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Sliding Mode Control of a UAV Based on Disturbance Observation

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Abstract: To address the degradation of trajectory tracking performance of quadrotor unmanned aerial vehicles (UAVs) under external disturbances, a sliding mode trajectory tracking control method based on disturbance observation is proposed in this paper. A unified dynamic model for the translational and attitude motions of the UAV is established, where external disturbances are treated as unknown equivalent inputs. Then, a sliding mode tracking controller is designed, and a disturbance observer is introduced to estimate external disturbances online. The estimated disturbances are compensated in a feedforward manner to enhance the disturbance rejection capability and tracking accuracy of the system. The proposed method does not rely on an accurate disturbance model and features a simple structure and strong robustness. Simulation studies based on spiral trajectory tracking are conducted to compare the performance of the sliding mode controller and the sliding mode controller with disturbance observation. The results demonstrate that the proposed method effectively suppresses the influence of external disturbances and significantly improves the position and attitude tracking performance of the quadrotor UAV, validating the effectiveness and feasibility of the proposed control strategy.

Keywords: Quadrotor UAV; Sliding mode control; Disturbance observer; Trajectory tracking; Robust control

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1. Introduction

Unmanned aerial vehicles (UAVs) have attracted significant attention in recent years due to their high maneuverability, flexible deployment, and relatively low operational cost. They have been widely applied in various fields such as environmental monitoring, disaster rescue, inspection, and military missions. With the increasing complexity of application scenarios, achieving high-precision trajectory tracking for UAVs under realistic operating conditions has become an essential requirement. However, practical UAV systems are inevitably affected by external disturbances, model uncertainties, and unmodeled dynamics, which can degrade tracking accuracy and even threaten system stability. Therefore, the development of robust trajectory tracking control strategies capable of handling disturbances and uncertainties remains a challenging and important research topic.

Sliding mode control (SMC) has been extensively employed in UAV trajectory tracking due to its inherent robustness against parameter variations and external disturbances. In recent studies, various SMC-based control schemes have been proposed to improve tracking performance under disturbed conditions. For instance, adaptive sliding mode and terminal sliding mode controllers have been developed to enhance robustness and convergence speed for quadrotor UAVs [1–3]. Non-singular and finite-time sliding mode control structures were further introduced to improve transient performance and avoid singularity issues [1]. Nevertheless, conventional sliding mode control often requires high switching gains to suppress disturbances, which may induce chattering and impose excessive stress on actuators in practical implementations.

To alleviate chattering and further improve disturbance rejection capability, disturbance observers (DOs) and extended state observers (ESOs) have been incorporated into sliding mode control frameworks. By estimating unknown disturbances online and compensating them in the control law, the required switching gain can be reduced while maintaining robustness. Sliding mode control was combined with active disturbance rejection concepts to achieve effective disturbance compensation [4]. Subsequently, disturbance observer-based and sliding mode observer-based approaches were proposed to enhance tracking accuracy under external disturbances and uncertainties [5–7]. Moreover, disturbance observer-enhanced adaptive and fault-tolerant control schemes have been investigated to cope with complex operating conditions, including actuator faults and dynamic disturbances [8,9].

Despite these advances, several issues still deserve further investigation. On one hand, some existing studies design separate models and control laws for different attitude channels, which increases system complexity and limits generality. On the other hand, the trade-off between disturbance observation dynamics and overall control performance has not been fully addressed in sliding mode control designs. Motivated by these considerations, this paper proposes a sliding mode trajectory tracking control method integrated with disturbance observation under a unified UAV motion modeling framework. Position and attitude dynamics are described and controlled in a consistent manner, while disturbance compensation is introduced to improve tracking accuracy and robustness. Simulation results demonstrate the effectiveness of the proposed approach in the presence of external disturbances.

2. UAV system modeling

2.1. Coordinate frame definition

Consider a rigid-body UAV whose motion involves both translational and rotational dynamics. To facilitate the description of the UAV motion in three-dimensional space, the relevant coordinate frames are defined first. In this paper, a modeling framework combining an inertial coordinate frame and a body-fixed coordinate frame is adopted, as illustrated in **Figure 1**. The coordinate frames are defined as follows.

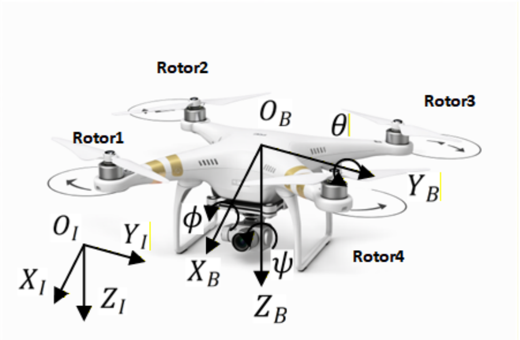


Figure 1. Coordinate frames of the quadrotor UAV.

The inertial coordinate frame is defined as

$$I=\{O_I,X_I,Y_I,Z_I\} \tag{1}$$

where O_I denotes the origin of the inertial frame, which is typically selected at the takeoff point or a fixed ground reference location. The axes X_I and Y_I lie in the horizontal plane, while the Z_I points vertically upward, forming a right-handed coordinate system.

This frame is used to describe the UAV position and its global motion trajectory in space.

The body-fixed coordinate frame is defined as

$$B = \{O_B, X_B, Y_B, Z_B\} \tag{2}$$

where O_B is fixed at the center of mass of the UAV. The X_B points forward along the Y_B body longitudinal direction, the Z_B points to the right, and the points downward, forming a right-handed coordinate system.

This frame is used to describe the UAV attitude dynamics and the directions of control input actions.

The UAV attitude with respect to the inertial coordinate frame is characterized by the rotational transformation from the body-fixed frame to the inertial frame, which is parameterized using Euler angles.

2.2. Dynamic model of the UAV

Consider a rigid-body unmanned aerial vehicle operating in the inertial frame I. The position of the vehicle's center of mass is defined as:

$$p = [x, y, z]^{\mathrm{T}} \tag{3}$$

The attitude is represented by Euler angles corresponding to roll, pitch, and yaw, respectively.

$$\eta = [\phi, \theta, \psi]^{\mathrm{T}} \tag{4}$$

To provide a unified description of translational and rotational motions, the generalized coordinate vector is defined as:

$$q = [p^{\mathrm{T}}, \eta^{\mathrm{T}}]^{\mathrm{T}} \in \mathbb{R}^6 \tag{5}$$

Considering external disturbances and modeling uncertainties, the generalized dynamic model of the UAV can be expressed as

$$M(q)\ddot{q} + C(q, \dot{q})\dot{q} + G(q) = u(t) + d(t) \tag{6}$$

Where $M(q)$ denotes the equivalent inertia matrix; $C(q, \dot{q})$ represents Coriolis and centrifugal effects; $G(q)$ denotes gravity-related terms; $u(t)$ is the control input vector; $d(t)$ represents lumped external disturbances and modeling uncertainties.

Notably, the yaw channel is not modeled separately but incorporated into the generalized coordinate vector, enabling a unified control framework for both translational and rotational dynamics.

2.3. Disturbance description and assumptions

During practical flight, the UAV is subject to wind disturbances, aerodynamic uncertainties, and parameter variations. Instead of distinguishing different disturbance sources, all uncertainties are lumped into the equivalent disturbance vector *d*(*t*). The following assumptions are made:

(1) Assumption 1: The disturbance vector *d*(*t*) is bounded, i.e.,

$$\|d(t)\| \leq d_{max} \tag{7}$$

(2) Assumption 2: The disturbance varies slowly over short time intervals, and its first derivative is bounded.

These assumptions are consistent with typical low-altitude flight conditions and facilitate the design of disturbance observation and prediction schemes.

2.4. Trajectory tracking formulation

Let the desired smooth reference trajectory be given by with continuous first- and second-order derivatives.

$$q_d(t) = [p_d^{\mathrm{T}}(t), \eta_d^{\mathrm{T}}(t)]^{\mathrm{T}} \tag{8}$$

Define the tracking errors as:

$$e = q - q_d, \quad \dot{e} = \dot{q} - \dot{q}_d \tag{9}$$

The control objective of this paper is to design a control law *u*(*t*) such that the tracking errors converge to zero asymptotically or within finite time, despite the presence of unknown disturbances, while ensuring system stability and robustness.

3. Control system design and stability analysis

Based on the dynamic model and trajectory tracking objective established, this chapter focuses on the control system design and stability analysis. A trajectory tracking control structure combining sliding mode control and disturbance observation is developed to handle unknown external disturbances. The overall control system block diagram is shown in **Figure 2** to illustrate the interactions among different functional modules.

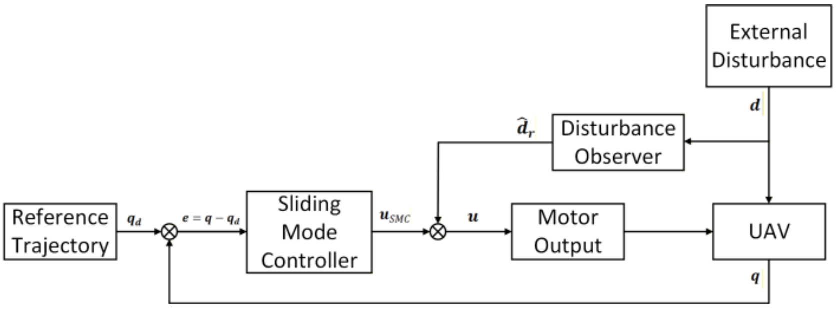


Figure 2. Block diagram of the control system.

3.1. Error dynamics and sliding surface construction

Based on the generalized dynamic model established above, as given in (6), and the defined tracking error vector in (9), a linear sliding surface is constructed to simultaneously constrain the tracking error and its rate of change.

$$s = \dot{e} - \Lambda e \tag{10}$$

where $\Lambda \in \mathbb{R}^{6\times6}$ is a positive definite diagonal gain matrix.

This sliding surface has a uniform structure for both translational and attitude channels, without distinguishing the yaw direction, which facilitates a unified control design.

Differentiating the sliding surface yields:

$$\dot{s} = \ddot{q} - \ddot{q}_d - \Lambda \dot{e} \tag{11}$$

Combining with the system dynamics:

$$\dot{s} = M^{-1}(q)(u + d - C\dot{q} - G) - \ddot{q}_d + \Lambda \dot{e} \tag{12}$$

In the presence of unknown disturbances, a sliding mode control law that does not rely on disturbance information is first designed as follows:

$$u_{SMC} = C\dot{q} + G + M(\ddot{q}_d - \Lambda \dot{e}) - Ksat\left(\frac{s}{\phi}\right) \tag{13}$$

where *K* is a positive definite diagonal switching gain matrix, ϕ is the boundary layer thickness vector, and sat(·) denotes the saturation function used to mitigate chattering.

Under this control law, the system exhibits a certain degree of robustness against bounded disturbances; however, the control accuracy is significantly affected by the disturbance magnitude, which motivates the introduction of disturbance observation and compensation.

3.2. Disturbance observer design and compensation control law

To enhance robustness, a linear disturbance observer is introduced:

$$\dot{\widehat{d}} =- L_d \widehat{d} + L_d(M(q)\ddot{q} - u + C(q,\dot{q})\dot{q} + G(q)) \tag{14}$$

where $\widehat{d}$ is the estimated disturbance and L_d is the observer gain. Define the estimation error $\widetilde{d} = d - \widehat{d}$, whose dynamics are:

$$\dot{\widetilde{d}} =- L_d \widetilde{d} + \dot{d} \tag{15}$$

Assuming the disturbance varies slowly and continuously, $\widetilde{d}$ is bounded and converges rapidly, providing reliable compensation for the control law.

The sliding mode control with disturbance compensation becomes:

$$u = M(q)(\ddot{q}_d + \Lambda \dot{e}) + C(q,\dot{q})\dot{q} + G(q) + K_s\, tanh\,(\kappa s) - \widehat{d} \tag{16}$$

By compensating the estimated disturbance, convergence along the sliding surface is preserved, significantly improving tracking performance.

For stability analysis, the Lyapunov function is chosen as:

$$V = \frac{1}{2} s^T s \tag{17}$$

The sliding surface dynamics are:

$$\dot{s} =- K_s s - K_\eta sat(s) + M^{-1}(q)\widetilde{d} \tag{18}$$

Its derivative:

$$\dot{V} = s^T \dot{s} =- s^T K_s s - s^T K_\eta sat(s) + s^T M^{-1}(q)\widetilde{d} \tag{19}$$

Since $M(q)$ is bounded and positive definite and $\tilde{d}$ is bounded, s is uniformly ultimately bounded (UUB), and the tracking error e asymptotically converges, ensuring system stability.

4. Simulation results and analysis

This section presents simulation results based on the sliding mode control (SMC) and the disturbance observer-enhanced SMC (SMC + Observer) proposed above. A spiraling ascending trajectory is used as the reference path. All simulations were conducted in MATLAB with a time step of 0.01 s over a total duration of 30 s. The performance of SMC and SMC combined with the disturbance observer is compared in terms of trajectory tracking and disturbance estimation.

4.1. Trajectory tracking performance

Figure 3 illustrates the UAV trajectory in three-dimensional space. The red curve represents the reference trajectory, the blue dashed curve represents SMC, and the green dash-dot curve represents SMC + Observer. Both controllers successfully track the reference path, while the addition of the disturbance observer improves the alignment with the reference, particularly in the Z-direction and in segments with rapid attitude changes.

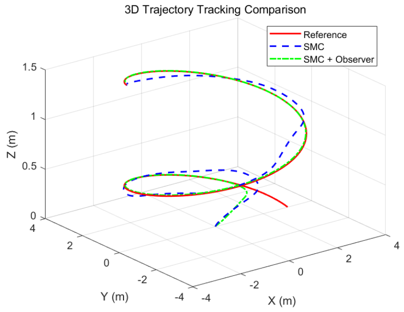
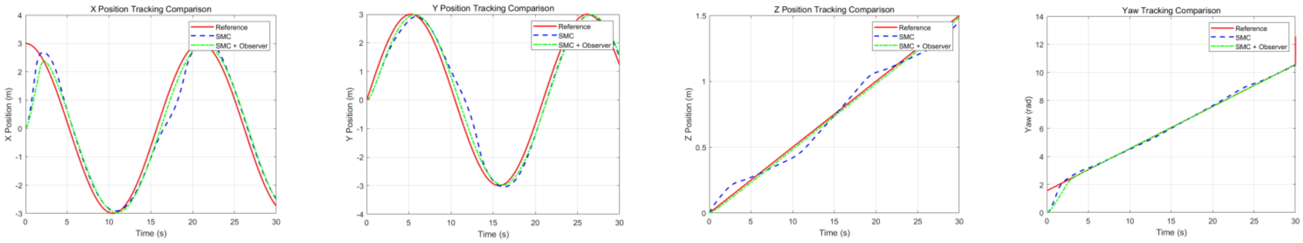


Figure 3. 3D trajectory tracking curve.

Figure 4 shows the tracking performance along X, Y, Z axes, and the Yaw angle over time. For the X, Y, and Z axes, the tracking error of SMC + Observer is significantly lower than that of SMC, especially during periods with large disturbances. For the Yaw angle, the observer reduces both deviation and oscillation, enhancing control accuracy.



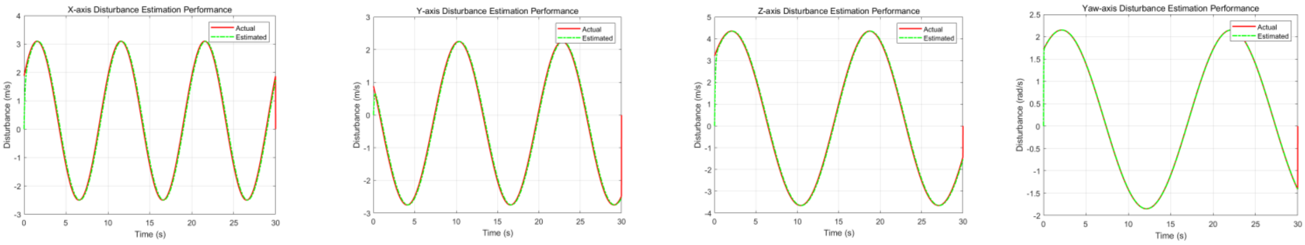
-axis Tracking Curve -axis Tracking Curve -axis Tracking Curve Tracking Curve

Figure 4. Position and attitude angle tracking curves.

Although SMC exhibits some tracking error, gain tuning ensures acceptable performance.

4.2. Disturbance estimation performance

Figure 5 present the disturbance estimation performance along , , axes, and the Yaw axis. The red curves represent actual disturbances, while the green dash-dot curves indicate estimated values. Estimated disturbances along , , and match the actual values closely, confirming the observer's accuracy.The Yaw disturbance estimation is stable throughout, without excessive oscillation or saturation, validating the chosen parameters.



-axis Observation Curve | -axis Observation Curve | -axis Observation Curve | Observation Curve

Figure 5. Disturbance observation curves.

Incorporating the disturbance observer provides effective feedforward compensation, reducing tracking errors and enhancing system robustness.

4.3. Comprehensive analysis

Comparing SMC with SMC + Observer demonstrates the following: SMC + Observer significantly improves tracking accuracy without increasing controller complexity, especially in the presence of external disturbances. The disturbance observer smooths the Yaw response and provides effective compensation in three-dimensional position control. Although SMC offers a degree of robustness, tracking errors are evident under high disturbance scenarios, highlighting the necessity of combining observation with control.

5. Conclusion

This paper investigated the trajectory tracking control problem of an unmanned aerial vehicle under external disturbances based on a unified generalized dynamic model. A robust control scheme combining sliding mode control and disturbance observation was developed, where translational and attitude channels share the same control structure without separating the yaw dynamics. A sliding mode controller was first designed without requiring disturbance information, ensuring system stability under bounded disturbances. To further improve tracking performance, a disturbance observer was introduced to estimate external disturbances online and provide compensation in the control law. Simulation results based on a three-dimensional spiral trajectory demonstrate that, compared with sliding mode control, the proposed method with disturbance observation compensation achieves higher tracking accuracy and smaller steady-state errors in both position and yaw channels. In addition, the disturbance observer effectively reconstructs the disturbance trends, thereby enhancing the disturbance rejection capability of the control system. In summary, the proposed control strategy improves tracking accuracy and robustness under external disturbances while maintaining a simple and unified control structure.

Disclosure statement

The author declares no conflict of interest.

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