20) can be calculated as:

$$\dot{s}_1 = \dot{e}_1 + \beta_1 \gamma_1 |\dot{e}_1|^{\gamma_1-1} \ddot{e}_1 \tag{21}$$

Substituting Eq. (21) into Eq. (14) yields:

$$u_{1e} = \bar{M}_1(\beta_1\gamma_1\text{sig}(\dot{e}_1)^{2-\gamma_1} + \ddot{q}_{1r}) + \hat{x}_3 \quad (22)$$

where u_{1e} is the equivalent input.

Furthermore, a fast terminal sliding mode type is brought as the reaching law in order to decrease chattering and fulfill the need for rapid finite-time convergence.

$$\dot{s}_1 = -k_{11}s_1 - k_{12}\text{sig}(s_1)^{p_1} \quad (23)$$

where $0 < p_1 < 1$, k_{11} and k_{12} are control parameters to be tuned.

With Eq. (23), the reaching control law can be designed as:

$$u_{1r} = k_{11}s_1 + k_{12}\text{sig}(s_1)^{p_1} \quad (24)$$

Combing the equivalent input (22) and reaching control law (24), one gets the integrated control law FNTSMC-LESO of q_1 as:

$$u_1 = u_{1e} + u_{1r} = \bar{M}_1(\beta_1\gamma_1\text{sig}(\dot{e}_1)^{2-\gamma_1} + \ddot{q}_{1r}) + \hat{x}_3 + k_{11}s_1 + k_{12}\text{sig}(s_1)^{p_1} \quad (25)$$

Similarly, the NFTSMC-LESO of q_2 as:

$$u_2 = u_{2e} + u_{2r} = \bar{M}_2(\beta_2\gamma_2\text{sig}(\dot{e}_2)^{2-\gamma_2} + \ddot{q}_{2r}) + \hat{x}_4 + k_{21}s_2 + k_{22}\text{sig}(s_2)^{p_2} \quad (26)$$

where $\beta_2 > 0$, $1 < \gamma_2 < 2$, $0 < p_2 < 1$, \ddot{q}_{2r} is the second derivative of the referenced joint, k_{21} and k_{22} are control parameters to be tuned, \hat{x}_4 is the estimation of N_2 .

3.3 Stability Analysis

The proposed FNTSMC-LESO controller's stability analysis is illustrated by using q_1 as an example.

Taking q_1 as an example to demonstrate the stability analysis of the proposed controller. The stability of the closed-loop system will be analyzed in three steps.

Step 1: Prove the convergence of LESO.

Recalling Eq. (18), the estimation error of the LESO is defined as:

$$e_{1\bar{z}} = \bar{z}_1 - \hat{z}_1 \quad (27)$$

Subtracting Eq. (18) from Eq. (17) yields:

$$\dot{e}_{1\bar{z}} = (\bar{A}_1 - L_1\bar{C}_1)e_{1\bar{z}} - E_1h_1 = A_{1e} - E_1h_1 \quad (28)$$

$$\text{where } A_{1e} = \begin{bmatrix} -\varsigma_{11}\omega_{1o} & 1 & 0 \\ -\varsigma_{12}\omega_{1o}^2 & 0 & 1 \\ -\varsigma_{13}\omega_{1o}^3 & 0 & 0 \end{bmatrix}.$$

A_{1e} contains three distinct eigenvalues. As a result, the following principles apply to an invertible real matrix T_1 :

$$A_{1e} = T_1 \text{diag}(-\lambda_1, -\lambda_2, -\lambda_3) T_1^{-1} \quad (29)$$

Eq. (29) can be rewritten as an exponential form:

$$e_1^{A_{1e}t} = T_1 \text{diag}(e_1^{-\lambda_1 t}, e_1^{-\lambda_2 t}, e_1^{-\lambda_3 t}) T_1^{-1} \quad (30)$$

with it follows that:

$$\|e_1^{A_1 e_1^t}\|_{m_\infty} \leq \varpi n_b e_1^{-\lambda_1 t} \tag{31}$$

where ϖ denotes a weight function. Notice that the m_∞ norm of a square matrix equals the product of the order value and the biggest element.

The solution to Eq. (28) is as follows:

$$e_{1\bar{z}}(t) = e^{A_1 e_1^t} e_{1\bar{z}}(0) + \int_0^t e^{A_1 e_1^{(t-\tau)}} E_1 h_1(\tau) d\tau \tag{32}$$

Under Remark 5, the estimation error (32) is convergent. Additionally, the compatibility of m_∞ norm and vector norm of a complex field yields:

$$\|e_{1\bar{z}}(t)\| \leq \|e^{A_1 e_1^t}\| \|e_{1\bar{z}}(0)\| + \left\| \int_0^t e^{A_1 e_1^{(t-\tau)}} E_1 h_1(\tau) d\tau \right\| \leq \varpi n_b e_1^{-\lambda_1 t} \|e_{1\bar{z}}(0)\| + \frac{\varpi n_b}{\lambda_1} (1 - e_1^{-\lambda_1 t}) \tag{33}$$

where $e_{1\bar{z}}(0)$ denotes the initial value. Since $\lim_{t \rightarrow \infty} e^{-\lambda_1 t} = 0$, the LESO asymptotically converges:

$$\|e_{1\bar{z}}(t)\| \leq \frac{\varpi n_b}{\lambda_1} \tag{34}$$

Remark 6. Assume that the lumped disturbance’s first-order derivative meets $\lim_{t \rightarrow \infty} \|\dot{N}_1\| = \lim_{t \rightarrow \infty} n_b = 0$, the estimation error approaches zero asymptotically, i.e., $\lim_{t \rightarrow \infty} \|e_{1\bar{z}}(t)\| = 0$.

Step 2: Prove the convergence of the NTSM variable s_1 .

Considering a normal Lyapunov function:

$$V_1 = \frac{1}{2} s_1^T s_1 \tag{35}$$

The Lyapunov function’s first-order derivative is given as follows:

$$\dot{V}_1 = s_1^T \dot{s}_1 \tag{36}$$

Combining Eqs. (14),(25) and (36) yields:

$$\dot{V}_1 = \beta_1 \gamma_1 |\dot{e}_1|^{p_1-1} (N_1 - \hat{x}_3) - \bar{k}_{11} s_1^2 - \bar{k}_{12} \text{sig}(s_1)^{p_1+1} \tag{37}$$

With $\bar{k}_{1i} (i = 1, 2)$ follows that:

$$\bar{k}_{1i} = \beta_1 \gamma_1 |\dot{e}_1|^{p_1-1} k_{1i} \tag{38}$$

Furthermore, Eq. (37) can be divided into two forms:

$$\dot{V}_1 = -[\bar{k}_{11} - \beta_1 \gamma_1 |\dot{e}_1|^{p_1-1} (N_1 - \hat{x}_3) s_1^{-1}] s_1^2 - \bar{k}_{12} |s_1|^{p_1+1} \tag{39}$$

$$\dot{V}_1 = -\bar{k}_{11} s_1^2 - [\bar{k}_{12} - \beta_1 \gamma_1 |\dot{e}_1|^{p_1-1} (N_1 - \hat{x}_3) \text{sig}(s_1)^{-p_1}] |s_1|^{p_1+1} \tag{40}$$

Since $\bar{k}_{11} - \beta_1 \gamma_1 |\dot{e}_1|^{p_1-1} (N_1 - \hat{x}_3) s_1^{-1}$ is positive definite, the SM surface will approach a certain area in finite time:

$$\|s_1\| \leq |\beta_1 \gamma_1 |\dot{e}_1|^{p_1-1} (N_1 - \hat{x}_3)| / \bar{k}_{11} = |N_1 - \hat{x}_3| / \bar{k}_{11} = \Delta_1 \tag{41}$$

Similarly, since $\bar{k}_{12} - \beta_1 \gamma_1 |\dot{e}_1|^{\gamma_1 - 1} (N_1 - \hat{x}_3) \text{sig}(s_1)^{-p_1}$ is positive definite, the SM surface will approach another certain area in finite time:

$$\|s_1\| \leq \left[|\beta_1 \gamma_1 |\dot{e}_1|^{\gamma_1 - 1} (N_1 - \hat{x}_3) | / \bar{k}_{12} \right]^{1/p_1} = (|N_1 - \hat{x}_3| / \bar{k}_{12})^{1/p_1} = \Delta_2 \quad (42)$$

Combining Eqs. (41) and (42), the SM surface will converge into the following region in finite time:

$$\|s_1\| \leq \Delta = \min(\Delta_1, \Delta_2) \quad (43)$$

Step 3: Prove the convergence of the tracking error e_1 .

Recalling Eq. (43), the FNTSM surface (20) can be rewritten as following:

$$e_1 + \left(\beta_1 - \frac{s_1}{\text{sig}(\dot{e}_1)^{\gamma_1}} \right) \text{sig}(\dot{e}_1)^{\gamma_1} = 0 \quad (44)$$

Since $\beta_1 - \frac{s_1}{\text{sig}(\dot{e}_1)^{\gamma_1}}$ is positive, Eq. (44) holds the form of NFTSM. The tracking error's first-order derivative will approach the following area:

$$|\dot{e}_1| \leq (\Delta / \beta_1)^{1/\gamma_1} \quad (45)$$

Combining Eqs. (44) and (45) yields:

$$|e_1| \leq \beta_1 |\dot{e}_1|^{\gamma_1} + |s_1| \leq 2\Delta \quad (46)$$

It indicates that the tracking error of joint 1 will asymptotically converge into a region under the proposed control law. Meanwhile, the same results hold true for the channel of joint 2.

4 Parameters Tuning

4.1 Algorithm Principles

In our proposed control structure, the parameters that have less influence on the control performance are treated as a priori and need no adjustment. As a result, $r_1 = r_2 = 1.5$, $p_1 = p_2 = 0.5$. In addition, each joint controller has four parameters to be tuned. There are a total of eight parameters that need to be tuned in the controller for the cable-driven aerial manipulator, i.e., ω_{i0} , β_i , k_{i1} and k_{i2} ($i = 1, 2$). These unknown control parameters will be determined by ISSA method.

According to previous work [48], SSA algorithm is one of metaheuristic algorithms, which is inspired by the navigating and foraging behaviors found in salps in deep oceans. The salps have a body structure that is very similar to that of jellyfish, which follows the same pattern of movement by pumping water through the body as they move forward. The swarming behavior of salps serves as an inspiration for the SSA algorithms, in which the chain of salps is created by a swarm. An individual at the front of each salp chain is referred to as a leader, while others who follow it are known as followers. The followers follow the leaders swarm into the foods. The basic principle of the SSA is described as follows.

The initial position of different salps are defined as $x_i = [x_i^1, x_i^2, \dots, x_i^D]$, where i lies in the range $[1, 2, \dots, N]$, N is the population size, D is the number of the unknown control parameters.

Here the position of food source F_j in the j th dimension ($j = 1, 2, \dots, D$) is considered as the objective function. The objective function established using ITAE performance index, which is

governed by:

$$F_j = \int_0^{T_{\max}} T e^2(T) dT \quad (47)$$

where $e(T)$ is the controller's tracking error, T and T_{\max} are the current iteration and maximum number of iterations, respectively.

The chain of salps is on the prowl for the finest food source in SSA. Thus, the leader's position is updated by:

$$x_1^j = \begin{cases} F_j + c_1 \cdot [(b_{uj} - b_{lj}) \cdot c_2 + b_{lj}], & c_3 \geq 0.5 \\ F_j - c_1 \cdot [(b_{uj} - b_{lj}) \cdot c_2 + b_{lj}], & c_3 < 0.5 \end{cases} \quad (48)$$

where x_1^j denotes the leader's position, b_{uj} and b_{lj} are the upper limit and lower limit of the leader's position in the j th dimension respectively, c_1 and c_2 are the random vectors in the range $[0,1]$, c_3 is the weight factor that can balance the exploration and exploitation tendencies:

$$c_3 = 2e^{-(4T/T_{\max})^2} \quad (49)$$

The position of follower is updated by the Newton equation:

$$x_i^j = 0.5at_a^2 + v_0t_a + x_i^j (i \geq 2) \quad (50)$$

where t_a is step size, v_0 is the initial velocity, $a = (v_{final} - v_0)/t_a$ is the acceleration, $v_{final} = (x_i^{j-1} - x_i^j)/t_a$ is the terminal velocity.

Since $v_0 = 0$, the above Eq. (51) becomes:

$$x_i^j = 0.5(x_i^j + x_i^{j-1}) \quad (51)$$

where $j \geq 2$ and x_i^j denotes the j th follower's position in the j th dimension search space.

The leader changes its position according to food source, and followers keep track over iterations. The optimal control parameters can be found with the mechanism of the SSA. However, the classical SSA has some drawbacks as well as other intelligent algorithms. The drawbacks are concluded as: 1) SSA requires the determination of three basic parameters c_1 , c_2 and c_3 to be determined, which makes the algorithm computationally complex. 2) SSA struggles with local optima stagnation and poor convergence. 3) Though the weight factor c_3 has a good balance between the exploitation and exploration, the performance of the algorithm needs to be improved.

4.2 Improved Operators

One-dimensional normal cloud model has been introduced in the update process of leader's position to avoid the SSA fall into the local optima stagnation. The cloud model is capable of an uncertain transition between qualitative and quantitative, which has three elements of expectation (Ex), entropy (En) and hyper entropy (He) [49–51]. A new objective function value F_j^{new} in the neighborhood of F_j in Eq. (48) can be generated by one-dimensional normal cloud model $C(Ex, En, He)$ with the mathematical formula given by:

$$F_j^{new} = \begin{cases} C(Ex, En, He), & \text{if } j = d \\ F_j, & \text{otherwise} \end{cases} \quad (52)$$

where d is a random integer in the range $[1, D]$.

One-dimensional normal cloud model $C(Ex, En, He)$ can be generated by the following steps:
 1) Generate a normal random number ε_1 whose expectancy value is En and hyper entropy is He .
 2) Calculate the membership degree through the formula below:

$$y_1 = \exp(-(u - En)^2/2He^2) \tag{53}$$

3) Repeat (1)~(2) until N cloud droplets fully produced.

Fig. 2 illustrates clouds made by one-dimensional normal cloud generator with various parameters. For example, take Ex as 0.5, En as 0.1 and 0.3, He as 0.03 and 0.1, respectively. As can be observed, the figures display the cloud model with 500 cloud drops. Each cloud droplet in the figure can be understood as a new food source obtained with 0.5 (expectation) as the initial food source with different entropy and super entropy. It can be seen the obvious differences in coverage and dispersion of the four cloud models, i.e., the higher the entropy, the larger the range of new food source search, and the higher the super entropy, the more discrete the new food source within the search range. The Ex denotes a prospective food location, the En denotes the search range, and the He denotes the search's stability.

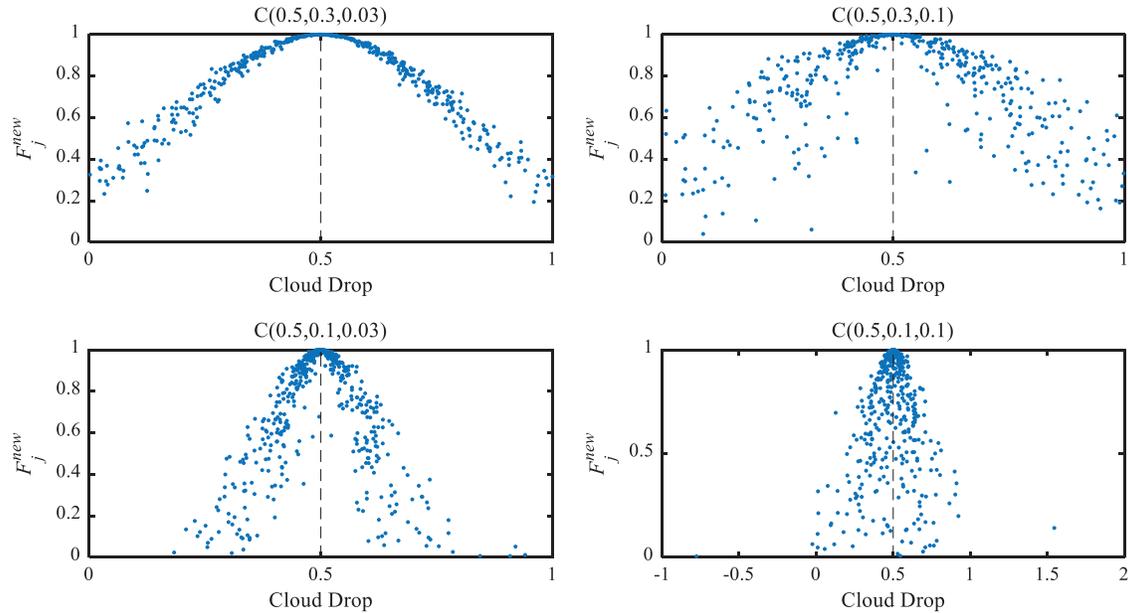


Figure 2: Clouds generated by one-dimensional normal cloud model

When the number of iterations reaches a certain value, the searched fitness value will be closer to the optimal value. To increase solution accuracy and manage the search range, the value of ex_j is adjusted using a nonlinear decreasing control technique.

$$ex_j = -(ub_j - lb_j) \cdot \left(\frac{T}{T_{\max}}\right)^2 + ub_j \tag{54}$$

In the follower position update process, the adaptive operator is used to help the SSA algorithm to escape the constraints of local optimality, so that the individual salp has a strong global convergence ability in the early stage, and relatively accurate results can be obtained in the later stage. The specific

form of the adaptive operator is:

$$x_i^j = w(T) \cdot (x_i^j + x_{i-1}^j) \tag{55}$$

$$w(T) = w_{\max} \cdot \text{rand} - \frac{T}{T_{\max}}(w_{\max} - w_{\min}) \tag{56}$$

where w_{\min} and w_{\max} are the lower and upper limits of the weight factor w , rand denotes a random number between 0 and 1.

Remark 7. If w is too large, the search efficiency of the algorithm is low, the local mining ability is insufficient, and it is difficult to obtain the optimal solution. On the contrary, if w is too small, the convergence accuracy of the algorithm is high, but the global search ability is weak, and the algorithm is easy to fall into local optimum. Eq. (55) can effectively solve the above problems.

5 Simulation Results

This article imports a 3D model of the aerial robot into the Matlab/Simscape platform for simulation. Fig. 3 depicts the control structure of the whole system, which uses the PID controller of the quadrotor aircraft and two FNSTSMC-LESO controllers for the rope-driven manipulator.

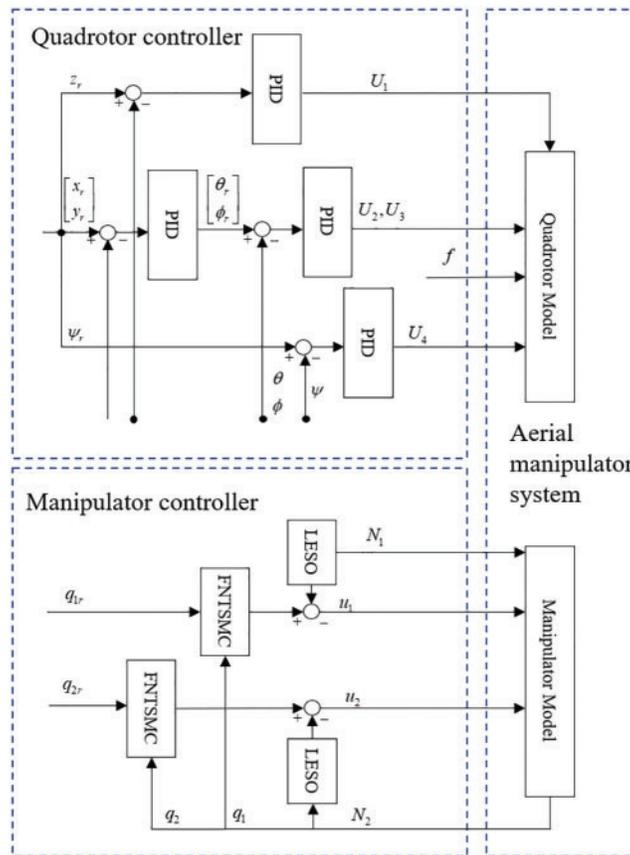


Figure 3: Control structure of the aerial robot

Case A. A step signal is designed to test the parameter tuning ability of the ISSA algorithm for the FNTSMC-LESO controller. The step values of the aerial manipulator are set as $q_r = [60^\circ, -60^\circ]$, and the other conditions all set as zeros. Moreover, a lumped disturbance $N = 2\cos(\pi t) \text{ N} \cdot \text{m}$ has been added to the two joint channels. Meanwhile, ABC and SSA are introduced as comparison to illustrate the performance of the ISSA. The three algorithms' parameters are shown in Table 1. Each algorithm is simulated 10 times, and the best result is selected. As shown in Fig. 4, it is obvious that the convergence rate of ISSA is the fastest in comparison with the other two algorithms. The objective function value obtained by ISSA is 0.013, which is 48% and 95.41% lower than that of SSA and ABC, respectively. The final controller parameters of FNTSMC-LESO tuned by ISSA are listed in Table 2. Furthermore, the corresponding results are depicted in Figs. 5 and 6, where both figures show the trajectory tracking performance of the joints optimized by three different algorithms. As observed from the results, the tracking performance obtained by ISSA is better than the other two swarm intelligent algorithms. In addition, Case A provides a set of expected control parameters for the next two cases.

Table 1: Parameters of the three algorithms

Algorithm	Parameters
IABC	$SN = 20, Limit = 5, T_{max} = 50$
SSA	$N = 20, T_{max} = 50$
ISSA	$N = 20, T_{max} = 50$

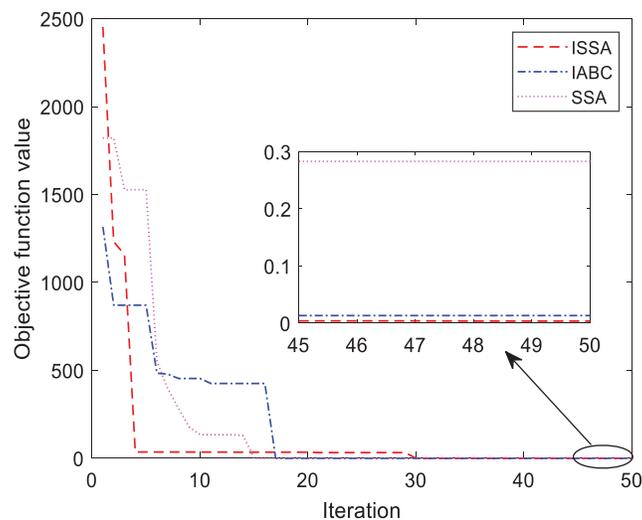
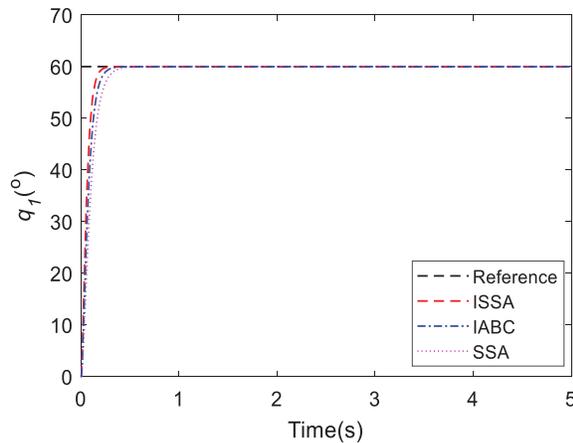
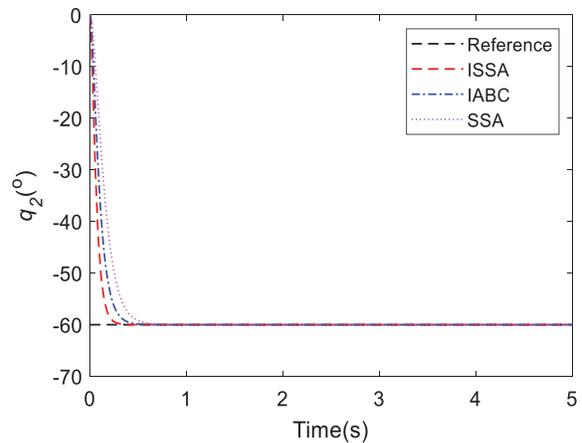


Figure 4: Iteration curves of the three algorithms

Table 2: Control parameters tuned by ISSA

Parameter	Value	Parameters	Value
ω_{1o}	500.25	ω_{2o}	142.14
β_1	0.045	β_2	0.038
k_{11}	9.55	k_{21}	39.99
k_{12}	394.70	k_{22}	386.46

**Figure 5:** Response of joint 1 in Case A**Figure 6:** Response of joint 2 in Case A

Case B. To assess the suggested FNTSMC-LESO method's performance, it is compared to LADRC and PID controllers. The other step values of the aerial manipulator are set as $q_r = [45^\circ, 45^\circ]$, and the other conditions all set as zeros. For the time between 0 to 5 s, the tracking responses of the proposed method and other control methods are similar, as observed in Figs. 7 and 8. Nonetheless, the FNTSMC-LESO controller has desirable control performance, such as smaller overshoot, shorter setting time, and higher tracking accuracy. From the error response shown in Figs. 9 and 10, we can see that the proposed controller provides the highest tracking precision in comparison with LADRC and PID. To accurately evaluate the control performance of the three controllers in the steady phase, the functions of the root-mean-squared error (RMSE) and maximum absolute error (MAE) are calculated using data from 1 to 5 s. As observed from the results, the FNTSMC-LESO method has an RMSE of 0.492 for joint 1 and 0.161 for joint 2, which are 74.66% and 68.27% of LADRC and 51.03% and 45.39% of PID, respectively. It is proved that the proposed controller is more effective than the others with lower chattering, higher accuracy, and faster convergence. The same calculated results can be obtained for MAE. The response of control torques are shown in Figs. 11 and 12, where the torques produced by PID cause undesirable performance, but FNTSMC-LESO and LADRC can output smooth control signals with the help of LESO. Hence, our provided controller offers optimal control performance over the other two controllers.

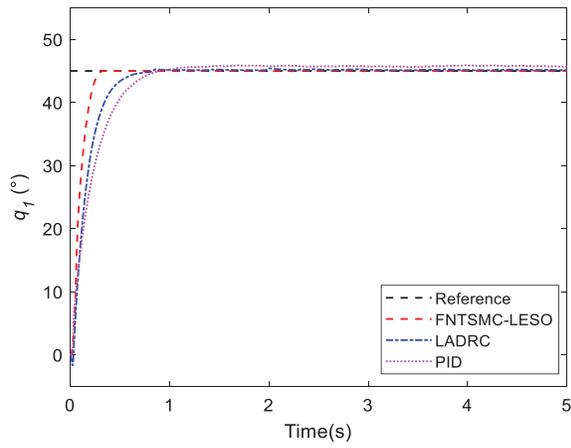


Figure 7: Response of joint 1 in Case A

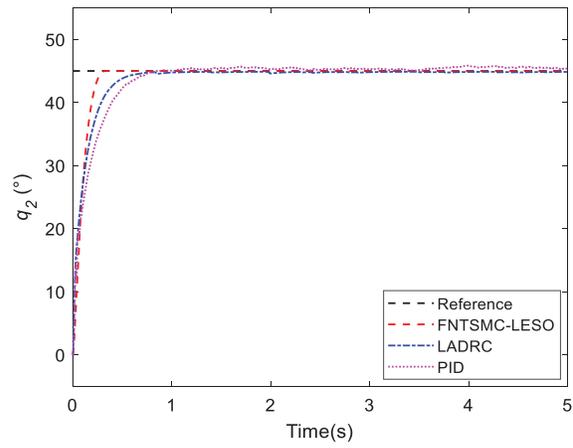


Figure 8: Response of joint 2 in Case B

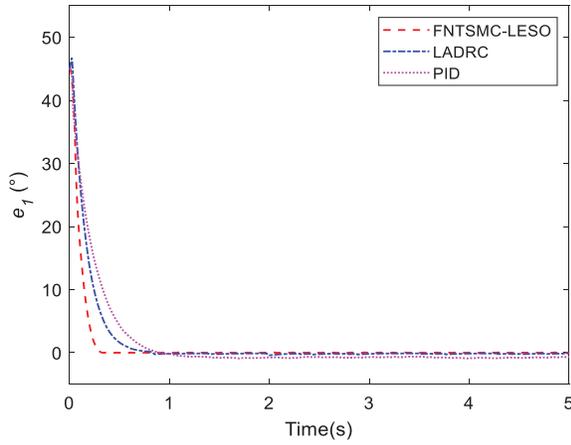


Figure 9: Tracking errors of joint 1 in Case B

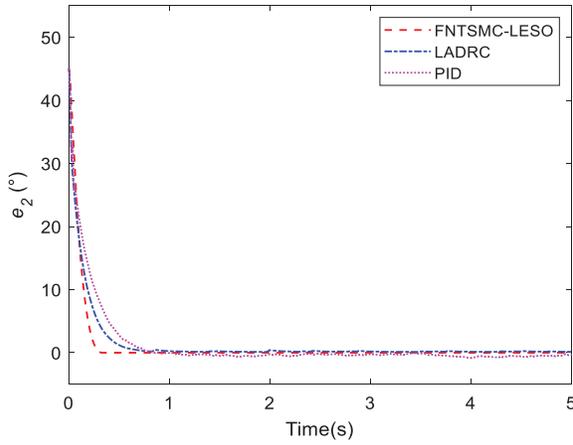


Figure 10: Tracking errors of joint 2 in Case B

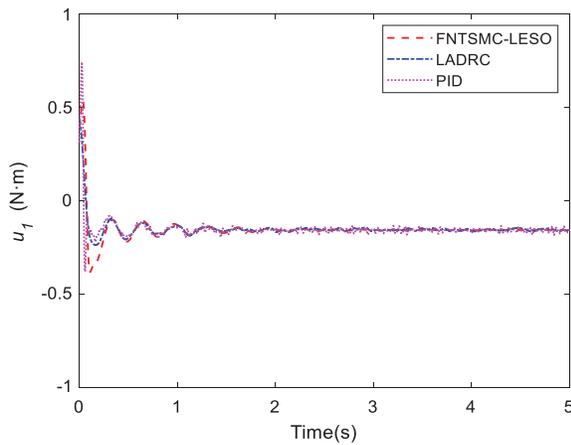


Figure 11: Comparison of torque 1 in Case B

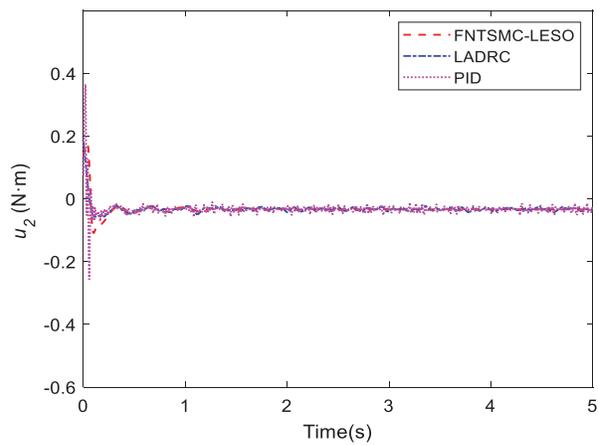


Figure 12: Comparison of torque 2 in Case B

Case C. In this simulation, the motion of the quadrotor and aerial manipulator are simulated. A special reference trajectory is set for the quadrotor which describes the phase from take-off to hover, as shown in Fig. 13. The controller parameters of PID are listed in Table 3. It can be observed that the quadrotor can track the reference trajectory well with the PID controller. Furthermore, the responses of the attitude and position are given in Figs. 14 and 15. When the quadrotor is in the hovering state, the reference trajectory of the manipulator is designed through the Cycloidal curve [52], and the initial angle of the two joints is set to 0. Considering that the manipulator will face the influence of disturbances, such as gust of wind, flexible deformation of the rope and mechanical vibration during actual work, a Gaussian noise with an amplitude of 1 N is added as the disturbance torque. The entire simulation time is set to 35 s. Similarly, LADRC and PID are used to control the cable-driven aerial manipulator respectively in the same environment, so as to compare the practicability of the three controllers. Figs. 16 and 17 show the output responses of the two joint angles under the three controllers. It can be seen that the three controllers can make the joint angles better track the reference trajectory. Furthermore, Figs. 18 and 19 show the tracking errors based on different controllers, and it can be seen that the trajectory tracking error obtained by the controller in this paper is the smallest. The root mean square error RMSE is used to evaluate the tracking accuracy. For q_1 , the RMSE of the controller in this paper is 0.638 which is 0.341 and 0.452 lower than that of LADRC and PID, respectively. For q_2 , the RMSE of the controller in this paper is 0.832, which is 0.299 and 0.557 lower than the RMSE of the latter two, respectively. This shows that the controller in this paper has high tracking accuracy and can effectively suppress the aggregate disturbance of the system. Finally, Figs. 20 and 21 show the comparison of the control torque of the three controllers. It can be observed from the figures that the proposed controller is the smoothest with almost no chattering phenomenon, which causes no harm to the actuator.

Table 3: PID parameters of the quadrotor

Channel	Controller parameter
x	$P_x = 120, I_x = 4, D_x = 0.01$
y	$P_y = 100, I_y = 5, D_y = 0.01$
z	$P_z = 320, I_x = 1, D_x = 0.001$
ϕ	$P_\phi = 10, I_\phi = 3, D_\phi = 0.001$
θ	$P_\theta = 10, I_\theta = 3, D_\theta = 0.001$
ψ	$P_\psi = 60, I_\psi = 1, D_\psi = 0.001$

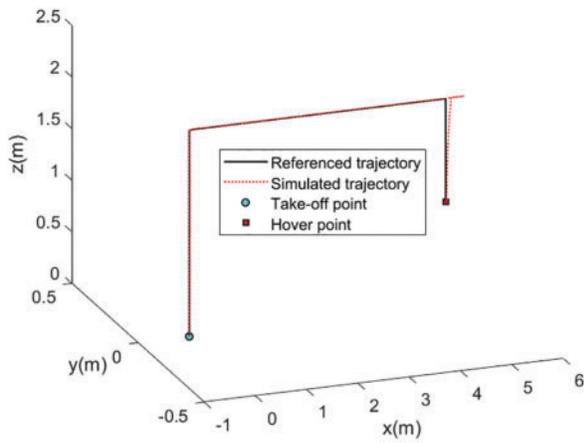


Figure 13: 3D flight trajectory of the quadrotor

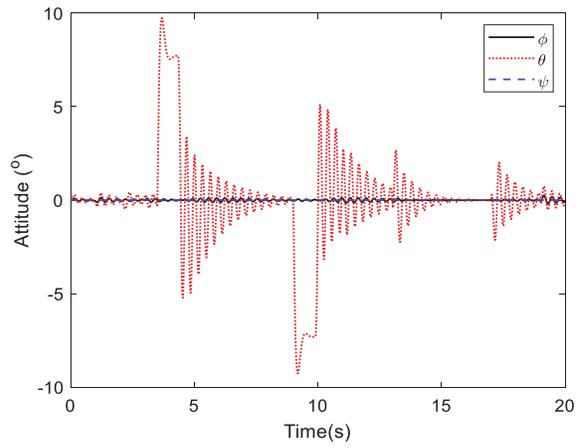


Figure 14: Attitude response of the quadrotor

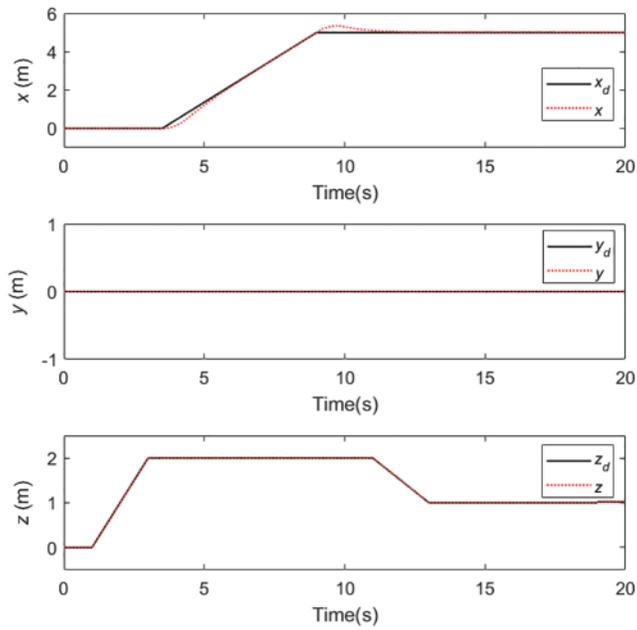


Figure 15: Position response of the quadrotor

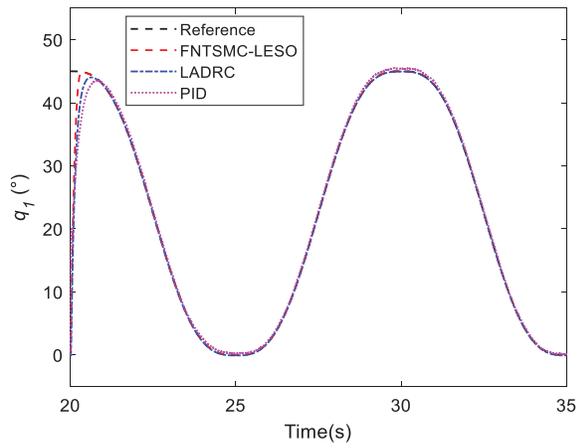


Figure 16: Response of joint 1 in Case C

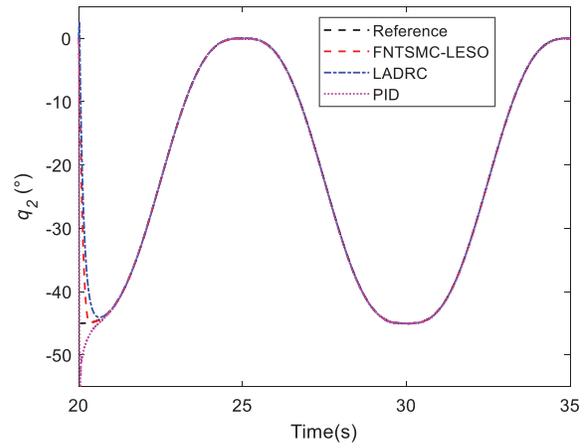


Figure 17: Response of joint 2 in Case C

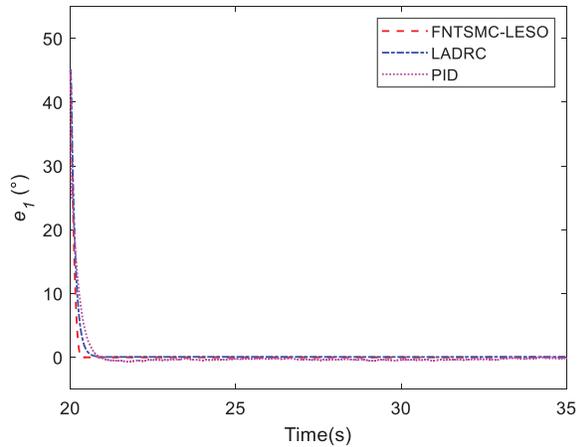


Figure 18: Tracking errors of joint 1 in Case C

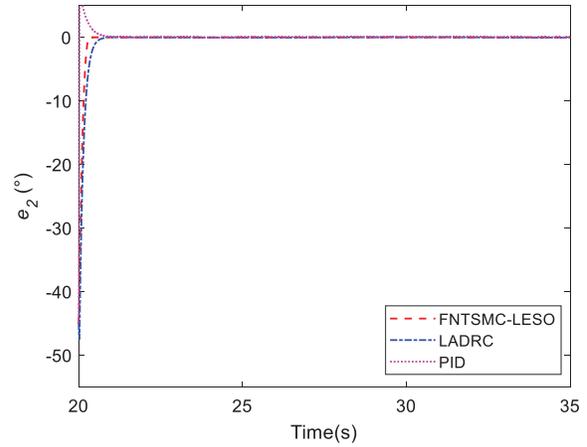


Figure 19: Tracking errors of joint 2 in Case C

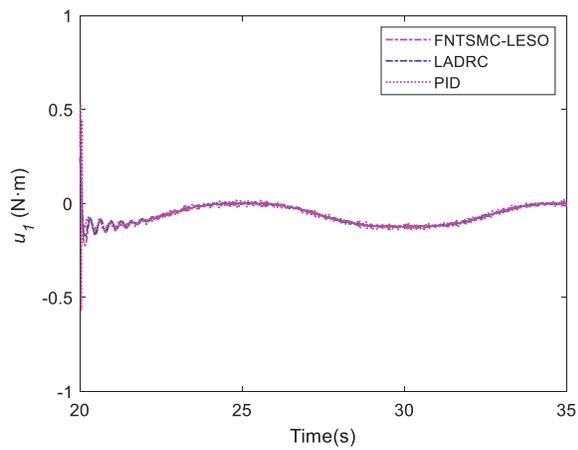


Figure 20: Comparison of torque 1 in Case C

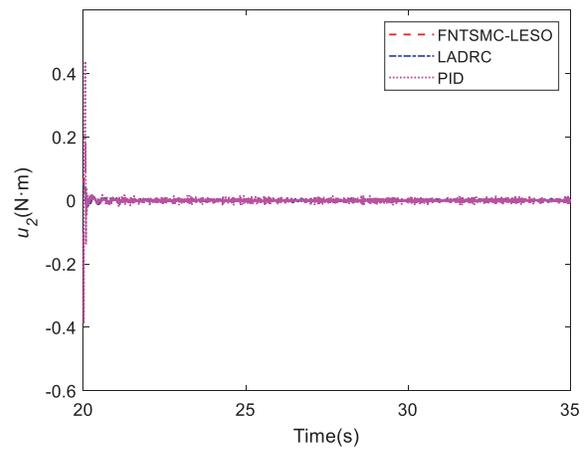


Figure 21: Comparison of torque 2 in Case C

6 Conclusions

In this paper, we have designed a novel cable-driven aerial manipulator applied for aerial tasks. Due to the use of cable-driven technology, the drive unit of the manipulator can be mounted at the base of the arm, simplifying the structure of the arm and reducing its quality. Meanwhile, a FNTSMC-LESO controller was proposed by combing the FNTMSC method with LESO technique. By using a nonlinear sliding mode surface, the FNTSMC-LESO control is capable of generating high precision and fast convergence. The nonlinear sliding mode surface, FNTSMC, can accelerate convergence in the region of the equilibrium point, which is of benefit to comprehensive performance. Furthermore, the parameter tuning of the proposed controller is conducted by ISSA. The simulation cases indicate that the proposed controller achieves a better control effect compared to LADRC and PID controllers.

In the future research, we will explore the other control strategy of the aerial manipulator and test the effectiveness of the proposed controller designed in this paper in the outdoor real flight test. In addition, we will further study the dynamic coupling law between the quadrotor and the cable-driven manipulator.

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Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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