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Comparative Study on Trajectory Tracking of Quadrotor UAV Based on PID, Sliding Mode Control and Integral Backstepping Sliding Mode Control

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Abstract. Accurate trajectory tracking serves as a core technology for quadrotor unmanned aerial vehicles to perform inspection, mapping, monitoring and low-altitude autonomous flight missions. Affected by underactuated, nonlinear and strongly coupled dynamics, the horizontal motion of quadrotors is realized by adjusting attitudes to change the direction of thrust, while attitude responses are jointly restricted by rotational coupling, inertia parameters and external disturbances. This study adopts three typical trajectory tracking methods, namely proportional-integral-derivative control, sliding mode control and integral backstepping sliding mode control, and constructs a performance evaluation framework from the perspectives of trajectory response, position error, attitude variation and comprehensive error indicators. The results indicate that the three-dimensional root mean square error and maximum three-dimensional error of PID control under periodic trajectories are 0.5836 m and 0.8560 m respectively, which proves that the basic feedback structure presents noticeable deviations in curve tracking. Sliding mode control reduces the maximum three-dimensional error to 0.0509 m, showing excellent capability in limiting error bounds. For integral backstepping sliding mode control, its three-dimensional root mean square error and terminal three-dimensional error are 0.0419 m and 0.0050 m separately. It demonstrates that integral compensation and backstepping sliding mode structure help enhance overall precision and terminal convergence performance. The findings clarify the differences among the three control structures in error suppression, attitude regulation and terminal accuracy, and can provide references for the selection of trajectory tracking controllers for quadrotor unmanned aerial vehicles.

Keywords: quadrotor unmanned aerial vehicle, trajectory tracking, PID control, sliding mode control, integral backstepping control, robust control

1. Introduction

Quadrotor unmanned aerial vehicles feature compact structure, vertical take-off and landing capability, excellent hovering performance and high maneuverability. They have been applied to various tasks including infrastructure inspection, precision agriculture, emergency monitoring, aerial mapping and low-altitude delivery. In autonomous flight scenarios, the UAV needs to move continuously along a given spatial trajectory on the premise of stable attitude, and maintain positional accuracy, rapid attitude response and smooth control during maneuvers. Therefore, trajectory tracking control is directly linked to the autonomous operation capability of quadrotor UAVs. High-performance tracking control is required to reduce transient deviation and steady-state error, while keeping coordinated attitude during curvilinear movement and altitude variation.

The major challenge for quadrotor trajectory tracking lies in its underactuated dynamic structure. Unlike ground vehicles, quadrotors cannot generate independent horizontal control force directly, and their translational motion relies on adjusting the direction of total lift via roll angle and pitch angle. This leads to strong coupling between the position loop and the attitude loop. Position errors will change the desired attitude, and the lag of attitude response will in turn aggravate position errors. Meanwhile, aerodynamic disturbances, parameter uncertainties, load variations, actuator saturation and sensor noise will all degrade tracking accuracy. When the reference trajectory involves periodic motion, curved paths or continuous altitude changes, the controller must simultaneously meet the requirements of response speed, steady-state accuracy, robustness and attitude smoothness.

With the advantages of easy implementation, low computational cost and intuitive physical meaning of parameters, PID control remains a fundamental scheme for quadrotor control. The proportional term responds to tracking errors, the integral term suppresses steady-state deviation, and the derivative term improves dynamic damping. Existing review studies have pointed out that PID control and its improved variants have a solid foundation for extensive engineering applications on quadrotor platforms [1]. Nevertheless, PID control conducts feedback correction mainly based on measured errors, and lacks explicit compensation for nonlinear coupling, external disturbances and model uncertainties. When tracking complex trajectories, this method can keep the flight system closed-loop stable, but it tends to cause phase lag, periodic deviation and residual terminal error, which undermines the trajectory coverage quality of high-precision inspection and mapping missions.

Sliding mode control is widely adopted for trajectory tracking of uncertain quadrotor systems due to its strong robustness. To address dynamic uncertainties, the neural network-based non-singular fast terminal sliding mode method can optimize error convergence and compensation for uncertain terms [2]. Comparative experiments on adaptive sliding mode control further verify the engineering applicability of such methods on quadrotors [3]. Under the coexistence of input saturation and external disturbances, adaptive sliding mode design can enhance the robustness of trajectory tracking [4]. Fixed-time adaptive tracking control expands relevant research by focusing on convergence time constraints under limited input [5]. The reaching-law-based non-singular terminal sliding mode method optimizes reaching law design and terminal error convergence, so as to improve tracking performance under disturbances [6]. Fuzzy attitude sliding mode control compensates for uncertainties in the attitude channel and helps strengthen the robustness of the attitude loop [7]. Fixed-time robust sliding mode control further ensures that tracking errors converge within a preset time range [8]. Sliding mode control restricts error dynamics through sliding surfaces and drives system states to approach the preset manifold. However, its switching term may lead to chattering and high-frequency attitude adjustment. Hence, the performance evaluation of SMC needs to take position error, attitude response and regulation smoothness into comprehensive consideration.

Backstepping control is applicable to nonlinear dynamic systems with cascade structures. It constructs virtual control variables layer by layer and establishes correlations among the position loop, attitude loop and torque input. When combined with integral compensation and sliding mode constraints, backstepping control can handle nonlinear coupling, persistent deviation and external disturbances simultaneously. Integral backstepping sliding mode control (IBS-SMC) integrates backstepping recursive structure, sliding mode robust constraints and integral deviation compensation, and shows great potential to improve terminal convergence in trajectory tasks involving continuous movement and long-term accumulation of minor errors.

Most existing studies focus on the derivation of control laws and stability proof for single control algorithms. Their conclusions can support the analysis of closed-loop convergence, but fail to fully illustrate the differences among various control structures in terms of trajectory characteristics, directional error, attitude response and numerical indicators. For engineering selection, stability proof alone is insufficient to define the applicable scope of basic feedback control, robust sliding mode control and nonlinear robust control with integral compensation in different tasks. For this reason, it is necessary to analyze the effects of PID, SMC and IBS-SMC on error boundary, terminal convergence and attitude regulation from the perspective of trajectory response and error indicators.

2. Methods

The trajectory tracking problem of quadrotor UAVs can be formulated as a cascade control structure consisting of an outer position loop and an inner attitude loop. The outer position loop receives the desired trajectory and actual position, and generates the desired lift direction and expected attitude. The inner attitude loop tracks the desired roll angle, pitch angle and yaw angle, and outputs the corresponding control torque. Let the position vector be $p=[x,y,z]^T$, the attitude angle vector be $\eta=[\varphi,\theta,\psi]^T$, the total lift be U1, the attitude torque be $U\eta$, the mass be m, the moment of inertia matrix be J, and the rotation matrix be $R(\eta)$. The dynamic equations of the quadrotor are summarized as follows:

$$\begin{gathered} m\ddot{\boldsymbol{p}} = R(\varphi,\theta,\psi)\begin{bmatrix}0\\0\\U_1\end{bmatrix} - \begin{bmatrix}0\\0\\mg\end{bmatrix}, \\ J\ddot{\boldsymbol{\eta}} = U_\eta - \dot{\boldsymbol{\eta}} \times J\dot{\boldsymbol{\eta}}. \end{gathered} \tag{1}$$

Equation (1) indicates that trajectory tracking is not a simple position servo problem. Horizontal acceleration is produced by the tilted thrust vector, so position commands are converted into attitude requirements. Meanwhile, the dynamic performance of the inner attitude loop in turn affects position errors. Excessively large attitude commands issued by the position loop may amplify position errors due to the tracking lag of the inner loop. Insufficient regulation of the attitude loop will also restrict trajectory accuracy. Therefore, the performance evaluation of controllers needs to examine both position tracking and attitude response. The closed-loop framework shown in Figure 1 illustrates the common structure of the three controllers. The reference trajectory is processed by the position controller to generate desired attitude and lift. The attitude controller then produces torque input. The quadrotor dynamics outputs position and attitude signals to form a closed feedback loop.

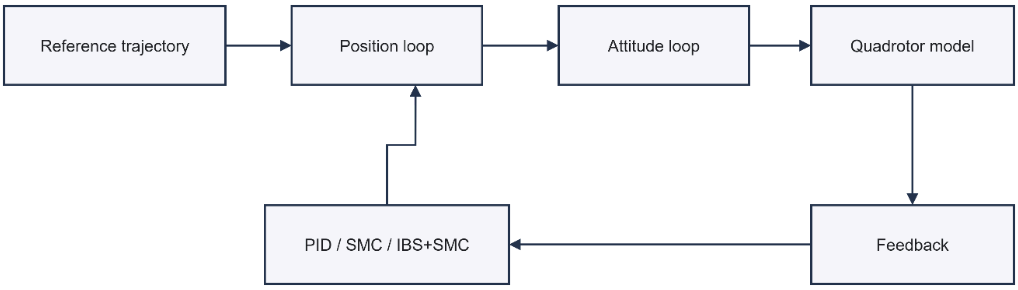

Figure 1. Control framework for quadrotor trajectory tracking

Cascade PID is adopted as the benchmark controller. In this structure, the outer loop calculates correction commands according to position errors, and the inner loop generates torque commands based on attitude errors. The PID structure is clear, with relatively straightforward parameter tuning and engineering implementation, and it does not rely on a complete nonlinear model. Its limitation lies in that control actions are triggered after errors occur. The suppression of nonlinear coupling and persistent disturbances depends heavily on gain tuning. Undersized gains lead to slow response and error accumulation, while oversized gains may increase the sensitivity of the attitude loop and cause oscillation. This benchmark scheme is used to compare the performance differences between robust control, integral nonlinear control and conventional feedback structures.

The second type of controller is SMC. Its core principle is to design sliding mode variables containing both tracking error and its derivative. When system states approach the sliding surface, error dynamics will be constrained by the surface. To uniformly describe the sliding mode structures in conventional sliding mode control and integral backstepping sliding mode control, the error constraint variable is defined as:

$$s = \left(\dot{e} + \lambda e\right) + \kappa \int e dt \tag{2}$$

In the formula, e denotes the tracking error, e is the derivative of tracking error, λ represents the positive convergence coefficient, and κ is the integral gain. When κ=0, the formula is simplified to the conventional sliding mode error structure. When κ>0, the integral term compensates for persistent deviations. This formula only describes the general form of error constraints, and specific control laws are determined separately for different control structures.

The above sliding mode expression shares the same idea of error constraint with the fast reaching non-singular terminal sliding mode [6]. The robustness of the attitude loop also affects position tracking performance, and fuzzy attitude sliding mode control provides solutions to uncertainties in this channel [7]. Designs of fixed-time sliding mode further prove that convergence time constraint is an important evaluation index for robust tracking of quadrotors [8]. In terms of control structure, SMC serves as a robust control scheme between benchmark PID and IBS-SMC. It features stronger capability to constrain error bounds, while chattering, intensity of attitude variation and switching gain tuning also need to be taken into evaluation.

IBS-SMC embeds an integral compensation mechanism into the backstepping framework, which further enhances the robust constraint capability of sliding mode control. The backstepping part arranges the position loop and attitude loop according to nonlinear dynamic characteristics. The sliding mode part restricts tracking errors, and the integral term accumulates persistent deviations and feeds them back to control input. Fault-tolerant neural terminal sliding mode control verifies that robust nonlinear compensation can improve the tracking performance of quadrotors under uncertain and faulty conditions [9]. The combination of hybrid backstepping control and radial basis function neural networks strengthens nonlinear approximation and trajectory tracking ability [10]. Relevant researches on trajectory tracking based on backstepping control and radial basis function neural networks further validate the effectiveness of such structures in quadrotor path tracking [11]. For tasks with continuously varying spatial trajectories and strict requirements on terminal positioning accuracy, IBS-SMC helps reduce accumulated deviations and terminal errors. Its downside lies in higher complexity of control structure and parameter tuning.

Since the reference trajectories and model settings of the three working conditions are not completely identical, the obtained results cannot be regarded as standard tests under the same trajectory. The focus of performance analysis is to identify the behavioral characteristics of different control structures under unified evaluation criteria. For each controller, the evaluation covers the fitting degree between actual position and reference position, time response of errors, characteristics of attitude variation and terminal approaching accuracy. This processing method retains the differences of working conditions and meanwhile reduces the interference caused by different trajectory scales on numerical comparison.

The above constraints define the scope of result interpretation. If differences in reference trajectories, parameters of controlled objects and disturbance conditions are ignored, the ranking of numerical results may be misinterpreted as universal conclusions. Therefore, performance evaluation is divided into two levels. First, the effectiveness of each controller for trajectory tracking under corresponding tasks is verified. Second, the error behaviors of the three control structures are analyzed, including periodic deviation, peak error constraint, attenuation of terminal deviation and amplitude of attitude regulation. The conclusions focus on the correlation between control mechanism and error response, rather than simply ranking algorithms regardless of actual working conditions.

Three-dimensional root mean square error is adopted to measure trajectory tracking accuracy, and its definition is as follows:

$$\mathrm{RMSE}_{3\mathrm{D}}=\sqrt{\frac{1}{\mathrm{N}}\sum_{\mathrm{i}=1}^{\mathrm{N}}\left[(\mathrm{x}_{\mathrm{d}}-\mathrm{x})^2+(\mathrm{y}_{\mathrm{d}}-\mathrm{y})^2+(\mathrm{z}_{\mathrm{d}}-\mathrm{z})^2\right]} \tag{3}$$

Apart from RMSE3D, maximum three-dimensional tracking error and terminal three-dimensional error are also included in the evaluation system. These three indicators respectively reflect the overall tracking quality, instantaneous deviation range and terminal positioning precision. Among them, maximum error is closely related to flight near obstacles and safety-critical inspection tasks, while terminal error directly affects the performance of arrival, landing and final positioning. Joint evaluation with multiple indicators avoids interpretation bias caused by a single statistical variable. A controller may have small average error but large peak deviation, or show good trajectory fitting with residual terminal error. Hence, graphical results and numerical indicators need to be analyzed comprehensively.

3. Results and discussion

3.1. Results of three-dimensional trajectory tracking

Figure 2 presents the three-dimensional tracking results of the three controllers in typical trajectory tasks. The PID controller is tested on an approximately horizontal closed trajectory, SMC on a larger-scale spatial trajectory, and IBS-SMC on a spiral ascending trajectory. Given the differences in scale and shape among the three trajectories, this figure does not serve as a direct comparative test under an identical reference path. Instead, it visually demonstrates the trajectory response characteristics of different control structures under unified evaluation standards, and lays a foundation for the subsequent analysis of error curves and quantitative indices.

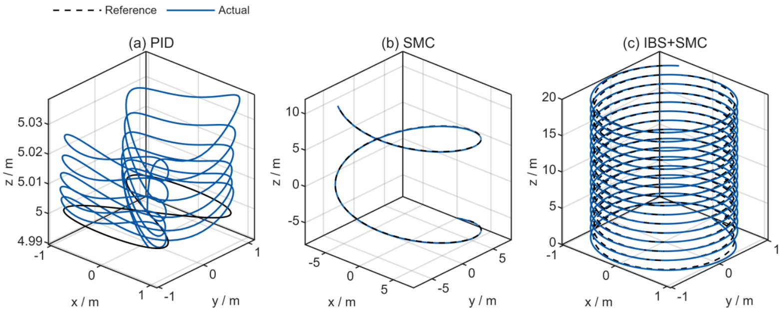

Figure 2. Three-dimensional trajectory tracking results of PID, SMC and IBS-SMC

The benchmark PID controller ensures stable closed-loop flight, yet noticeable deviations exist between the actual trajectory and the reference trajectory. This result reflects the inherent limitations of PID when tracking periodic paths. Since this controller conducts feedback correction merely based on generated errors and provides no explicit compensation for the coupling between translational and attitude dynamics, the system can only complete basic movements with limited tracking accuracy along curved routes. In high-precision inspection and mapping missions, recurring lateral deviations will impair the uniformity of trajectory coverage.

The trajectory obtained by SMC fits well with the reference path. In the spatial trajectory task, the actual curve basically overlaps with the expected one, proving that the sliding surface can effectively restrict error growth. This controller is capable of reducing deviations even when the system model is not fully accurate, which verifies the error suppression performance of robust sliding mode design. IBS-SMC also achieves favorable tracking performance in spiral trajectory tasks. A spiral path requires coordinated horizontal and vertical motions. The integral backstepping structure combined with sliding mode compensation helps maintain tracking quality during continuous altitude changes. As illustrated in Figure 2, PID only delivers basic closed-loop tracking capability, SMC strengthens the constraint on error bounds, and IBS-SMC optimizes the convergence performance under continuous altitude variation.

3.2. Analysis of position error and attitude response

Figure 3 shows the position tracking errors along three coordinate axes. The error curves of PID present obvious periodicity, especially in the horizontal directions, indicating phase lag during repeated trajectory movements. This phenomenon does not mean closed-loop instability, but manifests persistent tracking deviations. For inspection and mapping tasks, periodic errors will alter the observation perspective and reduce the consistency of data coverage.

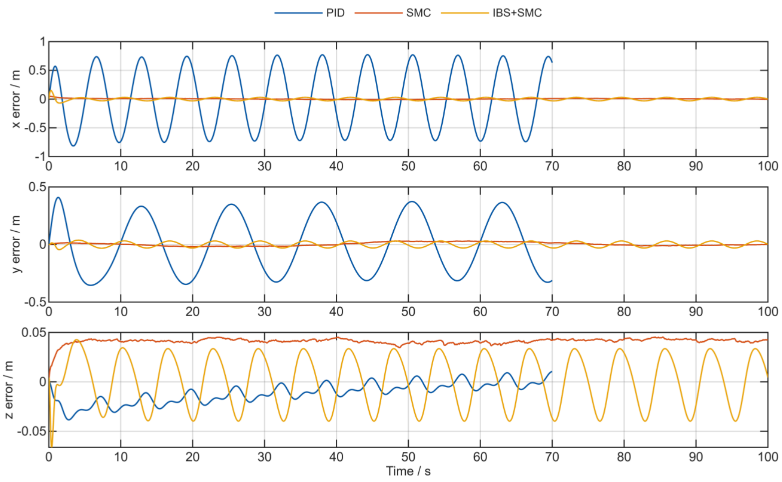

Figure 3. Position tracking errors of PID, SMC and IBS-SMC

Errors of SMC are kept within a narrow range, and the maximum error is strictly limited. It indicates that the sliding surface and robust terms can restrain error divergence. This characteristic meets the requirements of tasks demanding high safety margins and strict deviation limits, which is consistent with the conclusion that hyperplane fast terminal sliding mode control improves robust tracking performance under disturbances [12]. The error response of IBS-SMC still contains periodic fluctuations, but the overall error magnitude remains low and the terminal error is greatly reduced. This outcome conforms to the mechanism of integral compensation. The integral term cannot eliminate all dynamic oscillations during maneuvers, yet it can mitigate long-term accumulated deviations and improve final convergence. Therefore, the evaluation of IBS-SMC should take transient waveforms, terminal accuracy and persistent deviation suppression capacity into comprehensive consideration.

Figure 4 displays the attitude responses of the three controllers. The attitude curves of PID are relatively smooth, while the position errors remain large. It reveals that smooth attitude motion does not necessarily equate to high trajectory accuracy. The attitude response of SMC features more distinct fluctuations, which is caused by the intense corrective actions of sliding mode control to keep system states near the sliding surface. Such attitude adjustments do not lead to expanded position errors, but correspond to higher position tracking precision.

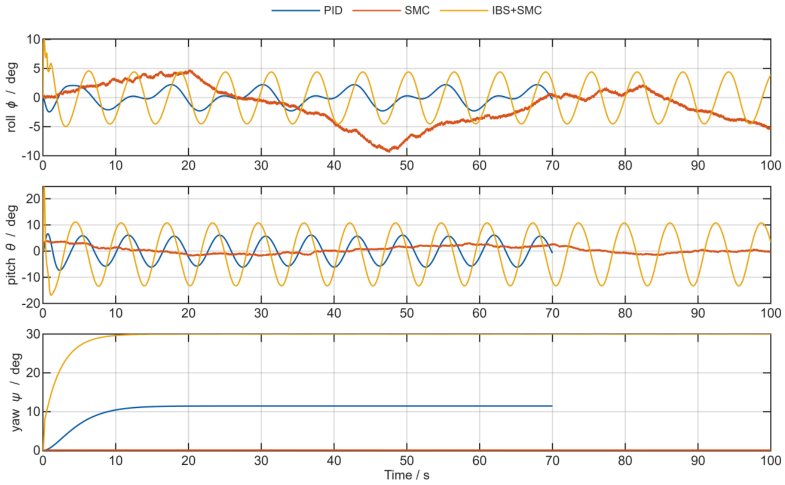

Figure 4. Attitude responses of PID, SMC and IBS-SMC

The attitude response of IBS-SMC matches the features of spiral trajectory and integral compensation. As the UAV needs to continuously adjust the thrust direction during ascent, periodic variations of roll angle and pitch angle are necessary attitude adjustments for trajectory tracking. Research on adaptive backstepping terminal sliding mode based on quaternions also points out that attitude representation and finite-time convergence exert vital influences on the tracking performance of quadrotors [13]. For quadrotors, attitude acts not only as a control output, but also as an intermediate variable for position tracking, so it should be analyzed together with position errors. Combining Figure 3 and Figure 4, it can be concluded that SMC focuses on error bound constraint, while IBS-SMC is optimized for robust tracking with terminal error correction.

3.3. Comprehensive performance comparison

Table 1. Position tracking performance indicators

Controller	RMSE_x/m	RMSE_y/m	RMSE_z/m	RMSE_3D/m	Maximum 3D Error/m	Terminal 3D Error/m
PID	0.5285	0.2472	0.0151	0.5836	0.8560	0.7062
SMC	0.0081	0.0156	0.0413	0.0449	0.0509	0.0431
IBS-SMC	0.0244	0.0220	0.0259	0.0419	0.1618	0.0050

Table 1 presents the position tracking performance indicators of the three controllers. Since PID, SMC and IBS-SMC are tested under different typical operating conditions with inconsistent reference trajectories, the numerical values in the table are mainly used to reflect the performance characteristics of each control structure. PID produces the largest errors because it lacks explicit robust compensation and relies primarily on feedback correction. SMC achieves the minimum maximum error, demonstrating its strong capacity to suppress instantaneous large deviations. IBS-SMC obtains the smallest overall three-dimensional root mean square error and the optimal terminal accuracy, which proves that the integral mechanism plays a positive role in compensating persistent deviations and improving final convergence. The above results are consistent with the theoretical expectations of the three control structures.

In practical engineering selection, the three controllers adapt to different performance requirements. PID is suitable for scenarios with low task risks, moderate accuracy requirements and limited implementation costs. SMC applies to tasks that require strictly bounded tracking errors under uncertain conditions and external disturbances. IBS-SMC is a better choice for missions focusing on terminal accuracy, persistent deviation suppression and long-duration tracking. Its structural complexity can bring prominent benefits in applications where final positioning accuracy is prioritized. If computational complexity, parameter tuning cost or attitude smoothness are major constraints, PID or SMC with smoothing processing will be more appropriate.

Controller evaluation should not rely on a single type of evidence. Trajectory diagrams reflect the overall fitting degree of flight paths but may conceal instantaneous error peaks. Error curves show dynamic deviations yet cannot independently evaluate the quality of attitude response. Attitude curves illustrate how roll and pitch motions act in translational control, but cannot replace the judgment of position accuracy. Numerical indicators provide statistical summaries, while their values are affected by trajectory scales and evaluation time windows. For this reason, trajectory patterns, error curves, attitude responses and statistical indicators shall be interpreted within a unified analytical framework and correlated with respective control structures.

The interpretation of results in this study is restricted by inconsistent operating conditions. The three groups of tests are carried out with different plant parameters, reference trajectories and disturbance inputs. Therefore, the indicators in the table shall not be regarded as a universal ranking of controller performance, but only as performance manifestations under corresponding working conditions. Further rigorous verification should be implemented on the three controllers with identical quadrotor models, reference trajectories and disturbance settings. Additional evaluation dimensions such as wind disturbance, actuator saturation, sensor noise, control energy consumption, chattering intensity and parameter sensitivity can also be incorporated.

There exists a trade-off between controller complexity and task performance. IBS-SMC excels in terminal convergence, but it requires more parameters and more complex nonlinear modeling compared with PID and conventional SMC. Relevant studies on disturbance observer based backstepping control have verified that introducing advanced compensation mechanisms is reasonable when unknown dynamics or severe disturbances impair task accuracy [14]. PID can meet basic tracking demands for low-complexity and low-risk tasks. SMC provides superior robustness for applications with bounded error requirements. IBS-SMC is more applicable to scenarios where terminal accuracy and accumulated error suppression are critical.

4. Conclusions

Aiming at the underactuated, nonlinear and strongly coupled characteristics of quadrotor UAV trajectory tracking, this study analyzes the performance differences of PID, SMC and IBS-SMC in terms of trajectory response, position error, attitude variation and quantitative indicators. The results show that PID features simple structure and low implementation cost, but generates considerable tracking errors when following periodic trajectories. SMC can greatly reduce the maximum tracking error and presents strong capability to constrain error bounds. IBS-SMC achieves the minimum overall three-dimensional root mean square error and terminal three-dimensional error, indicating that integral compensation effectively improves final convergence under persistent deviations. Accordingly, the selection of trajectory tracking controllers for quadrotors shall match task accuracy requirements, disturbance intensity, terminal positioning demands and implementation complexity. Follow-up research can conduct further verification under unified models and reference trajectories. Disturbance models, actuator constraints, control energy consumption and parameter sensitivity can be added into comprehensive evaluation, so as to more accurately analyze the trade-offs among robustness, tracking accuracy and motion smoothness.

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