

Research on the Flight Control Strategy of a New Concept Fuel-electric Hybrid Multi-rotor UAV

Xice Xu^{1,a,*}, Da Kong^{2,b}, and Yang Lu^{1,c}

¹National key laboratory of rotorcraft aeromechanics, nanjing university of aeronautics and astronautics, nanjing, 210016, China

²College of automation engineering, nanjing university of aeronautics and astronautics, nanjing, 210016, China

E-mail: ^aXuXiCeNUAA@163.com, ^bkd1997@nuaa.edu.cn, ^cnjluyang@163.com.

Abstract. In order to solve the shortcomings of conventional electric multi-rotor UAVs, such as low load, short range and endurance, a new concept of fuel-electric hybrid multi-rotor UAV, in which the lift and attitude control are separated, is presented in this paper. Firstly, to comprehend the control characteristics of this UAV and also to design its flight control law, the flight dynamics model of this kind of UAV is established. Subsequently, considering the control redundancy in the height channel of the main rotors and the auxiliary rotors of UAV, a power switch control strategy based on vertical acceleration is proposed. Further, in view of the control characteristics of the aircraft, according to the backstepping -PID control method, the attitude and speed controller are designed. The numerical simulation and the flight test of the prototype are carried out respectively in order to verify the control strategy. Both theoretical simulation and flight test results show that the designed UAV controller can satisfy the desired control effect.

1. Introduction

In recent years, multi-rotor UAVs have become a research hotspot in the field of unmanned aerial vehicles due to their excellent control characteristics [1], superior performance in hover and low speed flight. Usually, multi-rotor UAVs are driven by electric motor. However due to the limitation of energy density of lithium battery, the take-off weight of multi-rotor UAVs is seriously restricted. Moreover the range and endurance are limited. And as a result, its application field is narrow. One solution is to use a fuel-powered engine (such as a piston engine) as the power unit for multi-rotor. However, although the fuel-powered engine has the advantages of large power, low fuel consumption and high load capacity, its response speed is slow. Therefore, if it is used for attitude control, it can only keep the rotor speed constant and realize the effective control of attitude only through complex pitch control mechanism and flight control system. In this situation, it will cause the structure more complicated and increase the weight and cost. What's more, the high reliability of the multi-rotor UAVs is lost.

In order to solve the above problems, in this paper we propose and develop a new concept fuel-electric hybrid multi-rotor UAV. Figure. 1 shows the picture of this UAV. The main lift of this UAV is generated by two piston engines which are installed side by side in the center of the vehicle, while the attitude control of the vehicle is realized by the four small rotors which are driven by electric motors around the vehicle. In this way, the piston engines which are used to generate the main lift don't need to change the engine speed to adjust the lift. The lift produced by four auxiliary rotors which are driven by four independent adjustable attitude motors is small, so the consumption of power is also small, thus the weight of the battery needed is effectively reduced. This kind of aircraft can solve the



Content from this work may be used under the terms of the [Creative Commons Attribution 3.0 licence](https://creativecommons.org/licenses/by/3.0/). Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

contradiction between the high load capacity and the short range. Therefore it will have a wide application prospect. For convenience, this new concept fuel-electric hybrid multi-rotor UAV in which the lift and attitude control are separated is referred to as LAS-UAV (Lift/Attitude Separation Fuel-electric Hybrid Unmanned Aerial Vehicle).



Figure 1. LAS-UAV prototype

2. Dynamic model of LAS-UAV

2.1. Basic flight principle of LAS-UAV

Figure 2 and Figure 3 show the basic principle of LAS-UAV attitude control. In these Figure.s, rotor 1 to 4 are used as the auxiliary rotors for attitude adjustment, and rotor 5 and rotor 6 are used as the main rotor to produce lift. Among them, the sense of rotation of rotor 1, rotor 3 and rotor 5 is clockwise and the sense of rotation of rotor 2, rotor 4, rotor 6 is counterclockwise. The roll, pitch and yaw manipulation of LAS-UAV are the same as conventional four rotor UAV. It is realized by four auxiliary rotor respectively which are shown in Figure 2(a), Figure 2 (b) and Figure 3(a). The vertical climb is different, which is achieved through the lift combination of the two main rotors driven by two oil machines, as shown in Figure 3(b).

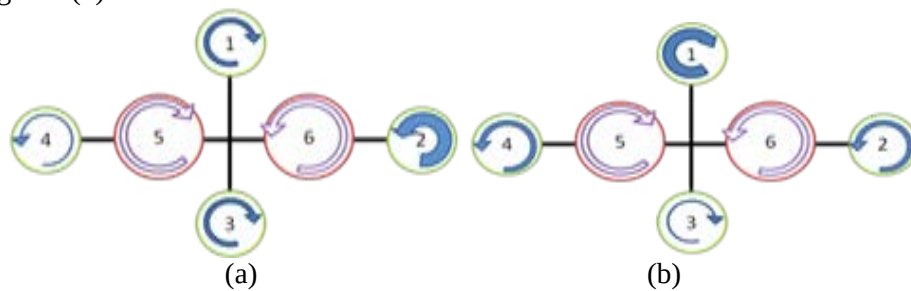


Figure 2. Schematic of LAS-UAV rolling (a) pitching (b) manipulation

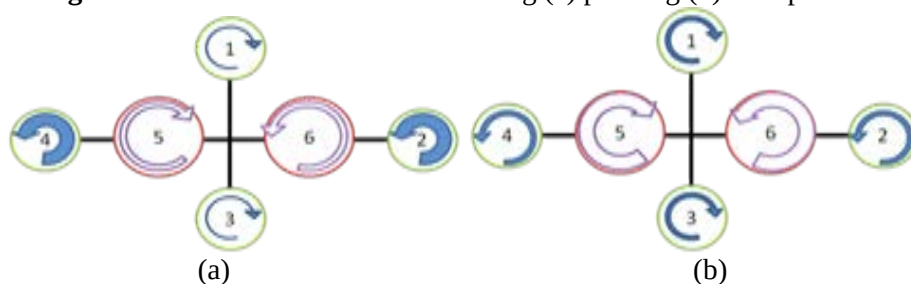


Figure 3. Schematic of LAS-UAV yawing (a) and climbing (b) manipulation

2.2. Flight dynamics model of LAS-UAV

Origin of the body axis coordinate used in LAS-UAV model is located in the centroid of LAS-UAV. The x axis is located at the symmetric section of the nose, and it points at the motor 1 in the nose. The y axis points at the right direction of the body and it is vertical to the x axis. The direction of the z axis meets with right hand rule. Pitch angle is positive when LAS-UAV noses up, roll angle is positive when LAS-UAV rolls right and yaw angle is positive when LAS-UAV yaws right.

For convenience, some assumptions are introduced here [2]: (1)The body of LAS UAV is an ideal rigid body, and its shape and mass distribution are symmetrical;(2) The rotor is an ideal rigid body and aerodynamic force is simplified as a function relationship of torque and rotational speed . Besides, because the flight speed of LAS-UAV is very low, the wind resistance of LAS-UAV is not considered, only the force and moment produced by the rotor are take into account.

Equation (1.1) - (1.4) gives the resultant external force and the resultant external troque of LAS-UAV. In these equations, Ω_i is the rotor speed of the i_{th} rotor. k_{11}, k_{12} are the lift coefficient and the torque coefficient of the auxiliary rotor. k_{21}, k_{22} are the lift coefficient and the torque coefficient of the main rotor. u_1, u_2, u_3, u_4 are input channels of hight, roll, pitch and yaw, l_1, l_2, l_3 are distance between motor 1 and motor 3, motor 2 and motor 4, motor 5 and motor 6.

$$u_1 = k_{11}(\Omega_1^2 + \Omega_2^2 + \Omega_3^2 + \Omega_4^2) + k_{12}(\Omega_5^2 + \Omega_6^2) \quad (1.1)$$

$$u_2 = k_{11}(\Omega_4^2 - \Omega_2^2)l_2 + k_{12}(\Omega_5^2 - \Omega_6^2)l_3 \quad (1.2)$$

$$u_3 = k_{11}(\Omega_1^2 - \Omega_3^2)l_1 \quad (1.3)$$

$$u_4 = k_{21}(\Omega_2^2 + \Omega_4^2 - \Omega_1^2 - \Omega_3^2) + k_{22}(\Omega_6^2 - \Omega_5^2) \quad (1.4)$$

According to the principle of dynamics, the six degree of freedom motion equation of LAS-UAV is established as follows:

$$\ddot{x} = -(\cos \psi \sin \theta \cos \phi + \sin \psi \sin \phi)u_1 / m \quad (1.5)$$

$$\ddot{y} = -(\sin \psi \sin \theta \cos \phi - \cos \psi \sin \phi)u_1 / m \quad (1.6)$$

$$\ddot{z} = g - \cos \theta \cos \phi u_1 / m \quad (1.7)$$

$$\dot{w}_x = (u_2 - J_1 w_x \Omega_{r1} - J_2 w_y \Omega_{r2} + (I_y - I_z)w_y w_z - l_3 u_1) / I_x \quad (1.8)$$

$$\dot{w}_y = (u_3 + J_1 w_x \Omega_{r1} + J_2 w_y \Omega_{r2} + (I_z - I_x)w_x w_z - l_3 u_1) / I_y \quad (1.9)$$

$$\dot{w}_z = (u_4 + (I_x - I_y)w_x w_y) / I_z \quad (1.10)$$

In these equations: J_1, J_2 are the rotational inertia of the auxiliary rotor and the main rotor. I_x, I_y, I_z are the inertia moment of LAS-UAV. W_x, W_y, W_z are the angular velocitys in the coordinate system of LAS-UAV. θ, ϕ, φ are pitch angle, roll angle and yaw angle respectively. g is acceleration of gravity. Ω_{r1}, Ω_{r2} are the fluctuation of auxiliary rotor speed and the fluctuation of the main rotor speed. m is total weight of LAS-UAV. The other three complementary equations can be obtained by the kinematic relationship between the attitude angle and the angular velocity.

From the relation of the rotation speed and the channel input in equation (1.1) to equation (1.4), it can be seen that when the controller gives four channel input requirements, the rotor speed of the six rotor could not be uniquely determined. Therefore, the two rotational speed constraints are supplemented as follows:

$$\Omega_5 = \Omega_6 \quad (1.11)$$

$$\Omega_1^2 + \Omega_2^2 + \Omega_3^2 + \Omega_4^2 \approx \text{const} \quad (1.12)$$

At this moment the rotational speed distribution exists and it is unique. The reason for increasing the above rotational speed constraint are: (1) The main rotor is powered by the oil, and almost all the lift is generated by the main rotor; (2) the single main rotor has larger torque moment and it is difficult to balance by the auxiliary rotor, so the two main rotors rotate reversely and the torque moment is offset with each other.

Based on the flight dynamics model of LAS-UAV which is established above, the model can be further simulated through SIMULINK.

3. Design of LAS-UAV control law

The design idea of the control law is to achieve the attitude and height control of LAS-UAV by closed loop control [3]. Currently, the design methods for the nonlinear controller mainly include dynamic inversion, H_∞ sliding mode, fuzzy, artificial neural networks and backstepping.

Backstepping is suitable for systems with strict feedback [4, 5]. Figure 4 gives the block diagram of backstepping. As an example, the pitch channel is suitable for using backstepping method because it is in strict feedback form which can be described as $u_3 \xrightarrow{(1.9)} w_y \xrightarrow{1/s} w_y \xrightarrow{\text{Kinematic}} \theta \xrightarrow{1/s} \theta$. However, in the past, backstepping controller parameters were constructed based on Lyapunov theory, which often resulted in more redundancy and non-intuitive physical significance. In addition, it is very inconvenient to be used to adjust the parameters in the field when the parameters of the model are not accurate.

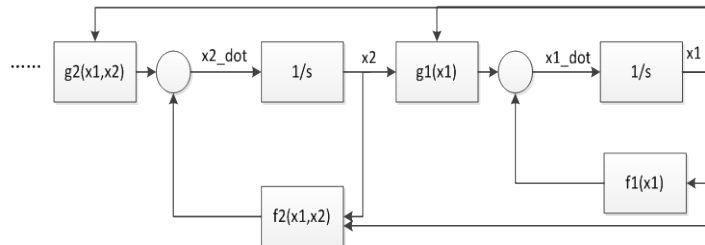


Figure 4. Block diagram of the backstepping

On the other hand, the PID controller is the most widely used control method in the industrial control field [6], since it has the advantages of simple structure, easy to implement and wide application. Therefore, the PID controller was used in this paper to ensure the stability of the control quantity in the backstepping loop.

The design process of the backstepping -PID controller is described as follows. Taking the pitch channel as an example, it can be easily changed into $u_3 \xrightarrow{(1.9)} \theta \xrightarrow{1/s} \dot{\theta} \xrightarrow{1/s} \theta$ through small-angle assumption. The output target θ_d is given by the horizontal channel controller, where θ_d is the virtual input of θ . A PID controller is used here to ensure that θ_d is followed by θ . Further, θ_d is the virtual input of $\dot{\theta}$, $\dot{\theta}_d$ is followed by $\dot{\theta}$ in the same way using the PID controller. The input parameter u_3 is obtained based on equation (1.9). The pitching channel controller is designed completely through the above ways. In the process of design, the parameters of the PID controller are specific and the pitch angle is followed by the following loop to facilitate the on-line parameter setting.

In accordance with the above design process, the control law of the pitching channel can be expressed as follow:

$$w_{dy} = U_{\theta 2} \quad (2.1)$$

$$u_3 = I_y U_{\theta 1} - J_1 \dot{\phi} \Omega_{r1} - J_2 \dot{\phi} \Omega_{r2} - (I_z - I_x) \dot{\phi} \dot{\psi} + I_3 u_1 \quad (2.2)$$

$$U_{\theta 1} = k_{pwy}(w_{dy} - w_y) + k_{iwy} \int (w_{dy} - w_y) dt + k_{dwy}(\dot{w}_{dy} - \dot{w}_y) \quad (2.3)$$

$$U_{\theta 2} = k_{p\theta}(\theta_d - \theta) + k_{i\theta} \int (\theta_d - \theta) dt + k_{d\theta}(\dot{\theta}_d - \dot{\theta}) \quad (2.4)$$

where, k defines the parameter of PID controller, the real input value u_3 is the pitch moment which is related to the rotor speed, w_d and θ_d are the target angular velocity and target pitch angle, $U_{\theta 1}$ and $U_{\theta 2}$ define the virtual input.

Based on the above backstepping -PID design process, the LAS-UAV's attitude, height and horizontal position control law were designed in this paper. Further, the controller was simulated based on SIMULINK. The block diagram of SIMULINK simulation is shown in Figure 5.

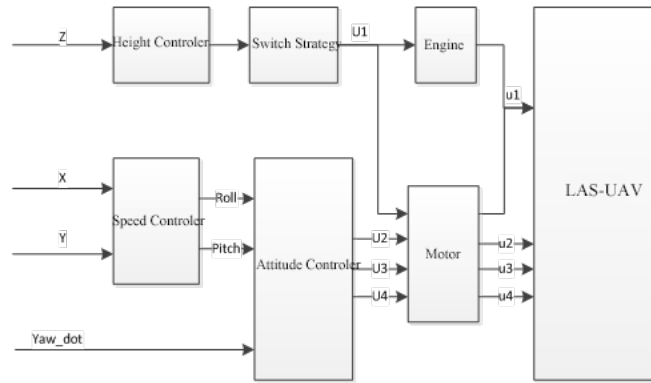


Figure 5. SIMULINK simulation block diagram of control system

As shown in Figure. 5, the LAS-UAV simulation model includes the motor model, the aerodynamic model and the dynamic model.

Navigation controller is used to realize the navigation of waypoint [7]. The initial position is the origin of the geodetic coordinate system, and the condition to judge the arrival point of the target is that the distance of the space Euclidean distance is less than 0.5m. In order to ensure the smoothness of the acceleration of the target speed, the amplitude limiting and low-pass filtering are conducted.

The autopilot controller is used to convert the target speed and the target angular rate to the speed control of the motor, where the target angular rate is obtained by the navigation controller. The angle which integral from target angular rate is inputted to the yaw controller. Because the control force for yaw channel is weak and slow to follow, a feed forward of the angular rate is added to the yaw controller.

The height channel is controlled by the main rotor as well as the auxiliary rotor. Considering the large inertia of the main rotor and relatively slow operation response, the authority control is added to the controller. Height channel control strategy can be expressed as:

$$\text{Height Control} : \begin{cases} \text{Engine}; S = 1 \\ \text{Motor}; S = 0 \end{cases} \quad (2.5)$$

$$S = \begin{cases} 1; & a_H \geq a_{\max} \\ 1; & (a_{\max} > a_H > a_{\min}, S = 1) \\ 0; & (a_{\max} > a_H > a_{\min}, S = 0) \\ 0; & a_H \leq a_{\min} \end{cases} \quad (2.6)$$

where, a_H , $a_{\max}$ and $a_{\min}$ define the expected height acceleration, the maximum and minimum of acceleration.

When $a_H > a_{\max}$, the main rotor control the height channel until $a_H < a_{\min}$. When $a_H < a_{\min}$, the four auxiliary rotors control the height channel until $a_H > a_{\max}$. To prevent oscillations occur near the boundary caused by the switching of authority, $(a_{\max} - a_{\min})$ defines the design threshold of the height channel.

As can be seen from equation (2.6), when the expected acceleration of the height channel is small, the height channel controller of the motor has the priority to control the height, since the motor can keep the height of LAS-UAV quickly. However, the motor is mainly used for the attitude control. When the control remainder of the motor for the height channel is insufficient, or attitude angle is much larger, or the aircraft is on climbing state, the authority switch will appoint the piston engine to control the height. In order to avoid interference to the high channel due to frequent switching of the authority controller, the height channel target is processed by low-pass filtering, meanwhile, the main rotor speed signal is also softened and slope restricted.

4. Navigation point flight simulation of LAS-UAV based on SIMULINK

The simulation object is LAS-UAV, and table 1 gives its main parameters.

Table 1. Main parameters of LAS-UAV

Parameter	Physical meaning	Numerical value	Unit
M	Total weight	70	Kg
I_x	Inertia moment	17.9	Kg*m*m
I_y	Inertia moment	4.6	Kg*m*m
I_z	Inertia moment	19.2	Kg*m*m
R	Main rotor radius	25	cm
r	Auxiliary rotor radius	12	cm
S_1	Main rotor speed	4000	rpm
s_1	Auxiliary rotor speed	2000	rpm

In order to verify the control effect of the controller, the flight simulation is carried out with the common navigation point mode, and the navigation point coordinates are as follows:

[0, 20, 100; 100, -5 100; 100, 0, 0; 0, 0, 0]m.

Balance point: $\theta = 0 \text{ deg}$; $\phi = 0 \text{ deg}$.

Figure 6 shows the simulation results of the navigation point location. From Figure. 6, it can be seen that from forward flight to hovering, the motion of LAS-UAV is from nose-down to nose-up, and the forward speed decreases. At this time, the main lift of the height channel increases, and the height increases. Then the main rotor speed decreases which is controlled by the controller. Finally LAS-UAV reaches hover state and maintain height. When the attitude is adjusted to the corresponding position, the main lift speed adjustment has two main reasons: (1) Due to the feedforward control from the attitude to the channel height, once attitude changes, the main rotor speed can be fixed immediately. And it can be corrected quickly, but not stable; (2) It is needed to produce altitude channel deviation by large current lift which contains the acceleration, speed and altitude. The acceleration response is fastest. Then the deviation is corrected by the height correction channel controller.

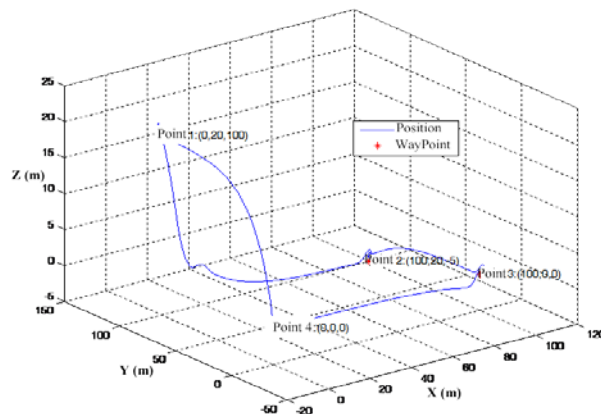


Figure 6. Simulation results of navigation point flight

Figure 7 gives the simulation results of the attitude angle following the actual attitude angle and the real-time speed of the main rotor when LAS-UAV is flying by the navigation point. The sampling rate of the abscissa is 1KHz. The posture of LAS-UAV has been largely changed when the target navigation point is switched, and the roll and pitch angle changes obviously. When the horizontal velocity reaches the desired speed, the attitude angle is stabilized in a trim state through a fluctuation, and the steady-state accuracy of the attitude control is within 1deg. During the process, the fluctuation of the main rotor and the auxiliary rotor speed are coupling to the yaw channel. It is obvious that the trend of the main rotor speed is roughly consistent with that of yaw angle, and the final variation of yaw angle is within 0.8deg. The rotational speed of the main rotor is equal to the 4300rpm.

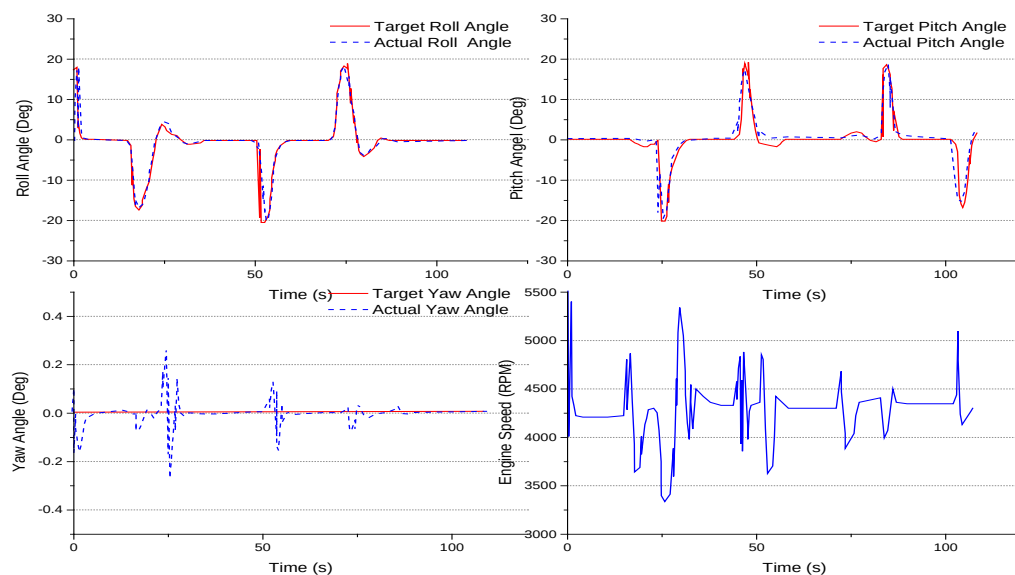


Figure 7. Attitude simulation results

Figure 8 gives the simulation results of the actual speed following the target velocity. It can be seen that from Figure. 8, during the flight, the following ability of forward and lateral velocity of LAS-UAV is good, and the delay time is about 0.5s. From the analysis due to the limited pitch angle and the roll angle, the acceleration performance is limited. But the steady-state precision of level speed controller is

not effected and the steady-state accuracy of level speed controller is within 0.8m/s. The variation trend of the vertical velocity is roughly in line with and the main rotor speed and the auxiliary rotor speed. Take 4.5×10^4 sampling point as an example, when the target vertical acceleration is more than $a_{\min}$, the controller will switch control access permissions to the height of the main rotor, and the main rotor speed increases. Then the height of LAS-UAV increases, and the target vertical acceleration decreases. At this time the main rotor loses altitude control authority, and the auxiliary rotor speed increases. Finally LAS-UAV is stable at the state of equilibrium.

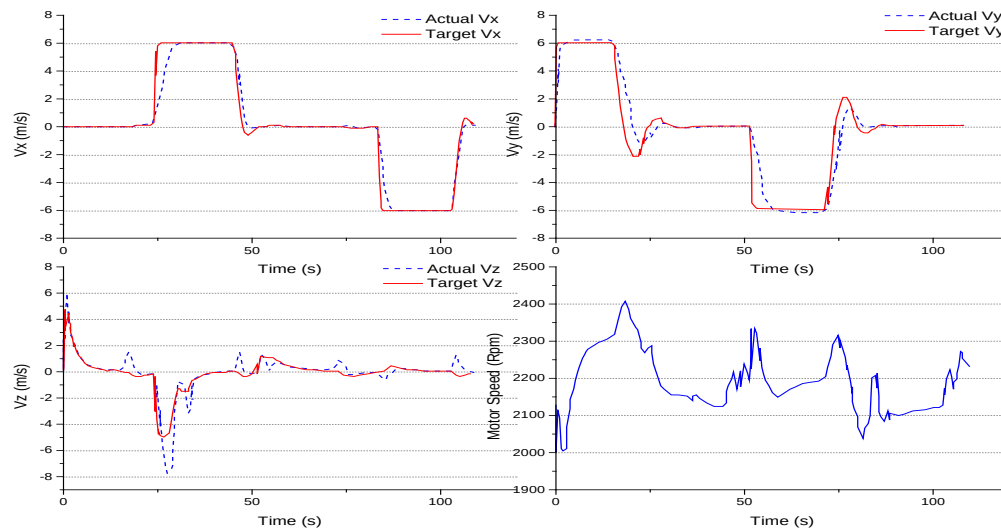


Figure 8. Speed simulation results

5. LAS-UAV flight test

The effectiveness of the controller structure designed in this paper was verified by the simulation research based on SIMULINK model. However, the controller parameters cannot be applied directly to the prototype [8]. The actual controller parameters still need to be adjusted online by the flight tests. Through a series of ground mooring tests, the free flight of LAS-UAV was successfully implemented finally. A photograph of the LAS-UAV flight test is shown in Figure 9.



Figure 9. Photograph of the LAS-UAV flight test

The test results of the roll angle and the pitching angle during the free flight of LAS-UAV are shown in Figure 10 and 11. The sampling frequency is 50Hz. As can be seen from Figure.10, for the first 600 sampling points, the target angles are relatively smaller and better following is happened in this case. Because of the large inertia of LAS-UAV, there is a certain lag in the control process. When the target

roll angle changes greatly, the roll torque generated by the auxiliary rotor is not enough to achieve the angular acceleration, which affects the dynamic following performance, such as 800 to 1100 sampling points, but does not affect the steady state.

As can be seen from Figure.11, the pitch angle of LAS-UAV has better following and smaller tracking error. However, error in the direction of nose-down is larger than that in the nose-up direction. The reason for this phenomenon is that the center of gravity of the LAS-UAV prototype is backward, which causes that higher speed of the latter rotor used to control the pitch channel is required to balance the front rotor. The speed of the front rotor is close to the lower limit, and meanwhile the speed of the latter rotor is close to the upper limit. The result is that the remainder of the nose-up control is greater than that of the nose-down control.

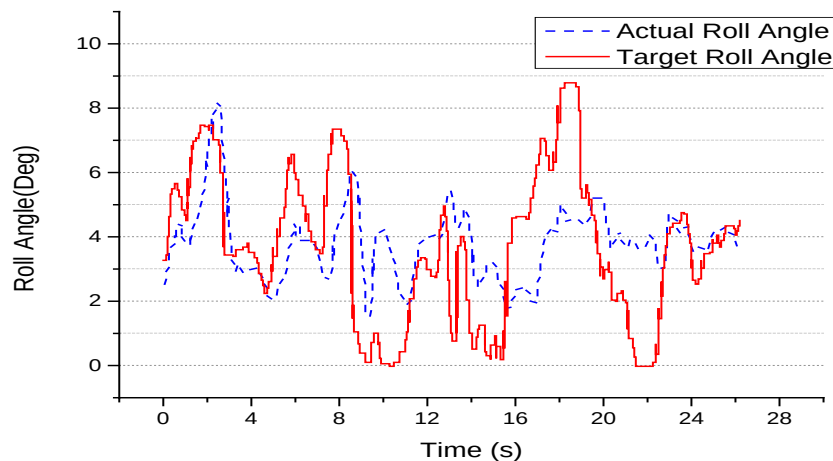


Figure 10. Test results of the roll angle

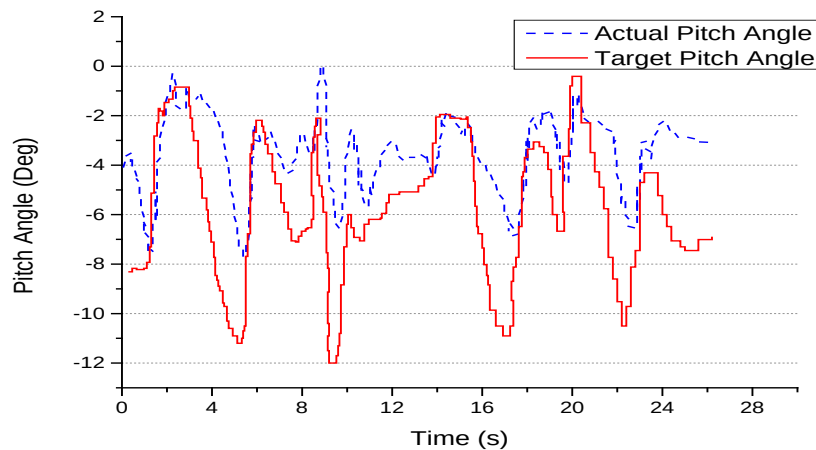


Figure 11. Test results of the pitching angle

6. Summary

In order to realize the free flight of LAS-UAV, the flight dynamics model of LAS-UAV is first built in this paper. On this basis, the flight control law is designed based on the backstepping -PID control method. Taking into account the unique control characteristics of LAS-UAV, a highly privileged controller is proposed in the design of the high controller. The effectiveness of each controller is preliminarily verified by the flight simulation of the flight point. Finally, the flight test is conducted and the results show that the controller designed in this paper can achieve the desired control effect.

7. References

- [1] YASUNORI SUGAWARA, AKIRA SHIMADA, Attitude Control of Quadrotor in Consideration of the Effects of a Pole Based on Limited Pole Placement, Electrical Engineering in Japan ,2017: 34~44.
- [2] GM. Cheng, Research on modeling and flight control of quadrotor, Harbin university of science and technology, 2011.
- [3] XL. Huang, Design of a flight controller for quadrotor, Nanjing university of science and technology, 2010.
- [4] Mohd Ariffanan Mohd Basri, Abdul Rashid Husain, Kumeresan A. Danapalasingam, Enhanced Backstepping Controller Design with Application to Autonomous Quadrotor Unmanned Aerial Vehicle, Journal of Intelligent & Robotic Systems, 2015: 295~321.
- [5] Mohd Ariffanan Mohd Basri, Abdul Rashid Husain, Kumeresan A. Danapalasingam, GSA-based optimal backstepping controller with a fuzzy compensator for robust control of an autonomous quadrotor UAV, Aircraft Engineering and Aerospace Technology: An International Journal, 2015: 493~505.
- [6] Yan-min Chen, Yong-ling He, Min-feng Zhou, Decentralized PID neural network control for a quadrotor helicopter subjected to wind disturbance, Journal of Central South University, 2015: 168~179.
- [7] JP. Zhong, Navigation and control of quadrotor, Harbin institute of technology, 2010.
- [8] Yun Dou Hu, Feng Fa Yue, Dan Dan Hu, Qing Ji Gao, Research of Robust Flight Control Algorithm for Quadrotor UAV, Applied Mechanics and Materials ,2015: 743~747.