A Non-Singular Finite-Time Backstepping Controller Design for Attitude Tracking of a Quadrotor UAV

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***Abstract*—This paper presents a non-singular finite-time backstepping controller design for attitude tracking of a quadrotor UAV. After the dynamical model of the quadrotor UAV is introduced, the non-singular finite-time backstepping controller structure is designed for each Euler angle. A modification is incorporated into the virtual controller signals to eliminate singularity at the origin while preserving finite-time convergence. The Lyapunov-based stability analysis proves practical finite-time stability of the closed-loop system. Simulation results demonstrate that the proposed approach guarantees non-singular control behavior and ensures smooth and fast convergence, making it suitable for desired attitude tracking applications.**

***Index Terms*—Quadrotor UAV, Non-singular Finite-Time Convergence, Backstepping Control, Attitude Control**

I. INTRODUCTION

Quadrotor unmanned aerial vehicles (UAVs) have attracted significant attention in recent years due to their agility, maneuverability, and wide range of applications such as surveillance, monitoring, and autonomous inspection. In many of these applications, accurate attitude regulation is essential because deviations in roll, pitch, or yaw may lead to sensor misalignment and degraded mission performance.

A quadrotor is an underactuated six-degree-of-freedom system with three translational and three rotational states. Although trajectory tracking is achieved primarily through translational control, safe and reliable operation requires precise attitude stabilization. Attitude control plays a fundamental role in quadrotor systems, as it directly governs the direction of thrust and consequently determines the vehicle's translational motion. In addition to these, to overcome the singularity in the controller signal, a singularity-free approach is proposed to avoid the potential singularities in the adaptation mechanism in many recent papers [1], [2], [3]. Therefore, accurate attitude stabilization without singularity is a prerequisite for achieving reliable trajectory tracking and maintaining overall system stability. Therefore, this paper focuses on the rotational subsystem and proposes a non-singular finite-time backstepping controller that eliminates recursive singularity. The proposed approach removes the singularity problem in the recursive virtual control design and simultaneously guarantees that the attitude angles remain within predefined admissible bounds.

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To address these challenges, nonlinear control techniques have been extensively investigated for quadrotor systems. Among them, backstepping-based control has been widely adopted for quadrotor attitude and trajectory regulation due to its systematic design procedure and capability to handle nonlinear dynamics. In [4], a backstepping controller is developed based on a nonlinear quadrotor model to stabilize the entire system and track Cartesian trajectories. Similarly, [5] experimentally compared backstepping and sliding-mode controllers on the OS4 micro quadrotor, demonstrating that backstepping yields smoother control inputs and more robust attitude regulation under disturbances. More recently, [6] proposed a backstepping-based trajectory tracking controller enhanced with radial basis function (RBF) neural networks to compensate for modeling uncertainties and external disturbances.

To further address unknown nonlinearities, learning-based and intelligent approaches have been incorporated into backstepping frameworks. Neural network-based backstepping controllers, particularly those employing RBF neural networks, have been extensively studied to approximate unmodeled dynamics and external disturbances [7]. Fuzzy logic systems have also been integrated with backstepping control to handle uncertainty and imprecise system descriptions [8]. Although these methods improve robustness, they typically guarantee only asymptotic or exponential stability and may involve high computational complexity.

Finite-time control has emerged as an effective solution to achieve faster convergence and higher tracking accuracy. In [9], an adaptive robust control scheme is developed for uncertain chaotic systems using smooth hyperbolic secant and inverse hyperbolic sine functions to reduce chattering and enhance convergence. The authors in [10], introduce a finite-time adaptive fuzzy event-triggered control approach employing command-filtered backstepping to achieve robust altitude and attitude control of UAVs in the presence of nonlinear dynamics and state constraints. In [11], the authors present a distributed finite-time containment control method for multi-UAV systems under disturbances and input saturation, using a hyperbolic tangent indicator for symmetric/asymmetric saturation and a fixed-time sliding mode differentiator within command-filtered backstepping to avoid repeated differentiation of virtual signals. In [12] a functional Lyapunov-Krasovskii approach was proposed to ensure contractive stability in finite-time under time-delay and H_∞ disturbances. In the UAV domain, [13] designed a nested-loop nonlinear controller with an inner-loop attitude regulator based on feedback linearization, achieving fast attitude stabilization. In safety-critical scenarios, this oversight poses a significant risk, as resolving mathematical singularities does not inherently guarantee that the system will remain within its predefined safe operational boundaries. In [14], proposed hybrid finite-time backstepping with super-twisting algorithm (STA) for 6-DOF quadrotor control. The STA ensures smooth control and robustness. In addition, researchers in [15] developed backstepping–terminal sliding mode control for a quadrotor using a smooth reaching law and hyperbolic tangent to reduce chattering. However, no formal singularity-free proof is provided in these references.

Finite-time backstepping controllers are inherently prone to singularity due to the recursive structure of the virtual control laws, particularly when fractional power terms are involved. As the tracking error approaches zero, the derivative of the virtual control may grow excessively large, leading to non-smooth or even impractical control inputs and potential numerical instability. Therefore, developing a non-singular finite-time backstepping approach that preserves the fast convergence properties of finite-time control while avoiding such issues remains an important challenge in quadrotor attitude stabilization.

In this study, a unified finite-time backstepping control framework using control Lyapunov functions is developed for quadrotor UAV attitude tracking. The proposed approach introduces a smooth modification of virtual control laws using exponential shaping functions, which effectively eliminates the singularities arising from negative-power terms in conventional finite-time backstepping. By ensuring that the virtual control signals remain differentiable, this design avoids discontinuities and eliminates the need for auxiliary techniques such as switching strategies. Furthermore, the framework simultaneously ensures finite-time convergence, explicitly compensates for nonlinear couplings, and strictly satisfies attitude constraints across the roll, pitch, and yaw channels within a single Lyapunov-based design. Maintaining a completely non-singular recursive structure is particularly vital for the real-time implementation on quadrotor systems. The effectiveness of the proposed controller is validated through comparative numerical simulations; while classical backstepping designs exhibit singular behavior, the proposed method yields smooth, bounded responses and meets all desired performance criteria without singularity.

The remainder of this paper is organized as follows: Section II presents the mathematical model of the quadrotor UAV's attitude. Section III details the design of the singularity-free backstepping controller design, including Lyapunov stability analysis with finite time convergence. Section IV provides numerical simulation results with comparative results to validate the proposed controller. Finally, Section V concludes the paper.

II. Problem Definition and Preliminaries

This section presents the necessary preliminaries and the dynamic model of the quadcopter. The attitude dynamics are introduced and reformulated into a strict-feedback state-space form suitable for backstepping controller design.

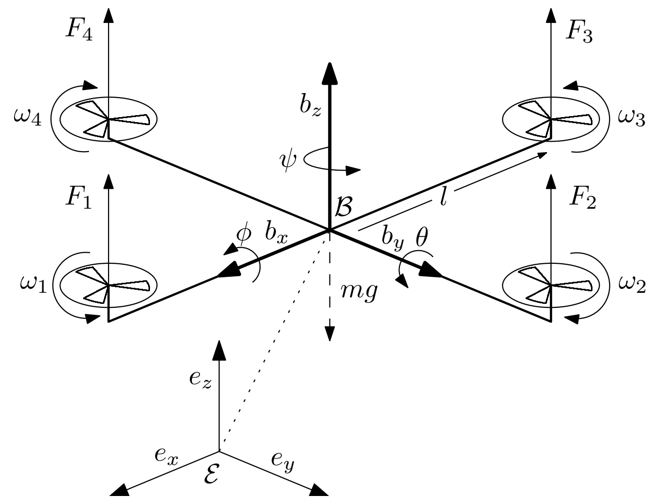

Fig. 1. Schematic of a quadcopter.

Lemma 1. *[16] Let $y_i \in \mathbb{R}_{\geq 0}$, $i = (1, 2, \ldots, n)$. Then for $0 < m_1 \leq 1$ and $m_2 \geq 1$, the following inequalities hold:*

$$\left(\sum_{i=1}^{n} y_i\right)^{m_1} \leq \sum_{i=1}^{n} y_i^{m_1} \leq n^{1-m_1}\left(\sum_{i=1}^{n} y_i\right)^{m_1},$$

$$n^{1-m_2}\left(\sum_{i=1}^{n} y_i\right)^{m_2} \leq \sum_{i=1}^{n} y_i^{m_2} \leq \left(\sum_{i=1}^{n} y_i\right)^{m_2}.$$

Lemma 2. *[17] For a nonlinear system $\dot{x} = f(x)$ with an initial state x_0, if there exist $c > 0$, $0 < \eta$ and $0 < \beta < 1$ such that $\dot{V}(x) \leq -cV^{\beta} + \eta$, then the system is practical finite-time (PFT) stable. The trajectories approach the convergence region*

$$x \in \left\{ x \mid V^{\beta}(x) \leq \frac{\eta}{(1-\theta)c} \right\}$$

where $0 < \theta < 1$ is a constant. The convergence occurs within a settling time T_s bounded by

$$T_s \leq \frac{V^{1-\beta}(x_0)}{c\theta(1-\beta)}.$$

A. Quadcopter Dynamic Model

Quadrotors are rotary-wing unmanned aerial vehicles that achieve translational and rotational motion via four motors positioned at the extremities of the airframe. By varying the speeds of these body-fixed motors, as illustrated in Fig. 1, the vehicle is capable of performing complex maneuvers across its degrees of freedom. The dynamical model of the quadcopter UAV system is a nonlinear and underactuated aerial vehicle with six degrees of freedom actuated by four independent rotors. Regarding the important usages of the UAVs, precise attitude regulation—including roll, pitch, and yaw—is critical to maintain sensor alignment with the desired trajectory and ensure accurate data acquisition. The attitude dynamics of the quadcopter are described by [18]:

$$\ddot{\phi}(t) = \frac{u_2 + qr(J_{yy} - J_{zz})}{J_{xx}} - \frac{k_4 p^2 + J_r q \Omega_r}{J_{xx}}, \tag{1}$$

$$\ddot{\theta}(t) = \frac{u_3 + pr(J_{zz} - J_{xx})}{J_{yy}} - \frac{k_5 q^2 - J_r p \Omega_r}{J_{yy}}, \tag{2}$$

$$\ddot{\psi}(t) = \frac{u_4 + pq(J_{xx} - J_{yy})}{J_{zz}} - \frac{k_6 r^2}{J_{zz}}. \tag{3}$$

Here, ϕ, θ, and ψ denote the roll, pitch, and yaw angles, respectively, while $p = \dot{\phi}$, $q = \dot{\theta}$, and $r = \dot{\psi}$ are the corresponding angular velocities. The control inputs u_1, u_2, u_3, and u_4 are related to the squared rotor speeds

$$\begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 0 & l & 0 & -l \\ -l & 0 & l & 0 \\ -b & b & -b & b \end{bmatrix} \begin{bmatrix} c\Omega_1^2 \\ c\Omega_2^2 \\ c\Omega_3^2 \\ c\Omega_4^2 \end{bmatrix}. \tag{4}$$

In this formulation, u_1 represents the total thrust along the body z-axis, u_2, u_3, and u_4 denote the control torques corresponding to roll, pitch, and yaw, respectively; J_{xx}, J_{yy}, and J_{zz} are the principal moments of inertia; k_4, k_5, and k_6 are aerodynamic drag coefficients; J_r denotes the inertia of the rotor and Ω_r represents the residual angular velocity of the rotor.

III. Controller Design

To enable systematic controller design, the attitude dynamics given in (1)-(3) is reformulated in a state-space form. using the structure of the quadrotor attitude dynamics, the system is decomposed into three subsystems corresponding to the Euler angles $\xi \in \{\phi, \theta, \psi\}$ and their associated angular rates $\omega \in \{p, q, r\}$. For clarity and without loss of generality, the control design is developed for the roll subsystem and subsequently extended to the pitch and yaw subsystems.

The roll dynamics are expressed as

$$\dot{\phi} = p, \tag{5}$$

$$\dot{p} = \frac{1}{J_{xx}} u_2 + \frac{qr(J_{yy} - J_{zz})}{J_{xx}} - \frac{k_4 p^2 + J_r q \Omega_r}{J_{xx}}. \tag{6}$$

For compact representation, the attitude dynamics for $\xi \in \{\phi, \theta, \psi\}$ and $\omega \in \{p, q, r\}$ can be written in the strict-feedback form

$$\dot{\xi} = \omega, \tag{7}$$

$$\dot{\omega} = \frac{1}{J_\xi} u_\xi + f_\xi \tag{8}$$

where, $J_\xi \in \{J_{xx}, J_{yy}, J_{zz}\}$, $u_\xi \in \{u_2, u_3, u_4\}$, and f_ξ represents the lumped nonlinear dynamics including gyroscopic coupling, aerodynamic drag, and rotor-induced effects appear in (5)- (6). The control objective is to design u_ξ so that ξ converges to ξ_d in finite time, where $\xi_d \in \{\phi_d, \theta_d, \psi_d\}$, with ϕ_d, θ_d, and ψ_d denoting the desired values of ϕ, θ, and ψ, respectively.

To initiate the backstepping design, the following change of variables is introduced:

$$z_1 = \xi - \xi_d, \tag{9}$$

$$z_2 = \omega - \alpha_\xi. \tag{10}$$

If z_1 goes to zero in finite-time, the angels ϕ, θ, ψ will converge to their desired values ϕ_d, θ_d, ψ_d within in a finite time. In (9) and (10), the term α_ξ denotes the virtual control law in the first step of the finite time approach and is proposed as follows:

$$\alpha_\xi = \dot{\xi}_d - k_1 z_1^{2s-1} \left(1 - e^{-\left(\frac{z_1}{l}\right)^2}\right) \tag{11}$$

where the constant s is a design parameter satisfying $0.5 < s < 1$, which is expressed as the ratio of two odd positive integers. Considering the derivative of error dynamics: $\dot{z}_1 = \omega - \dot{\xi}_d = z_2 + \alpha_\xi - \dot{\xi}_d$ along with α_ξ from (11) yields

$$\dot{z}_1 = z_2 - k_1 z_1^{2s-1} \left(1 - e^{-\left(\frac{z_1}{l}\right)^2}\right) \tag{12}$$

where $k_1 > 0$, $l > 0$. The fractional power term guarantees finite-time convergence and ensures smooth control behavior. It is worth noting that the derivative of the control law is not finite at the origin. The derivative of backstepping error z_2 is obtained as follows:

$$\dot{z}_2 = \frac{1}{J_\xi} u_\xi + f_\xi - \dot{\alpha}_\xi. \tag{13}$$

Then, following the same design philosophy, the generalized control law for each attitude channel ξ is given by

$$u_\xi = J_\xi \left(-f_\xi + \dot{\alpha}_\xi - z_1 - k_2 z_2^{2s-1}\right) \tag{14}$$

where $k_2 > 0$ is a design parameter. With this proposed control input, $\dot{z}_2$ is as follows:

$$\dot{z}_2 = -z_1 - k_2 z_2^{2s-1}. \tag{15}$$

Accordingly, explicit roll control torques are obtained as

$$u_2 = J_{xx}\Big(- \frac{qr(J_{yy} - J_{zz})}{J_{xx}} + \frac{k_4 p^2 + J_r q \Omega_r}{J_{xx}} + \dot{\alpha}_\phi - \phi + \phi_d - k_2 z_\phi^{2s-1}\Big). \tag{16}$$

To show the convergence analysis of the closed-loop roll dynamics, consider the candidate Lyapunov function:

$$V = V_1(z_1) + V_2(z_2) = 0.5 z_1^2 + 0.5 z_2^2 \tag{17}$$

using the dynamics of the angles, the control input u_ξ, and the derivative of the error dynamics, $\dot{V}$ is obtained as follows:

$$\begin{aligned} \dot{V} &= z_1 \dot{z}_1 + z_2 \dot{z}_2 \\ &= -k_1 z_1^{2s} \left(1 - e^{-\left(\frac{z_1}{l}\right)^2}\right) + z_1 z_2 - k_2 z_2^{2s} - z_1 z_2. \end{aligned}$$

Noting that $z_1^2 = 2V_1$ and $z_2^2 = 2V_2$, we can write from (17):

$$\dot{V} = -k_1 (2V_1)^s \left(1 - e^{-\left(\frac{z_1}{l}\right)^2}\right) - k_2 (2V_2)^s. \tag{18}$$

It can be shown that the term $k_1(2V_1)^s e^{-(\frac{z_1}{l})^2}$ has a global maximum. Let's name its maximum value M. Then, we have:

$$\dot{V} \leq -k_1(2V_1)^s - k_2(2V_2)^s + M. \tag{19}$$

Defining $\bar{k} = 2^s \min\{k_1, k_2\}$ and using Lemma 1, it follows from Lemma 1 that $\dot{V} \leq -\bar{k}V^s + M$. According to Lemma 2, the inequality above guarantees that the roll angle and angular rate converge to a bounded neighborhood of the origin in finite time. Similar to the roll angle, the pitch and yaw dynamics can be expressed as

$$\dot{\theta} = q, \tag{20}$$

$$\dot{q} = \frac{1}{J_{yy}}u_3 + \frac{pr(J_{zz} - J_{xx})}{J_{yy}} - \frac{k_5 q^2 - J_r p\Omega_r}{J_{yy}}, \tag{21}$$

$$\dot{\psi} = r, \tag{22}$$

$$\dot{r} = \frac{1}{J_{zz}}u_4 + \frac{pq(J_{xx} - J_{yy})}{J_{zz}} - \frac{k_6 r^2}{J_{zz}}. \tag{23}$$

It can be observed that subsystems have the same structural form as the roll dynamics. Therefore, following the same control design procedure used for the roll subsystem, the controllers u_3 and u_4 can be designed accordingly, as follows:

$$\begin{aligned} u_3 = J_{yy}\Big(&- \frac{pr(J_{zz} - J_{xx})}{J_{yy}} + \frac{k_5 q^2 - J_r p\Omega_r}{J_{yy}} \\ &+ \dot{\alpha}_\theta - \theta + \theta_d - k_2 z_\theta^{2s-1}\Big), \end{aligned} \tag{24}$$

$$\begin{aligned} u_4 = J_{zz}\Big(&- \frac{pq(J_{xx} - J_{yy})}{J_{zz}} + \frac{k_6 r^2}{J_{zz}} \\ &+ \dot{\alpha}_\psi - \psi + \psi_d - k_2 z_\psi^{2s-1}\Big). \end{aligned} \tag{25}$$

Consequently, the finite-time stability analysis developed for roll angle can be directly applied to the pitch and yaw subsystems. Thus, the closed-loop attitude dynamics for error dynamics are obtained with finite-time stability.

IV. Simulation Results

To validate the effectiveness of the proposed non-singular finite-time backstepping control attitude controller, numerical simulations are performed on the quadrotor rotational dynamics described in Section III. The inertia parameters are selected as $J_{xx} = 3.83 \times 10^{-3}\text{kg}{\cdot}\text{m}^2$, $J_{yy} = 3.67 \times 10^{-3}\text{kg}{\cdot}\text{m}^2 J_{zz} = 7.32 \times 10^{-3}\text{kg}{\cdot}\text{m}^2$. The control gains are chosen as $k_1 = 2, k_2 = 2$ and the finite-time exponent is selected as $2s - 1 = \frac{1}{7}$. The exponential smoothing parameter is set to $l = 0.1$, and the rotor speed is $\Omega_r = 10$. The desired attitude trajectories are chosen as time-varying signals to evaluate the tracking performance under dynamic conditions such as $\phi_d(t) = 2\sin(t) + \cos(2t)$, $\theta_d(t) = 0.3\sin(0.8t)$ and $\psi_d(t) = 0.1\sin(t) + \cos(t)$. To ensure a fair comparison, identical initial conditions are adopted: $x(0) = [\phi(0),\, p(0),\, \theta(0),\, q(0),\, \psi(0),\, r(0)]^T = [0.39,\ 0.48,\ 0.25,\ 1,\ 0.3,\ 0.1]^T$.

Fig 2 shows the trajectories of the system under the proposed controller. The attitude angles accurately track their reference trajectories with highly precision, smooth transients, and negligible steady-state error. Moreover, the angular velocities remain bounded and evolve smoothly without oscillatory or abrupt variations. Figs. 3 and 4 present a comparative evaluation of the classical backstepping controller (CBSC) and the proposed non-singular finite-time backstepping method in terms of tracking errors and control inputs for all attitude channels. As shown in Fig 3, both controllers drive the tracking errors z_1 to the origin. However, the proposed non-singular finite-time controller achieves faster convergence for all channels, with sharper yet smooth and oscillation-free transients. In contrast, the classical backstepping method exhibits slower and more gradual error convergence. Fig 4 shows the corresponding control inputs u_ξ. The classical controller produces smooth, low-amplitude signals, while the proposed method applies slightly higher control effort during the transient phase to enable faster convergence. Importantly, the control inputs remain continuous and bounded, with no singularities or impulsive peaks.

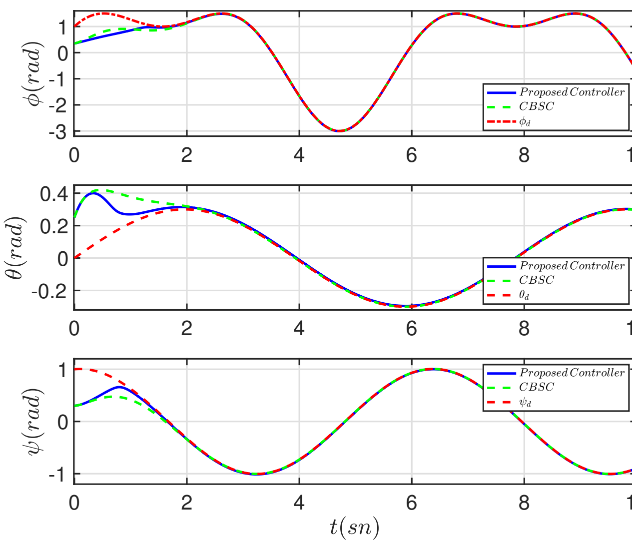

Fig. 2. Comparison attitude angles (ϕ, θ, ψ) with the classical backstepping controller (CBSC) and finite-time non-singular backstepping controller (Proposed Controller).

To further highlight the limitations of the classic finite-time backstepping methods, Figs. 5 and 6 present the performance of the singular finite-time backstepping controller. The control inputs exhibit sharp peaks, indicating the presence of singularity and rendering the controller unsuitable for practical implementation. In contrast, the proposed non-singular finite-time backstepping controller successfully eliminates this issue while preserving fast convergence.

The results highlight that the proposed backstepping controller strikes a much better balance between fast convergence and smooth control action, while completely avoiding singularity issues and ensuring practical implementability.

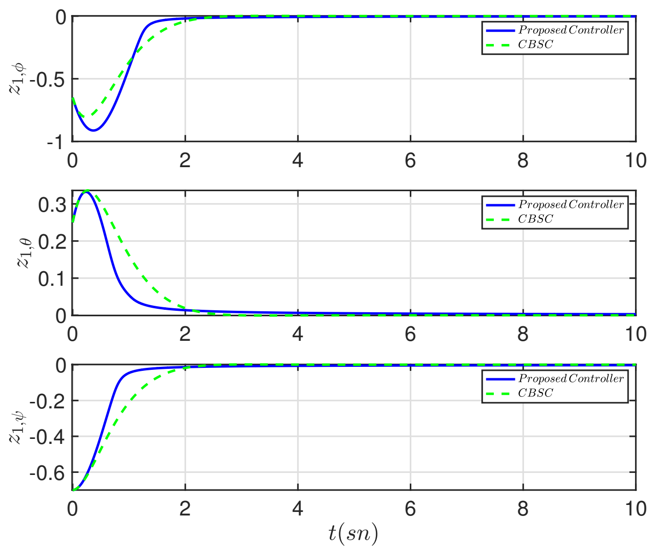

Fig. 3. Comparison of tracking errors of the classical backstepping controller (CBSC) and finite-time non-singular backstepping controller (Proposed Controller) for all attitude channels roll, pitch, and yaw.

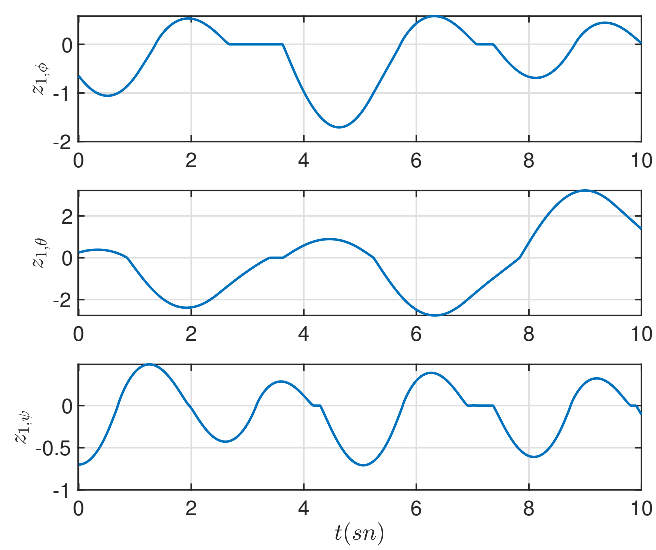

Fig. 5. Tracking errors of sigular finite-time backstepping controller(SFTBSC) for all attitude channels roll, pitch, and yaw.

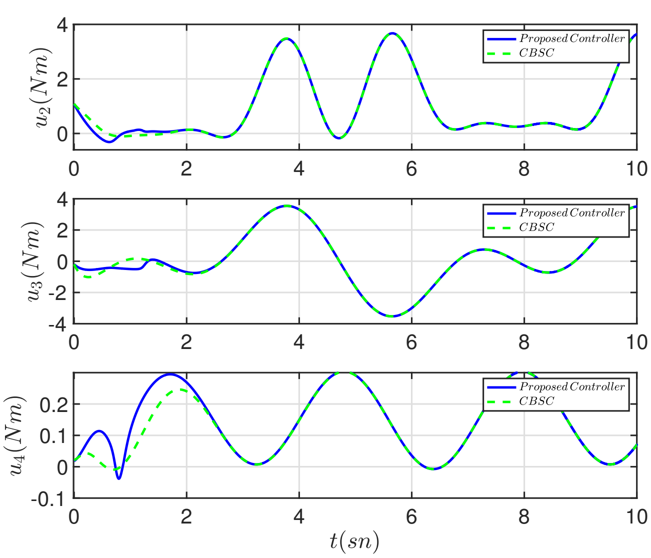

Fig. 4. Comparison control inputs u_ξ with the classical backstepping controller (CBSC) and finite-time non-singular backstepping controller (Proposed Controller) for all attitude channels roll, pitch, and yaw.

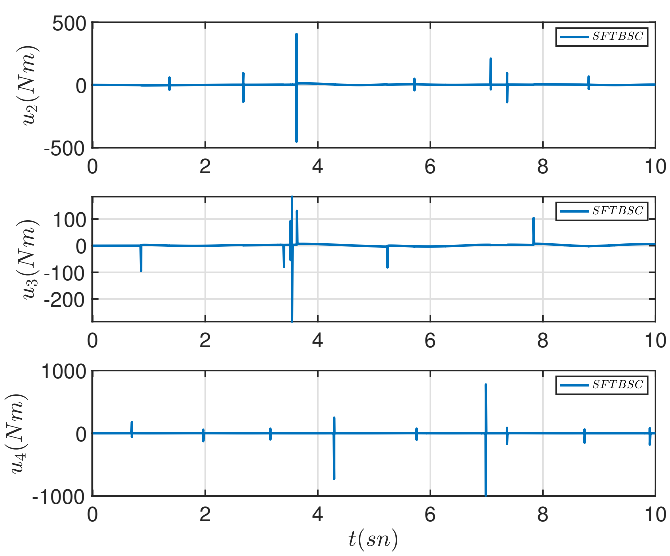

Fig. 6. Control inputs u_ξ of the singular finite-time backstepping controller(SFTBSC) for all attitude channels roll, pitch, and yaw.

V. Conclusion

This paper presents a singularity-free practical finite-time backstepping controller for quadrotor attitude control. By incorporating a modified virtual control design, the proposed method effectively addresses the singularity problem that typically arises in conventional finite-time backstepping approaches, leading to smooth and well-defined control signals.

The controller guaranties practical finite-time convergence of the attitude tracking errors while preserving a fully nonsingular structure throughout the design. The simulation results confirm that the proposed approach achieves fast and accurate trajectory tracking, with control inputs remaining continuous and bounded. In comparison with classical backstepping, the method provides a noticeably faster convergence rate, and unlike standard finite-time techniques, it completely avoids singular behavior. In summary, the proposed controller offers a reliable and practically implementable solution for the nonlinear attitude control of quadrotor UAVs. Future work will focus on extending the proposed controller to account for parameter variations and unmodeled dynamics. Specifically, robustness analysis under uncertainties such as variations in the moments of inertia, aerodynamic drag coefficients, and rotor dynamics will be investigated. To guarantee robustness against such perturbations, adaptive mechanisms will be incorporated into the proposed framework, compensating for unknown dynamics while preserving the finite-time convergence and singularity-free properties of the design.

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