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Synthesis of an Adaptive Sliding Backstepping Controller for the DJI-F450 Quadcopter

Le Ngoc Giang[1*], *Nguyen Van Phon*[2]

[1]*Doctor, Lecturer, Faculty of Fundamental Technics, AD-AF Academy of Viet Nam, Ha Noi, Vietnam*

[2]*Graduate Student, SMS-1, AD-AF Academy of Viet Nam, Ha Noi, Vietnam*

** Email: lengocgianglinh@gmail.com*

A B S T R A C T

A Quadrotor is an object operating in a complex environment, affected by random factors, such as: wind, air flow, etc. Besides the flexibility that the 4 blades create, it also poses many challenges in the control method. Synthesis of the Quadrotor motion control research problem shows that the main control goal of the problems is to stabilize the flight trajectory, improve the dynamic quality of the system, and reduce control energy. This paper describes a design method for a strong nonlinear object, that combines adaptive backstepping and sliding mode control. The proposed controller is applied to the system in the strict-feedback form of the DJI-F450 Quadcopter. Simulation results show that the control strategy proposed in this paper is effective and has strong robustness in the presence of disturbance and parameter uncertainty.

Keywords: DLQR controller, DJI-F450 Quadcopter, flight trajectory.

1. Introduction

In practice, the slip control law needs to take into account the uncertainty of the system and the effect of noise. The sliding control law has two components: The nominal control component, also known as the equivalent control component. The robust control component, also known as the correction control component, compensates for the system uncertainty and has a value that depends on the upper bounds of the system uncertainty. To calculate the equivalent control component, it is required to know the object's nominal functions fully; To calculate the robust control component, it is necessary to know the upper bounds of uncertainty and noise.

The study of reducing the vibration effect in the sliding control system has an extremely important application significance. In the paper, the author does not use the conventional sliding control method, but rather combines the adapted-sliding-backstepping method for the quadrotor. The adaptive self-correction function can estimate uncertainties, ensuring stable control without having to know the upper bounds of uncertainty and noise.

2. Quadrotor mathematical model

2.1. Mathematical model of the quadrotor without taking into account the uncertainties

To establish a mathematical model for the quadrotor, we need to consider some related coordinate systems as shown in Figure 1. In which Oxyz is the inertial coordinate system and Bxyz is the associated coordinate system. Bxyz is fastened to the stationary frame of the quadrotor. The three Euler angles

* *Corresponding author:* Le Ngoc Giang. Tel.: +84969896136
E-mail address: *lengocgianglinh@gmail.com*

of the quadrotor around the three axes respectively as shown in the figure are: Roll angle Φ, Pitch angle θ, Yaw angle Ψ. Thrust caused by 4 propellers is F_1, F_2, F_3, F_4.

To analyze the dynamics of the quadrotor, we consider it as an absolutely rigid body moving freely through space. We divide the motion of the quadrotor into two components: the translational motion of the center of mass and the rotation of the quadrotor about its three axes. The translational motion is caused by the drag and lift components, and the rotational motion is caused by the force moments.

For convenience and simplicity when considering the kinematics of the quadrotor, we do not consider the part of the DC motor that rotates the propeller, and the control signal of the system is reduced to the force as well as the torque to be generated. Therefore, the principle of controlling the quadrotor is as follows: Its motion is controlled through 4 components:

F denotes the total axial force Bz; Tx denotes the moment of force on the axis Bx; Ty denotes the moment of force on the By axis; Tz denotes the moment of force on the axis Bz; and F_L denotes the combined force.

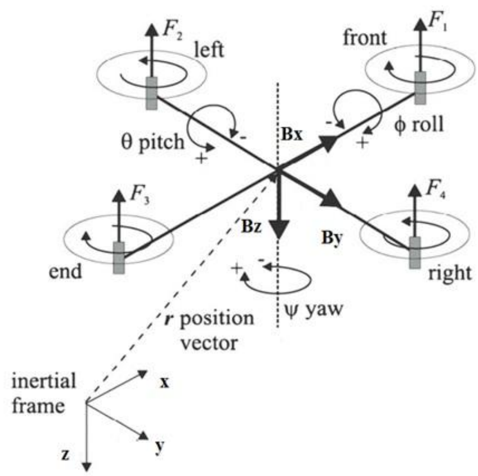

Fig.1 - Coordinate systems associated with quadrotor

Assuming small Euler angles and little influence on the rotation of the quadrotor. Ignoring the effect of the gyroscope effect on it caused by the four propeller engines, we get the full nonlinear dynamics model as follows:

$$\begin{cases} \ddot{\Phi} = \dot{\Psi}\dot{\theta}\dfrac{J_{yy} - J_{zz}}{J_{xx}} + \dfrac{T_x}{J_{xx}} \\ \ddot{\theta} = \dot{\Psi}\dot{\Phi}\dfrac{J_{zz} - J_{xx}}{J_{yy}} + \dfrac{T_y}{J_{yy}} \\ \ddot{\Psi} = \dfrac{T_z}{J_{zz}} \\ \ddot{x} = \left(\cos\Phi\sin\theta\cos\Psi + \sin\Phi\sin\Psi\right)\dfrac{1}{m}\left(-F_L\right) \\ \ddot{y} = \left(\cos\Phi\sin\theta\sin\Psi - \sin\Phi\cos\Psi\right)\dfrac{1}{m}\left(-F_L\right) \\ \ddot{z} = g + \cos\Phi\cos\theta\dfrac{1}{m}\left(-F_L\right) \end{cases} \quad (1)$$

Where m denotes mass and g denotes gravity's acceleration. Jxx, Jyy, Jzz are the moments of inertia on the quadrotor's axes.

2.2. Mathematical model of a quadrotor taking into account uncertainties

The system of equations (1) is the calculation result after applying a few assumptions to simplify, such as: Consider the angle Φ and the angle θ as two small motion angles; remove the effect of gyro torque on channel Φ.

In fact, the mathematical model is much more complicated with the cross-relationship between the channels Φ, θ and Ψ. There is also a gyro torque component. We consider the angle Ψ to coincide with the direction of movement. Therefore, the actual mathematical model of the object will contain uncertain components:

$$\begin{cases} \ddot{\Phi} = \dot{\Psi}\dot{\theta}\dfrac{J_{yy}-J_{zz}}{J_{xx}} + \dfrac{T_x}{J_{xx}} + f_1\dot{\theta} + f_2\theta + f \\ \ddot{\theta} = \dot{\Psi}\dot{\Phi}\dfrac{J_{zz}-J_{xx}}{J_{yy}} + \dfrac{T_y}{J_{yy}} + f_3\dot{\Phi} + f_4\Phi + f \\ \ddot{x} = (\cos\Phi\sin\theta\cos\Psi + \sin\Phi\sin\Psi)\dfrac{1}{m}(-F_L) - f_x\dot{x} \\ \ddot{y} = (\cos\Phi\sin\theta\cos\Psi - \sin\Phi\sin\Psi)\dfrac{1}{m}(-F_L) - f_y\dot{y} \\ \ddot{z} = g + \cos\Phi\cos\theta\dfrac{1}{m}(-F_L) + f_z \end{cases} \quad (2)$$

Where fi are the uncertainty coefficients.

3. Quadrotor controller design

Below, the author synthesizes backstepping, backstepping-sliding, and backstepping-sliding-adaptive controllers as follows:

3.1. Design of a backstepping controller

The main content of the synthesis of the backstepping controller is to give the control law for each control channel, provided that the parameters in the kinematic model of the quadrotor are clear. Below are the steps to synthesize the backstepping controller according to the z-height channel. The synthesis of the backstepping controller for the x, y channels and the corner channels Φ, Ψ, θ is also completely similar.

The dynamic equation for the z channel:

$$\ddot{z} = g + \cos\Phi\cos\theta\frac{1}{m}(-F_L)$$

Put $X_1 = z$; $X_2 = \dot{z}$ and $F_L = U_1$ therefore $\dot{X}_1 = \dot{z}$ và $\dot{X}_2 = \ddot{z}$. From this, the model of strict-feedback along the z-channel is:

$$\begin{cases} \dot{X}_1 = X_2 \\ \dot{X}_2 = g + \cos\Phi\cos\theta\dfrac{1}{m}(-U_1) \end{cases} \quad (3)$$

Let z_d be the desired altitude signal.

Step 1. Set $Z_1 = X_1 - z_d$ Inferred $\dot{Z}_1 = \dot{X}_1 - \dot{z}_d = X_2 - \dot{z}_d$

Choose the Lyapunov control function $V_1(Z_1) = \frac{1}{2}Z_1^2$

Conditions to signal $X_1 \to z_d$, when:

$$\dot{V}_1(Z_1) = Z_1\dot{Z}_1 = Z_1(X_2 - \dot{z}_d) < 0; (\forall Z_1 \neq 0)$$

Considering X_2 as a virtual control signal, deducing the virtual control law that ensures the stability criterion of Lyapunov is: $X_{2d} = -C_1Z_1 + \dot{z}_d$ with $C_1 > 0$.

Step 2. Set $Z_2 = X_2 - X_{2d}$;

$$\dot{Z}_2 = \dot{X}_2 - \dot{X}_{2d} = g + \cos\Phi\cos\theta\frac{1}{m}(-U_1) + C_1\dot{Z}_1 - \ddot{z}_d \quad (4)$$

Infer $\dot{V}_1(Z_1) = Z_1(-C_1Z_1 + Z_2)$

Choose the Lyapunov control function $V_2(Z_1, Z_2) = V_1 + \frac{1}{2}Z_2^2$

Conditions to signal $X_2 \to X_{2d}$ when: $\dot{V}_2 = \dot{V}_1 + Z_2\dot{Z}_2 < 0; (\forall Z_1, Z_2 \neq 0)$

$$\dot{V}_2 = -C_1Z_1^2 + Z_1Z_2 + Z_2(g + \cos\Phi\cos\theta\frac{1}{m}(-U_1) + C_1\dot{Z}_1 - \ddot{z}_d) \quad (5)$$

According to the Lyapunov stability criterion, for a globally asymptotic stable system, the control law U_1 has the form:

$$U_z = m\frac{1}{\cos\Phi\cos\theta}(Z_1 + g + C_1Z_2 - C_1^2Z_1 - \ddot{z}_d + C_2Z_2); \qquad C_1, C_2 > 0 \quad (6)$$

In a similar investigation, we have control laws for channels x, y, and Φ, θ, Ψ là:

$$\begin{cases} U_x = m\frac{1}{U_z}\left(Z_3 + C_4Z_4 + C_3Z_4 - C_3^2Z_3 - \ddot{x}_d\right) \\ U_y = m\frac{1}{U_z}\left(Z_5 + C_6Z_6 + C_5Z_6 - C_5^2Z_5 - \ddot{y}_d\right) \\ U_\Phi = J_{xx}(-Z_7 - \dot{\Psi}\dot{\theta}\frac{J_{yy} - J_{zz}}{J_{xx}} - C_8Z_8 - C_7Z_8 + C_7^2Z_7 - \ddot{\Phi}_d) \\ U_\theta = J_{yy}(-Z_9 - \dot{\Psi}\dot{\Phi}\frac{J_{zz} - J_{xx}}{J_{yy}} - C_{10}Z_{10} - C_9Z_{10} + C_9^2Z_9 - \ddot{\theta}_d) \\ U_\Psi = J_{zz}\left(-Z_{11} - C_{12}Z_{12} - C_{11}Z_{12} + C_{11}^2Z_{11} - \ddot{\Psi}_d\right) \end{cases} \quad (7)$$

where C_i is a positive design constant.

3.2. Slide-Backstepping controller design

In Section 3.1, according to formula (6), we have synthesized the backstepping control law for channel z of the form:

$$U_z = m\frac{1}{\cos\Phi\cos\theta}(Z_1 + g + C_1Z_2 - C_1^2Z_1 - \ddot{z}_d + C_2Z_2); \qquad C_1, C_2 > 0$$

To synthesize the sliding backstepping control law, we apply the sliding control to the result of the backstepping control law synthesis. The calculation process is as follows:

$$\begin{cases} V_1 = \frac{1}{2}Z_1^2 \\ V_2 = \frac{1}{2}Z_1^2 + \frac{1}{2}s_z^2 \end{cases} \qquad \begin{cases} Z_1 = X_{1d} - X_1 \\ \dot{V}_2 = Z_1\dot{Z}_1 + s_z\dot{s}_z \\ s_z = Z_2 = X_2 - \dot{X}_{1d} - C_1Z_1 \end{cases} \quad (8)$$

We can calculate the slip surface as follows:

$$\begin{cases} \dot{s}_z = -k\,\mathrm{sign}(s_z) - q_1s_z \\ \dot{s}_z = \dot{X}_2 - \ddot{X}_{1d} - C_1\dot{Z}_1 \end{cases} \quad (9)$$

To synthesize a stable control signal in the sliding mode, it is necessary to ensure the necessary slip condition $s\dot{s} < 0$. Then, by solving the system of equations (9), we get the sliding backstepping control law for the z channel as follows:

$$U_z = m\frac{1}{\cos\Phi\cos\theta}\left(k_1\mathrm{sign}(s_z) + q_1s_z + g - \ddot{X}_{1d} - C_1(\dot{X}_{1d} - X_2)\right) \quad (10)$$

Doing the same, we have the sliding backstepping control law for the remaining channels as follows:

$$\begin{cases} U_x = m\dfrac{1}{U_z}\left(k_x \text{sign}(s_x) + q_x s_x - \ddot{X}_{3d} - C_x(\dot{X}_{3d} - X_4)\right) \\ U_y = m\dfrac{1}{U_z}\left(k_y \text{sign}(s_y) + q_y s_y - \ddot{X}_{5d} - C_y(\dot{X}_{5d} - X_6)\right) \\ U_\Phi = J_{xx}[-k_2 \text{ sign}(s_\Phi) - q_\Phi s_\Phi - \dot{\Phi}\dot{\theta}\dfrac{J_{yy} - J_{zz}}{J_{xx}} + \ddot{X}_{7d} + C_2(\dot{X}_{7d} - X_8)] \\ U_\theta = J_{yy}[-k_3 \text{ sign}(s_\theta) - q_\theta s_\theta - \dot{\Psi}\dot{\Phi}\dfrac{J_{zz} - J_{xx}}{J_{yy}} + \ddot{X}_{9d} + C_3(\dot{X}_{9d} - X_{10})] \\ U_\Psi = J_{zz}[-k_4 \text{sign}(s_\Psi) - q_\Psi s_\Psi + \ddot{X}_{11d} + C_4(\dot{X}_{11d} - X_{12})] \end{cases} \tag{11}$$

3.3. Adaptive-sliding-backstepping controller design

The mathematical model of channel Φ takes into account the uncertainty components in the strict-feedback form:

$$\begin{cases} \dot{X}_7 = X_8 \\ \dot{X}_8 = \dot{\Psi}\dot{\theta}\dfrac{J_{yy} - J_{zz}}{J_{xx}} + f_1\dot{\theta} + f_2\theta + f + \dfrac{U_2}{J_{xx}} \end{cases} \tag{12}$$

Let the desired signal of angle Φ be: Φ_d , $X_7 = \Phi$. Put $Z_7 = X_7 - \Phi_d$, if $X_7 \to \Phi_d$ then $Z_7 \to 0$. Put $Z_8 = X_8 - X_{8d}$, if $X_8 \to X_{8d}$ then $Z_8 \to 0$. We get:

$$\begin{cases} \dot{Z}_7 = X_8 - \dot{\Phi}_d \\ \dot{Z}_8 = \dot{\Psi}\dot{\theta}\dfrac{J_{yy} - J_{zz}}{J_{xx}} + f_1\dot{\theta} + f_2\theta + f + \dfrac{U_2}{J_{xx}} - \dot{X}_{8d} \end{cases} \tag{13}$$

From the result of synthesizing backstepping control rules for channel Φ, the adaptive control law has the form:

$$U_\Phi = J_{xx}(-Z_7 - \dot{\Psi}\dot{\theta}\frac{J_{yy} - J_{zz}}{J_{xx}} - C_7 Z_8 + C_7^2 Z_7 - C_8 Z_8 - \hat{f}_1\dot{\theta} - \hat{f}_2\theta - \hat{f}) \tag{14}$$

In there $\hat{f}_1$, $\hat{f}_2$ and $\hat{f}$ are the estimates of the uncertainty components.

Let the estimated errors be $\tilde{f}_1 = f_1 - \hat{f}_1$; $\tilde{f}_2 = f_2 - \hat{f}_2$; $\tilde{f} = f - \hat{f}$

The following is the control function for estimated error components:

$$V_8(Z_7, Z_8, \tilde{f}_1, \tilde{f}_2, \tilde{f}) = V_8(Z_7, Z_8) + \frac{1}{2\gamma_1}\tilde{f}_1^2 + \frac{1}{2\gamma_2}\tilde{f}_2^2 + \frac{1}{2\gamma}\tilde{f}^2 \tag{15}$$

In there $\gamma_1, \gamma_2, \gamma$ are the adaptation coefficients. Taking the time differential of V_8, we get:

$$\dot{V}_8 = -C_7 Z_7^2 + Z_8[Z_7 + \dot{\Psi}\dot{\theta}\frac{J_{yy} - J_{zz}}{J_{xx}} + f_1\dot{\theta} + f_2\theta + f + \frac{U_2}{J_{xx}} + C_7\dot{Z}_7] + \frac{1}{\gamma_1}\tilde{f}_1\dot{\tilde{f}}_1 + \frac{1}{\gamma_2}\tilde{f}_2\dot{\tilde{f}}_2 + \frac{1}{\gamma}\tilde{f}\dot{\tilde{f}} \tag{16}$$

Substituting U_Φ, we get:

$$\dot{V}_8 = -C_7 Z_7^2 + Z_8(-C_8 Z_8 + \tilde{f}_1\dot{\theta} + \tilde{f}_2\theta + \tilde{f}) + \frac{1}{\gamma_1}\tilde{f}_1\dot{\tilde{f}}_1 + \frac{1}{\gamma_2}\tilde{f}_2\dot{\tilde{f}}_2 + \frac{1}{\gamma}\tilde{f}\dot{\tilde{f}} \tag{17}$$

For the system to be globally asymptotically stable according to the Lyapunov stability criterion, then $\dot{V}_8 = -C_7 Z_7^2 - C_8 Z_8^2$ must be defined negative.

As a result, the correction law for estimating uncertain parameters is:

$$\begin{cases} \frac{1}{\gamma_1}\dot{\tilde{f}}_1 + Z_8\dot{\theta} = 0 \\ \frac{1}{\gamma_2}.\dot{\tilde{f}}_2 + Z_8.\theta = 0 \\ \frac{1}{\gamma}\dot{\tilde{f}} + Z_8 = 0 \end{cases} \Rightarrow \begin{cases} \dot{\tilde{f}}_1 = -Z_8\dot{\theta}\gamma_1 \\ \dot{\tilde{f}}_2 = -Z_8.\theta.\gamma_2 \\ \dot{\tilde{f}} = -Z_8\gamma \end{cases} \Rightarrow \begin{cases} \dot{\hat{f}}_1 = Z_8\dot{\theta}\gamma_1 \\ \dot{\hat{f}}_2 = Z_8.\theta.\gamma_2 \\ \dot{\hat{f}} = Z_8\gamma \end{cases} \quad (18)$$

We can derive an adaptive sliding backstepping control law for channel Φ:

$$U_\Phi = J_{xx}[-k_2\text{sign}(s_\Phi) - q_2 s_\Phi - \dot{\Psi}\dot{\theta}\frac{J_{yy}-J_{zz}}{J_{xx}} + \ddot{X}_{7d} + C_2(\dot{X}_{7d} - X_8) - \hat{f}_1\dot{\theta} - \hat{f}_2\theta - \hat{f}] \quad (19)$$

Similarly, we have an adaptive sliding backstepping control law for channel θ as follows:

$$U_\theta = J_{xx}[-k_3\text{sign}(s_\theta) - q_\theta s_\theta - X_8X_{11}\frac{J_{zz}-J_{xx}}{J_{yy}} + \ddot{X}_{9d} + C_3(\dot{X}_{9d} - X_{10}) - \hat{f}_3\dot{\Phi} - \hat{f}_4\Phi - \hat{f}] \quad (20)$$

The correction law is defined as follows:

$$\dot{\hat{f}}_3 = Z_{10}\dot{\Phi}\gamma_3; \quad \dot{\hat{f}}_4 = Z_{10}\dot{\Phi}\gamma_4; \quad \dot{\hat{f}} = Z_{10}\gamma \quad (21)$$

Similarly, we have an adaptive sliding backstepping control law for channels x, y, z as follows:

$$\begin{cases} U_x = m\frac{1}{U_1}\left(k_x\text{sign}(s_x) + q_x s_x - \ddot{X}_{3d} - C_x(\dot{X}_{3d} - X_4) - \hat{f}_x(-C_3Z_3 + Z_4)\right) \\ U_y = m\frac{1}{U_1}\left(k_y\text{sign}(s_y) + q_y s_y - \ddot{X}_{5d} - C_y(\dot{X}_{5d} - X_6) - \hat{f}_y(-C_5Z_5 + Z_6)\right) \\ U_z = m\frac{1}{\cos\Phi\cos\theta}\left(k_1\text{sign}(s_z) + q_1 s_z + g - \ddot{X}_{1d} - C_1(\dot{X}_{1d} - X_2) - \hat{f}_z\right) \end{cases} \quad (22)$$

The correction law is defined as follows:

$$\dot{\hat{f}}_x = (-Z_4^2 + C_3Z_3Z_4)\gamma_x; \quad \dot{\hat{f}}_y = (-Z_6^2 + C_5Z_5Z_6)\gamma_y; \quad \dot{\hat{f}}_z = Z_2\gamma_z \quad (23)$$

Thus, the author has synthesized the adaptive sliding backstepping control law for the control channels of the quadrotor. Below, the author will apply Matlab software to survey and compare the quality of sliding backstepping controller with adaptive sliding backstepping controller.

4. Simulated Analysis

4.1. DJI F450 quadcopter parameters

DJI F450 quadcopter parameters are selected in table 1.

Table 1. DJI F450 quadcopter parameters

Parameter	Description	Value
L	Arm length	0.225m
b	Thrust coefficient	$9.8x10^{-6}$ N/m^2
d	Drag coefficient	$1.6x10^{7}$
m	Mass	2 kg
J_{xx}, J_{yy}, J_{zz}	Moments of inertia	0.0035; 0.0035; 0.005 kg.m^2
J_r	Rotor inertia	$2.8x10^{-6}$ kg.m^2

The parameters of the motor and the initial parameters K_t=0,0052; Ra=0,9Ω; L_a=2*mH*; K_b=0,0057; K_m=7,5.10^{-7}; K_f =3,13.10^{-5}.

4.2. Evaluate the slide backstepping controller

To evaluate the quality of the controller, the author conducted a survey of the position control loop of the quadrotor in two cases: with noise and without noise impact. When there is a noise impact, we put the noise into the z-height channel. The other channels do the same.

The block diagram of the sliding backstepping controller is shown below:

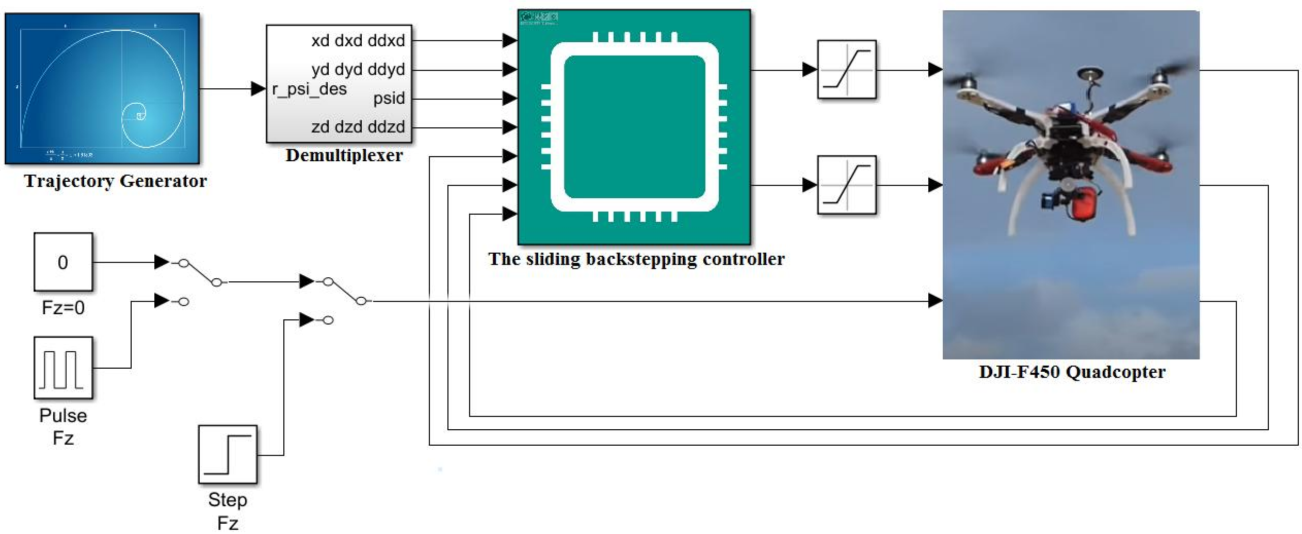

Fig.2 - The block diagram of the sliding backstepping controller for quadrotor

With the block diagram as above, the trajectory generator will create a spiral path that is a combination of linear and rotational motion with a diameter of 8 (m). The controller will control the quadrotor to follow the trajectory. When there is no interference, the tracking results are as follows:

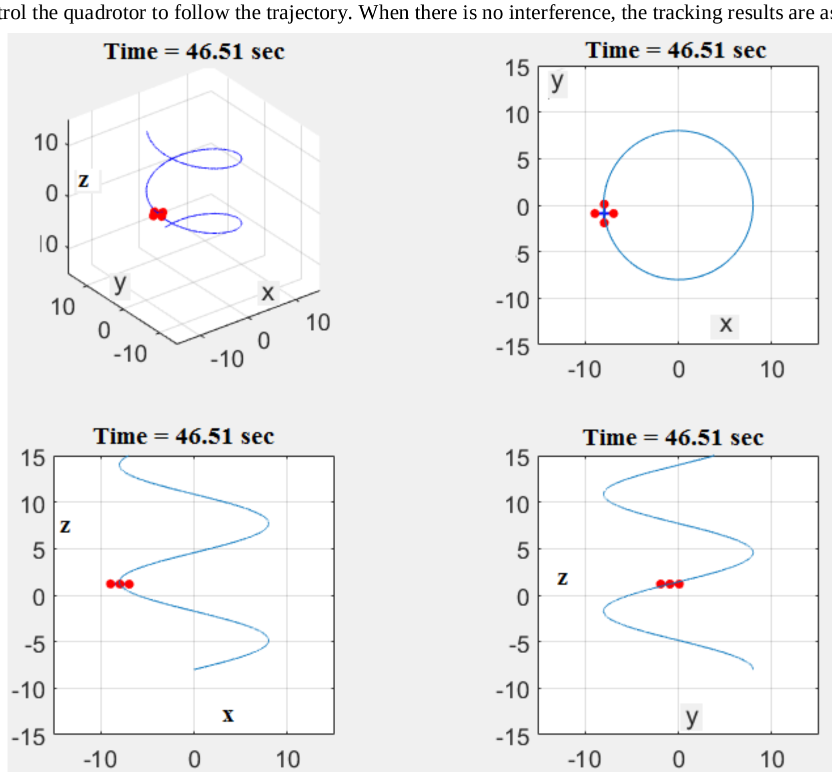

Fig.3 - Tracking results of a sliding backstepping controller when without noise impact

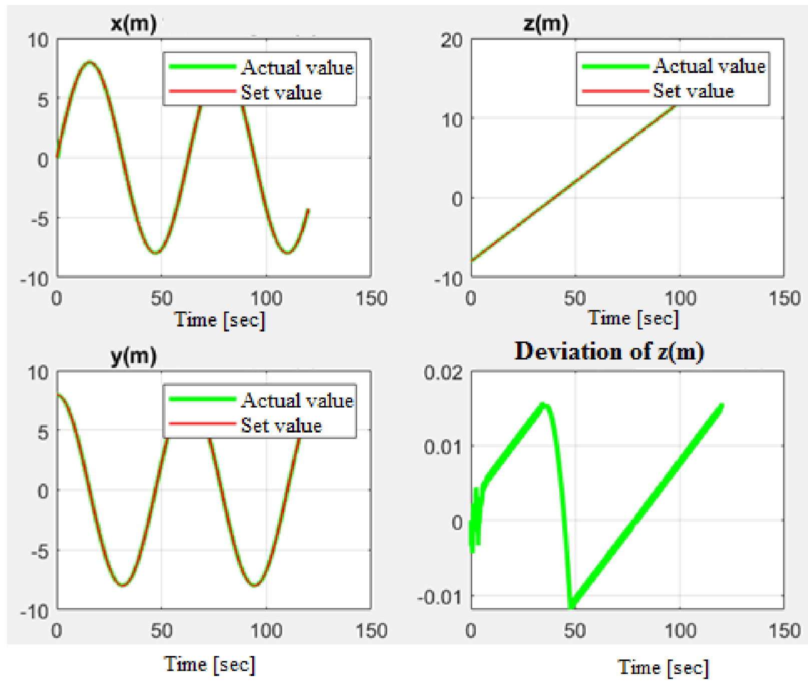

Fig.4 - Tracing error of a sliding backstepping controller when without noise impact

The quadrotor closely follows the given spiral trajectory, with a very small error on the z channel (0.015 m). Let the noise acting on the z channel be a pulse function with a very large amplitude of 5 (m), a period of 50 (s), and a pulse width of 95%. Then, the result of closely follows the spiral trajectory is as follows:

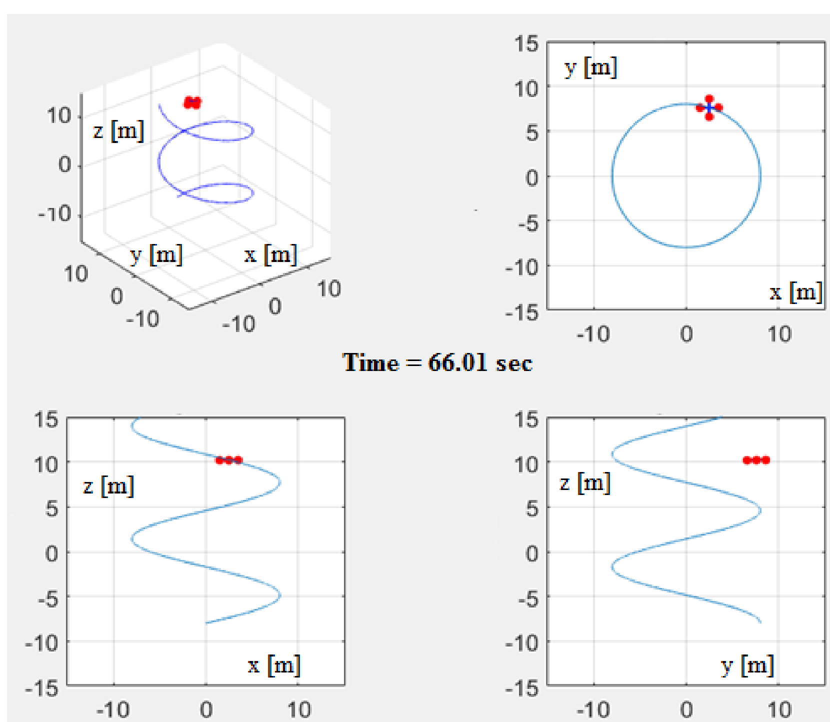

Fig.5 - Tracking results of a sliding backstepping controller when with noise impact

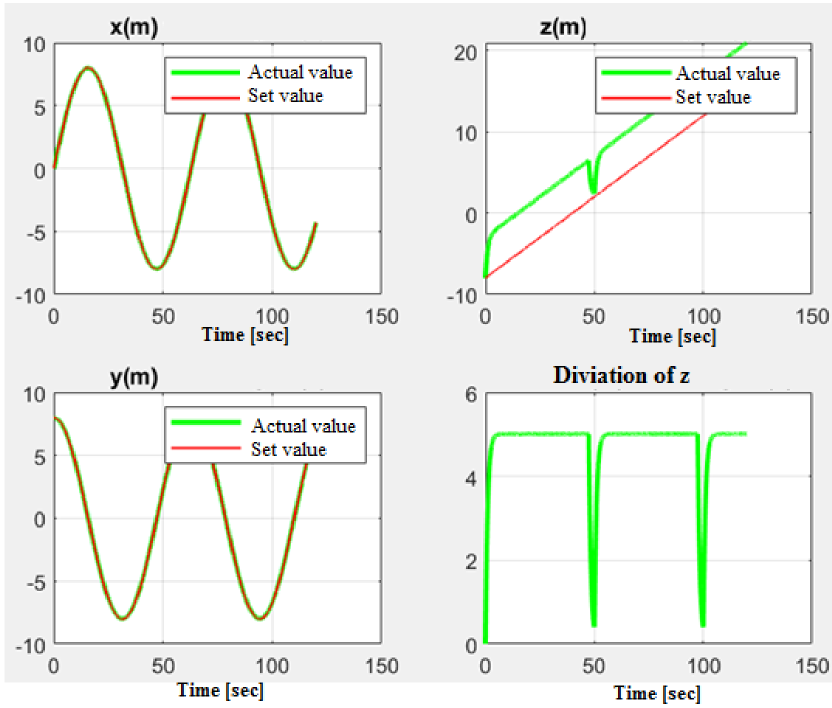

Fig.6 - Tracing error of a sliding backstepping controller when with noise impact

When with noise impact, the quadrotor still closely follows the x and y axes, but there is a large error in the z axis, making it almost unable to extinguish the impact uncertainty. The quadrotor was knocked out of orbit and barely followed the z-axis. The requirement is that you need a more powerful and superior controller.

4.3. Evaluate the adaptive slide backstepping controller

In the quadrotor's model, there are uncertain components. Due to the existence of uncertainty components, changes in weight, noise and aerodynamic drag impact, etc. The efficiency analysis of the adaptive sliding backstepping controller on the z-channel is performed below. Other channels do the same. The Simulink diagram of the adaptive sliding backstepping controller is as follows:

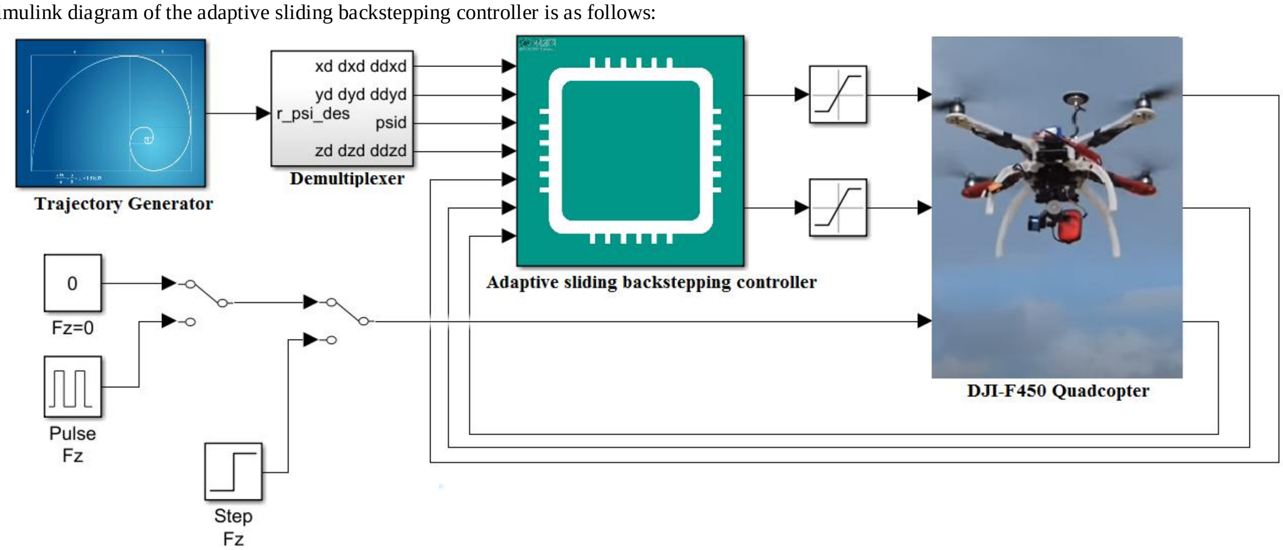

Fig.7 - The block diagram of the adaptive sliding backstepping controller for quadrotor

The survey results are as follows:

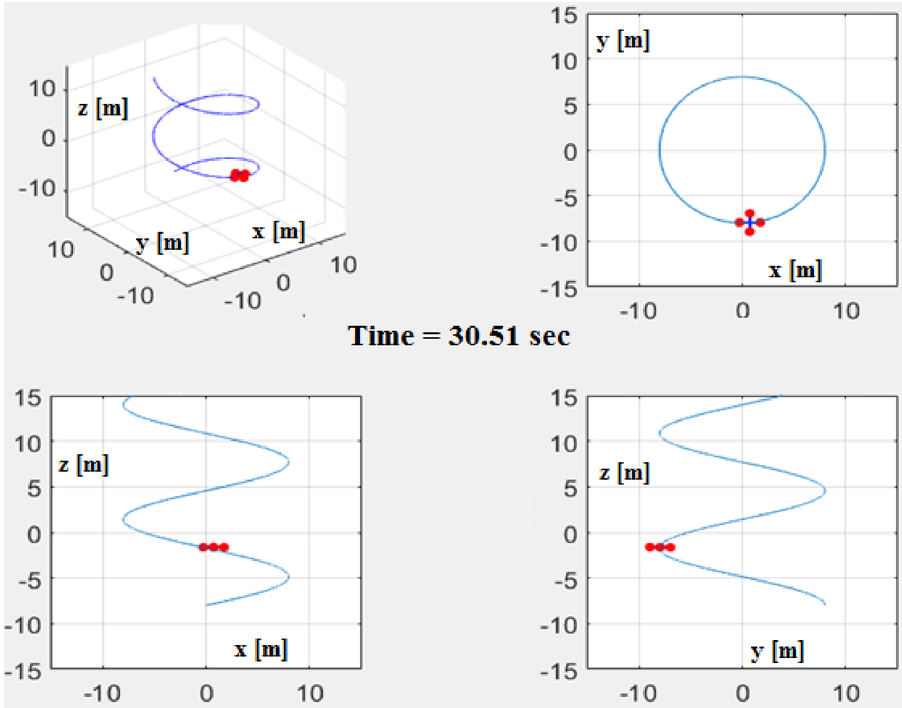

Fig.8 - Tracking results of a adaptive sliding backstepping controller when with noise impact

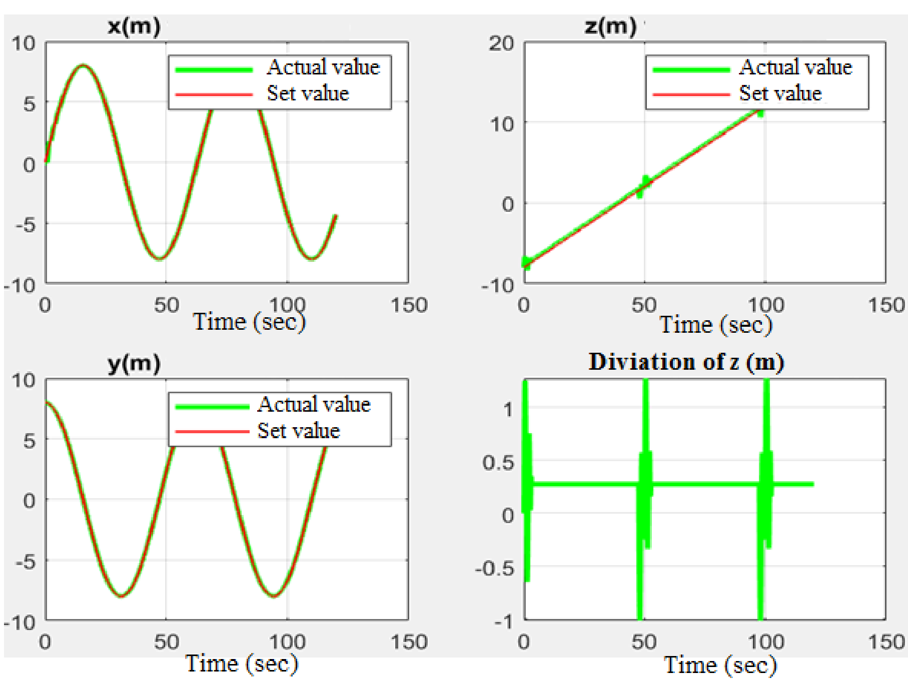

Fig.9 - Tracing error of an adaptive sliding backstepping controller when with noise impact

When with noise impact, we see that the adaptive sliding backstepping controller maintains the quadrotor well following the spiral trajectory, even though there is an uncertainty component that acts continuously with large amplitudes. The quadrotor oscillates around the equilibrium position and takes only 2 seconds to reset to the desired set value. The error as well as the overshoot are greatly reduced compared with the sliding backstepping controller. In summary, the adaptive sliding backstepping controller meets the requirements set out well.

5. Conclusion

The simulation results show that the outstanding advantage of the adaptive sliding backstepping controller compared to the sliding backstepping controller is shown in the good control quality, short transient time, and wider quadrotor working range, creating the possibility of high maneuverability, suppressing the influence of uncertain components and reducing the influence of noise during operation. For strong nonlinear systems such as the DJI-F450 Quadcopter, the control law designed by the adaptive sliding backstepping method is able to compensate for the model uncertainties and improve the robustness of the control system.

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