IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received December 6, 2018, accepted December 23, 2018, date of publication January 1, 2019, date of current version January 29, 2019.

Digital Object Identifier 10.1109/ACCESS.2018.2890450

Altitude Control for Variable Load Quadrotor via Learning Rate Based Robust Sliding Mode Controller

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This work was supported in part by the Natural Science Foundation of China under Grant 61672430, in part by the Shaanxi Key Research and Development Program under Grant S2019-YF-ZDCXL-ZDLGY-0227, in part by the Aeronautical Science Fund under Grant BK1829-02-3009, and in part by the NWPU Basic Research Fund under Grant 3102018jcc001.

ABSTRACT This paper aims to solve the problem of altitude control of the variable load quadrotor unmanned aerial vehicle. Generally, the controller parameters of the quadrotor are adjusted for constant load and external disturbance factors. However, whether in military fields or civilian fields, the quadrotor will encounter variable load situations, such as throwing weapons or delivering express. Variable load as a large internal disturbance factor results in control instability. Toward this end, a novel robust sliding mode controller SMC) is designed to track the desired trajectory promptly under variable load condition while restraining the chattering problem. This novel controller consists of learning rate-based sliding mode surface and inverse hyperbolic function-based adaptive sliding mode reaching law. It is worth mentioning that a mass estimation algorithm is added to the proposed novel SMC to estimate the real-time mass of the quadrotor in the air, which improves the quadrotor's performance in restraining the large variable load disturbance impact. In addition, the altitude control law is derived on the basis of the Lyapunov stability theory. Finally, the simulation and experimental results are carried out to show the effectiveness and robustness of the proposed controller in terms of altitude tracking, mass estimation, and disturbance resistance.

INDEX TERMS Altitude control, variable load, quadrotor UAV, sliding mode control.

I. INTRODUCTION

In recent years, the development of unmanned aerial vehicles (UAV) has attracted significant attention of many industries and scholars because of its widely range of applications. The quadrotor form is a typical kind of UAV, which has the advantages of vertical take-off and landing aircraft meanwhile increased payload capacity. The quadrotor form not only has its own inherent hover stability, but also enhances its operability. In addition, its most important advantage over traditional aircraft is that it has reduced the mechanical complexity. With the development of technology, quadrotor UAV can be used to achieve some high-risk works, high-intensity works or works that can be significantly improved efficiency, such as military activities, spraying pesticides, express delivery, which drew heated discussions recently [1]. An unavoidable problem with these applications is that if the load is unknown or variable, the altitude control of the quadrotor UAV will be unstable, so air hovering or maintaining stable high altitude flight cannot be achieved. Therefore, it is significant important to design a robust altitude control system to maintaining the stability of the altitude and tracking the desired trajectory. The linear control strategy serves as an attempt to control UAV, whose control effect is restricted and needs to meet certain conditions to be effective. What's more, the linear controller cannot solve the drift and hover conditions [2]. A linear Proportional-Integral-Derivative(PID) control strategy is proposed to explore the effect of helicopter of dynamic load disturbances introduced by instantaneously increased payload mass in [3]. According to the description of this control strategy, due to the control of the PID, the helicopter can reduce the increased load offset within a relative extent, and the cyclic boundary limit plays a major role within the specified load range. However, the control input is not stable, which has a large floating range and long convergence time. For the altitude control of the variable load UAV, one of the important steps is to estimate the mass. Since we can not directly measure the quadrotor UAV mass when it is in the air, altitude control is quite difficult if the mass cannot be accurately estimated. Reference [4] proposed a mass estimation algorithm to estimate the inertial parameters of the grasped object, and to adapt the controller and improve performance during flight. For unknown payloads, [5] proposed an adaptive robust control (ARC) to compensate for the parametric uncertainty. However, when the desired output was constant, the parameter estimate could not approach to its true value.

The sliding mode control (SMC) technique is a kind of nonlinear control method. Compared to other control algorithms, the advantage of sliding mode control is that it is widely used to make the system robust to external disturbances, unmodeled dynamic characteristics and parameter uncertainties [6], moreover, the tracking errors of system can converge to desired value in finite time. Many SMC methods have been proposed for the quadrotor UAV controller design [7]–[10]. Recently, researchers have proposed various extended SMC control strategy for altitude control of quadrotor UAV. High-order sliding mode controller (HOSMC) is used to stabilize the altitude of the quadrotor UAV because it can overcome the chatter phenomenon in the classic first-order sliding mode control while maintaining the invariance of the sliding mode [11], [12]. Adaptive sliding mode control can effectively estimate uncertainty and adjust controller parameter [13]–[16]. Shtessel *et al.* [17], Mefoued [18], Rajappa *et al.* [19], Derafa *et al.* [20], Shtessel *et al.* [21], Utkin [22], and Utkin and Poznyak [23] proposed an adaptive super-twisting sliding mode control in order to reduce at minimum the chattering phenomena by using the super-twisting reaching law for the control gains. Terminal sliding mode controller (TSMC) for a quadrotor UAV is proposed in [24]–[26], which is able to guarantee that the tracking errors of all system state variables converge to zero in finite time. Moreover, TSMC can eliminate the chattering phenomenon caused by the switching control action and realize the high precision performance.

In this paper, a learning rate based sliding mode control algorithm is proposed to improve the quadrotor's altitude control performance under variable load disturbance condition. what's more, a novel mass estimation algorithm is put forward to estimate quadrotor's real-time mass in the air. These two algorithms are combined to obtain the robust altitude controller. On the one hand, this controller allows the quadrotor to converge to the desired value promptly under variable load disturbances condition, while restraining the chattering problem. On the other hand, this controller can track the mass change so that the quadrotor can convergence to desired value accurately and remain stable. The main innovations and contributions of this paper are as follows:

1. A novel learning rate based sliding mode surface is proposed, which maintains the advantages of the high convergence speed of the traditional terminal sliding mode control strategy, and the convergence speed will slow down when the error variable approaching the sliding mode surface, so that chattering problem that caused by the high convergence speed can be restrained.

2. A novel sliding mode reaching law is proposed, which is combined with the inverse hyperbolic function term and adaptive algorithm to improve the traditional two-power reaching law. This novel reaching law improves the performance of dynamic characteristics that increase the approach speed to the sliding surface while reducing the amplitude of the control input signal. Moreover, adaptive module is added to eliminate the influence of external uncertain disturbance factors.

3. A mass estimation algorithm for the quadrotor UAV in the air is proposed to get real-time mass of quadrotor and track quality change accurately.

The following organizational structure of this article is as follows. The second part introduces the dynamic modeling of the quadrotor UAV. The third section introduces the proof of principle of the proposed controller and the control inputs on quadrotor. Simulation results are presented in the fourth part. Conclusion in the fifth part.

II. QUADROTOR DYNAMICAL MODEL

The structure of the quadrotor UAV is shown in Fig.1. Four motors and propellers are used as power units to increase maneuverability and load capacity. The lift is changed by adjusting the speed of the motor. The lift difference is generated by adjusting the rotational speed of the four motors to change the attitude of the quadrotor. The power unit is divided into two opposing rotor pairs (rotor 1, 3 and rotor 2, 4) for eliminating anti-torque, one of which pair rotating clockwise while the other rotating clockwise [27].

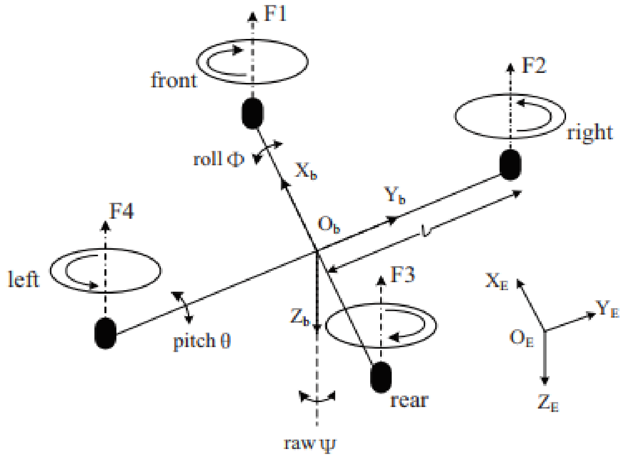

FIGURE 1. Configuration of the quadrotor.

The earth-frame is defined as E $= [O_E, X_E, Y_E, Z_E]$ with $O_E Z_E$ pointing upward. The body-frame is defined as B $= [O_b, X_b, Y_b, Z_b]$ whose origin O_b is at the center of gravity of the quadrotor, $O_b X_b$ points to the forward of the quadrotor, $O_b Y_b$ points to the right of the quadrotor,

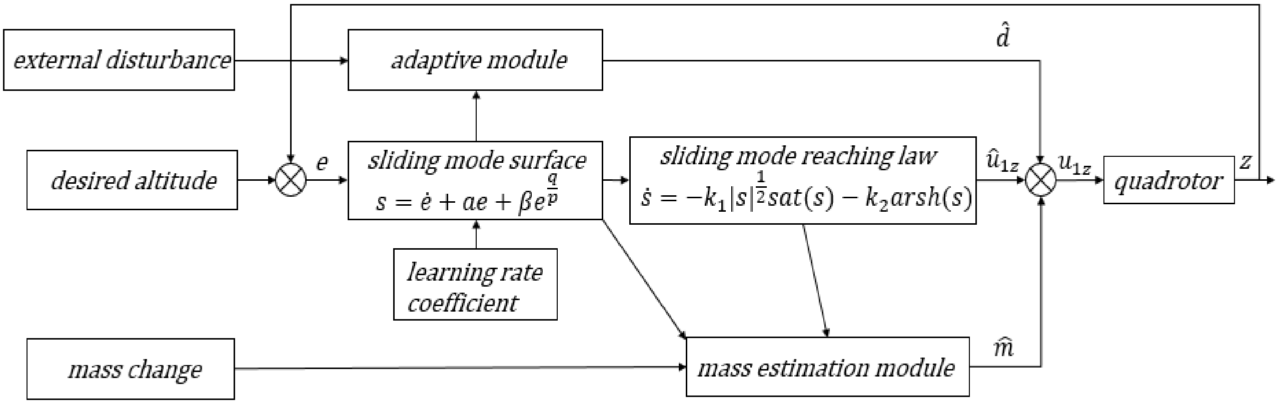

FIGURE 2. The structure of the proposed novel SMC strategy.

O_bZ_b completes the right-hand orthogonal coordinate system. Both of earth-frame and body-frame conform to the right-hand rule. Euler angles are denoted as $[\phi, \theta, \psi]$, which represent roll, pitch, and yaw respectively. Considering the transformation from Earth-fixed frame E to Body-fixed frame B can get the rotation matrix as follows:

$$R = \begin{bmatrix} c\theta c\psi & s\phi s\theta c\psi - c\phi s\psi & c\phi s\theta c\psi + s\phi s\psi \\ c\theta s\psi & s\phi s\theta s\psi + c\phi c\psi & c\phi s\theta s\psi - s\phi c\psi \\ -s\theta & s\phi c\theta & c\phi c\theta \end{bmatrix} \quad (1)$$

where s. and c. are abbreviations for sin(·) and cos(·).

According to Lagrange approach, a simplified dynamical model of quadrotor can be obtained as follow [28]:

$$\begin{aligned} \ddot{x} &= u_1(cos\phi sin\theta \cos\psi + \sin\phi \sin\psi) + d/m \\ \ddot{y} &= u_1(cos\phi sin\theta \sin\psi - \sin\phi \cos\psi + d/m \\ \ddot{z} &= u_1(cos\phi \cos\theta) - g + d/m \\ \ddot{\phi} &= \dot{\theta}\dot{\psi}(\frac{I_y - I_z}{I_x}) - \frac{J_R}{I_x}\dot{\theta}\Omega_R + u_2 \\ \ddot{\theta} &= \dot{\phi}\dot{\psi}(\frac{I_z - I_x}{I_y}) - \frac{J_R}{I_y}\dot{\phi}\Omega_R + u_3 \\ \ddot{\psi} &= \dot{\phi}\dot{\theta}(\frac{I_x - I_y}{I_z}) - u_4 \end{aligned} \quad (2)$$

where (x, y, z) denote the real time position of quadrotor in the earth-frame, g is the gravity acceleration, d is external uncertain interference factor, J_R and Ω_R are the moments of inertia and angular velocity of the propeller blades. I_x, I_y, I_z are the moments of inertia with respect to the axes, u_i are the inputs terms defined as follow:

$$\begin{cases} u_1 = (F_1 + F_2 + F_3 + F_4)/m \\ u_2 = l(-F_1 - F_2 + F_3 + F_4)/I_x \\ u_3 = l(-F_1 + F_2 + F_3 - F_4)/I_y \\ u_4 = c(F_1 - F_2 + F_3 - F_4)/I_z \end{cases} \quad (3)$$

where F_i are thrusts provided by four rotors which can be regarded as the real control inputs to the system, m is the total mass of the structure, l is the lever length, and c is a parameter as a moment scaling factor.

III. CONTROLLER DESIGN

The learning rate based adaptive sliding mode controller is proposed to track the desired altitude and maintain altitude stability. The proposed controller consist of learning rate based sliding mode surface and inverse hyperbolic function based sliding mode reaching law. The learning rate based sliding mode surface is combined with the novel mass estimation algorithm and the adaptive algorithm. The novel sliding mode reaching law combined with inverse hyperbolic function and saturation function. The Z-axis direction equation, as the dynamic equation, is substituted into the sliding mode surface and reaching law to obtain the control input. The structure of the proposed novel SMC control strategy is shown in Fig.2.

A. CONTROL ALGORITHM DESIGN

1) LEARNING RATE BASED SLIDING MODE SURFACE

The novel learning rate based sliding mode surface is designed as

$$s = \dot{e} + ae + \beta e^{\frac{q}{p}} \quad (4)$$

where e is defined as $e = z - z_d$ represent the tracking error that, $\dot{e}$ represent the derivative of the tracking error, and β is positive constant, p>q>0 are odd numbers, the coefficient a is defined as

$$a = a_0 + \alpha\,|\dot{e}| \quad (5)$$

where α is learning rate, which is defined as $\alpha = b^{|e|} - 1$, a_0 is positive constant, $b > 0$, $b \neq 1$.

According to the (4), the variable coefficient a can adjust the speed that the altitude tracking error converge to zero. In the initial stage, the altitude tracking error is relatively large, the rate of change of the tracking error is also large due to the effect of the sliding mode surface. The learning rate changes at an exponential rate with the rate of change of the altitude tracking error, so that the coefficient a rapidly changes with the change of the altitude tracking error, eventually causing the altitude tracking error to converge at a fast speed. However, the relatively high tracking error rate cause the problem of system chattering when the error reaches the sliding mode surface. The learning rate will follow the change with the tracking error rate, making the coefficient a change into a small number, so that the tracking error approaches the sliding mode surface at a low speed, which greatly restrains the system chattering.

Theorem 1: When the system reaches any point of the designed sliding mode surface, for any given initial state, the system can be stable and reach the equilibrium point within a limited time.

Proof 1: s = 0 when the system on the sliding mode surface, it can be obtained from (4) that

$$\dot{e} = -ae - \beta e^{\frac{q}{p}}. \tag{6}$$

Construct the Lyapunov function as follows:

$$V_1(e) = \frac{1}{2}e^2. \tag{7}$$

Differentiating (7) with respect to time and using (6), it can be obtained that:

$$\begin{aligned} \dot{V}_1(e) &= e\dot{e} \\ &= -ae^2 - \beta e e^{\frac{q}{p}} \le 0. \end{aligned} \tag{8}$$

According to the Lyapunov stability principle, the system is asymptotically stable and error will converge to zero along with the desired sliding mode surface.

2) SLIDING MODE REACHING LAW

A novel sliding mode reaching law, which improves the dynamic characteristics of the sliding mode and the approach speed to the sliding surface, is designed as

$$\dot{s} = -k_1|s|^{\frac{1}{2}}sat(s) - k_2 arsinh(s) \tag{9}$$

where the coefficients k_1, k_2 are positive constants, arsinh(s) is inverse hyperbolic function, sat(s) denotes the saturation function defined by

$$sat(s_i) = \begin{cases} 1, & s_i > \delta \\ \eta s_i, & |s| \le \delta \\ -1, & s_i < -\delta \end{cases} \tag{10}$$

where $\delta > 0$, $\eta = \frac{1}{\delta}$ denotes the thickness of boundary layer. Traditional sliding mode controller, which use the sign function, has the problem of switch discontinuities and it assumes that the control signal can switch from one value to another indefinitely and fast. However, because of finite time delays for the control computation and limitations of physical, it is impossible to achieve infinitely fast switching control in practical systems. Due to imperfect switching in practice, it raises the issue of chattering which is highly undesirable. In this paper, sign function is replaced by saturation function and the introduced boundary layer η so that a certain range of state points can be attracted to the boundary layer of the switch surface, which greatly restrains the chattering.

According to the (9), the second term arsinh(s) improves the dynamic characteristics of the sliding mode and the approach speed of the sliding surface, what's more, arsinh(s) playing a role of smoothing and limiting amplitude to reduce the amplitude of the sliding mode control input signal.

B. CONTROLLER DESIGN

According to the learning rate based sliding mode adaptive control strategy, altitude controller is designed to ensure that the quadrotor can track the desired altitude and maintain the altitude when mass change. Specifically, the novel controller is designed to calculate the control law u_1 to track the desired position by means of the translational subsystem and calculate the desired attitude (ϕ_d, θ_d) for the rotational subsystem. In order to simplify the quadrotor dynamical model, the new control inputs u_{1x}, u_{1y}, u_{1z} are proposed as

$$\begin{cases} u_{1x} = u_1(cos\phi sin\theta \cos\psi + \sin\phi \sin\psi) \\ u_{1y} = u_1(cos\phi sin\theta \sin\psi - \sin\phi \cos\psi) \\ u_{1z} = u_1(cos\phi \cos\theta) \end{cases} \tag{11}$$

The quadrotor dynamical model can be denoted as

$$\begin{cases} \ddot{x} = u_{1x} + d/m \\ \ddot{y} = u_{1y} + d/m \\ \ddot{z} = u_{1z} - g + d/m \end{cases} \tag{12}$$

As for the control of altitude, its dynamic equation is:

$$\ddot{z} = u_{1z} - g + \frac{d}{m}. \tag{13}$$

Suppose that $u_0 = mu_{1z}$, so the dynamic equation can be rewritten as:

$$\ddot{z} = \frac{1}{m}(u_0 + d) - g. \tag{14}$$

In order to solve the altitude control problem of variable load quadrotor UAV, the learning rate based sliding mode surface is proposed as (4) described. According to the derivative of (4), it can be obtained that:

$$\begin{aligned} \dot{s} &= \ddot{e} + a\dot{e} + \beta\frac{q}{p}e^{\frac{q}{p}}\dot{e} \\ &= \ddot{z} - \ddot{z}_d + a\dot{e} + \beta\frac{q}{p}e^{\frac{q}{p}}\dot{e}. \end{aligned} \tag{15}$$

Substituting (14) into (15), it can be obtained as

$$\dot{s} = \frac{1}{m}(u_0 + d) - g - \ddot{z}_d + a\dot{e} + \beta\frac{q}{p}e^{\frac{q}{p}}\dot{e}. \tag{16}$$

Suppose that

$$\hat{u}_{1z} = \frac{1}{m}(u_0 + d), \tag{17}$$

it can be obtained that:

$$\dot{s} = \hat{u}_{1z} - \ddot{z}_d - g + a\dot{e} + \beta\frac{q}{p}e^{\frac{q}{p}}\dot{e}. \tag{18}$$

Substituting (9) into (18) gives

$$\hat{u}_{1z} = \ddot{z}_d + g - a\dot{e} - \beta\frac{q}{p}e^{\frac{q}{p}}\dot{e} - k_1|s|^{\frac{1}{2}}sat(s) - k_2 arsinh(s). \tag{19}$$

In order to combine adaptive control strategy with controller, the altitude control input u_0 can be designed as

$$u_{put} = \hat{m}\hat{u}_{1z} - \hat{d} \tag{20}$$

where $\tilde{m} = m - \hat{m}$, $\tilde{d} = d - \hat{d}$, $\hat{m}$ is the estimated value of m, $\hat{d}$ is the estimated value of d.

The control input u_{put} can be designed as

$$\begin{aligned} u_{put} &= \hat{m}[\ddot{z}_d + g - a\dot{e} - \beta \frac{q}{p} e^{\frac{q}{p}} \dot{e} \\ &\quad - k_1|s|^{\frac{1}{2}} sat(s) - k_2 arsinh(s)] - \hat{d}. \end{aligned} \tag{21}$$

Substituting sliding mode reaching law (9) and (20) into (16), it can be obtained as

$$\begin{aligned} \dot{s} &= \frac{1}{m}(\hat{m}\hat{u}_{1z} - \hat{d} + d) - \ddot{z}_d - g + a\dot{e} + \beta \frac{q}{p} e^{\frac{q}{p}} \dot{e} \\ &= \frac{1}{m}(\hat{m}\hat{u}_{1z} + \tilde{d}) - \hat{u}_{1z} - k_1|s|^{\frac{1}{2}} sat(s) - k_2 arsinh(s) \\ &= \frac{1}{m}(\tilde{d} - \tilde{m}\hat{u}_{1z}) - \hat{u}_{1z} - k_1|s|^{\frac{1}{2}} sat(s) - k_2 arsinh(s). \end{aligned} \tag{22}$$

Construct the Lyapunov function as follows:

$$V_2 = \frac{1}{2}s^2 + \frac{1}{2m\gamma_1}\tilde{d}^2 + \frac{1}{2m\gamma_2}\tilde{m}^2 \tag{23}$$

where γ_1, γ_2 are positive constants, substituting the adaptive sliding mode reaching law, the time derivative of V_2 is derived as

$$\begin{aligned} \dot{V}_2 &= s\dot{s} + \frac{1}{m\gamma_1}\tilde{d}\dot{\tilde{d}} + \frac{1}{m\gamma_2}\tilde{m}\dot{\tilde{m}} \\ &= s[\frac{1}{m}(\tilde{d} - \tilde{m}\hat{u}_{1z}) - \hat{u}_{1z} - k_1|s|^{\frac{1}{2}} sat(s) \\ &\quad - k_2 arsinh(s)] + \frac{1}{m\gamma_1}\tilde{d}\dot{\tilde{d}} + \frac{1}{m\gamma_2}\tilde{m}\dot{\tilde{m}} \\ &= -k_1|s|^{\frac{3}{2}} sat(s) - k_2 s arsinh(s) \\ &\quad + \frac{1}{m}s\tilde{d} - \frac{1}{m}s\tilde{m}\hat{u}_{1z} + \frac{1}{m\gamma_1}\tilde{d}\dot{\tilde{d}} + \frac{1}{m\gamma_2}\tilde{m}\dot{\tilde{m}} \\ &= -k_1|s|^{\frac{3}{2}} sat(s) - k_2 s arsinh(s) \\ &\quad + \frac{\tilde{d}}{m}(s + \frac{1}{\gamma_1}\dot{\tilde{d}}) + \frac{\tilde{m}}{m\gamma_2}(\dot{\tilde{m}} - \gamma_2 s\hat{u}_{1z}). \end{aligned} \tag{24}$$

Suppose the variable d is slowly changing, it can be obtained that $\tilde{d} = -\dot{\hat{d}}$. The system is stable when the UAV is not in loading or unloading state, so it can be obtained that $\dot{\tilde{m}} = -\dot{\hat{m}}$, then

$$\begin{aligned} \dot{V}_2 &= -k_1|s|^{\frac{3}{2}} sat(s) - k_2 s arsinh(s) \\ &\qquad + \frac{\tilde{d}}{m}(s - \frac{1}{\gamma_1}\dot{\hat{d}}) - \frac{\tilde{m}}{m\gamma_2}(\dot{\hat{m}} + \gamma_2 s\hat{u}_{1z}). \end{aligned} \tag{25}$$

When $\dot{\hat{d}}$ and $\dot{\hat{m}}$ satisfy the following conditions as

$$\begin{cases} \dot{\hat{d}} = \gamma_1 s \\ \dot{\hat{m}} = -\gamma_2 s\hat{u}_{1z}, \end{cases} \tag{26}$$

the $\dot{V}_2 \leq 0$ satisfy the Lyapunov stability theory. When the UAV is in loading or unloading state, assuming that the m estimate satisfies the following conditions as

$$\begin{cases} m(t_{unload}) - \hat{m} > 0 \\ m(t_{load}) - \hat{m} < 0 \end{cases} \tag{27}$$

where t_{unload} is denoted the time point of unloading, t_{load} is denoted the time point of loading, then $\dot{V}_2 < 0$ satisfy the Lyapunov stability theory.

According to the equation (11), (20) and (21), the control law u_1 is given as

$$u_1 = \frac{u_{put}}{m\cos\phi\cos\theta}. \tag{28}$$

IV. SIMULATION RESULTS

In this section, the efficiency and robustness of the proposed novel control strategy for altitude control problem of variable load quadrotor UAV is verified by simulation experiments. In order to simplify the model and avoid unnecessary uncertain interference problems, a reasonable assumption is proposed that when the load of the quadrotor UAV changes, the center of gravity does not shift, that is, the center of gravity of the UAV is the origin of the fixed reference frame of the body invariably.

TABLE 1. **Parameters of the quadrotor UAV in simulations.**

Symbol	Quantity	Uuit
m	2	kg
l	0.2	m
I_1=I_2	1.25	kg·m^2
I_3	2.5	kg·m^2
K_1, K_2, K_3	0.010	Ns/m
K_4, K_5, K_6	0.012	Ns/m

TABLE 2. **Controller parameters.**

Symbol	value	Symbol	value
a_0	10	k_1	7.5
b	3	k_2	8
β	1.5	γ_1	1.5
p	1	γ_2	2
q	3	β_{ST}	1.25
δ	1	k_3	3.5
g	9.8	k_4	6

To verify the performance of control strategy proposed in this section, MATLAB as an experimental platform implement simulations. The parameters of quadrotor UAV are shown in Table 1. All values of parameters used in simulations are shown in Table 2. The common Super-Twisting sliding mode controller (ST-SMC) is proposed as the comparison object, whose control input is shown as [29]:

$$u_{ST} = m[g + \ddot{z}_1^d - \beta_{ST}\dot{e} - k_3|s|^{1/2} sign(s) - k_4 \int_0^t sign(s) d\tau] \tag{29}$$

where $\ddot{z}_1^d$ denotes desired altitude, the coefficients β_{ST}, k_3, k_4 are positive constants, sign(s) denotes the sign function.

A. TRAJECTORY TRACKING

This subsection involves the altitude tracking performance using proposed novel SMC and common ST-SMC to verify the convergence speed and robustness of the proposed controller. As shown in Fig.3, the proposed controller can allow the quadrotor to converge to the reference value in about 3s, and the common ST-SMC takes 12s to converge. Moreover, the proposed controller is more stable after quadrotor converge to reference.

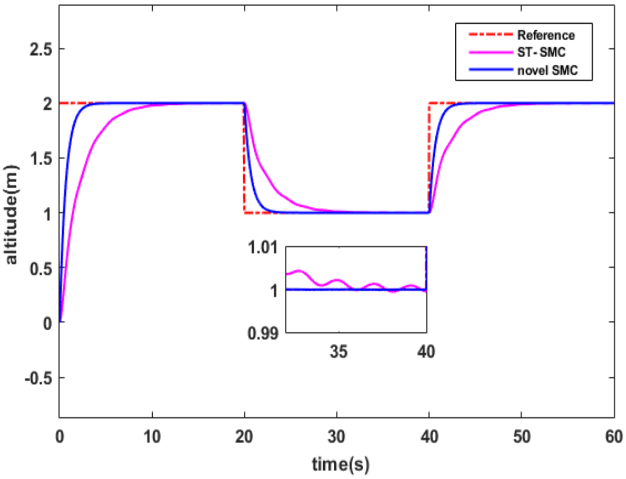

FIGURE 3. Comparison of altitude tracking performance using common ST-SMC controller and proposed novel controller.

B. VARIABLE LOAD

This subsection shows the effects of various control items. Fig.4 shows the simulation response of altitude stability performance using common ST-SMC and proposed novel SMC under the condition of variable load. The load is added 1kg at time t = 20s and reduced load 0.5kg at time t = 40s. For the proposed novel controller, the convergence time is about 4s, relatively, the common ST-SMC's convergence time is about 12s. The vibration amplitude of the proposed novel controller is 40% of the common controller.

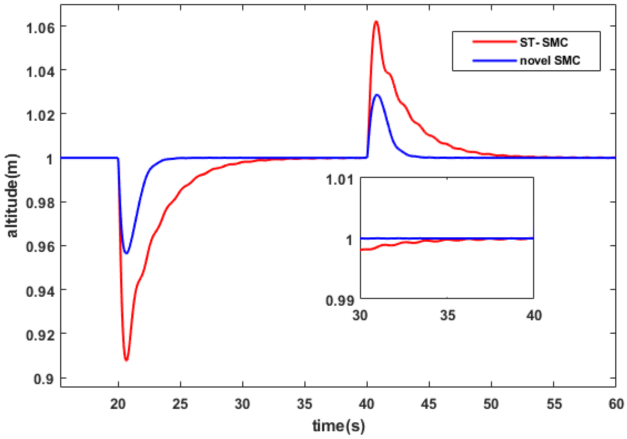

FIGURE 4. Simulation response of altitude stability performance using common ST-SMC and proposed novel SMC.

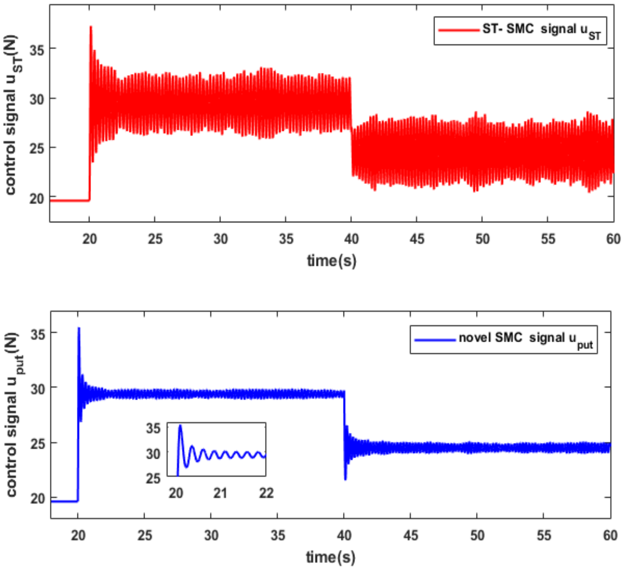

FIGURE 5. Simulation response of control signal using common ST-SMC and proposed novel SMC.

Comparison of the control inputs are shown in Fig.5, which can be obtained that common ST-SMC control input has a significant vibration with 4% amplitude and the proposed novel controller has fluttering with tiny amplitude about 0.5%. As shown in Fig.6, the real-time mass can be estimated and tracked in 2s, and remain stable after convergence without chattering. As shown in Fig.7, the z-axis velocity reaches 0.1m/s when mass change abruptly and maintain stable for the rest time.

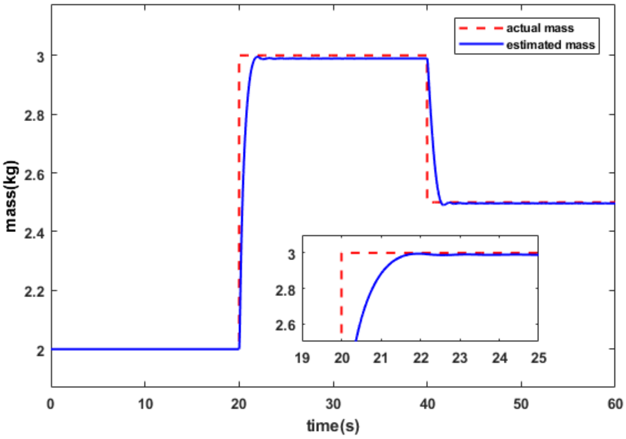

FIGURE 6. Simulation response of estimated value of mass.

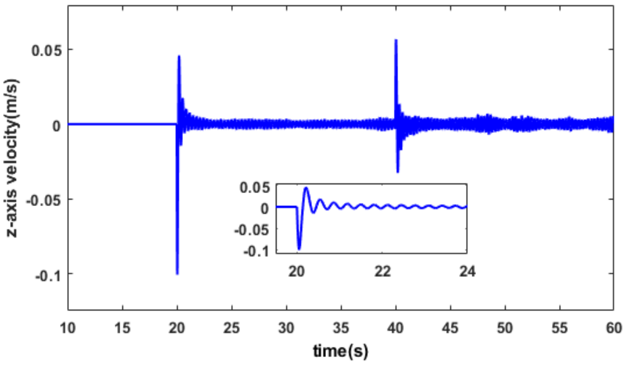

FIGURE 7. Simulation response of z-axis velocity tracking error.

C. EXTERNAL INTERFERENCE

This section shows the effects of adaptive control item of novel controller under the condition of external interference. Fig.8 shows the comparison of altitude tracking performance using common ST-SMC and proposed SMC with external interference. The disturbance signal used in the test is set as d = 3sint. The common ST-SMC with no adaptive control item is greatly affected by the interference, and novel controller significantly reduces the effects of interference on the output.

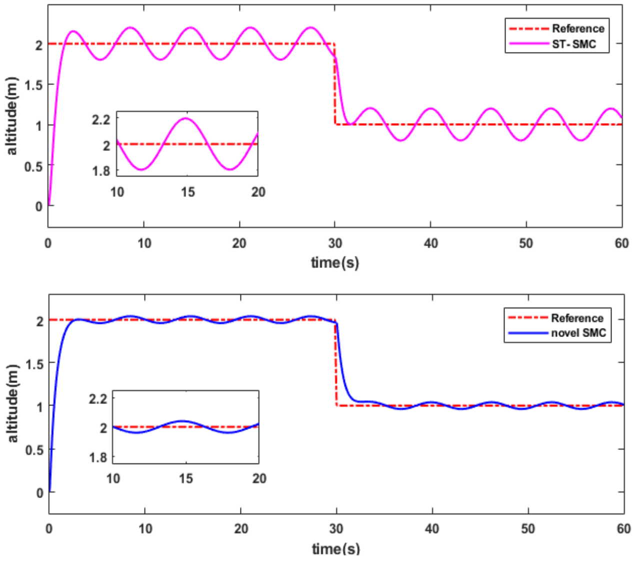

FIGURE 8. Simulation response of altitude tracking performance with external interference.

V. EXPERIMENTAL RESULTS

FIGURE 9. The quadrotor UAV.

FIGURE 10. RTK system is used to obtain the precise altitude of the quadrotor UAV.

The proposed control method was verified on the quadrotor UAV experimental platform at the Northwestern Polytechnical University. The experimental platform consists of a quadrotor UAV as shown in Fig.9, a PC ground station running QGroundControl [30], and a real-time kinematic (RTK) system with two C-RTK module to obtain the accurate altitude. As Fig.10 shown, the RTK system integrates two 600MHz ARM processors and two high-speed floating-point arithmetic processors, which provide cm-level position accuracy. The PX4 is used as an autopilot for quadrotor UAV, including a 216-MHz STM32F765 processor, an accelerometer, and a gyroscope. Four Sunnysky 980-kV brushless motors and multirotor propellers are used as power units. FUTABA 2.4GHZ FASST is used to pass command signals to adjust the altitude of the quadrotor. The mass of quadrotor is 1.3kg and is powered by a 5300-mAh LiPo battery.

This chapter is to verify the effectiveness of the simulation test. The experiment is carried out at an outdoor experimental site, and the external disturbance factors of the experimental site include wind and other unknown factors. The first part of the experiment is altitude tracking test to show the high convergence speed using proposed controller. The desired altitude is set as 8m in t = 0s - 25s, 5m in t = 25s - 50s, and 8m in t = 50s - 70s. The parameters used in this experiment are consistent with the simulation test. According to the experimental results, as shown in Fig.11, the quadrotor can track the desired altitude in about 5 seconds and remain stable at this altitude, the trajectory tracking speed is basically

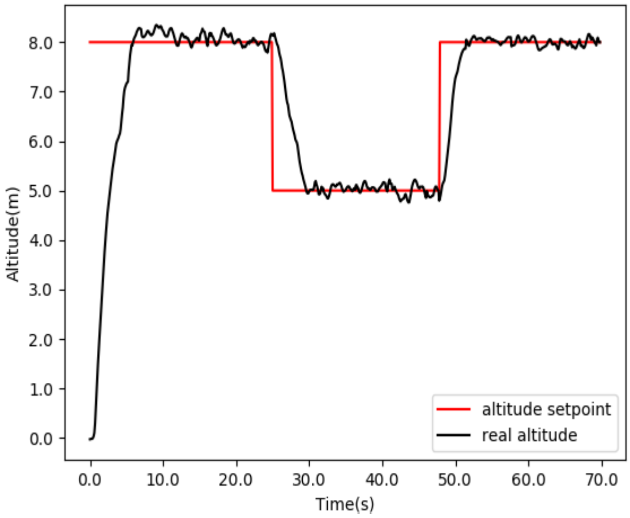

FIGURE 11. Experimental response of trajectory tracking performance.

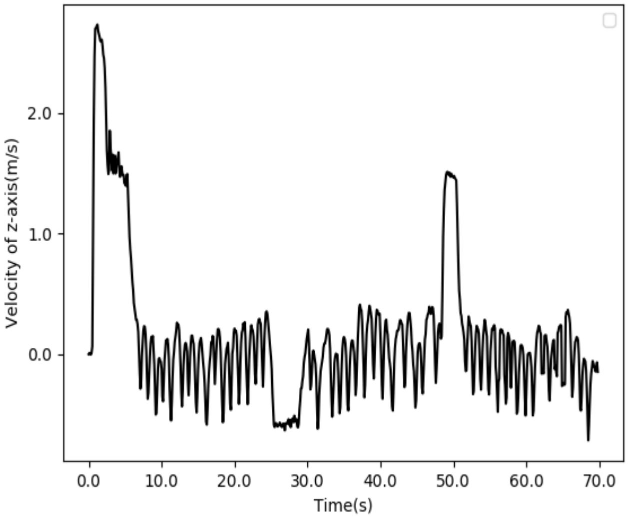

FIGURE 12. Experimental response of velocity of z-axis.

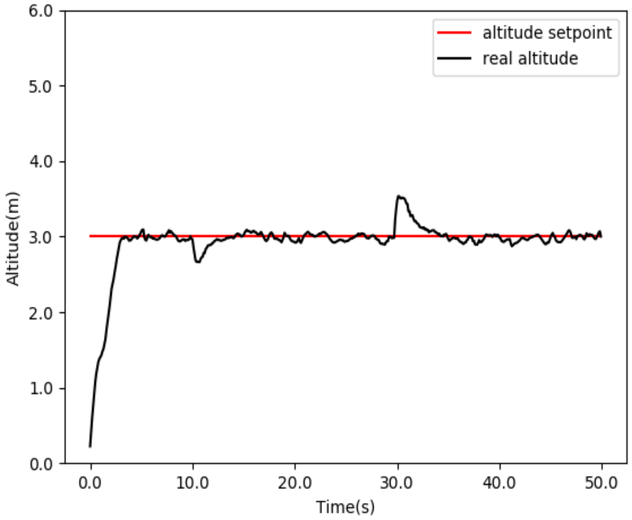

FIGURE 13. Experimental response of altitude stable under variable load conditions.

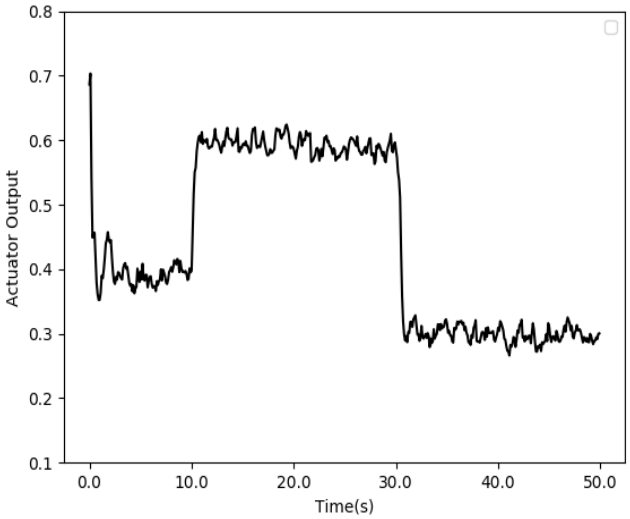

FIGURE 14. Experimental response of actuator output under variable load conditions.

similar to the simulation response. Fig.12 shows the velocity of the quadrotor on the Z-axis direction.

The second part of the experiment is to verify the altitude stable performance of the quadrotor UAV under variable load conditions. The initial altitude of the quadrotor is $z = 0$m and the take-off load is 0.5kg. An external load as 1kg is added to the quadrotor at time $t = 10$s. The added load is about 75% of the mass of the quadrotor, and the load weight is about 34% of the lift limit of the quadrotor. As Fig.13 shown, the amplitude of the vibration is about 0.3m. Then, at time $t = 30$s, unload the whole load of the quadrotor, which is about 115% of the net weight of the quadrotor, the amplitude of the vibration is about 0.5m. The experimental result shows that the quadrotor can converge to the altitude setpoint in 5s when subjected to large load disturbance. Fig.14 shows the actuator output under variable load conditions, it can be seen that the actuator output can be quickly tracked and stabilized after the mass change.

VI. CONCLUSION

In this paper, a learning rate based sliding mode controller is proposed for variable load quadrotor altitude control. Moreover, the novel controller is optimized by adding a mass estimation algorithm. The control performance is achieved by: a) a learning rate based sliding mode controller for improving the convergence performance of altitude tracking; b) a quality estimation algorithm for improving the tracking accuracy under large variable load disturbance condition. The effectiveness and accuracy of the controller are verified by simulation and experimental results.

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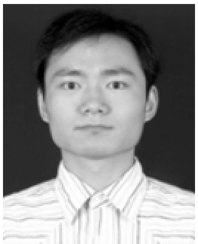

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