Quadrotor UAV attitude control of super-twisting sliding mode based on disturbance observer

Ming Zhao, Shanshan Zhang

Abstract— **In this paper, we introduce a novel approach combine the high-gain disturbance observer and super-twisting sliding mode control strategy. In this method, the disturbance observer is cleverly used to generate accurate estimates of the disturbance in real time, and then these estimates are incorporated into the control law to achieve effective compensation for the disturbance effect. By using a single parameter, the observer can be stabilized while the parameter tuning effort is reduced. In addition, interference estimation is combined with a super-twisting sliding mode controller to reduce the chattering effect caused by discontinuity. In order to ensure the stability of the system, Lyapunov stability analysis is further carried out to ensure that the tracking error is kept within the bounded range. To comprehensively evaluate the efficacy of the proposed control methods, this paper adopts a combined approach, encompassing both simulation and experimental methods. The research data show that the tracking accuracy and stability of the quadrotor UAV controller are significantly improved when the disturbance observer is introduced into the controller.**

Index Terms—**High-gain Disturbance Observer, Super-twisting , Quadrotor UAV.**

I. INTRODUCTION

Unmanned Aerial Vehicle(UAV) is a onboard programmed flight device that can fly missions without a human pilot. In recent years, with technological advances and cost reductions, that UAVs have begun to gain widespread attention and application. They began to be used in more fields, such as agriculture, environmental monitoring, emergency rescue, aerial photography and other fields [1]. However, due to the characteristics of multi-input, multi-output, strongly coupled and underactuated, the quadrotor UAV is very vulnerable to external disturbances, which may eventually lead to crash accidents. Therefore, how to control the quadrotor UAV is particularly important

To address the tracking control challenge posed by quadrotor Unmanned Aerial Vehicles (UAVs), numerous methods have been proposed, such as Fuzzy-Logic [2], Back-stepping [3], Active Disturbance Rejection Control (ADRC)[4], Event -triggered [5] and Sliding Mode Control (SMC)[6-7]. Classical sliding mode control, though robust to parameter changes and perturbations without precise modeling, suffers from high-frequency chattering that can damage the system and actuators, posing a risk of loss of control.

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To solve these problems, a high order SMC is proposed to counteract the chattering phenomenon caused by discontinuity. Super-twisting sliding mode control (STW)[8-9]is a typical high-order sliding mode control with finite-time convergence, stability and robustness to the system and has been widely used in many practical fields[10-11].

To mitigate chattering, we integrate a disturbance observer into the super-twisting algorithm. This observer detects real-time disturbances and generates compensatory signals to reduce the switching amplitude and weaken chattering. [12-13]

[14] introduced a sliding mode interference observer with an adaptive law based on equivalent control to compensate for uncertainties. The interference suppression control is real -ized by combining adaptive law, sliding mode interference observer and terminal sliding mode controller. Aiming at the two potential influencing factors of external disturbance and parametric disturbance. In [15], proposed a fast terminal sliding mode control strategy with adaptive approximation law, which is based on disturbance observer. This adaptive approach law is designed to effectively inhibit the over-adjustment of UAV state variables. At the same time, the disturbance observer has the function of compensating external and para- meter disturbance, that significantly enhances the anti-interference ability of the UAV and ensures to achieve the high-pre cision trajectory tracking. In [16], designed a control strategy grounded in super-twisting algorithm for compensating sliding mode observation, aiming at the problem that quadrotor aircraft is vulnerable to external interference in flight. This strategy significantly improves controller's ability to resist external interference. At the same time, the controller can effectively reduces the chattering phenomenon and also realizes the smooth transition of the sliding mode control curve. After verification, the control method based on disturbance observer shows its effectiveness. However, many existing disturbance observers have complex structural designs, which increase the computational requirements of the quadrotor UAV controller. At the same time, the responsible disturbance observer usually involves multiple tuning parameters, which makes the tuning process cumbersome. Therefore, it is urgent to develop a simple and computationally efficient disturbance observer.

Based on this, a super-spiral strategy with a high-gain disturbance observer is designed for robust and precise attitude angle tracking of UAVs. Main contributions are:

1. A controller combining STW and disturbance observer is designed
2. By using the disturbance observer, the system disturbance is effectively estimated and compensated in the control law.
3. By designing a high-gain disturbance observer , selecting a single scalar design parameter, the complexity of

parameter adjustment is reduced, and the disturbance can be observed more quickly and accurately.

The remainder of article is organized as follows: Section 2 delves into the quadrotor model. Section 3 delves into the design of the STW and the disturbance observer. Section 4 presents the simulation and experimental results. Lastly, Section 5 concludes the article.

II. System Description

The following UAV model is studied in this paper:

$$\ddot{\Theta} = [M(\Theta)]^{-1}\left[\Psi^T(\Theta)u - C(\Theta,\dot{\Theta})\dot{\Theta}\right] + d \tag{1}$$

where $M(\Theta) = \Psi^T(\Theta)J\Psi(\Theta)$ is a positive auxiliary inertia matrix, $J \in R^{3\times 3}$ represents the total inertia matrix, u and d represents the control input and the external disturbance, and $C(\Theta,\dot{\Theta})$ can be expressed as:

$$C(\Theta,\dot{\Theta}) = -M(\Theta)\Psi^{-1}(\Theta)\dot{\Psi}(\Theta) - \Psi^T(\Theta)sk[J\Psi(\Theta)\dot{\Theta}]\Psi(\Theta) \tag{2}$$

where:

$$\Psi(\Theta)=\begin{bmatrix}1 & 0 & -\sin\theta\\ 0 & \cos\phi & \cos\theta\sin\phi\\ 0 & -\sin\phi & \cos\theta\cos\phi\end{bmatrix}, J=\begin{bmatrix}J_{xx} & 0 & 0\\ 0 & J_{yy} & 0\\ 0 & 0 & J_{zz}\end{bmatrix}, sk[\beta]=\begin{bmatrix}0 & -\beta_3 & \beta_2\\ \beta_3 & 0 & -\beta_1\\ -\beta_2 & \beta_1 & 0\end{bmatrix}$$

$$M(\Theta)=\begin{bmatrix}J_{xx} & 0 & -J_{xx}\sin\theta\\ 0 & J_{yy}\sin^2\phi+J_{zz}\cos^2\phi & (J_{yy}-J_{zz})\cos\theta\cos\phi\sin\phi\\ -J_{xx}\sin\theta & (J_{yy}-J_{zz})\cos\theta\cos\phi\sin\phi & J_{xx}\sin^2\theta+\cos^2\theta(J_{yy}\sin^2\phi+J_{zz}\cos^2\phi)\end{bmatrix}$$

According to (1), the following state variables are defined:

$$x_1 = \Theta,\quad x_2 = \dot{\Theta} \tag{3}$$

Express the system as:

$$\begin{cases}\dot{x}_1 = x_2\\ \dot{x}_2 = [M(\Theta)]^{-1}\left[-C(\Theta,\dot{\Theta})\dot{\Theta}\right] + [J\Psi(\Theta)]^{-1}u + d\end{cases} \tag{4}$$

III. Attitude Controller Design

A. Disturbance Observer Design

A high-gain disturbance observer is proposed to estimate the disturbance in this section. The idea behind it is to construct the following observer:

$$\dot{\hat{d}} = \frac{1}{\varepsilon}\left(d - \hat{d}\right) \tag{5}$$

where, $\frac{1}{\varepsilon}$ is observer gain. However, the perturbation is unknown, and according to the formula (3), we can get:

$$\dot{\hat{d}} = \frac{1}{\varepsilon}\left(-[M(\Theta)]^{-1}\left[-C(\Theta,\dot{\Theta})\dot{\Theta}\right] - [J\Psi(\Theta)]^{-1}u + \dot{x}_2 - \hat{d}\right) \tag{6}$$

It can be seen from (6) that the diagonal velocity of the interference observer involved is dependent. However, in practice, obtaining accurate and effective information regarding the angular velocity signal poses a significant challenge., so the following auxiliary variables are introduced:

$$z = \hat{d} - \frac{1}{\varepsilon}x_2 \tag{7}$$

Therefore, the derivative of z is:

$$\begin{aligned}\dot{z} &= \dot{\hat{d}} - \frac{1}{\varepsilon}\dot{x}_2\\ &= \frac{1}{\varepsilon}\left[-[M(\Theta)]^{-1}\left[-C(\Theta,\dot{\Theta})\dot{\Theta}\right] - [J\Psi(\Theta)]^{-1}u - \frac{1}{\varepsilon}x_2 - z\right]\end{aligned} \tag{8}$$

Then, the error of the perturbed observation is expressed as:

$$\tilde{d} = d - \hat{d} \tag{9}$$

From the above series of formulas, the derivative of the disturbance observation value is derived as:

$$\dot{\hat{d}} = \frac{1}{\varepsilon}\tilde{d} \tag{10}$$

Therefore, the derivative of the observed error is:

$$\dot{\tilde{d}} = \dot{d} - \frac{1}{\varepsilon}\tilde{d} \tag{11}$$

Since prior knowledge of perturbation differentials is often lacking in practical applications, it is reasonable to assume in this case that the perturbation changes gradually and slowly relative to the dynamic characteristics of the observer. Based on this assumption, $\dot{d} = 0$ is selected as a reference basis. This decision is intended to ensure that subsequent analyses are built on a robust and reliable basis to more accurately reveal the dynamic relationship between the observer and the interference.

B. Super-twisting SMC design

Considering the nonlinear second-order system(3), a STW controller based on the design is designed, wherein the sliding mode variable is defined:

$$s = ce + \dot{e} \tag{12}$$

where $e = x_1 - x_{1d}$, $\dot{e} = x_2 - x_{2d}$ and $c \in R^{3\times 3}$ is a 3×3 diagonal positive definite matrix.

Because when it finally reaches the sliding mode surface, $s = \dot{s} = 0$,an equivalent control law will be obtained:

$$\begin{aligned}\dot{s} &= c\dot{e} + \ddot{e}\\ &= c\dot{e} + [M(\Theta)]^{-1}\left[-C(\Theta,\dot{\Theta})\dot{\Theta}\right] + [J\Psi(\Theta)]^{-1}u - \ddot{x}_{1d} + \hat{d}\end{aligned} \tag{13}$$

We design the super-twisting control law as:

$$\begin{aligned}u_{stw} &= -k_1|s|^{\frac{1}{2}}\varphi(s,\delta) + \eta\\ \dot{\eta} &= -k_2\varphi(s,\delta)\end{aligned} \tag{14}$$

where $\delta > 0$ and $\varphi(s,\delta)$ can be defined as:

$$\varphi(s,\delta) = \begin{cases}1 & s \geq \delta\\ \dfrac{s}{\delta} & -\delta < s < \delta\\ -1 & s \leq -\delta\end{cases} \tag{15}$$

Therefore, the total control law can be obtained as:

$$u = [J\Psi(\Theta)]^{-1}\left[-c\dot{e} - M^{-1}\left[-C(\Theta,\dot{\Theta})\dot{\Theta}\right] + \ddot{x}_{1d} - k_1|s|^{\frac{1}{2}}\varphi(s,\delta) - k_2\int_0^t \varphi(s,\delta)dt - \hat{d}\right] \tag{16}$$

C. System Stability Analysis

Assumption 1 First of all, the perturbation term d is bounded, assuming that its bound is an unknown positive constant M , and its first derivative with respect to time is also bounded, set to a constant N , and $\dot{d}$ is quadratically integrable , that is, the following formula can be obtained: $|d| < M$, $\dot{d} = h(t)$, with $\dot{d} < N$, $\dot{d} < N$.

Theorem 1 As shown by Assumption 1, $\tilde{d}$ is globally consistent and bounded, so the error of the perturbation observation $\tilde{d}$ can be infinitesimal as long as the appropriate ε is chosen.

Proof: First, choose a suitable Lyapunov function as:

$$V = \frac{1}{2}\tilde{d}^T\tilde{d} \tag{17}$$

Thus, The temporal derivative of V is expressed as:

$$\dot{V} = \tilde{d}^T\dot{\tilde{d}} = \tilde{d}^T\dot{d} - \tilde{d}^T\frac{1}{\varepsilon}\tilde{d} \tag{18}$$

Then, we can get :

$$\dot V \le -\tilde d^T \frac{1}{\varepsilon}\tilde d + \frac{1}{2}\tilde d^T \tilde d + \frac{1}{2}\dot d^T \dot d \le -2\alpha V + \frac{1}{2}h^2(t) \tag{19}$$

where $\alpha = \lambda_{\min}\left(\frac{1}{\varepsilon}\right) - \frac{1}{2}$,and when $\alpha > 0$, multiplying both sides of the formula by $e^{2\alpha t}$ and integrating it over the range $[0, t]$ yields the following:

$$V(t) \le V(0)e^{-2\alpha t} + \frac{1}{2}\int_0^t e^{-2\alpha(t-y)}h^2(y)\,dy \tag{20}$$

Because the $\int_0^t e^{-2\alpha(t-y)}h^2(y)\,dy$ in the formula satisfies the following inequality:

$$\begin{aligned}&\int_0^t e^{-2\alpha(t-y)}h^2(y)dy \\ &\le e^{-2\alpha t}\sup_{y\in[0,t]}\left[h^2(t)\right]\int_0^t e^{2\alpha y}dy \\ &= \frac{1}{2\alpha}\sup_{y\in[0,t]}\left[h^2(t)\right]\end{aligned} \tag{21}$$

We can get:

$$V(t) \le V(0)e^{-2\alpha t} + \frac{1}{4\alpha}\sup_{y\in[0,t]}\left[h^2(t)\right] \tag{22}$$

After in-depth analysis, it can be verified that the function $V(t)$ has an upper bound and a lower bound, which means that the error of the perturbation observer is also constrained by the bound and can be concretely expressed as $|\tilde d| < d_0$. Further, according to the formula derivation, the derivative of the disturbance error of the observer is also constrained by the bound and can be expressed as $|\dot{\tilde d}| < d_1$. Therefore, to guarantee the stability of the disturbance observer, it is only necessary to carefully select the appropriate observer gain so that the error limit is small enough to meet the requirements of system stability.

Theorem 2 By applying the design of disturbance observer (4) and control law (16), the quadrotor UAV system can achieve effective tracking of the desired trajectory.

First, from (14) and (17)we can get :

$$\begin{aligned}\dot s_1 &= -k_1|s_1|^{\frac{1}{2}}\varphi(s_1,\delta) + s_2 \\ \dot s_2 &= -k_2\varphi(s_1,\delta) + \dot{\tilde d}\end{aligned} \tag{23}$$

Among them, for the stability analysis of propulsion systems, we define $\rho(s_1,\delta) = \mathrm{sgn}(s_1) - \varphi(s_1,\delta)$.

Therefore, the relevant information about $\rho(s_1,\delta)$ can be obtained as follows:

(1) According to the formula , when $\delta > 0$, for all real numbers s_1 , the range of $\rho(s_1,\delta)$ can be determined as $|\rho(s_1,\delta)| \le 1$.

(2) When s_1 meets the condition $s_1 \in (-\infty,-\delta]\cup[\delta,+\infty)$, then $\rho(s_1,\delta) = 0$ can be obtained.

(3) When s_1 satisfies the condition $s_1 \in \mathbb{R} - \{0\}$,we can get $\lim_{\delta\to 0}\rho(s_1,\delta) = 0$.

Proof : Based on the above analysis, formula (23) is expressed as:

$$\begin{aligned}\dot s_1 &= -k_1|s_1|^{\frac{1}{2}}\mathrm{sgn}(s_1) + s_2 + k_1|s_1|^{\frac{1}{2}}\rho(s_1,\delta) \\ \dot s_2 &= -k_2\mathrm{sgn}(s_1) + q + k_2\rho(s_1,\delta)\end{aligned} \tag{24}$$

where, $q = \dot{\tilde d}$ .Then ,the following definitions are made:

$$z = \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = \begin{bmatrix} |s_1|^{\frac{1}{2}}\mathrm{sgn}(s_1) \\ s_2 \end{bmatrix} \tag{25}$$

So, we can get:

$$\dot z = |s_1|^{-\frac{1}{2}}Aw + q(t) + \xi(s_1,\delta) \tag{26}$$

with:

$$A = \begin{bmatrix} -\frac{1}{2}k_1 & \frac{1}{2} \\ -k_2 & 0 \end{bmatrix},\ q(t) = \begin{bmatrix} 0 \\ q \end{bmatrix},\ \xi(s_1,\delta) = \begin{bmatrix} \frac{1}{2}k_1 \\ k_2 \end{bmatrix}\rho(s_1,\delta)$$

When $\rho(s_1,\delta) \equiv 0$, that is $\delta = 0$, it can be seen that when q is globally bounded, there is a gain k_1, k_2 , which guarantees that the matrix P, Q are positive definite, that is, it can be expressed as:

$$\mathbf{P} = \begin{bmatrix} p_1 & p_2 \\ p_2 & p_3 \end{bmatrix},\ \mathbf{Q} = \begin{bmatrix} q_1 & q_2 \\ q_2 & q_3 \end{bmatrix} \tag{27}$$

where p_1, p_3, q_1, q_3 are all positive numbers, and there are absolutely continuous Lyapunov functions $V = z^T Pz$ that satisfy $\dot V \le -|z_1|^{-1} z^T\mathbf{Q}z \le -c\sqrt{V}$, $c > 0$. Therefore, the derivative with respect to time can be obtained as:

$$\dot V \le -|z_1|^{-1} z^T\mathbf{Q}z + 2z^T\mathbf{P}\xi \tag{28}$$

Therefore, consider the following two cases: First, when $s_1 \ge \delta$, then $\xi(s_1,\delta) = 0$ and $\dot V \le -c\sqrt{V} < 0$ can be obtained.Therefore, the system can achieve asymptotic stability. In the second case, $s_1 < \delta$ or the equivalent definition of $z_1 \ge \sqrt{\delta}$, it can be obtained that $\dot V$ satisfies the following formula:

$$\dot V \le -\frac{1}{\sqrt{\delta}}z^TQz + 2z^TP\xi \tag{29}$$

In order for the system to be stable, it must therefore be, so, according to the formula, only the following formula needs to be true:

$$-z^T\mathbf{Q}z + 2\sqrt{\delta}z^T\mathbf{P}\xi < 0 \tag{30}$$

Since the state vector $\xi(s_1,\delta)$ in the (32) satisfies:

$$\begin{aligned}&|\xi(s_1,\delta)| \\ &= |\rho(s_1,\delta)|\sqrt{\frac{1}{4}k_1^2 + k_2^2} \\ &\le \sqrt{\frac{1}{4}k_1^2 + k_2^2} = \lambda\end{aligned} \tag{31}$$

We can get:

$$\begin{aligned}&-z^T\mathbf{Q}z + 2\sqrt{\delta}z^T\mathbf{P}\xi \\ &\le -q_3|s_2|^2 + \mu|s_2| + \gamma\end{aligned} \tag{32}$$

where $\mu = 2\sqrt{\delta}\left(|q_2| + \lambda\sqrt{p_2^2 + p_3^2}\right)$ and $\gamma = 2\delta\lambda\sqrt{p_1^2 + p_2^2}$.

Then we defined $f(x_2) = -q_3|s_2|^2 + \mu|s_2| + \gamma$,so when $\delta > 0$, it can be determined that there are two different real roots, so we can get :

$$\max(m_1, m_2) = \frac{\sqrt{\delta}}{q_3}\left|\left(|q_2| + \lambda\sqrt{p_2^2 + p_3^2}\right) + \sqrt{\left(|q_2| + \lambda\sqrt{p_2^2 + p_3^2}\right)^2 + 2q_3\lambda\sqrt{p_1^2 + p_2^2}}\right| \tag{33}$$

Therefore, for all $|x_2| > \max(m_1, m_2)$, there exist $f(x_2) > 0$. Thus, this means that, for each $\delta > 0$, existence $0 < \varepsilon_0(\delta) \le \max(m_1, m_2)$, makes it possible for $|x_2| > \varepsilon_0$, existence $f(x_2) < 0$, that means $f(x_2) < 0$ can be to obtained, and thus it can be shown that the system is asymptotically stable.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

Table 1. The pivotal parameters of the quadrotor UAV.

Parameter	Value	Parameter	Value
Mass(Kg)	2.85	c_1	3
$J_{xx}(kgm^2)$	0.0552	c_2	2.5
$J_{yy}(kgm^2)$	0.0552	c_3	3
$J_{zz}(kgm^2)$	0.1104	ε	[0.03,0.03,0.03]
k_1	[6;5;7]	k_2	[5,5,6]

For this experiment, the model parameters of the quadrotor UAV are shown in Table 1. The initial attitude Angle and angular velocity are respectively: $\Theta(0) = [12,10,5]^T$ rad, $\Omega(0) = [0,0,0]^T$ rad, the reference trajectory required for tracking is expressed as: x_{1d}=[3sin(0.5t);3cos(0.5t);4sin(0.5t)+1].

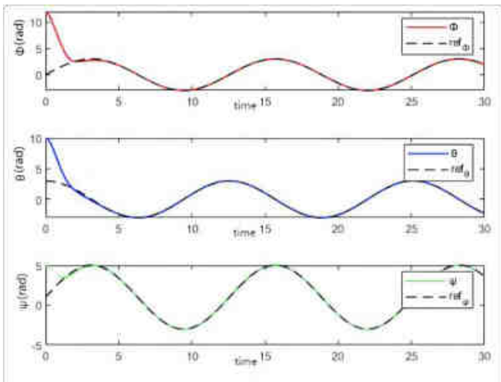

Fig. 1. Attitude control Angle

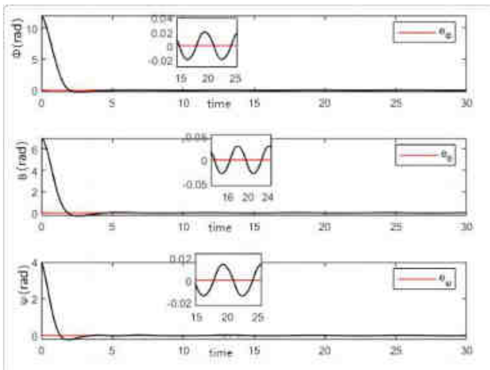

Fig. 2. Attitude control Angle error

According to the information shown in Fig. 1., all three attitude angles can track the reference attitude Angle. Fig. 2. reflects the error changes of each attitude Angle of the quadrotor UAV. According to Fig. 2., The tracking errors pertaining to all three attitude angles converge towards the origin., and the errors of attitude angles are 2×10^{-2}, 4×10^{-2}, 2×10^{-2} degrees. Fig. 3. and Fig. 4. respectively reflect the changes of the control input and sliding mode variables of the attitude control of the quadrotor UAV. It can be seen from the

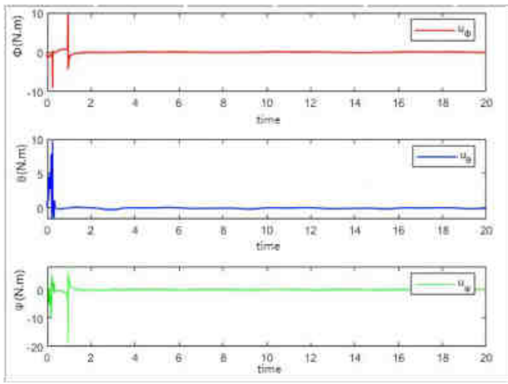

Fig. 3. Control input

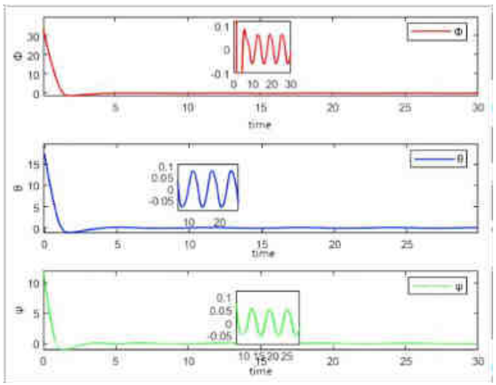

Fig. 4. Sliding mode variables

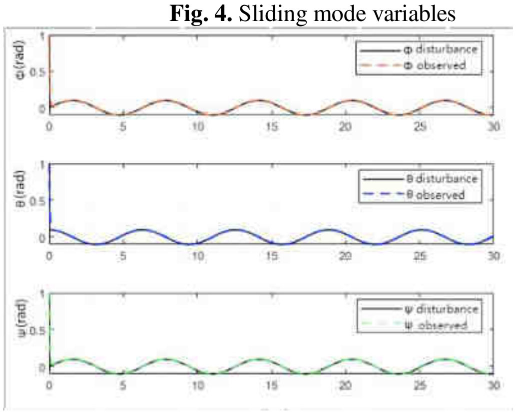

Fig. 5. Observed and the actual disturbance

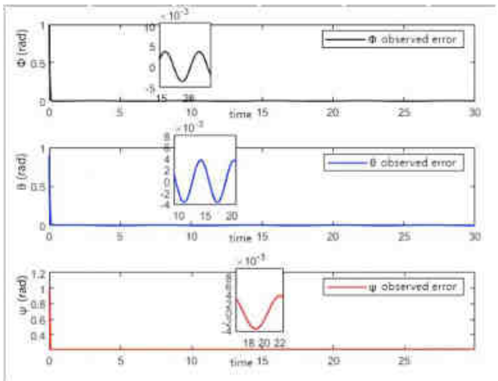

Fig. 6. Observed error of the disturbance

two figures that the control input of this control method is smoother and can effectively overcome the chattering problem. At the same time, the sliding mode variables also converge significantly near the origin. Finally, Fig. 5. shows the changes of the observed disturbance and the actual disturbance, and Fig. 6. shows the changes of the observed error of the disturbance. According to the information in the figure, the error ranges of the observed disturbance are 0.004, 0.004, 0.004 respectively. The results indicate that the designed disturbance observer is capable of effectively estimating the interference.

V. CONCLUSION

This paper aims to address the challenges posed by external disturbances and modeling errors on the attitude control of quadrotor UAVs. To enhance the attitude tracking control performance under unknown external disturbances and modeling errors, a super-twisting sliding mode control method integrated with a high-gain disturbance observer is proposed. An interference observer is introduced to estimate the unknown external interference and system modeling errors. By estimating the disturbance observer in real-time, accurate perturbation information can be obtained. Based on this, a super-twisting sliding mode controller is designed. By incorporating the estimation results from the disturbance observer, the residual error in disturbance compensation can be further reduced, ultimately enhancing the overall control performance of the system.

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