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Quadcopter Robust Adaptive Second Order Sliding Mode Control Based on PID Sliding Surface

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ABSTRACT We present a robust adaptive second-order sliding mode controller that rejects external disturbances and uncertainties to improve the tracking performance of attitude and altitude in a quadcopter based on a Proportional–Integral–Derivative sliding surface. The algorithm provides a rapid adaptation and strict robustness of the flight control for the vehicle under the effect of perturbations. The proposed controller design is based on the theory of second order sliding mode technique that eliminates the chattering phenomenon present in first-order sliding mode controllers. In addition, we derive an adaptive law from the Lyapunov stability to ensure the robust control for the quadcopter even without knowing the upper bound for disturbances. Applying the same external disturbances, we use a numerical simulation to compare our algorithm to recent alternatives, such as normal adaptive sliding mode control, super-twisting sliding mode control, modified super-twisting sliding mode control, and nonsingular terminal sliding mode control. The results demonstrate the effectiveness of our proposed algorithm.

INDEX TERMS PID sliding surface, second order sliding mode control, quadcopter, disturbance rejection, adaptive control.

I. INTRODUCTION

Unmanned Aerial Vehicles (UAVs) are being used in an increasing number of practical applications, and quadcopters, in particular, are expected to replace manned or fixed wing aircraft UAVs in a variety of activities, including data collection [1], [2], search and rescue tasks [3], [4], crop spraying pesticide in agriculture [5]–[7], payload carrying [8], [9], and military operations [10], [11]. Quadcopters enjoy a growing popularity due to their flexibility and versatility. Among their principal advantages are their capability of rapid changes in direction and their ability to perform vertical takeoffs and landings. In addition, quadcopters can hover over fixed locations and possess rapid acceleration and deceleration capabilities. Due to their high maneuverability, quadcopters are often chosen for applications in hazardous working conditions that have strict limitations on direct human interference due to health and safety concerns. As the technological development of electronics, computers, control theories, and communication technologies advances further, the range of uses for quadcopters is likely to expand even further in the future. However, their usability still faces several control challenges such as ensuring stable, safe, and efficient operation in often extremely complicated working environments. From a theoretical perspective, it can be stated that: (i) mathematical models of quadcopters are nonlinear systems typically containing unstable open loops. Hence, the requirement of a controller must be sufficiently fast response; (ii) the system has six degrees of freedom (DOFs), which is controlled by four input signals. It also means that a strong coupling between the dynamic states is inevitable. These systems are also referred to as underactuated. Hence, in order to control the quadcopter, the full control scheme of the vehicle is usually proposed as a multi-loop consisting of an inner loop for attitude control and an outer loop for position control; and (iii) the parameters of the quadcopter's dynamic model such as moments of inertia and aerodynamic coefficients cannot be measured exactly. Moreover, the operation of the vehicle is strongly affected by the aerodynamics of the multi-rotors which makes them more sensitive to external disturbances, especially wind.

Regardless of whether the vehicle operates in the hover flight or mission modes, it is obvious that a robust stabilization control is a vital requirement to guarantee the safe operation of the vehicle. A robust attitude controller not only maintains the stability of attitude performance but also guarantees the accuracy of the vehicle's position in the tasks it is set to perform. In addition, the ability to maintain a desired altitude during autonomous flight is an indispensable requirement in many applications. Improving and developing a robust adaptive controller for the attitude and altitude makes the vehicle more flexible and adaptable to sudden changes of the working environment such as perturbations or uncertainties.

A. RELATED WORKS

Several linear controllers have been proposed for attitude and altitude control of quadcopters such as the conventional PID or Linear Quadratic Regulator (LQR) [12]–[17]. However, these methods offer only a limited performance in the presence of external disturbances and uncertainties. The Sliding Mode Control (SMC), on the other hand, is well known for the robustness of its control technique in many dynamic and complex environments, mainly due to its inherent ability to reject uncertainties and eliminate external disturbances. Therefore, classical SMC and extended SMC are popular methods that are commonly applied to various UAVs. Nevertheless, the control technique always suffers from the so-called chattering phenomenon due to a discontinuous term in the sign function of the switching law. This may lead to the damage of the electromechanical systems. Many studies on the high order SMC or extended SMC have been published that aim to overcome this disadvantage. References [18] and [19] presented Lyapunov theory-based second order SMC for attitude and position tracking control. In [20], an adaptive back-stepping sliding mode algorithm for stabilizing the quadcopter's attitude has been proposed, using a nested double loop structure approach in the inner loop of the control system. The Proportional Derivative (PD) controller is used for position control in the outer loop. In [21] and [22], a fully robust back-stepping sliding mode controller has been presented for both attitude and position control, based on a combination of sliding mode algorithms and back-stepping techniques. Although the authors clearly demonstrated the stability of the controller, the controller gains are difficult to obtain. In [23], an extended state observer is used to estimate unknown parameters and external perturbations. This information is fed to a robust controller for attitude and position control loops which is based on a combination of SMC and back-stepping control techniques. Reference [24] presented a robust flight controller based on SMC driven by a sliding mode disturbance observer (SMC-SMDO) to provide robust attitude and position control for a small quadcopter. However, this SMC-SMDO controller was designed for particular fixed perturbation limits and is therefore not useable in environment that are highly variable or where these limits are unknown. Reference [25] presented a flight controller based on the global fast dynamic terminal SMC for both attitude and position tracking control of a small quadcopter. A different approach has been presented in [26], using a combination of adaptive fuzzy system and SMC to provide a fault tolerant attitude control. They test their approach on a quadcopter with simulated actuator fault. The adaptive fuzzy system is used to compensate faulty parts or errors in the nonlinear functions. However, the procedure to obtain a controller is not a simple one, making it difficult to implement in real world applications.

Reference [27] developed a robust adaptive tracking control for the attitude dynamics of a quadrotor without knowledge of the inertia matrix of the vehicle. Instead, the inertial matrix is estimated and updated online. In [28], an adaptive SMC algorithm based on the estimation of the unknown parameters is presented for stabilization and position tracking control with parametric uncertainties. However, the presented controllers exhibit a limited performance in the presence of external perturbations. Yet another approach has been presented in [29], where the authors used a robust adaptive tracking controller for an underactuated quadcopter based on the immersion and invariance methodology (I&I). A robust integral of the signum of error was used for attitude control to reject the disturbances. The I&I method was applied in the position control to compensate for parameter uncertainties. In [30]–[32], an adaptive controller has been proposed for attitude and position tracking based on combining integral sliding mode control, robust back-stepping sliding mode control, and the radial basic function neural network method (RBFNN). The unknown parameters are estimated online using the neural network algorithm, requiring intensive computation. Hence, this approach may not be suitable for compact UAVs. In [33], an adaptive robust controller was introduced for attitude and position tracking of a quadcopter while considering the perturbations and parameter uncertainties. The system stability was demonstrated from Lyapunov theory. Reference [34] introduced a robust attitude controller capable of dealing with external disturbances, uncertainties, and delays of the quadrotor. Their algorithm includes a nominal state feedback control method and a robust compensator for disturbances to obtain the desired control performance. Generally, these published algorithms are capable of solving the problems of attitude and position tracking control in an environment where external disturbances and uncertainties are present. However, most methods are highly complicated, computationally expensive, with inherent difficulties to obtain the controller gains.

B. MAIN CONTRIBUTIONS

In this study, we focus on designing a simple adaptive control law for attitude and altitude control while simultaneously considering the occurrence of perturbations on the rotational dynamics in three DOF (roll, pitch, and yaw) and altitude dynamics. We introduce a robust adaptive second order sliding mode controller based on the PID sliding surface. The adaptive law is obtained from Lyapunov stability

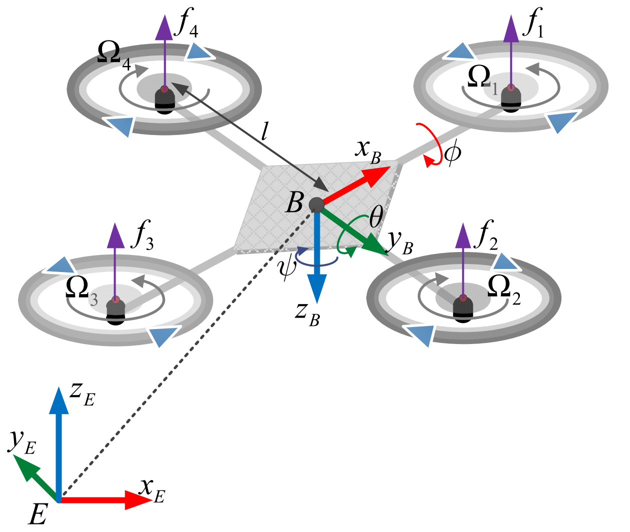

FIGURE 1. Configuration of an underactuated quadcopter, the lift forces $f_i = b\,\Omega_i$ ($i = 1, 2, 3, 4$) produced by four motors.

to ensure a fast response and rapid adaptation in the presence of disturbances. We demonstrate the technological advantages of our approach through a comparison of simulation results from the new adaptive controller and previous approaches. They can be briefly summarized as follows: (i) the chattering effect is almost eliminated, resulting in a more stable performance with respect to the typical adaptive SMC suggested in [35]; (ii) the attitude and altitude tracking performance are more robust and faster to adapt in comparison with Super-Twisting Sliding Mode Control (ST-SMC), Modified ST-SMC, and Nonsingular Terminal Sliding Mode Control (NT-SMC) (see [36] and [37]), regardless of the upper bound of disturbances; and (iii) our controller is simple, practical, robust, and effective in comparison to other methods [38]–[40], especially with regard to the real-time implementation in the embedded system.

The remainder of this article is organized as follows: Section 2 briefly introduces the mathematical model of the quadcopter, while the flight controller design is presented in Section 3. The simulation results and discussion are presented in Section 4, with the conclusions of the study provided in Section 5.

II. MODELING QUADCOPTER DYNAMICS

The dynamics modeling of the underactuated quadcopter is proposed and used by many previous researches in [41]–[47]. The brief mathematic model of a quadcopter is presented in this section. The essential frames consist of an Earth frame, E, and body frame, B, of the vehicle shown as Figure 1. The quadcopter's vertical momentum is achieved through the lift forces provided by the rotating propellers. Horizontal momentum is achieved through differences in the rotational angles such as roll, pitch, and yaw. Let $\phi, \theta, \psi \in \mathbb{R}$, $(-\pi/2 \leq \phi \leq \pi/2,\ -\pi/2 \leq \theta \leq \pi/2,\ -\pi \leq \theta \leq \pi)$ denote the roll, pitch and yaw angles, respectively. Let $x, y, z \in \mathbb{R}$ represent the position of the vehicle in the Earth frame, E. Then a nonlinear dynamical model for a quadcopter that accounts for external disturbances and uncertainties can be formulated as follows [41].

TABLE 1. Quadcopter dynamic system parameters.

System parameters	Description
I_{xx}, I_{yy}, I_{zz} (kgm^2)	Moments of inertia along three axes x, y, and z in the Earth reference frame.
m (kg)	Total mass of the vehicle
l (m)	Arm length of the quadcopter frame
b (Ns^2)	Thrust coefficient
d (Nms^2)	Drag coefficient
J_r (kgm^2)	Moment of inertia of a rotor

$$\begin{bmatrix} \ddot{\phi} \\ \ddot{\theta} \\ \ddot{\psi} \\ \ddot{z} \\ \ddot{x} \\ \ddot{y} \end{bmatrix} = \begin{bmatrix} \frac{I_{yy}-I_{zz}}{I_{xx}}\dot{\theta}\dot{\psi} + \dot{\theta}\frac{J_r}{I_{xx}}\Omega_r + \frac{l}{I_{xx}}U_2 \\ \frac{I_{zz}-I_{xx}}{I_{yy}}\dot{\phi}\dot{\psi} - \dot{\phi}\frac{J_r}{I_{yy}}\Omega_r + \frac{l}{I_{yy}}U_3 \\ \frac{I_{xx}-I_{yy}}{I_{zz}}\dot{\theta}\dot{\phi} + \frac{1}{I_{zz}}U_4 \\ g - \frac{(\cos\phi\cos\theta)\,U_1}{m} \\ \frac{U_1}{m}(\cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi) \\ \frac{U_1}{m}(\cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi) \end{bmatrix} + \begin{bmatrix} \xi_\phi(t) \\ \xi_\theta(t) \\ \xi_\psi(t) \\ \xi_h(t) \\ 0 \\ 0 \end{bmatrix} \quad (1)$$

where $U_i \in \mathbb{R}$, $i = 1, 2, 3, 4$ are the control inputs for a quadcopter, which are described as:

$$\begin{bmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \\ \Omega_r \end{bmatrix} = \begin{bmatrix} b\left(\Omega_1^2 + \Omega_2^2 + \Omega_3^2 + \Omega_4^2\right) \\ b\left(-\Omega_2^2 + \Omega_4^2\right) \\ b\left(\Omega_1^2 - \Omega_3^2\right) \\ d\left(-\Omega_1^2 + \Omega_2^2 - \Omega_3^2 + \Omega_4^2\right) \\ -\Omega_1 + \Omega_2 - \Omega_3 + \Omega_4 \end{bmatrix} \quad (2)$$

Ω_r denotes the total residual angular speed of motors and $g = 9.81\ \mathrm{m/s^2}$ is the gravitational acceleration. The terms $\xi_\phi, \xi_\theta, \xi_\psi, \xi_h : \mathbb{R} \to \mathbb{R}$ represent the disturbances affecting roll, pitch, yaw, and altitude dynamics, respectively. The remaining parameters from Eqs.(1) and (2) are described in Table 1.

Let $X \in \mathbb{R}^{12\times 1}$ be a state variable vector defined as:

$$X = [x_1, x_2, \ldots, x_{12}]^T = [\phi, \dot{\phi}, \theta, \dot{\theta}, \psi, \dot{\psi}, z, \dot{z}, x, \dot{x}, y, \dot{y}]^T$$
$$\dot{X} = [\dot{x}_1, \dot{x}_2, \ldots, \dot{x}_{12}]^T = [\dot{\phi}, \ddot{\phi}, \dot{\theta}, \ddot{\theta}, \dot{\psi}, \ddot{\psi}, \dot{z}, \ddot{z}, \dot{x}, \ddot{x}, \dot{y}, \ddot{y}]^T$$

where $x_1 = \phi$, $x_2 = \dot{x}_1 = \dot{\phi}$, $x_3 = \theta$, $x_4 = \dot{x}_3 = \dot{\theta}$, $x_5 = \psi$, $x_6 = \dot{x}_5 = \dot{\psi}$, $x_7 = z$, $x_8 = \dot{x}_7 = \dot{z}$, $x_9 = x$, $x_{10} = \dot{x}_9 = \dot{x}$, $x_{11} = y$, $x_{12} = \dot{x}_{11} = \dot{y}$.

Eq.(1) can be formulated in state space as:

$$\dot{X} = f\left(X(t), U_i(t)\right) + \xi_i(t) \quad (3)$$

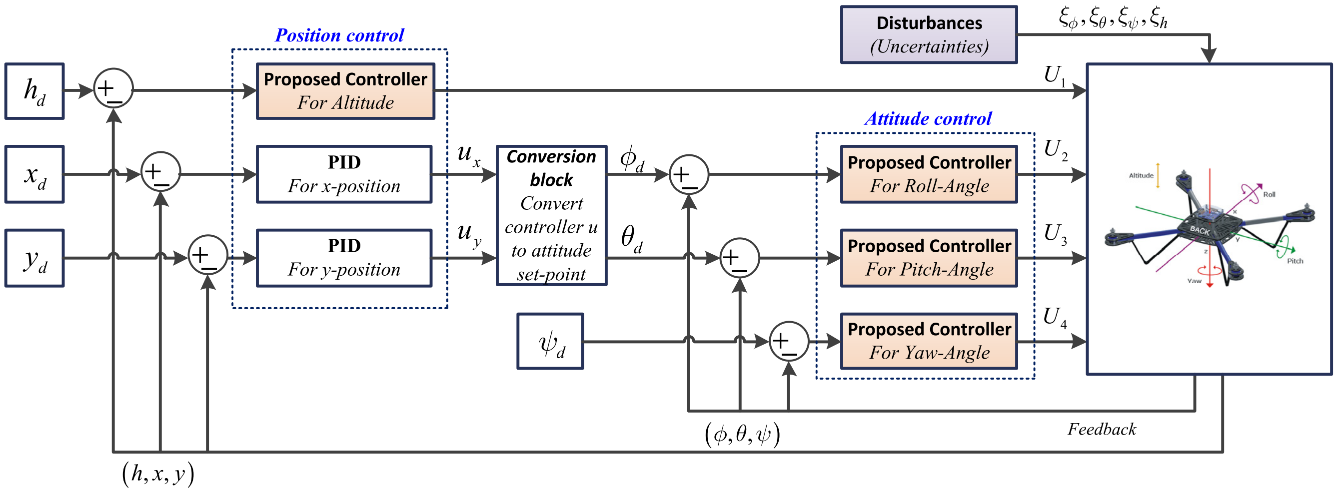

FIGURE 2. Full controller scheme of the underactuated quadcopter, the proposed robust adaptive controller is used in the attitude and altitude control. The traditional PID is applied in horizontal position control only.

where $\xi_i(t)$, $(i = 1, 2, \ldots, 12)$ denote the disturbances, with:

$$f\left(X(t), U_i(t)\right) = \begin{bmatrix} x_2 \\ x_4x_6a_1 + x_4a_2\Omega_r + b_1U_2 \\ x_4 \\ x_2x_6a_3 + x_2a_4\Omega_r + b_2U_3 \\ x_6 \\ x_2x_4a_5 + b_3U_4 \\ x_8 \\ g - \frac{1}{m}(\cos x_1 \cos x_3)\, U_1 \\ x_{10} \\ \frac{1}{m}u_xU_1 \\ x_{12} \\ \frac{1}{m}u_yU_1 \end{bmatrix} \tag{4}$$

and

$$\xi_i(t) = \left[0, \xi_\phi(t), 0, \xi_\theta(t), 0, \xi_\psi(t), 0, \xi_h(t), 0, 0, 0, 0\right]^T \tag{5}$$

where

$$\begin{aligned} a_1 &= \left(I_{yy} - I_{zz}\right)/I_{xx}, \quad a_2 = J_r/I_{xx}, \\ a_3 &= (I_{zz} - I_{xx})/I_{yy}, \quad a_4 = (-J_r)/I_{yy}, \\ a_5 &= \left(I_{xx} - I_{yy}\right)/I_{zz}, \quad b_1 = l/I_{xx}, \\ b_2 &= l/I_{yy}, \quad b_3 = 1/I_{zz}, \\ \begin{bmatrix} u_x \\ u_y \end{bmatrix} &= \begin{bmatrix} \cos x_1 \sin x_3 \cos x_5 + \sin x_1 \sin x_5 \\ \cos x_1 \sin x_3 \sin x_5 - \sin x_1 \cos x_5 \end{bmatrix} \end{aligned} \tag{6}$$

III. CONTROLLER DESIGN

The full control scheme of the system is proposed as a multi-loop consisting of an inner loop that controls attitude and an outer loop to control position (Figure 2).

The primary objective is to design a simple robust adaptive controller for attitude and altitude dynamics that guarantees a fast response, rapid adaptation, and good tracking performance without the need to know the upper bound of possible disturbances. The general controller is considered as:

$$U_i = U_i^E + U_i^S, \quad (i = 1, \ldots 4) \tag{7}$$

where $U_i^E \in \mathbb{R}$ denotes the equivalent control law producing the main control signal for normal operation of the quadcopter, i.e., in the absence of any disturbances ($\xi_i = 0$). $U_i^S \in \mathbb{R}$ denotes the switching control law to provide additional control for disturbance rejection. A PID sliding surface for switching controller is considered as:

$$\dot{s}_i(t) + \beta_i s_i(t) = k_{pi}e_i(t) + k_{\text{inti}}\int_0^t e_i(\tau)d\tau + k_{di}\dot{e}_i(t) \; (i = 1, \ldots, 4) \tag{8}$$

where $k_{pi}, k_{\text{inti}}, k_{di}, \beta_i \in \mathbb{R}^+$ are constants. The second derivative of the sliding surface is expressed as follows:

$$\ddot{s}_i(t) + \beta_i\dot{s}_i(t) = k_{pi}\dot{e}_i(t) + k_{\text{inti}}e_i(t) + k_{di}\ddot{e}_i(t) \tag{9}$$

If $s_i(t) = \dot{s}_i(t) = \ddot{s}_i(t) = 0$, then the error $e_i(t) \to 0$ when the controller gains k_{pi}, k_{inti} and k_{di} are appropriately chosen. Therefore, the polynomial on the right-hand of Eq.(9) $\left(k_{pi}\dot{e}_i(t) + k_{\text{inti}}e_i(t) + k_{di}\ddot{e}_i(t) = 0\right)$ is strictly Hurwitz. In the second order sliding mode technique, both the sliding surface and its derivative must satisfy:

$$s_i(t) = \dot{s}_i(t) = 0 \tag{10}$$

A. ATTITUDE CONTROLLER

Let ϕ_d, θ_d, and ψ_d be the desired states of roll, pitch, and yaw angles, respectively. In order to obtain the roll controller, U_2, the tracking errors of roll angle and its first and second derivative, are computed as: $e_2 = \phi_d - x_1$, $\dot{e}_2 = \dot{\phi}_d - x_2$, and

$\ddot{e}_2 = \ddot{\phi}_d - \dot{x}_2$. The second time derivative, $\ddot{e}_2$, can be rewritten based on Eqs.(3), (4) and (5) as follows:

$$\ddot{e}_2 = \ddot{\phi}_d - x_4 x_6 a_1 - x_4 a_2 \Omega_r - b_1 U_2 - \xi_\phi \tag{11}$$

Substituting $\ddot{e}_2$ in Eq.(9) with Eq.(11), the close loop error dynamics of roll angle become:

$$\begin{aligned} \ddot{s}_2 + \beta_2 \dot{s}_2 = {} & k_{p2}\dot{e}_2 + k_{int2} e_2 \\ & + k_{d2}\left(\ddot{\phi}_d - x_4 x_6 a_1 - x_4 a_2 \Omega_r - b_1 U_2 - \xi_\phi\right) \end{aligned} \tag{12}$$

As per Eq.(7), the equivalent controller for roll dynamic, U_2^E, is obtained from Eq.(12) when $\ddot{s}_2 = 0$, and there are no disturbances present ($\xi_\phi = 0$).

$$\begin{aligned} U_2^E = {} & \frac{1}{k_{d2} b_1}\left(-\beta_2 \dot{s}_2 + k_{p2}\dot{e}_2 + k_{int2} e_2 \right. \\ & \left. + \; k_{d2}\left(\ddot{\phi}_d - x_4 x_6 a_1 - x_4 a_2 \Omega_r\right)\right) \end{aligned} \tag{13}$$

However, undesired disturbances are almost always present in a normal working environment ($\xi_\phi \neq 0$). Therefore, a switching control law is added to rapidly reject the perturbations. The switching control law for roll dynamics is chosen as:

$$U_2^S = \frac{1}{k_{d2} b_1}\left(\lambda_2 s_2 + k_{s2}\operatorname{sgn}(\dot{s}_2)\right) \tag{14}$$

where $\lambda_2, k_{s2} \in \mathbb{R}^+$ are constants, and the sign function is defined as [48]:

$$\operatorname{sgn}(\dot{s}(t)) = \begin{cases} +1, & \text{if } \dot{s}(t) > 0 \\ 0, & \text{if } \dot{s}(t) = 0 \\ -1, & \text{if } \dot{s}(t) < 0 \end{cases} \tag{15}$$

The controller for roll angle, U_2, is obtained by combining Eqs. (7), (13) and (14):

$$\begin{aligned} U_2 = {} & \frac{1}{k_{d2} b_1}\left(-\beta_2 \dot{s}_2 + k_{p2}\dot{e}_2 + k_{int2} e_2 \right. \\ & \left. + \; k_{d2}\left(\ddot{\phi}_d - x_4 x_6 a_1 - x_4 a_2 \Omega_r\right) + \lambda_2 s_2 + k_{s2}\operatorname{sgn}(\dot{s}_2)\right) \end{aligned} \tag{16}$$

The second derivative of the sliding surface, $\ddot{s}_2$, is obtained by combining Eqs.(12) and (16):

$$\ddot{s}_2 = -\lambda_2 s_2 - k_{s2}\operatorname{sgn}(\dot{s}_2) - k_{d2}\xi_\phi \tag{17}$$

The stability of the roll subsystem with the controller U_2 is proven from Lyapunov theory through the following steps:

The Lyapunov function candidate and its derivative are chosen as:

$$\begin{aligned} V &= \frac{1}{2}(s_2)^2 + \frac{1}{2}(\dot{s}_2)^2 \\ \dot{V} &= s_2\dot{s}_2 + \dot{s}_2\ddot{s}_2 \\ &= s_2\dot{s}_2 + \dot{s}_2\left(-\lambda_2 s_2 - k_{s2}\operatorname{sgn}(\dot{s}_2) - k_{d2}\xi_\phi\right) \\ &= \dot{s}_2\left(s_2 - \lambda_2 s_2 - k_{d2}\xi_\phi\right) - k_{s2}\left|\dot{s}_2\right| \\ &\leq \left|\dot{s}_2\right|\left(s_2(1-\lambda_2) - k_{d2}\xi_\phi - k_{s2}\right) \\ &\leq \left|\dot{s}_2\right|\left(\left|s_2\right|(1-\lambda_2) + k_{d2}\xi_\phi^{\max} - k_{s2}\right) \end{aligned}$$

where $\xi_\phi^{\max} \in \mathbb{R}^+$ is the upper bound of disturbances, such that $\left|\xi_\phi\right| \leq \xi_\phi^{\max}$. In order to obtain the negative value of $\dot{V}$, the controller gains λ_2, k_{s2} must satisfy:

$$\begin{cases} \lambda_2 > 1 \\ k_{s2} > k_{d2}\xi_\phi^{\max} \end{cases} \tag{18}$$

Thus, in order to obtain k_{s2}, the upper bound for disturbances, $\xi_\phi^{\max}$, must be known in advance. It easy to see that shortly after takeoff, the quadcopter is at low altitudes where the effect of external disturbances (e.g., from wind) is small. In this stage of the flight, the upper bound, $\xi_\Phi^{\max}$, can be easily predicted by the user. However, $\xi_\Phi^{\max}$, will change as the quadcopter gains in altitude. As a rule of thumb: the higher the altitude, the more pronounced external disturbances are likely to be. Hence, the upper bound $\xi_\Phi^{\max}$ may no longer be estimated with any reasonable level of precision. As a result, the stability of the system is no longer guaranteed. In order to overcome this problem, the controller needs to automatically adjust the control gain to ensure that the vehicle adapts to any changes in the order of magnitude of external disturbances. This can be achieved by using an adaptive law in the switching controller to guarantee the robustness of vehicular control under variable environmental conditions.

An adaptive switching control law that does not require knowledge of the upper bound of disturbances can be formulated using the following assumptions:

Let us assumes that $\exists \Gamma_2^d \in \mathbb{R}^+$ is constant and always satisfies:

$$\Gamma_2^d > k_{d2}\xi_\phi^{\max} \tag{19}$$

Further, let U_2^{AS} denotes an adaptive switching control law for roll control, which is chosen as:

$$U_2^{AS} = \frac{1}{k_{d2} b_1}\left(\lambda_2 s_2 + \hat{\Gamma}_2\operatorname{sgn}(\dot{s}_2)\right) \tag{20}$$

where $\hat{\Gamma}_2 \in \mathbb{R}^+$ is the estimate of Γ_2^d. Then the new adaptive controller, U_2^A, can be obtained by combining Eqs.(7), (13) and (20):

$$\begin{aligned} U_2^A = {} & \frac{1}{k_{d2} b_1}\left(-\beta_2 \dot{s}_2 + k_{p2}\dot{e}_2 + k_{int2} e_2 \right. \\ & \left. + \; k_{d2}\left(\ddot{\phi}_d - x_4 x_6 a_1 - x_4 a_2 \Omega_r\right) + \lambda_2 s_2 + \hat{\Gamma}_2\operatorname{sgn}(\dot{s}_2)\right) \end{aligned} \tag{21}$$

By substituting U_2 in Eq.(12) with U_2^A in Eq.(21), the second derivative of the adaptive sliding surface, $\ddot{s}_2$, becomes:

$$\ddot{s}_2 = -\lambda_2 s_2 - \hat{\Gamma}_2\operatorname{sgn}(\dot{s}_2) - k_{d2}\xi_\phi \tag{22}$$

Clearly, if we can find an adaptive law such that $\hat{\Gamma}_2 \to \Gamma_2^d$, as $t \to \infty$, then the roll dynamics is strictly controlled by Eq.(21).

Let $\tilde{\Gamma}_2$ represent the adaptive error.

$$\tilde{\Gamma}_2 = \hat{\Gamma}_2 - \Gamma_2^d \tag{23}$$

Consider a Lyapunov function:

$$V_1(t) = \frac{1}{2}(s_2)^2 + \frac{1}{2}(\dot{s}_2)^2 + \frac{1}{2}\alpha_2\left(\tilde{\Gamma}_2\right)^2 \quad (24)$$

where $\alpha_2 \in \mathbb{R}^+$ is constants.

Then, from Eqs.(22), (23) and (24), the derivative of $V_1(t)$ becomes:

$$\begin{aligned}\dot{V}_1 &= s_2\dot{s}_2 + \dot{s}_2\ddot{s}_2 + \alpha_2\tilde{\Gamma}_2\dot{\hat{\Gamma}}_2\\ &= s_2\dot{s}_2 + \dot{s}_2\left(-\lambda_2 s_2 - \hat{\Gamma}_2\mathrm{sgn}(\dot{s}_2) - k_{d2}\xi_\phi\right)\\ &\quad + \alpha_2\left(\hat{\Gamma}_2 - \Gamma_2^d\right)\dot{\hat{\Gamma}}_2\\ &= \dot{s}_2\left(s_2 - \lambda_2 s_2 - k_{d2}\xi_\phi\right) - \hat{\Gamma}_2|\dot{s}_2| + \alpha_2\left(\hat{\Gamma}_2 - \Gamma_2^d\right)\dot{\hat{\Gamma}}_2\\ &\leq |\dot{s}_2|\left(s_2(1-\lambda_2) - k_{d2}\xi_\phi - \hat{\Gamma}_2\right) + \alpha_2\left(\hat{\Gamma}_2 - \Gamma_2^d\right)\dot{\hat{\Gamma}}_2\\ &\leq |\dot{s}_2|\left(|s_2|(1-\lambda_2) + k_{d2}\xi_\phi^{\max} - \hat{\Gamma}_2\right)\\ &\quad + \alpha_2\left(\hat{\Gamma}_2 - \Gamma_2^d\right)\dot{\hat{\Gamma}}_2\end{aligned}$$

In order to obtain a negative value for $\dot{V}_1(t)$, the adaptive law, $\dot{\hat{\Gamma}}_2$, and λ_2 are chosen as:

$$\begin{cases}\lambda_2 > 1\\ \dot{\hat{\Gamma}}_2 = \dfrac{1}{\alpha_2}|\dot{s}_2|\end{cases} \quad (25)$$

From Eq.(25) it can be seen that the adaptive law is easily obtained, and regardless of the upper bound for disturbances, by tuning α_2. In order to reduce the chattering effect, a thin boundary layer neighboring the switching law has been introduced by [49]–[51]. Thus, instead of using $\hat{\Gamma}_2\mathrm{sgn}(\dot{s}_2)$ as we did in Eq.(20), the alternative term of $\hat{\Gamma}_2 sat(\dot{s}_2/\Phi_2)$ is applied, where $\Phi_2 \in \mathbb{R}^+$ is constant and defines the thickness of a thin boundary layer [50]:

$$sat(\dot{s}_2/\Phi_2) = \begin{cases}-1, & \text{if } \dot{s}_2/\Phi_2 \leq -1\\ \dot{s}_2/\Phi_2, & \text{if } -1 < \dot{s}_2/\Phi_2 \leq 1\\ 1, & \text{if } \dot{s}_2/\Phi_2 > 1\end{cases}$$

The robust adaptive controller for pitch (U_3) and yaw (U_4) dynamics can be designed in a similar fashion to the roll controller. Hence, the equivalent controller, U_3^E, and the adaptive switching controller, U_3^{AS}, for pitch dynamics are designed as follows:

$$\begin{aligned}U_3^E = \frac{1}{k_{d3}b_2}&\left(-\beta_3\dot{s}_3 + k_{p3}\dot{e}_3 + k_{int3}e_3\right.\\ &\left. + k_{d3}\left(\ddot{\theta}_d - x_2x_6a_3 - x_2a_4\Omega_r\right)\right) \quad (26)\end{aligned}$$

where, $e_3 = \theta_d - x_3$, and $\dot{e}_3 = \dot{\theta}_d - x_4$

Let $\Gamma_3^d \in \mathbb{R}^+$ be a constant that always satisfies $\Gamma_3^d > k_{d3}\xi_\theta^{\max}$, where $\xi_\theta^{\max} \in \mathbb{R}^+$ is the upper bound of disturbances affecting pitch dynamic, such that $|\xi_\theta| \leq \xi_\theta^{\max}$.

Then, the adaptive switching controller for the pitch subsystem then becomes:

$$U_3^{AS} = \frac{1}{k_{d3}b_2}\left(\lambda_3 s_3 + \hat{\Gamma}_3\mathrm{sgn}(\dot{s}_3)\right) \quad (27)$$

where $\hat{\Gamma}_3 \in \mathbb{R}^+$ is the estimate of Γ_3^d. The adaptive law, $\dot{\hat{\Gamma}}_3$, and λ_3 are chosen as:

$$\begin{cases}\lambda_3 > 1\\ \dot{\hat{\Gamma}}_3 = \dfrac{1}{\alpha_3}|\dot{s}_3|\end{cases} \quad (28)$$

where $\alpha_3 \in \mathbb{R}^+$ is constant.

The term $\hat{\Gamma}_3 sat(\dot{s}_3/\Phi_3)$ is used again instead of $\hat{\Gamma}_3\mathrm{sgn}(\dot{s}_3)$ to reduce the chattering effect.

Similarly, the equivalent controller U_4^E and adaptive switching law U_4^{AS} for yaw dynamic are designed as follows:

$$\begin{aligned}U_4^E = \frac{1}{k_{d4}b_3}&\left(-\beta_4\dot{s}_4 + k_{p4}\dot{e}_4 + k_{int4}e_4\right.\\ &\left. + k_{d4}\left(\ddot{\psi}_d - x_2x_4a_5\right)\right) \quad (29)\end{aligned}$$

Let $\Gamma_4^d \in \mathbb{R}^+$ be a constant that always satisfies $\Gamma_4^d > k_{d4}\xi_\psi^{\max}$, where $\xi_\psi^{\max} \in \mathbb{R}^+$ is the upper bound value of disturbances affecting yaw dynamic, such that $\left|\xi_\psi\right| \leq \xi_\psi^{\max}$. Then, the adaptive switching controller for the yaw subsystem can be expressed as:

$$U_4^{AS} = \frac{1}{k_{d4}b_3}\left(\lambda_4 s_4 + \hat{\Gamma}_4\mathrm{sgn}(\dot{s}_4)\right) \quad (30)$$

where $\hat{\Gamma}_4 \in \mathbb{R}^+$ is the estimate of Γ_4^d. The adaptive law, $\dot{\hat{\Gamma}}_4$, and λ_4 are chosen as:

$$\begin{cases}\lambda_4 > 1\\ \dot{\hat{\Gamma}}_4 = \dfrac{1}{\alpha_4}|\dot{s}_4|\end{cases} \quad (31)$$

where $\alpha_4 \in \mathbb{R}^+$ is constant.

$\hat{\Gamma}_4 sat(\dot{s}_4/\Phi_4)$ is used instead of $\hat{\Gamma}_4\mathrm{sgn}(\dot{s}_4)$ to reduce the chattering effect.

B. ALTITUDE CONTROLLER

Let h_d represents the desired altitude. To obtain the altitude controller, the tracking error and its first and second time derivative are computed as follows: $e_1 = h_d - x_7$, $\dot{e}_1 = \dot{h}_d - x_8$, $\ddot{e}_1 = \ddot{h}_d - \dot{x}_8$, and from the Eqs.(3), (4) and (5), the second time derivative, $\ddot{e}_1$, is rewritten as:

$$\ddot{e}_1 = \ddot{h}_d - g + \frac{1}{m}(\cos x_1 \cos x_3)U_1 - \xi_h \quad (32)$$

Substituting $\ddot{e}_1$ in Eq.(9) with Eq.(32), the closed loop error dynamics for altitude is obtained from:

$$\begin{aligned}\ddot{s}_1 + \beta_1\dot{s}_1 = k_{p1}\dot{e}_1 + k_{int1}e_1&\\ + k_{d1}\left(\ddot{h}_d - g + \frac{1}{m}(\cos x_1\cos x_3)U_1 - \xi_h\right)&\end{aligned} \quad (33)$$

The equivalent controller for altitude dynamics, U_1^E, is obtained from Eq.(33) when $\ddot{s}_1 = 0$ and the disturbances are not present ($\xi_h = 0$).

$$\begin{aligned}U_1^E = &\frac{-m}{k_{d1}(\cos x_1\cos x_3)}\\ &\times\left(-\beta_1\dot{s}_1 + k_{p1}\dot{e}_1 + k_{int1}e_1 + k_{d1}\left(\ddot{h}_d - g\right)\right) \quad (34)\end{aligned}$$

Let $\Gamma_1^d \in \mathbb{R}^+$ be a constant that always satisfies $\Gamma_1^d > k_{d1}\xi_h^{\max}$, where $\xi_h^{\max} \in \mathbb{R}^+$ is the upper bound of disturbances affecting altitude, i.e., $|\xi_h| \le \xi_h^{\max}$. Then, the adaptive switching control law for altitude can be chosen as:

$$U_1^{AS} = \frac{-m}{k_{d1}\left(\cos x_1 \cos x_3\right)}\left(\lambda_1 s_1 + \hat{\Gamma}_1 \operatorname{sgn}(\dot{s}_1)\right) \quad (35)$$

where $\hat{\Gamma}_1 \in \mathbb{R}^+$ is the estimate of Γ_1^d. The adaptive law, $\dot{\hat{\Gamma}}_1$, and λ_1 are chosen as:

$$\begin{cases} \lambda_1 > 1 \\ \dot{\hat{\Gamma}}_1 = \dfrac{1}{\alpha_1}\left|\dot{s}_1\right| \end{cases} \quad (36)$$

where $\alpha_1 \in \mathbb{R}^+$ is constant.

$\hat{\Gamma}_1 sat(\dot{s}_1/\Phi_1)$ is used instead of $\hat{\Gamma}_1 \operatorname{sgn}(\dot{s}_1)$ to reduce the chattering effect.

(The proof of stability is entirely similar to the roll controller)

IV. SIMULATION RESULTS AND DISCUSSIONS

The numerical simulation is performed to prove the effectiveness of the proposed robust adaptive second order sliding mode control based PID sliding surface, presented in this section. The equation governing quadcopter dynamics (Eq.(1)) is used to verify the robustness of the proposed algorithm for attitude and altitude control under the influence of external perturbations on the vehicle. The advantages of the proposed controller will be discussed and compared with the recently suggested techniques such as normal adaptive SMC in [35], the ST-SMC, Modified ST-SMC, and NT-SMC which are proposed in [36] and [37] to highlight the contribution of this study.

A. SIMULATION ASSUMPTIONS

The simulation is based on several assumptions: (i) the attitude of a quadcopter is determined by an inertial navigation system (INS), and the altitude is measured by a barometer or laser sensor; and (ii) the disturbances simultaneously affect roll, pitch, yaw, and altitude dynamics. The candidate functions of disturbance are given as following the Eq.(37). The remaining parameter values for the quadcopter, the controller, as well as initial conditions and reference values for attitude and altitude for numerical simulations are shown in the Tables 2 and 3.

$$\begin{aligned} \xi_\phi(t) &= \xi_\theta(t) = 7 + 2\cos\left(\frac{2\pi}{3}t\right) \\ \xi_\psi(t) &= 5 + 2\cos\left(\frac{\pi}{2}t\right) \\ \xi_h(t) &= 18 + 4\cos\left(\frac{\pi}{6}t\right) \end{aligned} \quad (37)$$

B. SIMULATION RESULTS

To clearly demonstrate the improved performance of the proposed robust adaptive controller with respect to previous approaches, the simulation results are discussed in two stages. The first stage covers the time period from take-off until five seconds into the flight, i.e., from $t=0s$ to $t<5s$, during which we assume the effect of external disturbances on the vehicle to be zero ($\xi_{\text{Phi}} = \xi_{\text{Phi}} = \xi_{\text{Phi}} = \xi_{\text{Phi}} = 0$). The second stage covers times $t \ge 5s$, during which external disturbances impact both attitude and altitude dynamics of the quadcopter as per Eq.(37).

TABLE 2. System parameters and initial values for simulations.

Parameters	Value	Unit
m	1.12	kg
I_x	0.0119	kg.m^2
I_y	0.0119	kg.m^2
I_z	0.0223	kg.m^2
b	7.73213 (10^{-6})	Ns^2
d	1.27513 (10^{-7})	Nms^2
J_r	8.5 (10^{-4})	kg.m^2
l	0.23	m
ϕ_0, ϕ_d	10, 0	degree
θ_0, θ_d	10, 0	degree
ψ_0, ψ_d	5, 0	degree
h_0, h_d	0, 5	m

TABLE 3. Parameters of controllers for simulations.

Parameters	Roll (ϕ)	Pitch (θ)	Yaw (ψ)	Altitude (h)
k_p	1.2	1.2	1.2	5.62
k_{int}	3.1	3.1	3.1	7.2
k_d	0.08	0.08	0.03	1.0
β	1.0	1.0	3	2.0
λ	1.2	1.2	4	1.01
α	0.001	0.001	0.001	0.01
Φ	0.01	0.01	0.001	0.1

For comparison, we also simulated the performance of four other types of controller, prescribing the same flight conditions: normal adaptive SMC, ST-SMC, Modified ST-SMC, and NT-SMC. Comparing the simulation results (Figures 3 to 6), it can be seen that during the disturbance-free early flight stage (t<5s) the responses of attitude (roll, pitch, and yaw angles) and altitude are nearly identical in all five controllers, both in the time-course of their response and the tracking performance. The output feedback rapidly tracks the desired state without any oscillations or steady state errors.

If we look at the later flight stages ($t \ge 5s$), however, when disturbances are no longer zero, our adaptive controller exhibits a significantly superior performance compared to other approaches. As per the Table 4, the attitude performances of NT-SMC, ST-SMC, and Modified ST-SMC exhibit a large oscillation. For NT-SMC it reaches about 6.6° for roll and pitch (Figures 3 and 4) and 3.6° for yaw angles (Figure 5). For ST-SMC, the corresponding values are 6.1° for roll and pitch and 2.7° for yaw. For the Modified ST-SMC, we obtain 4.8° for roll and pitch, and 2.1° for yaw. In addition, the time convergence to the steady state of attitude feedback in these three controllers is about 2.5 seconds (at time t=7.5s), which means that it takes nearly 2.5 seconds from the time the disturbance is applied until the vehicle

TABLE 4. Comparison of control performance results.

Parameters	Roll (°)	Pitch (°)	Yaw (°)	Altitude (m)
NT SMC	6.6	6.6	3.6	5.55
ST-SMC	6.1	6.1	2.7	5.57
Modified ST-SMC	4.8	4.8	2.1	5.56
Normal Adaptive SMC	0.26	0.26	0.25	5.02
Proposed Controller	0.04	0.04	0.02	5.03

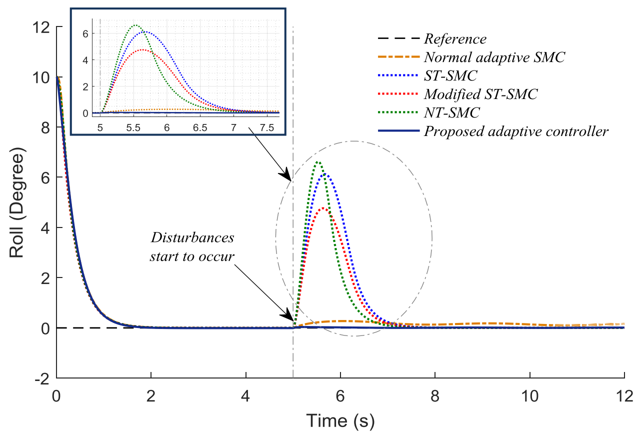

FIGURE 3. Comparison of roll angle performance between the proposed adaptive controller with other approaches.

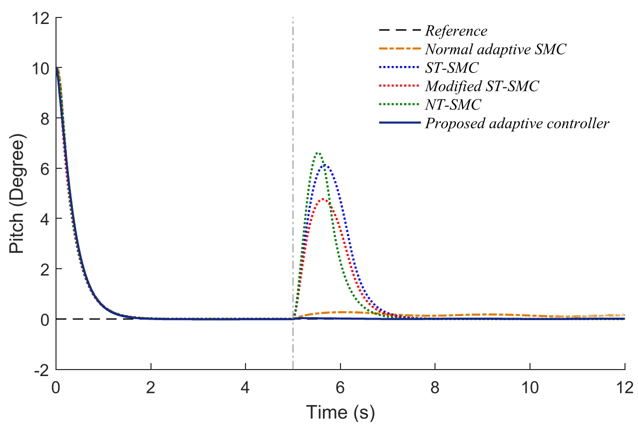

FIGURE 4. Comparison of pitch angle performance between the proposed adaptive controller with other approaches.

returns to a steady state. These performances demonstrate that these three controllers have significant difficulties to cope with sudden disturbances.

The normal adaptive SMC uses an adaptive law for switching control of the SMC which results in a clearly improved performance of the attitude control in the presence of a disturbance. While the initial oscillation remains small, the output response never converges to zero for longer times and a small steady state error persists in roll, pitch, and yaw angles (Figures 3 to 5). In addition, a large chattering effect is generated by the controllers U_2, U_3 and U_4 at time t>10s

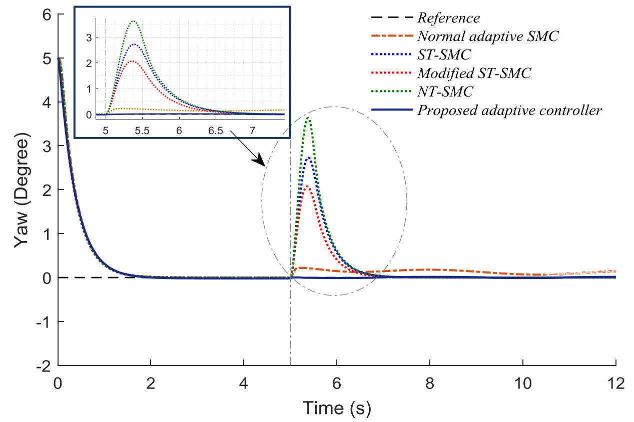

FIGURE 5. Comparison of yaw angle performance between the proposed adaptive controller with other approaches.

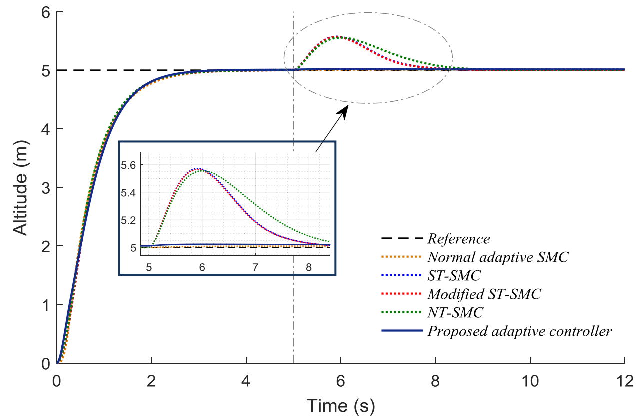

FIGURE 6. Comparison of altitude performance between the proposed adaptive controller with other approaches.

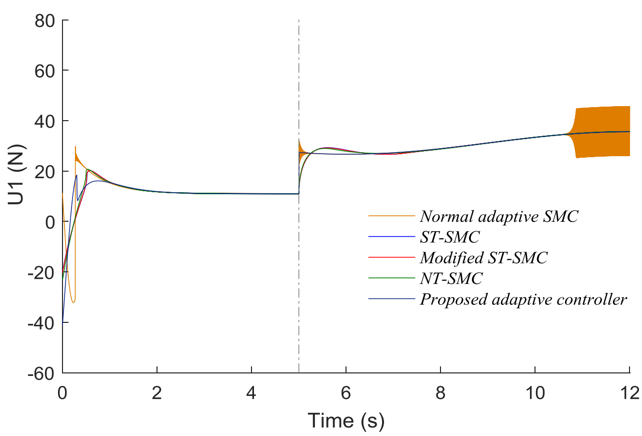

FIGURE 7. Comparison of controller U_1 between the proposed adaptive controller with other approaches.

(Figures 8 to 10), although we employed the saturation method to reduce this phenomenon.

Conversely, the proposed adaptive controller presented in this study shows only a negligible initial oscillation and quickly recovers the steady state. Once the external disturbance is applied, the controller seems to be able to

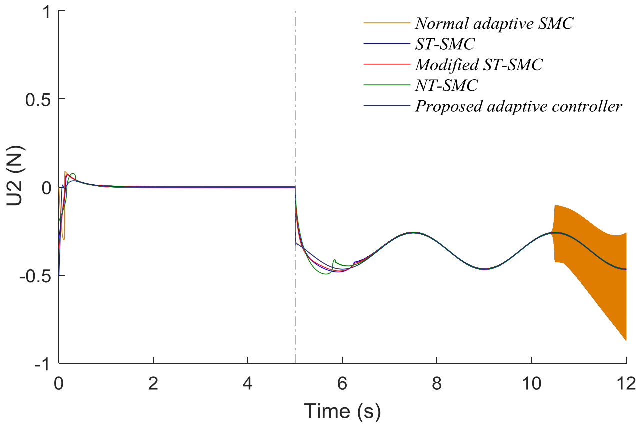

FIGURE 8. Comparison of controller U_2 between the proposed adaptive controller with other approaches.

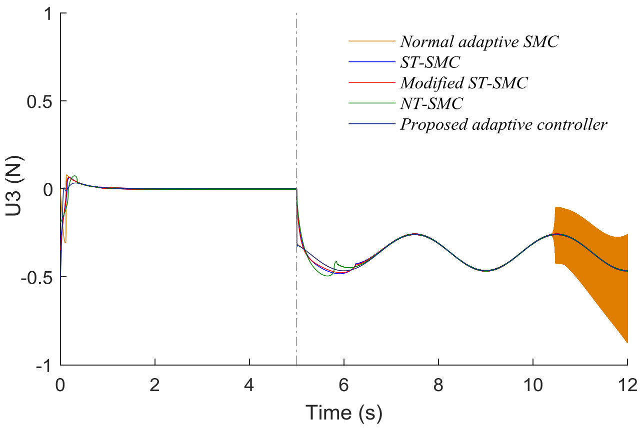

FIGURE 9. Comparison of controller U_3 between the proposed adaptive controller with other approaches.

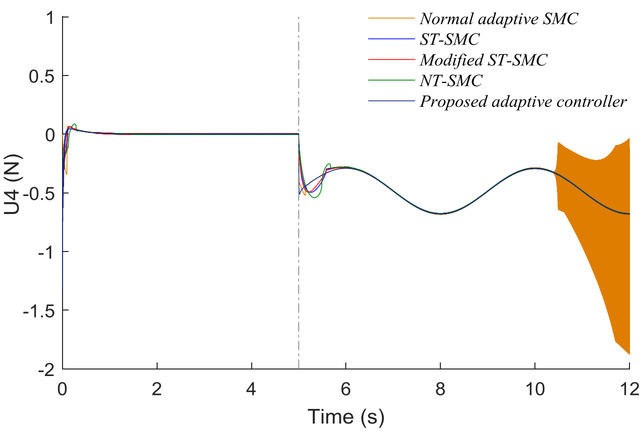

FIGURE 10. Comparison of controller U_4 between the proposed adaptive controller with other approaches.

immediately compensate its effects (Figures 8 to 10). Hence, only a very small oscillation (about 0.04° for roll and pitch, and 0.02° for yaw) in attitude is generated (Figures 3 to 5) while the chattering affect has effectively been eliminated.

The altitude performance of the five tested controlers presents a simular image to their attitude control. Before any disturbance is applied (t<5s), the altitude responses in all five controllers is nearly identical, both in terms of tracking performance and time response (Figure 6). Once disturbances are present ($t \geq 5s$), the altitude performance of the quadcopter is clearly affected, showing relatively large oscillations in compared to normal adaptive SMC and our proposed adaptive controller. Furthermore, ST-SMC, Modified ST-SMC, and NT-SMC also exhibit a greater delay before converging to the steady state, about 3s after the disturbance has been applied to the vehicle (Figure 6). While the normal adaptive SMC performs well, it generates a large chattering phenomenon for t>10s (Figure 7). Our proposed adaptive controller seems to have the best overall performance: good tracking (Figure 6) and only negligible chattering (Figure 7), proving the effectiveness of our proposed algorithm with regard to altitude control.

In summary, the simulation results showed that while all five tested approaches performed equally well in the absence of external disturbances, i.e., they exhibited both a fast response and good tracking performance, clear performance differences appeared once external perturbations were applied to the system. ST-SMC, Modified ST-SMC, and NT-SMC did not adapt well to these disturbances, resulting in relatively large oscillations in roll, pitch, yaw, and altitude. The normal adaptive SMC exhibited a much better tracking performance for attitude and altitude but showed a persistent and significant steady state error and chattering phenomenon. The best overall performer was the proposed adaptive algorithm presented in this study which guaranteed the stability of the vehicle, exhibiting a fast response, rapid adaptation, and no chattering.

V. CONCLUSIONS

In this study, we introduced a simple robust adaptive second order sliding mode controller, based on PID sliding surface to improve quadcopter tracking performance of attitude and altitude. We could demonstrate that this adaptive method represents a significant advancement of the existing state-of-the-art. The proposed algorithm will be capable to extend the range of environmental conditions under which quadcopters can be deployed as it is capable to quickly stabilize the vehicle even when there are wind gusts of unknown magnitude and duration. This is achieved through an adaptive controller that automatically adjusts the control values to compensate the changes in magnitude of the disturbance signal.

Numerical simulations were performed and clearly demonstrated the effectiveness of the proposed method. The experimental validation of this proposed adaptive controller is the subject of a planned future study.

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