Attitude Tracking Control of Quadcopter Unmanned Aerial Vehicle Based On Adaptive Event Triggering Mechanism

Xiaohui An, Ying Zhang

Abstract- **To address the update frequency of control signals for quadcopter unmanned aerial vehicles, an event triggering mechanism has been designed, which only triggers control updates when the system state deviates from the preset threshold, effectively reducing the update frequency of control signals. This design not only significantly reduces the consumption of computing resources, but also extends the lifespan of actuators, while ensuring the global stability of the system. To solve the attitude tracking problem of quadcopter unmanned aerial vehicles with unknown disturbance boundaries, this study adopts a double-layer nested adaptive gain mechanism, which can dynamically track and adaptively adjust the control gain for unknown disturbances. Through rigorous stability analysis of Lyapunov functions, it has been proven that the proposed method can ensure the global asymptotic stability of closed-loop systems. The effectiveness of the proposed method has been verified through numerical simulation experiments, and the results show that the method significantly reduces the control update frequency while ensuring control performance.**

Index Terms— **Quadcopter unmanned aerial vehicle; Sliding mode control;Adaptive algorithm; Event triggering mechanism**

I. INTRODUCTION

It is worth noting that the inherent discontinuity of sliding mode control algorithm can lead to vibration. This situation may hinder its practical application. In response to the disadvantage of the sliding mode control algorithm relying on prior information related to uncertainty limits, many scholars have proposed adaptive algorithms. In reference [1], an adaptive algorithm was proposed to automatically update the closed-loop cutoff frequency by updating the feedback gain, improving the closed-loop performance of the controller. In reference [2], a new adaptive high-order hyper spiral control algorithm was proposed, which introduces adaptive control gain to improve response speed and attenuate chattering, compensate for matching interference, and achieve finite time convergence. Reference [3] proposed an adaptive sliding mode method based on average control to handle disturbances of unknown boundaries in nonlinear objects. The developed method allows for ideal sliding modes and reduces chattering phenomena. In order to achieve robust control of nonlinear systems with uncertain parameters, a novel adaptive sliding mode controller design scheme was proposed in reference [4]. Its core innovation lies in the development of an adaptive method that does not require high-frequency switches to handle unknown but bounded system uncertainties, ensuring its tracking performance. In response to the stability and tracking control issues of quadcopter unmanned aerial vehicles with uncertainties, reference [5] combines robust control and adaptive control theory to design an adaptive autonomous sliding mode tracking system. Compared with other existing adaptive backstepping designs, the proposed method is very simple and feasible because it does not require multiple design steps, does not enhance signals, and has no prior known uncertainty limits. Reference [6] proposes an adaptive sliding mode control algorithm for finite time stability of unmanned aerial vehicle systems with parameter uncertainty in order to achieve stability and tracking control of the flight system in the presence of parameter uncertainty. In response to the challenges of highly nonlinear, coupled dynamics, and underactuated systems in quadcopter drones, reference [7] proposed an integral adaptive sliding mode control scheme to control the system, using adaptive switching gain to achieve rapid adaptation to uncertainty.

II. PRELIMINARIES AND MODEL FORMULATION

A. Mathematical model of quadrotor UAVs

This chapter mainly introduces the tracking error and simplified attitude dynamics model of quadcopter unmanned aerial vehicles. The preliminary results included aim to provide basic information for subsequent controller design, lay a model foundation for stable tracking control of quadcopter unmanned aerial vehicles, and introduce relevant stability concepts, including Lyapunov stability theory, asymptotic time stability theory, finite time stability theory, adaptive algorithms, and event triggering mechanisms, laying the groundwork for the subsequent proof of stability tracking control of quadcopter unmanned aerial vehicles.

B. Model building

By considering the above system, we will define the following variables related to attitude state:

$$\hat{x}_1 = \Theta, \quad \hat{x}_2 = \dot{\Theta} \tag{1}$$

The state space form of this model is as follows:

$$\begin{cases} \dot{\hat{x}}_1 = \hat{x}_2 \\ \dot{\hat{x}}_2 = f(\hat{x},t) + g(\hat{x},t)u + d(t) \end{cases} \tag{2}$$

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$u = \Gamma$ Indicate control input, $d(t) = \Gamma_{ext}$ Indicate external interference.The following provides vectors $f(\hat{x},t)$ and matrices $g(\hat{x},t)$:

$$f(\hat{x},t) = [M(\Theta)]^{-1}[-C(\Theta,\hat{\Theta})\hat{\Theta}]; \quad g(\hat{x},t) = [J\Psi(\Theta)]^{-1}$$

III. Adaptive Algorithmic Control

This chapter introduces the adaptive concept of equivalent control. In order to effectively reduce the influence of high-frequency flutter of control signals and allow for automatic adjustment of the gain of discontinuous control terms based on the rate of change of interference, a double-layer nested adaptive gain scheme based on equivalent control is considered. This scheme does not require prior boundedness of disturbances and their rates of change.

Based on the dynamic model of quadcopter unmanned aerial vehicle described above, the sliding surface is designed in the following form:

$$s = Cx = \dot{x} + \lambda x \tag{3}$$

where $x = \hat{x}_1 - \hat{x}_{1d}$, $\quad \dot{x} = \hat{x}_2 - \hat{x}_{1d}$

By taking differentiation s, we can obtain

$$s = \psi_{\text{nom}}(\hat{x},t) + d(t) + g(\hat{x},t)u \tag{4}$$

where

$$\psi_{\text{nom}}(\hat{x},t) = -[M(\theta)]^{-1}C(\theta,\dot{\theta})\dot{\theta} - \hat{x}_{1d} + \lambda\dot{x} \tag{5}$$

In order to achieve robust control of quadcopter unmanned aerial vehicles, we designed a controller consisting of two parts:

$$u = u_1 + u_2 \tag{6}$$

where

$$u_1 = [J\Psi(\theta)][-\psi_{\text{nom}}(\hat{x},t)], \quad u_2 = [J\Psi(\theta)][-k(t)\text{sign}(s)]$$

Due to the fixed constants k in the previous control gains, high-frequency oscillations may occur when multiplied by the sign function term. Therefore, this chapter considers changing the variable k in the control gain with the disturbance. The design of adaptive gain is based on the equivalent control concept:

$$u_{eq}(t) = -d(t) \tag{7}$$

However, disturbances are difficult to measure in practical environments, so in sliding $|u_{eq}(t)| = |d(t)|$,Because equivalent control is an abstract method, a low-pass filter is introduced,make it satisfying

$$\bar{u}_{eq}(t) = \frac{1}{\tau}\left(-(k(t))\text{sign}(s) - \bar{u}_{eq}(t)\right) \tag{8}$$

where $\tau > 0$ is a very small constant, $\left|\bar{u}_{eq}(t) - u_{eq}(t)\right|$ can be very small, and it meets the following conditions:

$$\left\| \bar{u}_{eq}(t) \right| - \left| u_{eq}(t) \right\| < \epsilon_1 \left| u_{eq}(t) \right| + \epsilon_0 \tag{9}$$

By using the low-pass filter designed above, the boundary conditions for the outermost adaptive rate of the double-layer nested structure are designed as follows:

$$k(t) > \frac{1}{\theta}\left|\bar{u}_{eq}(t)\right| + \epsilon \tag{10}$$

Because the construction of double-layer nested adaptive in this chapter relies on two error variables:

$$e_1(t) = k(t) - \frac{1}{\theta}\left|\bar{u}_{eq}(t)\right| - \epsilon$$
$$e_2(t) = \frac{\mu d_1}{\theta} - r(t) \tag{11}$$

Now move on to the first layer of adaptive control elements in formula (8). The specific definition is:

$$k(t) = -w(t)\text{sign}(e_1(t)) \tag{12}$$

Among them, w (t) is a variable, and the structure of w (t) is related to r (t). The following is the relationship between r (t):

$$w(t) = r_0 + r(t) \tag{13}$$

The second layer adaptive variable in formula (13) is the two-layer nested adaptive gain scheme.

Due to the unknown disturbance of quadcopter drones, we design the second layer of adaptive laws as follows:

$$r(t) = \begin{cases} \alpha\,|e_1(t)| & \text{if } |e_1(t)| > e_0 \\ 0 & \text{otherwise} \end{cases} \tag{14}$$

Theorem 1: Considering that the disturbance of quadcopter drones is finite, but in reality, the disturbance is unknown. Therefore, we chose ϵ to meet:

$$\frac{1}{4}\epsilon^2 > e_0^2 + \frac{1}{\alpha}\left(\frac{\mu d_1}{\theta}\right)^2 \tag{15}$$

Force $|e_1(t)| < \epsilon/2$, within a limited time to ensure that sliding motion can continue. In addition, the gain w(t) and k(t) remain bounded.

Proof: First, take the derivative of the two errors :

$$\dot{e}_1(t) = \left(r_0 + \frac{\mu d_1}{\theta} - e_2(t)\right)\text{sign}(e_1(t)) + \frac{1}{\theta}\left|\dot{u}_{eq}(t)\right|$$
$$\dot{e}_2(t) = -\alpha\,|e_1(t)|, \quad |e_1(t)| > e_0 \tag{16}$$

Once again, regarding the construction of two Lyapunov functions with errors:

$$V = \tfrac{1}{2}e_1(t)^2 + \tfrac{1}{2\alpha}e_2(t)^2 \tag{17}$$

Derive it to obtain:

$$\begin{aligned}
V_0 &= e_1(t)^2 - \frac{1}{\alpha}e_2(t)^2 \\
&= e_1(t)\left(\left(e_2(t) - z_0 - \frac{\mu d_1}{\theta}\right)\text{sign}(e_1(t)) - \frac{1}{\theta}\dot{u}_{eq}(t)\right) - \frac{1}{\alpha}e_2(t)^2 \\
&\le -e_0\,|e_1(t)| + |e_1(t)|\left(e_2(t) - \frac{\mu d_1}{\theta}\right) + |e_1(t)|\frac{\mu d_1}{\theta} - \frac{1}{\alpha}e_2(t)^2 \\
&= -e_0\,|e_1(t)| + e_2(t)\,|e_1(t)| - \frac{1}{\alpha}e_2(t)^2
\end{aligned}$$

At that time $|e_1(t)| > e_0$, there was the following deduction:

$$\begin{aligned}
V_0 &\le -e_0\,|e_1(t)| + e_2(t)\,|e_1(t)| - \frac{1}{\alpha}e_2(t)^2 \\
&= -e_0\,|e_1(t)| + e_2(t)\,|e_1(t)| - e_2(t)\,|e_1(t)| \\
&= -e_0\,|e_1(t)|
\end{aligned} \tag{18}$$

In order to $e_2(t)$ always satisfied $e_2(t) < \mu d_1/\theta$,we design ed a rectangular area about two errors：

$$\square = \left\{(e_1,e_2) : |e_1(t)| < e_0, 0 \le e_2 < \frac{\mu d_1}{\theta}\right\} \tag{19}$$

In order to meet the requirements $\dot{V}_0 \le -e_0\,|e_1(t)|$ beyond the rectangle. Therefore, set $\bar{V}$ the minimum ellipse centered around the origin of form (19)

$$\bar{V} = \left\{ (e_1, e_2) : \forall (e_1, e_2) < \frac{1}{2} e_0^2 + \frac{1}{2\alpha} \left(\mu d_1 / \theta \right)^2 \right\} \quad (20)$$

If the solution (e_1, e_2) has not been entered $\bar{V}$, considering the derivation (3-20), we obtain:

$$\begin{aligned} &\int_0^{+\infty} \dot{V}_0 dt \\ &= V_0(+\infty) - V_0(0) \\ &= -V_0(0) \\ &\le \int_0^{+\infty} -e_0 |e_1(t)| dt \end{aligned} \quad (21)$$

Therefore, the parameters that can ensure a gain greater than the disturbance satisfy formula (15) and $|e_1(t)| < \varepsilon / 2$ will also be obtained within a finite time. Considering the analysis of the two scenarios mentioned above, we can conclude that the same conclusion $|e_1(t)| < \varepsilon / 2$ will be achieved. Therefore, we will go further:

$$|e_1(t)| = \left| k(t) - \frac{1}{\theta} |\bar{u}_{eq}(t)| - \varepsilon \right| < \frac{\varepsilon}{2} \quad (22)$$

By removing the absolute value from formula (22), we can obtain:

$$e_1(t) = k(t) - \frac{1}{\theta} |\bar{u}_{eq}(t)| - \varepsilon > -\frac{\varepsilon}{2} \quad (23)$$

By further combining formula (10), we can further derive

$$k(t) > |\bar{u}_{eq}(t)| \quad (24)$$

Therefore, the proof is complete

Note: Based on the above inférence, the design k(t) is a method that varies with the disturbance, always greater than the upper bound of the disturbance, and can closely track the attitude tracking of quadcopter drones. Compared with the chattering caused by the multiplication of ordinary constants k and sign terms, the design k(t) in this chapter can effectively reduce high-frequency chattering and maintain its good tracking effect.

IV. Event Triggered Attitude Tracking Control

In the adaptive method designed above, this section further proposes an event triggering method, in which the sliding mode controller is only intermittently updated under this event triggering strategy. The execution sequence after the event is triggered uses t0 t1、... The corresponding control input sequence is represented by u(t0), u(t1)、... express. Between control updates, the input value u remains unchanged and is equal to the last control update. Therefore, under the event triggering strategy, the control input formula (6) can be described as:

$$u(t) = u(t_1), \quad \forall t \in [t_1, t_{i+1}) \quad (25)$$

Where $u(t_i) = u_1(t_i) + u_2(t_i)$

$$u_1(t_i) = [J\Psi(\Theta)][-\Psi_{\text{nom}}(\hat{x}, t)]$$

$$u_2(t_i) = [J\Psi(\theta)][-k(t)\text{sign}(s)],$$

The control law formula (25) is updated again and remains unchanged until the next trigger execution.

Therefore, first, let the measurement error caused by the event triggering strategy be $e(t) = x(t_i) - x(t)$ for all,i=0,1. Consider triggering conditions

$$t_{i+1} = \min\{t \ge t_i : \| e(t) \| \ge \beta\} \quad (26)$$

Among them,β>0 is the threshold parameter triggered by the event that determines the final bound of e (t).

Theorem 2: According to the double-layer nested adaptive method mentioned above in formulas (25) and (26), a suitable control gain will be selected so that the system's attitude tracking can reach a region near the sliding surface and stay on it over time.

$$k_i > a_1 \beta + d_0 \quad (27)$$

Proof: Using Lyapunov function, we can now take the derivative of V(t) and obtain:

$$\begin{aligned} V_1 &= s^T \hat{s} \\ &= s^T \left(\psi_{\text{nom}}(t_i) + d(t) + g(t_i) u(t_i) \right) \\ &= s^T \left(\psi_{\text{nom}}(t_i) + d(t) + g(t_i) u(t_i) + g(t_i)(u - u(t_i)) \right) \\ &= s^T \left(-\kappa_i \text{sign}(s) + g(t_i)(u - u(t_i)) + d(t) \right) \\ &\le s^T \left(-\kappa_i \text{sign}(s) + a_1 L \| e(t) \| + d(t) \right) \\ &\le s^T \left(-\kappa_i \text{sign}(s) + a_1 \beta + d(t) \right) \\ &\le -(\kappa_i - a_1 \beta - d_0) |s| \\ &= -\eta |s| \end{aligned}$$

In order to satisfy the condition of η>0, it is necessary to ensure that the attitude tracking of the system can be driven and maintained near the sliding surface. Prove that it has been completed.

V. Numerical Simulation Results

In this section, a simulation example is given to demonstrate the effectiveness of the event triggered attitude tracking algorithm design based on adaptive algorithm proposed for quadcopter unmanned aerial vehicles. For the relevant parameters of quadcopter unmanned aerial vehicles, reference[8] can be made, and specific values are given for other parameters, β=1. The given external disturbance is d (t)=[3sin (t), 3cos (t), 3sin (2t)]. The simulation is as follows: The selected reference trajectory is as follows:

$$\begin{cases} \Phi_d = 3\sin(0.5t) \\ \theta_d = 3\cos(0.5t) \\ \psi_d = 4\sin(0.5t) + 1 \end{cases} \quad (28)$$

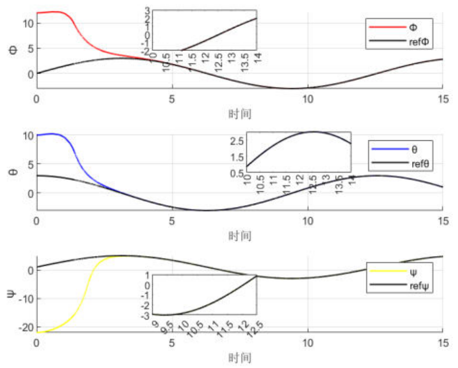

Figure 1 UAV attitude tracking results

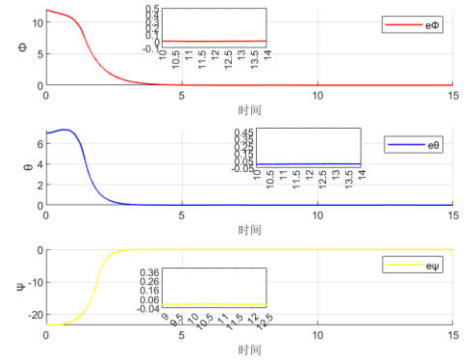

Figure 2 UAV attitude tracking error

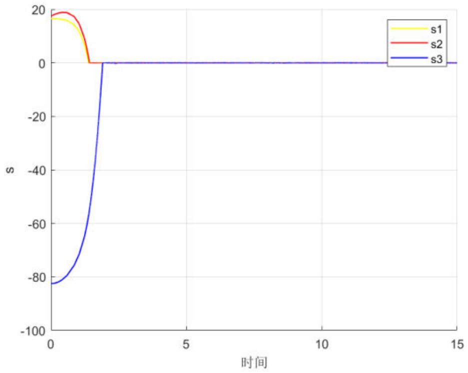

Figure 3 Sliding mode variables under sliding mode control

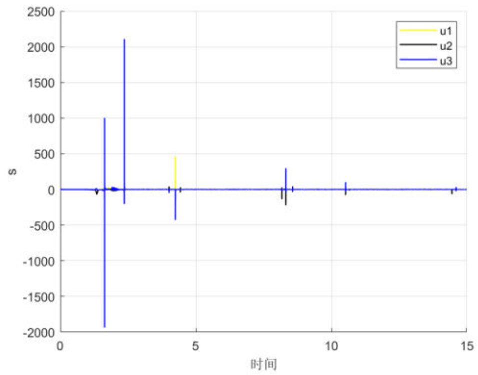

Figure 4 Control Input under Sliding Mode Control

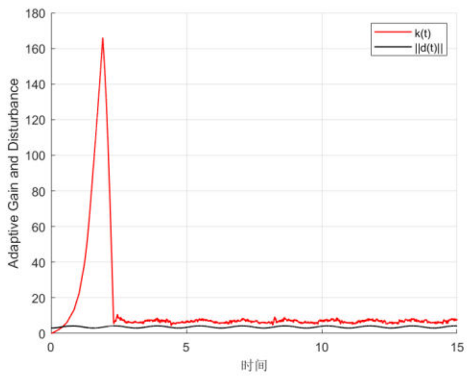

Figure 5 Changes in Control Gain and Time Varying Disturbance

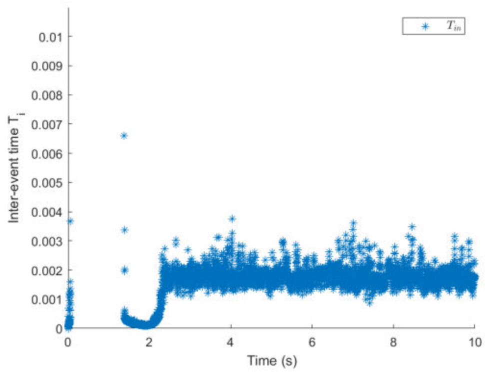

Figure 6 Time variation diagram of internal events triggered by events

Figure 1 shows the attitude tracking results of a quadcopter unmanned aerial vehicle on the axis, and the dynamic response characteristics of the system at different time scales can be clearly observed from the figure. By comparing the ideal trajectory with the actual output curve, the tracking performance of the control algorithm can be intuitively evaluated. Figure 2 further presents the tracking error curve of the drone, which provides important basis for quantitative analysis of control accuracy. It is worth noting that the error curve shows a trend of rapid convergence followed by stability, indicating that the designed control algorithm has good dynamic response and steady-state performance. Figure 3 shows the periodic evolution process of sliding variables in quadcopter unmanned aerial vehicles. From the figure, it can be observed that the closed-loop system quickly enters the sliding surface within a finite time and eventually converges to the origin. This phenomenon validates the effectiveness of the designed sliding mode control algorithm and also reflects the good convergence characteristics of the system. Of particular note is that the system exhibits strong anti-interference ability after entering the sliding surface, which lays the foundation for subsequent performance optimization. Figure 4 compares the control input curves of traditional sliding mode control with those introduced with adaptive and event triggered mechanisms. Through comparative analysis, it can be found that although the introduction of adaptive and event triggered mechanisms has to some extent reduced the chattering phenomenon of control inputs, there are still some high-frequency oscillations. This phenomenon provides important research motivation and optimization direction for proposing the hyper spiral algorithm in subsequent chapters. It is worth noting that the smoothness of the control input directly affects the service life of the actuator and system energy consumption, so solving this problem has important practical significance. Through in-depth analysis of the adaptive gain variation curve in Figure 5, we can conclude that the adaptive gain can be dynamically adjusted according to changes in the disturbance upper bound, and always maintain a small difference from the disturbance upper bound. This adaptive mechanism not only ensures the robustness of the closed-loop system, but also effectively reduces the chattering phenomenon. Specifically, when the system is subjected to significant external disturbances, the adaptive gain will correspondingly increase to enhance the system's anti-interference ability; When the disturbance decreases, the gain will also decrease accordingly, thus avoiding excessive control input. This dynamic adjustment mechanism provides important guarantees for achieving precise control.

This study proposes an event triggered intelligent control strategy to address the inherent characteristics of the quadcopter unmanned aerial vehicle system, such as underactuated characteristics, strong coupling effects, and multivariable nonlinearity, while considering the constraints of computing power, communication resources, and energy consumption in practical engineering applications. This strategy constructs a state dependent trigger function that updates control variables only when the system dynamically reaches specific conditions, effectively reducing the transmission frequency of control instructions and achieving collaborative optimization of computing resources, communication bandwidth, and energy consumption. Figure 6 shows the time variation of internal events under the event triggering mechanism of quadcopter unmanned aerial vehicles. From the figure, it can be observed that the update of the control signal presents a non-uniform time interval distribution, which is in sharp contrast to the traditional fixed time sampling mechanism.

VI. Conclusion

In this chapter, an event triggered mechanism scheme for attitude tracking control of quadcopter unmanned aerial vehicles was developed. A triggering condition and a threshold parameter triggered by events have been proposed. The results indicate that both tracking error and sliding variables can converge to the sliding mode region related to the event triggering threshold parameter and effectively avoid the occurrence of Zeno phenomenon. And a double-layer nested adaptive scheme is adopted. Compared with the maximum gain and high-frequency chattering considered in traditional sliding mode control, this scheme does not require information about the upper bound and derivative of the disturbance, and can achieve the control gain changing with the disturbance, effectively reducing the chattering problem. The simulation results demonstrate the effectiveness of the obtained results.

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