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A Comprehensive Review of Flight Control Strategies for Quadrotor UAVS and Performance Analysis Using a Backstepping Control Method

Vu Xuan Tung, Le Thi Thu Ha, Nguyen Hoai Nam

Thai Nguyen University of Technology

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ABSTRACT

This paper presents a structured review of flight control strategies for quadrotor unmanned aerial vehicles and identifies key research gaps affecting reliable operation under uncertain conditions. The study applies a systematic classification and analytical comparison of control approaches, including linear control, nonlinear Lyapunov-based methods, sliding mode control, adaptive and observer-based control, predictive control, and learning-enhanced strategies. Based on this review, a backstepping-based trajectory tracking controller is developed as a representative case study. The quadrotor dynamic model is established using Newton–Euler equations and organized into a cascade control structure with an outer-loop position controller and an inner-loop attitude controller. Stability of the closed-loop system is ensured using Lyapunov theory. Simulation results show that the proposed controller achieves accurate trajectory tracking with position and attitude errors converging to zero within approximately 5–8 seconds, while maintaining stable and feasible control inputs. The results confirm that backstepping provides strong theoretical stability and good tracking performance under nominal conditions; however, its robustness remains limited when disturbances and uncertainties are present. Therefore, integrating disturbance observers and adaptive mechanisms into backstepping control is identified as a promising direction for improving robustness and practical applicability in quadrotor control systems.

Keywords: Quadrotor UAV; flight control; backstepping; adaptive control; trajectory tracking

INTRODUCTION

Quadrotor unmanned aerial vehicles have attracted extensive attention because they combine vertical takeoff and landing capability, hovering, compact structure, and high maneuverability. These characteristics make them suitable for inspection, mapping, surveillance, logistics, and rescue applications [1], [2]. However, despite their mechanical simplicity, quadrotors exhibit nonlinear, coupled, and underactuated dynamics, which make flight control a challenging problem.

A practical controller must ensure attitude stabilization and trajectory tracking while remaining robust to wind disturbances, sensor noise, payload variation, actuator limits, and parameter uncertainty [3], [4], [8]. For this reason, a wide range of control methods has been reported in the literature, including classical proportional–integral–derivative and linear quadratic regulator methods, nonlinear Lyapunov-based methods, sliding mode control, adaptive and observer-based approaches, predictive control, and learning-enhanced strategies [2]–[12]. Existing studies show that no single controller can simultaneously achieve low computational cost, strong robustness, and rigorous stability guarantees over the entire operating envelope [2], [3], [10].

Linear control methods such as proportional–integral–derivative and linear quadratic regulator remain widely used because of their simplicity and low computational cost. However, their performance deteriorates under strong nonlinearities, large maneuvers, and time-varying disturbances [2], [3]. Nonlinear Lyapunov-based methods, especially backstepping, are attractive because they match the cascade structure of quadrotor dynamics and provide explicit stability guarantees. Their main limitation is sensitivity to modeling errors and external disturbances when no additional compensation mechanism is included [5]–[7]. Sliding mode control provides

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strong robustness to matched disturbances, but chattering remains a significant drawback that may degrade actuator smoothness and increase wear [5], [11]. Adaptive and observer-based methods improve performance under uncertainty by estimating parameters or disturbances online, although they usually increase design and tuning complexity [4], [6], [9]. Model predictive control is effective for multivariable optimization and constraint handling, but its computational demand remains a limitation for embedded implementation [10]. Learning-enhanced control methods offer higher flexibility in complex environments, but stability certification and real-time reliability are still open issues [9], [12].

Among nonlinear methods, backstepping remains particularly attractive because quadrotor dynamics can be organized in a cascade structure that is suitable for recursive Lyapunov design [5]–[7]. Recent studies also show that backstepping can be extended with disturbance observers, adaptive laws, and intelligent estimators to improve robustness [4]–[7], [9], [11]. Overall, the literature shows that no single controller simultaneously provides simplicity, robustness, and strict stability guarantees. Backstepping remains a promising baseline because of its analytical transparency and compatibility with quadrotor cascade dynamics, but practical deployment requires augmentation through disturbance estimation or adaptive compensation.

Therefore, this paper provides a concise review of recent quadrotor control strategies and presents a backstepping-based trajectory tracking controller as a representative case study. The paper aims to identify current research gaps and highlight promising directions for robust quadrotor control. The main contributions of this paper can be summarized as follows: (1) a structured and up-to-date review of quadrotor control strategies covering recent developments from 2022 to 2025; (2) an analytical comparison of classical, nonlinear, robust, adaptive, predictive, and learning-based control approaches; (3) a backstepping-based trajectory tracking controller as a representative case study linking theoretical analysis with practical implementation; (4) identification of key research gaps, particularly the need to balance robustness, computational efficiency, and experimental validation; and (5) proposed future research directions emphasizing disturbance-observer-assisted and adaptive backstepping control architectures.

Proposed Control Strategy for the Case Study

Quadrotor Dynamic Model

Figure 1 illustrates the quadrotor geometry and the coordinate frames used in the dynamic model.

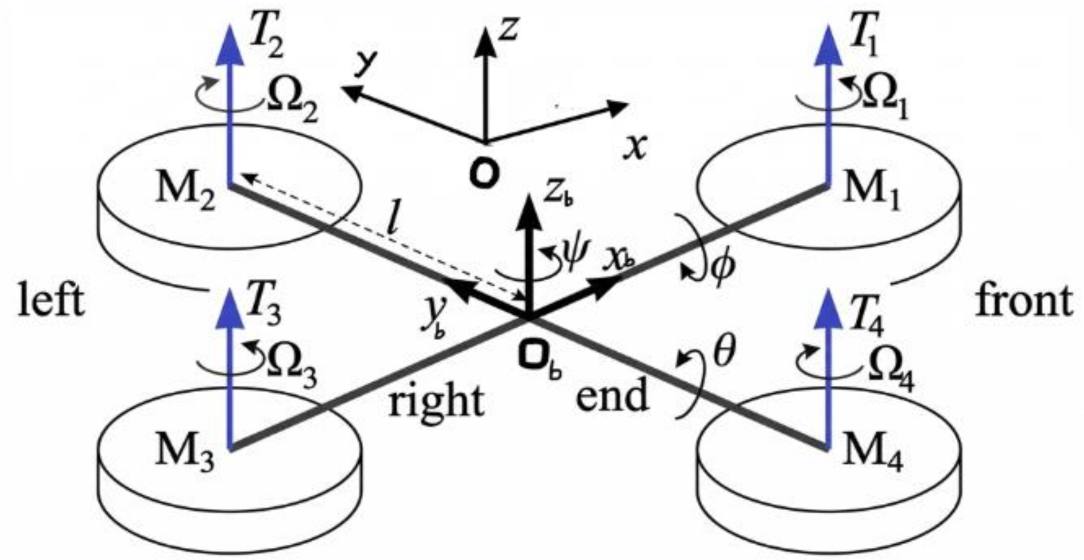

Figure 1. Quadrotor geometry and coordinate frames used for dynamic modeling.

The quadrotor operates by independently controlling the rotational speed of four rotors to generate lift and control torque. Figure 1 illustrates the direction of rotation of the rotors and the direction of thrust generated. As the rotors rotate, they generate torque in the opposite direction to the direction of rotation. Therefore, designing

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symmetrical rotors rotating in opposite directions (motors 1 and 3 rotate in the same direction, opposite to motors 2 and 4) helps to cancel out the total torque, preventing the quadrotor from rotating unintentionally.

Figure 2 shows the basic motion primitives of the quadrotor, including vertical motion, yaw, roll, and pitch generated by rotor-speed variation.

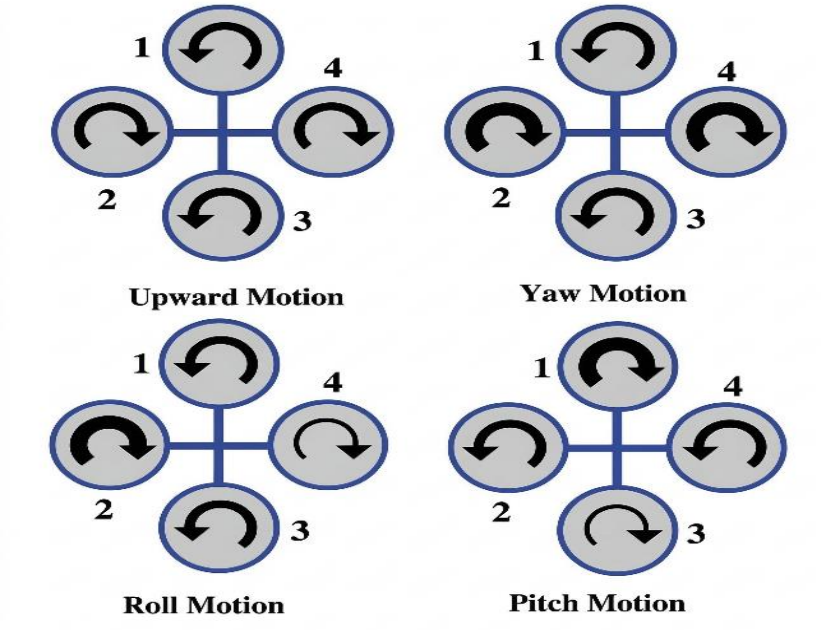

Figure 2. Quadrotor motion primitives: (a) vertical motion, (b) yaw, (c) roll, and (d) pitch.

The quadrotor performs an upward movement, with its four propellers rotating at the same speed and in opposite directions to generate a combined lift force large enough to overcome the drone's gravity and propel it upwards. To achieve the yaw (rotation around the vertical axis) of the quadrotor, by varying the speed of propeller pairs rotating in the same direction (e.g., increasing the speed of pair 1-3 and decreasing the speed of pair 2-4), the system creates a torque difference in the opposite direction, allowing the device to perform a body rotation without changing altitude. The roll control mechanism creates a lift difference between the left and right sides; specifically, the rotation speed of engine number 2 increases (bold line) while engine number 4 decreases (thin line), creating torque around the vertical axis of the aircraft body, causing the quadrotor to tilt to the right. Pitch motion occurs through the creation of a lift difference between the front and rear engine pairs. Specifically, as engine speed increases (bold line) and engine speed decreases (thin line), torque is generated around the horizontal axis of the fuselage, causing the Quadrotor to perform pitching or tilting maneuvers.

The Quadrotor's dynamic model is based on Newton-Euler equations in both fixed and object-attached reference frames. The equations of motion are described as follows:

$$\begin{cases} \ddot{x} = \dfrac{1}{m}\left(C_\phi S_\theta C_\psi + S_\phi S_\psi\right)T - \dfrac{A_x}{m}\dot{x} + d_x \\ \ddot{y} = \dfrac{1}{m}\left(C_\phi S_\theta S_\psi - S_\phi C_\psi\right)T - \dfrac{A_y}{m}\dot{y} + d_y \\ \ddot{z} = \dfrac{1}{m}\left(C_\phi C_\theta\right)T - \dfrac{A_z}{m}\dot{z} + d_z \\ \ddot{\phi} = \dot{\theta}\dot{\psi}\dfrac{I_{yy} - I_{zz}}{I_{xx}} - \dot{\theta}\dfrac{I_r}{I_{xx}}\omega_\Gamma + \dfrac{\tau_\phi}{I_{xx}} + d_\phi \\ \ddot{\theta} = \dot{\phi}\dot{\psi}\dfrac{I_{zz} - I_{xx}}{I_{yy}} + \dot{\phi}\dfrac{I_r}{I_{yy}}\omega_\Gamma + \dfrac{\tau_\theta}{I_{yy}} + d_\theta \\ \ddot{\psi} = \dot{\phi}\dot{\theta}\dfrac{I_{xx} - I_{yy}}{I_{zz}} + \dfrac{\tau_\psi}{I_{zz}} + d_\psi \end{cases} \quad (1)$$

In this case, the symbols C(.) and S(.) respectively represent the cos(.) and sin(.) functions of the Euler angles.

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The total lift force of the 4 propellers is:

$$T = \sum_{i=1}^{4} T_i = k\sum_{i=1}^{4} \omega_i^2 = k\left(\omega_1^2 + \omega_2^2 + \omega_3^2 + \omega_4^2\right) \tag{2}$$

The torque acting on each axis of rotation is:

$$\begin{cases} \tau_\phi = kl(\omega_4^2 - \omega_2^2) \\ \tau_\theta = kl(\omega_3^2 - \omega_1^2) \\ \tau_\psi = b(-\omega_1^2 + \omega_2^2 - \omega_3^2 + \omega_4^2) \end{cases} \tag{3}$$

Backstepping Controller Design

Figure 3 presents the cascade backstepping control architecture used in this study.

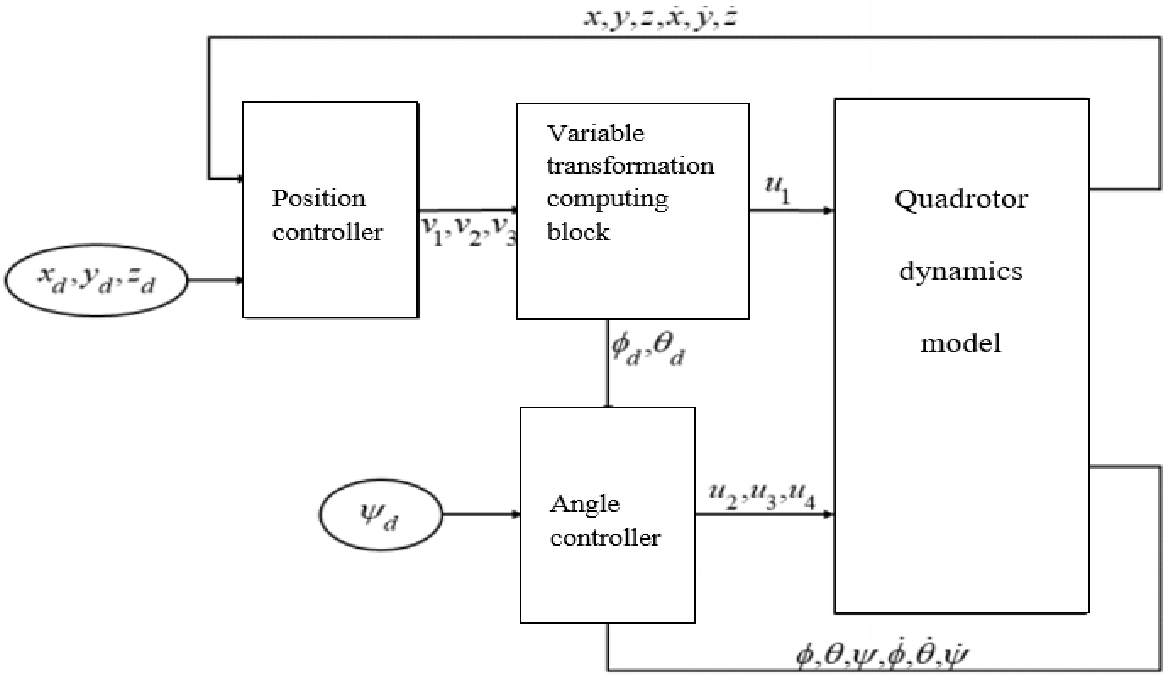

Figure 3. Cascade backstepping flight-control architecture: outer-loop position control and inner-loop attitude control.

The control structure is divided into two loops. The outer loop regulates translational motion and produces virtual control signals for x, y, and z tracking. These virtual signals are then converted into desired roll and pitch references and a collective thrust command. The inner loop stabilizes roll, pitch, and yaw through backstepping laws obtained by recursive Lyapunov design. Each subsystem is expressed in a backstepping-compatible form and equipped with Lyapunov functions whose time derivatives become negative under the selected virtual and actual control laws.

Lemma 1: Consider a linear system with the following backpropagation structure:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = u + f\left(x_1, x_2\right) \end{cases} \tag{4}$$

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The controller $u = -x_1 - a_0\dot{x}_1 - f(x_1, x_2) - a_1(x_2 + a_0x_1)$ with $a_0, a_1 > 0$ makes the (4) system asymptotically stable globally.

Prove:

Consider the Lyapunov function:

$$V_1 = \frac{1}{2}x_1^2 \rightarrow \dot{V}_1 = x_1\dot{x}_1 = x_1.x_2 \tag{5}$$

Therefore, with a virtual control signal, $x_2 = r_1(x_1) = -a_0x_1, a_0 > 0$ then

$$\dot{V}_1 = -a_0x_1^2 \leq 0, \forall x_1 \tag{6}$$

Consider the Lyapunov function:

$$V_2 = V_1 + \frac{1}{2}(x_2 - r_1(x_1))^2 \tag{7}$$

Therefore:

$$\begin{aligned} \dot{V}_2 &= \dot{V}_1 + (x_2 - r_1(x))(\dot{x}_2 - \dot{r}_1(x)) \\ &= -a_0x_1^2 + (x_2 + a_0x_1)(u + f(x_1, x_2) + a_0\dot{x}_1 + x_1) \end{aligned} \tag{8}$$

Select a controller:

$$u = -x_1 - a_0\dot{x}_1 - f(x_1, x_2) - a_1(x_2 + c_0x_1), a_1 > 0 \tag{9}$$

Replace equation (9) with equation (8).

$$\dot{V}_2 = -a_0x_1^2 - a_1(x_2 + a_0x_1)^2 \leq 0, \forall x_1, x_2 \tag{10}$$

The equality sign "=" occurs if and only if $x_1 = x_2 = 0$

The main benefit of this strategy is analytical clarity: the underactuated quadrotor is decomposed into tractable subsystems, global asymptotic stability is argued in the nominal case, and trajectory tracking can be implemented without requiring online optimization. However, the nominal design neglects exogenous disturbances during controller synthesis, which motivates the future addition of a disturbance observer or adaptive estimator.

RESULTS AND DISCUSSION

Quadrotor Specifications:

Parameter	Value	Parameter	Value
m	0.8(kg)	g	9.8
k	2.98e-5	I_{xx}	0.01
b	3.23e-7	I_{yy}	0.01
l	0.3	I_{zz}	0.0148

Simulation results:

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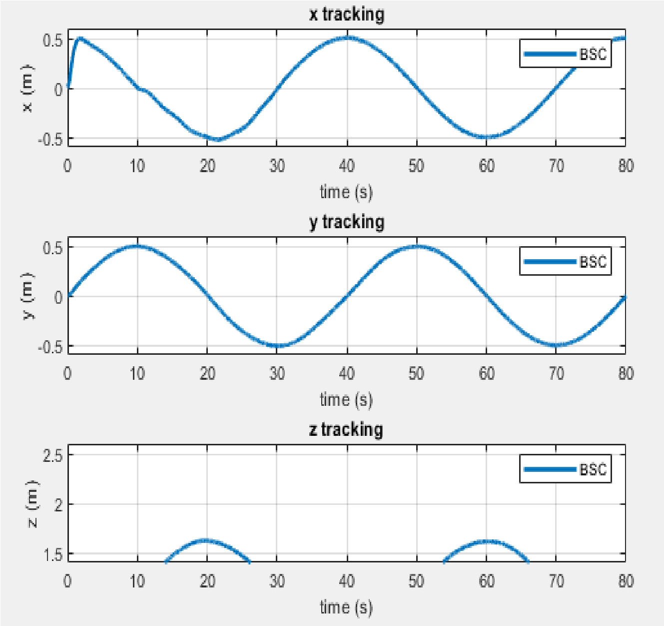

Figure 4: Position responses during trajectory tracking.

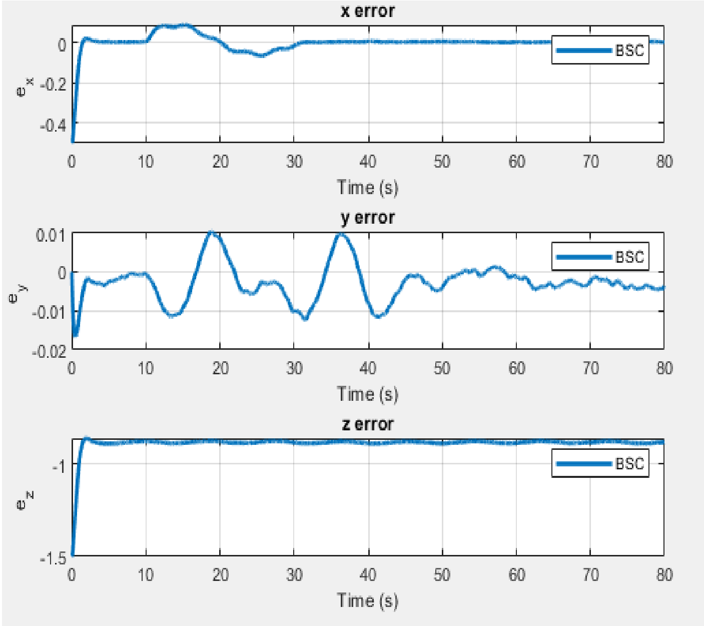

Figure 5. Position tracking errors along the x, y, and z axes

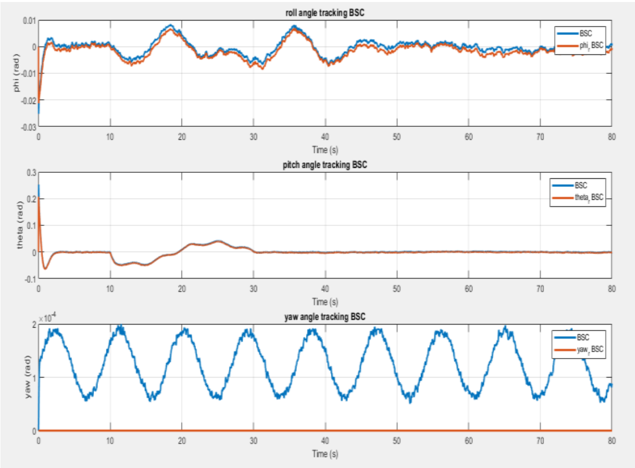

Figure 6. Attitude responses in roll, pitch, and yaw.

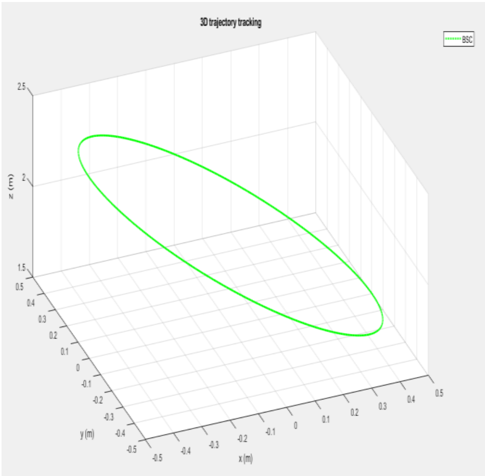

Figure 7. Overall three-dimensional flight path during trajectory tracking.

Figure 4 shows the time responses of the x, y, and z coordinates during trajectory tracking. The actual states follow the reference signals with small steady-state deviation after the initial transient. Figure 5 presents the corresponding position errors, indicating that the tracking errors along the three axes decrease rapidly and remain close to zero after approximately 5–8 seconds. Figure 6 displays the attitude responses, showing that roll, pitch, and yaw tracking remains bounded and stable during the maneuver. Figure 7 illustrates the overall three-dimensional flight path and confirms that the vehicle follows the desired spatial trajectory without instability.

Overall, the simulation results indicate that the proposed backstepping controller provides stable nominal tracking with smooth responses and feasible control behavior. These observations are consistent with the expected properties of a Lyapunov-based cascade design. However, the study still has three practical limitations: model parameters are assumed rather than experimentally identified, no disturbance observer is included, and the controller has not yet been validated on hardware. Accordingly, the current design should be viewed as a baseline controller that is suitable for further development toward disturbance-observer-assisted or adaptive backstepping schemes.

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CONCLUSION

This study combined a concise review of recent quadrotor control strategies with a backstepping-based trajectory-tracking case study. The review indicates that current research is moving toward hybrid controllers that combine model-based design with disturbance estimation, adaptation, or learning support. Within this context, backstepping remains useful because it fits the cascade structure of quadrotor dynamics and provides a clear Lyapunov-based design framework.

In the simulated case considered here, the controller was able to follow the prescribed trajectory with stable position and attitude responses, and the main tracking errors decreased to near zero after about 5–8 s. These results show that backstepping is still a practical baseline for nominal quadrotor control. At the same time, the present model does not explicitly compensate for disturbances, parameter mismatch, or hardware effects. Future work will therefore focus on integrating disturbance observation or adaptive compensation into the current design and validating the method on an experimental platform.

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