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Robust Trajectory Tracking Control for Quadrotor UAVs with Prescribed Performance Constraints

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Abstract

Achieving high-precision trajectory tracking for quadrotor unmanned aerial vehicles (UAVs) is frequently impeded by complex operating environments involving aerodynamic disturbances, parameter uncertainties, and potential actuator performance degradation. To guarantee flight safety and tracking accuracy under these adversarial conditions, this paper presents a robust control strategy that integrates a prescribed performance mechanism with sliding mode control. First, to decouple the tracking precision from system uncertainties, a prescribed performance envelope is constructed. By transforming the tracking error dynamics, this mechanism ensures that the positional and attitudinal deviations are strictly confined within a predefined decaying funnel, guaranteeing convergence irrespective of the initial error magnitude. Second, a robust nonsingular fast terminal sliding mode controller is synthesized based on the transformed dynamics. Unlike complex composite methods that rely on explicit fault estimation units, this controller utilizes a robust reaching law to directly suppress the lumped uncertainties and stabilize the system in finite time. Numerical simulations confirm that the proposed scheme effectively restricts tracking errors within the user-defined boundaries even in the presence of simultaneous actuator faults and external disturbances, demonstrating superior robustness and transient performance.

Keywords: Quadrotor UAV, Prescribed Performance Control (PPC), Sliding Mode Control (SMC), Robust Control, Trajectory Tracking

1. Introduction

With the rapid maturation of aviation technology, the ”low-altitude economy” is emerging as a new engine for global economic growth, reshaping industries ranging from logistics and agriculture to aerial inspection and urban air mobility [1-2]. As the primary execution platform within this ecosystem, quadrotor Unmanned Aerial Vehicles (UAVs) have garnered ubiquitous attention from both academia and industry. Their mechanical simplicity, vertical take-off and landing (VTOL) capabilities, and agile maneuverability make them ideal for diverse and complex missions [3-4]. However, as application scenarios expand into unstructured and hostile environments, quadrotors are increasingly confronted with severe operational challenges. These systems are inherently underactuated, strongly coupled, and highly nonlinear [5]. Furthermore, during prolonged operations, they are inevitably subjected to a confluence of adverse factors, including turbulent aerodynamic disturbances, payload variations, and actuator performance degradation [6], [7]. Specifically, actuator faults—such as the partial loss of thrust efficiency due to motor aging or propeller damage—can induce significant asymmetric torques, potentially leading to catastrophic system instability if not properly compensated [8-9]. Therefore, designing a control architecture that ensures rigorous tracking precision and flight safety under these compounded uncertainties remains an imperative research priority.

To tackle the control problems of nonlinear systems subject to uncertainties, a myriad of methodologies have been investigated, including Proportional-Integral-Derivative (PID) control, H_∞ robust control, and Adaptive Control [10-12]. Among these, Sliding Mode Control (SMC) has established itself as a dominant paradigm due to its structural simplicity and inherent invariance to matched uncertainties once the system states are driven onto the sliding manifold [13]. Conventional linear SMC, however, theoretically guarantees only asymptotic convergence, implying that the tracking error approaches zero as time tends to infinity. This characteristic is often insufficient for time-critical missions requiring rapid response. To ameliorate the convergence rate, Terminal Sliding Mode Control (TSMC) was introduced, which incorporates nonlinear fractional-power terms into the sliding surface to enforce finite-time convergence [14-15]. Despite this improvement, standard TSMC suffers from the singularity problem—where the control input may become unbounded—and slow convergence rates when system states are far from the equilibrium.

To overcome these limitations, advanced variants such as Fast Terminal Sliding Mode Control (FTSMC) and Nonsingular Fast Terminal Sliding Mode Control (NFTSMC) have been developed [16-17]. By designing specific recursive sliding surfaces, NFTSMC achieves both singularity avoidance and rapid convergence near and far from the equilibrium [18]. Nevertheless, a persistent challenge in SMC design is the trade-off between disturbance rejection capability and control smoothness. High-gain switching terms, often employed to dominate large lumped disturbances (including faults), inevitably induce high-frequency chattering [19]. This phenomenon not only excites unmodeled structural dynamics but also accelerates actuator wear, which is detrimental to the hardware longevity of small-scale quadrotors. Consequently, there is a pressing need for a ”streamlined” robust control strategy that leverages the fast convergence of NFTSMC while mitigating chattering without relying on computationally expensive observation units. Furthermore, in safety-critical aerial operations—such as maneuvering through cluttered urban canyons or interacting with dynamic obstacles—ensuring stability alone is insufficient. It is equally critical to guarantee that the trajectory tracking errors evolve strictly within permissible geometric boundaries to prevent collisions or aggressive overshoots [20]. To address this, Prescribed Performance Control (PPC) was pioneered by Bechlioulis and Rovithakis [21], offering a systematic framework to impose rigorous constraints on both transient and steady-state responses. By transforming the constrained error dynamics into an equivalent unconstrained form using decaying envelope functions, PPC ensures that the system states evolve exclusively within a pre-defined ”funnel” [22]. This methodology has been successfully applied to various robotic systems to decouple tracking performance from initial conditions [23]. However, applying PPC to underactuated quadrotors subject to aggregated disturbances remains nontrivial. Existing solutions often resort to complex approximation structures, such as Neural Networks or Fuzzy Logic systems, to compensate for the transformed nonlinearities [24], [25]. While effective, these data-driven approaches impose a substantial computational burden on the onboard processors of small-scale UAVs and may suffer from training uncertainties.

Despite the extensive literature on SMC and PPC individually, there remains a scarcity of research that organically integrates the rigorous safety constraints of PPC with a streamlined, computation-efficient robust sliding mode framework. Most existing ”fault-tolerant” schemes rely heavily on active Fault Detection and Diagnosis (FDD) modules or disturbance observers to estimate uncertainties [26]. While these observers enhance performance, they inevitably introduce estimation latency and increase the algorithmic complexity. For highly dynamic quadrotors operating in real-time, there is a distinct need for a control strategy that can handle simultaneous actuator faults and external disturbances via intrinsic robustness, without the need for explicit fault estimation or complex model approximation.

In light of the aforementioned challenges, this paper proposes a composite robust control architecture tailored for quadrotor UAVs operating under adversarial conditions. Departing from complex observer-based paradigms, this work focuses on a model-independent strategy. The central innovation lies in the synergistic integration of a standard exponential prescribed performance mechanism with a robust Nonsingular Fast Terminal Sliding Mode Control (NFTSMC) scheme. By mathematically transforming the tracking error dynamics, the proposed framework effectively ”encapsulates” the system irregularities—ranging from external aerodynamic disturbances to internal actuator efficiency losses—into a bounded uncertainty term, which is then stabilized by the robust controller.

The salient contributions distinguishing this work from prior art are articulated as follows:

1) **Construction of a Safety-Critical Constraint Mechanism:** A prescribed performance formulation is constructed to impose rigorous geometric constraints on the quadrotor’s trajectory tracking errors. Unlike asymptotic methods, this mechanism guarantees that the position and attitude deviations remain strictly confined within a user-defined, exponentially decaying funnel throughout the entire mission profile [27]. This effectively decouples the transient performance from the initial conditions and system uncertainties, ensuring predictable operational safety.

2) **Synthesis of a Streamlined Robust Controller:** A robust tracking controller is developed by leveraging a nonsingular fast terminal sliding mode surface based on the transformed error dynamics. Distinct from conventional strategies that rely on auxiliary disturbance observers, this controller utilizes an inherent robustness margin to directly suppress the lumped uncertainties. This design significantly reduces the algorithmic

complexity and eliminates the dependency on precise fault modeling, making it highly suitable for real-time implementation on resource-constrained aerial platforms.

The remainder of this paper is structured as follows. Section III establishes the mathematical foundations, describing the quadrotor dynamics and the problem formulation. Section IV details the derivation of the prescribed performance transformation and the synthesis of the robust sliding mode controller. Section V presents a comprehensive numerical validation under simulated fault scenarios. Finally, Section VI concludes the paper and outlines directions for future inquiry.

2. System Modeling And Problem Formulation

The quadrotor UAV is modeled as a rigid body operating within the inertial North-East-Down (NED) frame. For mathematical tractability, the structure is assumed to be symmetric with the center of mass coinciding with the geometric center. While the effects of Earth's curvature are negligible, the dynamics are subject to aerodynamic drag and unknown disturbances.

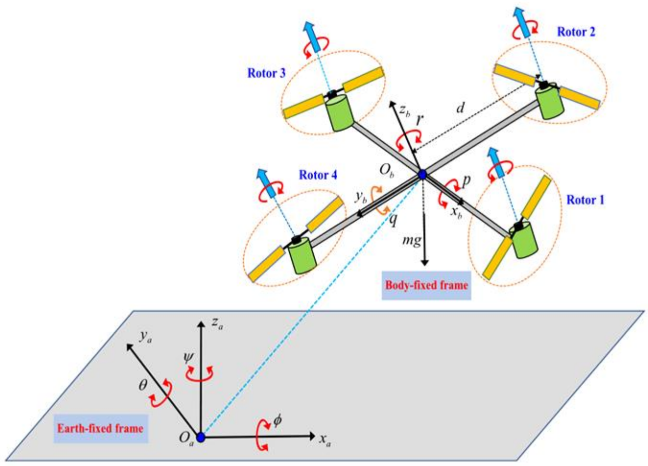


Figure 1. Schematicrepresentationofthequadrotorconfgura-tion,illustratingtheinertialframe(O_I)andthebody-fxed frame(O_B).

A. Dynamic Equations

By applying the Newton-Euler formalism, the translational and rotational motions are governed by the following differential equations:

1) Translation Subsystem:

$$\ddot{x} = \frac{U_1}{m}(\cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi) - \frac{c_x}{m}\dot{x} + d_x \quad (1)$$

$$\ddot{y} = \frac{U_1}{m}(\cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi) - \frac{c_y}{m}\dot{y} + d_y \quad (2)$$

$$\ddot{z} = \frac{U_1}{m}\cos\phi\cos\theta - g - \frac{c_z}{m}\dot{z} + d_z \quad (3)$$

2) Rotation Subsystem:

$$\ddot{\phi} = \frac{U_2}{I_{xx}} + \dot{\theta}\dot{\psi}\frac{I_{yy} - I_{zz}}{I_{xx}} - \frac{c_\phi}{I_{xx}}\dot{\phi} + d_\phi \quad (4)$$

$$\ddot{\theta} = \frac{U_3}{I_{yy}} + \dot{\phi}\dot{\psi}\frac{I_{zz} - I_{xx}}{I_{yy}} - \frac{c_\theta}{I_{yy}}\dot{\theta} + d_\theta \quad (5)$$

$$\ddot{\psi} = \frac{U_4}{I_{zz}} + \dot{\phi}\dot{\theta}\frac{I_{xx} - I_{yy}}{I_{zz}} - \frac{c_\psi}{I_{zz}}\dot{\psi} + d_\psi \quad (6)$$

In the above formulation, $U1$ denotes the total thrust, while $U2$, $U3$, $U4$ represent the control torques for roll, pitch, and yaw, respectively. The terms $d(\cdot)$ signify the external disturbances and unmodeled aerodynamics acting on each channel.

B. Unified Control Formulation

To facilitate the robust controller design, the system dynamics (1)–(6) are rewritten into a unified affine nonlinear form:

$$\ddot{\nu}_i = F_i(\boldsymbol{\nu}, \dot{\boldsymbol{\nu}}) + B_i U_i + D_i(t), \quad i = 1, \ldots, 6 \qquad (7)$$

sents the known nonlinear dynamics (Coriolis, centripetal, and gravitational forces), and B_i is the control gain (e.g., $1/m$ or $1/I_{xx}$).

Remark on Uncertainties: The term $D_i(t)$ represents the *lumped uncertainty*. In this study, $D_i(t)$ accounts for not only external environmental disturbances but also internal parameter perturbations and *actuator efficiency losses* (i.e., faults). Since the proposed control strategy is robust by design, explicit modeling of these faults is not required; instead, they are treated as bounded disturbances to be suppressed by the controller

C. Reference Generation

Given the underactuated nature of the quadrotor, the desired roll (ν_4^d) and pitch (ν_5^d) angles are derived from the virtual positional control inputs using the standard inverse kinematic mapping:

$$\nu_4^d = \arcsin\left(\frac{U_{1x}\sin\nu_6^d - U_{1y}\cos\nu_6^d}{\sqrt{U_{1x}^2 + U_{1y}^2 + (U_{1z}+g)^2}}\right) \qquad (8)$$

$$\nu_5^d = \arctan\left(\frac{U_{1x}\cos\nu_6^d + U_{1y}\sin\nu_6^d}{U_{1z}+g}\right) \qquad (9)$$

where U_{1x}, U_{1y}, U_{1z} are the virtual accelerations computed by the position loop controllers.

3. Robust Control Design

A. Prescribed Performance Constraint Formulation

To guarantee that the quadrotor achieves the desired transient behavior and steady-state tracking precision, a prescribed performance mechanism is adopted. The primary objective is to confine the tracking error $e_i(t)$ strictly within a decreasing region bounded by a smooth envelope function $\delta_i(t)$. This constraint is mathematically expressed as:

$$-\delta_i(t) < e_i(t) < \delta_i(t), \quad \forall t \geq 0 \qquad (10)$$

In this study, to ensure a smooth convergence profile without singularity issues, a standard exponential decay function is selected for the performance boundary $\delta_i(t)$:

$$\delta_i(t) = (\delta_{i,0} - \delta_{i,\infty})\exp(-l_i t) + \delta_{i,\infty} \qquad (11)$$

where $\delta_{i,0} > |e_i(0)|$ represents the initial permissible range, $\delta_{i,\infty} > 0$ denotes the maximum allowable steady-state error, and the positive constant l_i governs the convergence rate of the funnel.

To facilitate the controller design, the constrained error $e_i(t)$ is transformed into an unconstrained variable $\xi_i(t)$ using the inverse hyperbolic tangent function. This transformation allows the constrained problem to be solved using standard stabilization techniques:

$$\xi_i(t) = \text{arctanh}\left(\frac{e_i(t)}{\delta_i(t)}\right) \qquad (12)$$

It is theoretically proven that if the transformed state $\xi_i(t)$ is bounded, the original tracking error $e_i(t)$ is guaranteed to remain strictly within the prescribed boundaries defined in (10).

B. Robust Control Synthesis via Nonsingular Sliding Manifold

Based on the transformed error dynamics derived in (**??**), the control objective is converted into stabilizing the variable $\xi_i(t)$. To achieve this while ensuring rapid convergence and avoiding the singularity issues often found in conventional terminal sliding modes, a specific nonsingular fast terminal sliding manifold is constructed. Unlike linear hyperplanes, this manifold is formulated as:

$$S_i(t) = \dot{\xi}_i(t) + \alpha_i \xi_i(t) + \beta_i \varphi(\xi_i(t)) \qquad (13)$$

where the nonlinear term is defined as $\varphi(\xi_i) = |\xi_i|^{\gamma_i} \mathrm{sign}(\xi_i)$. The parameters α_i , $\beta_i > 0$ regulate the convergence speed, and the exponent is selected as $0 < \gamma_i < 1$ to guarantee finite-time reachability near the equilibrium.

The temporal evolution of the sliding variable is obtained by differentiating (13) and incorporating the open-loop dynamics:

$$\dot{S}_i(t) = \tilde{F}_i + \tilde{G}_i U_i(t) + \tilde{D}_i + \alpha_i \dot{\xi}_i + \beta_i \gamma_i |\xi_i|^{\gamma_i - 1} \dot{\xi}_i \qquad (14)$$

To effectively suppress the lumped uncertainty $\tilde{D}_i$ (which is assumed to be upper-bounded by $\bar{D}_i$) and force the system trajectory onto the sliding surface $S_i(t) = 0$, the control actuation signal $U_i(t)$ is synthesized as follows:

$$U_i(t) = -\tilde{G}_i^{-1} \left[\tilde{F}_i + \Phi_i(\xi_i, \dot{\xi}_i) + \mathcal{U}_{rob,i}(t) \right] \qquad (15)$$

In the above control law, $\Phi_i(\cdot) = \alpha_i \dot{\xi}_i + \beta_i \gamma_i |\xi_i|^{\gamma_i - 1} \dot{\xi}_i$ compensates for the known system dynamics. The term $\mathcal{U}_{rob,i}(t)$ serves as the robust component, designed to dominate the disturbances:

$$\mathcal{U}_{rob,i}(t) = k_{s,i} S_i(t) + (\bar{D}_i + \eta_i)\mathrm{sign}(S_i(t)) \qquad (16)$$

where $k_{s,i} > 0$ is the feedback gain and $\eta_i > 0$ is a small margin constant ensures that the reaching condition is met.

Stability Verification: The stability can be verified through the scalar potential function $V_i = 0.5 S_i^2$. By applying the control command (15), the time derivative of V_i satisfies:

$$\dot{V}_i = S_i \tilde{D}_i - k_{s,i} S_i^2 - (\bar{D}_i + \eta_i)|S_i| \qquad (17)$$

Given that $S_i \tilde{D}_i \le |S_i| \bar{D}_i$, the inequality simplifies to $\dot{V}_i \le -k_{s,i} S_i^2 - \eta_i |S_i|$, which implies that the sliding variable is driven to zero in finite time, consequently ensuring the convergence of the tracking error $\xi_i(t)$.

4. Numerical Validation

The operational capability and resilience of the designed control architecture are examined through numerical trials on a modeled quadrotor platform. Geometric and inertial specifications of the system are detailed in Table I. The central aim of this investigation is to substantiate that the tracking deviations remain encapsulated within the prescribed envelopes, even under scenarios involving significant actuator degradation and external excitations.

Table 1. Physical Model Parameters.

Symbol	Value	Units
m	0.8	kg
g	9.81	m/s^2
I_{xx}, I_{yy}	0.082	kg·m^2
I_{zz}	0.149	kg·m^2
d	0.45	m
b	2×10^{-6}	N/(rad/s)^2
d_{drag}	2.1×10^{-7}	N·m/(rad/s)^2

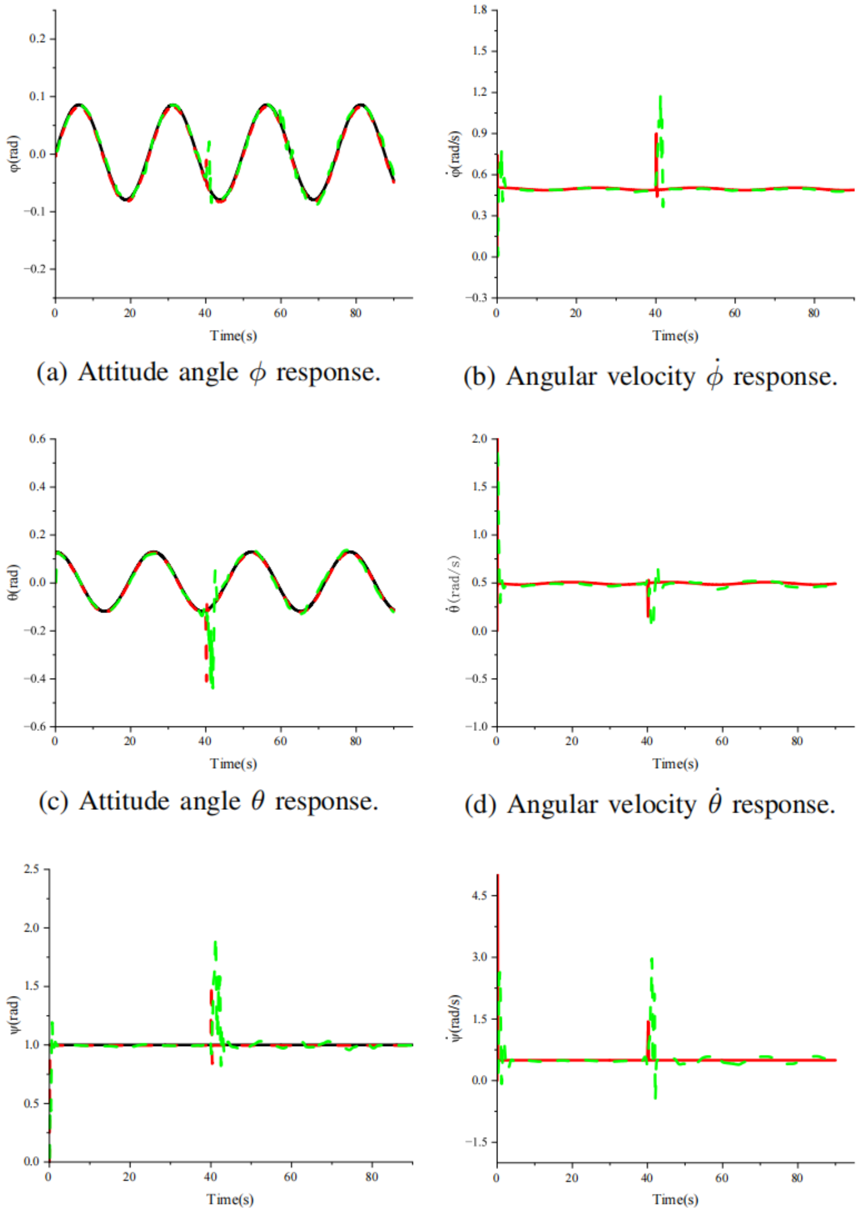
A. Performance Assessment under Adversarial Conditions

To rigorously challenge the system's robustness, a com posite adversarial scenario is synthesized. While tracking the reference trajectory, the UAV encounters a sudden onset of multiple perturbations at the timestamp $t = 40$ s:

1) **Propulsion Efficiency Decay:** A multiplicative loss is imposed on the four rotors with factors of 0.85, 0.80, 0.75, and 0.70, respectively, mimicking partial component failure.

2) **Environmental Perturbations:** Time-varying external torques, modeled as $d(t) = [1 + e^{-t/2} + \sin(t), \ldots]^T$, are superimposed onto the attitude dynamics. Inspection of the trajectory outcomes in Fig. 2 reveals the system's

dynamic behavior. It is evident that concurrent with the fault injection at the 40-second mark, transient oscillations occur across the state variables. However, driven by the robust compensation terms within the sliding mode law, the controller swiftly suppresses these unmatched uncertainties.



(a) Attitude angle ϕ response. (b) Angular velocity $\dot{\phi}$ response.

(c) Attitude angle θ response. (d) Angular velocity $\dot{\theta}$ response.

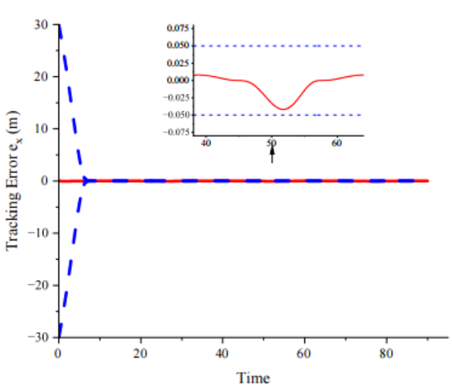
(e) Attitude angle ψ response. (f) Angular velocity $\dot{\psi}$ response.

Figure 2. System response under simultaneous fault injection and disturbances at $t = 40$s. The dashed red trajectories (Proposed) exhibit rapid recovery to the black reference lines, indicating strong disturbance rejection.

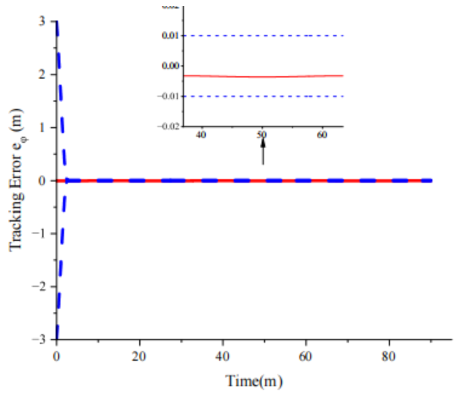
Consequently, the UAV state restores alignment with the desired path rapidly, avoiding divergent behavior or prolonged instability.

Crucially, Fig. 3 visualizes the error dynamics in relation to the imposed constraints. As depicted, the tracking deviations for all axes are rigidly confined within the shrinking funnels (blue dashed boundaries) throughout the entire flight duration. Even under the abrupt dynamic shifts caused by the composite disturbances, the error signals do not breach the safety envelopes. This empirical evidence corroborates that the error transformation mechanism effectively decouples control precision from model inaccuracies, thereby guaranteeing predictable system behavior.

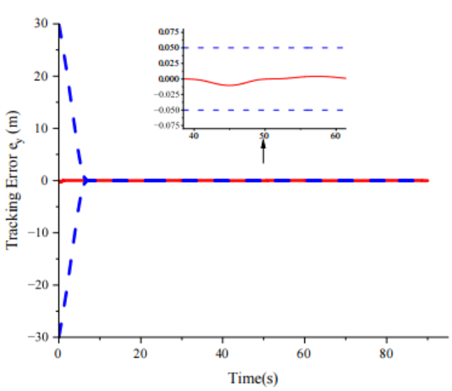
Collectively, the numerical data confirms that the proposed robust scheme delivers precise tracking and rapid stabilization, successfully mitigating the effects of component degradation and environmental interference without relying on explicit fault estimation units.



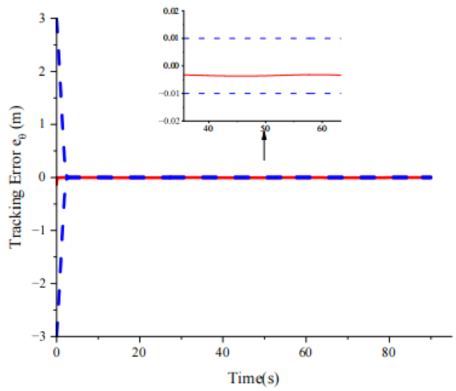
(a) Position error in x-axis.



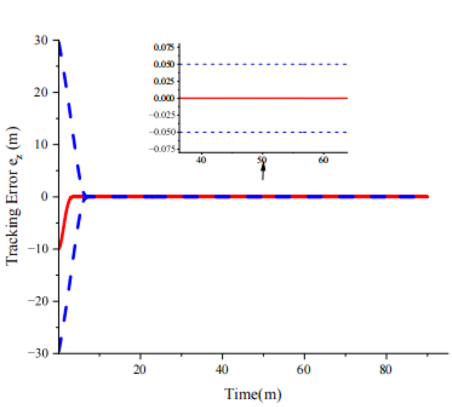
(b) Attitude error for ϕ.



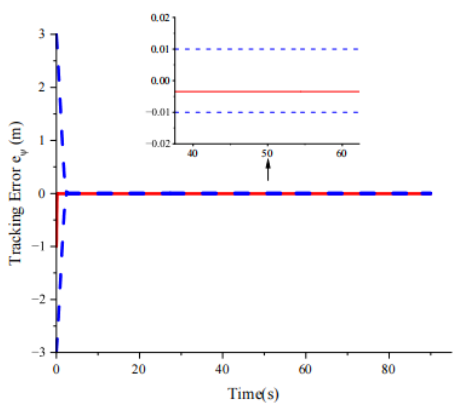
(c) Position error in y-axis.



(d) Attitude error for θ.



(e) Position error in z-axis.



(f) Attitude error for ψ.

Figure 3. Visualization of tracking errors constrained by the prescribed performance funnels. The actual error signals (solid red) are strictly bounded by the decaying envelopes (dashed blue), verifying the safety mechanism.

5. Conclusion

This work has investigated the robust tracking control problem for quadrotor UAVs operating in the presence of model uncertainties and actuator efficiency loss. Unlike conventional fault-tolerant schemes that rely on complex fault estimation units, a streamlined robust control architecture was developed. By integrating a prescribed performance mechanism with a nonsingular fast terminal sliding mode strategy, the proposed framework ensures that position and attitude tracking errors are strictly confined within a user-defined decaying envelope. This design guarantees finite-time convergence and operational safety independent of the initial error conditions.

Numerical validations have confirmed the efficacy of the approach. The results demonstrate that the system maintains high-precision tracking and rapid stabilization capabilities even when subjected to simultaneous aerodynamic disturbances and partial rotor failures. The control law effectively suppresses unmatched perturbations via its inherent robustness.

Future research directions will focus on two primary aspects. First, since the current framework relies on accurate state measurements, subsequent work will address the impact of sensor noise and measurement delays, potentially by incorporating filtering techniques or state observers. Second, while numerical simulations have verified the theoretical claims, efforts will be made to validate the proposed algorithm on a physical quadrotor platform to assess its real-time performance in outdoor environments.

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