Design of Quadrotor Unmanned Aerial Vehicle

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Abstract. This paper designs the dynamic system and main control circuit of quadrotor unmanned aerial vehicle (UAV). Power system of the quadrotor UAV includes brushless DC motor (BDCM), matching paddle, power lithium battery and drive circuit of (BDCM). Its main control hardware circuit includes the main controller minimum system, the sensor module, the wireless communication module and the power module. The attitude algorithm and attitude control algorithm are designed. The Kalman filter algorithm is used to calculate the attitude of quadrotor UAV. The cascade PID control algorithm is used to control attitude. Finally, a quadrotor UAV prototype was trial-produced, and the tested results show that the aerial vehicle meets the design requirements.

Keywords: Quadrotor Unmanned Aerial Vehicle (UAV) · Attitude control · Cascade PID control algorithm

1 Introduction

Compared with the traditional fixed-wing aerial vehicle, the quadrotor UAV has many irreplaceable advantages, such as hovering in the air, vertical take off and landing, low-speed flight and indoor flight. Having been widely concerned in road cruising, unmanned investigation, traffic monitoring, forest fire prevention, aerial photography and so on, the quadrotor UAV has become an international research hot spots in recent years. GRASP laboratory of Pennsylvania University researches a small indoor quadrotor UAV which can be multi-aircraft co-flight in a small space, and has done the experiment bee colony technology of the quadrotor UAV. With the principle of same behavior, in the absence of leadership control of the case, the bee colony of quadrotor UAV can complete the complex behavior or task. Stanford University developed Mesicopter micro quadrotor UAV only a little more than a dollar coin, The prototype can fly at a small drop point, which the research goal is also multi-machine bee collaboration [5]. In 2006, Germany Microdrones GmbH pushed out the MD4-200, an electric quadrotor unmanned flight system, which is specially used in the field of specialization. MD4-200 is widely used in fire, security, geology, surveying and mapping, environmental protection, film and television, police and other industries. In 2010, Parrot (France) pushed out AR. Drone micro quadrotor UAV, which can be controlled by Apple's Iphone through the WIFI. In 2014, Taijiang innovation

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technology company produced its latest commercialized high-performance quadrotor UAV Inspire 1, which internal integrated aircraft control board with good environmental adaptability. Its aerial functions such as single shooting and continuous shooting can be realized through the plug-in three-axis stabilization platform equipped with wide-angle 12 million pixel high-definition camera. In order to solve the problem that the conventional unmanned aerial vehicle is large and can not be applied to the narrow space flight, this paper designs a quadrotor UAV to calculate its current attitude by the measurement system composed of three-axis gyroscope and three-axis accelerometer, and control its flight attitude adopting based on Euler angle feedback then by the remote control of the appropriate manual adjustment, the quadrotor UAV can in stable and flexible flight in a small complex indoor space

2 Establishment of Mathematical Model of the Quadrotor UAV

The gravity of the UAV is:

$$G = mg \tag{1}$$

The lift to each blade is:

$$F_{li} = \frac{1}{2} \rho \, C_l \, \omega_i^2 \tag{2}$$

The resistance to each blade is:

$$F_{ri} = \frac{1}{2} \rho \, C_r \, \omega_i^2 \tag{3}$$

The total lift of the UAV in the body coordinate system can be set as:

$$F_{Bl} = \begin{bmatrix} 0 \\ 0 \\ U_l \end{bmatrix} U_1 = F_{l1} + F_{l2} + F_{l3} + F_{l4} = \sum_1^4 b \, \omega_i^2 \tag{4}$$

Where “ω” is the rotational angular velocity of the blade.

The lift of the UAV in the ground coordinate system is:

$$F_{El} = U_l \begin{bmatrix} \cos \alpha \sin \beta \cos \gamma + \sin \alpha \sin \gamma \\ \cos \alpha \sin \beta \sin \gamma - \sin \alpha \cos \gamma \\ \cos \alpha \cos \beta \end{bmatrix} \tag{5}$$

Where ‘α, β, γ’ represents the roll angle, pitch angle and heading angle of the UAV respectively.

In the ground coordinate system, the displacement vector of the vehicle is $r = [x \quad y \quad z]^T$, then the linear displacement equation of the system is:

$$\begin{cases} \ddot{x} = U_l(\cos \alpha \sin \beta \cos \gamma + \sin \alpha \sin \gamma)/m \\ \ddot{y} = U_l(\cos \alpha \sin \beta \sin \gamma - \sin \alpha \cos \gamma)/m \\ \ddot{z} = U_l(\cos \alpha \cos \beta)/m - g \end{cases} \tag{6}$$

Supposed the angular velocity as $[p \quad q \quad r]^T$, the moment of inertia matrix is:

$$I = \begin{bmatrix} I_x & I_{xy} & I_{xz} \\ I_{xy} & I_y & I_{yz} \\ I_{xz} & I_{yz} & I_z \end{bmatrix} \tag{7}$$

So the moment matrix of the aircraft is:

$$\begin{bmatrix} M_x \\ M_y \\ M_z \end{bmatrix} = \begin{bmatrix} \dot{p}I_x - \dot{r}I_{xz} + qr(I_z - I_y) - pqI_{xz} \\ \dot{q}I_y + pr(I_x - I_z) + (p - r)I_{xz} \\ \dot{r}I_z - \dot{p}I_{xz} + pq(I_y - I_x) + qrI_{xz} \end{bmatrix} \tag{8}$$

The angular velocity of the aircraft has the following relationship with the attitude angle:

$$\begin{bmatrix} p \\ q \\ r \end{bmatrix} = \begin{bmatrix} 1 & 0 & -\sin \beta \\ 0 & \cos \alpha & \sin \alpha \cos \beta \\ 0 & -\sin \alpha & \cos \alpha \cos \beta \end{bmatrix} \begin{bmatrix} \dot{\alpha} \\ \dot{\beta} \\ \dot{\gamma} \end{bmatrix} \tag{9}$$

The attitude angle is very small when the UAV is stable, so it is approximated to have this relationship:

$$[p \quad q \quad r]^T = [\dot{\alpha} \quad \dot{\beta} \quad \dot{\gamma}]^T$$

Then,

$$\begin{bmatrix} \ddot{\alpha} \\ \ddot{\beta} \\ \ddot{\gamma} \end{bmatrix} = \begin{bmatrix} \left[M_x + \dot{\beta}\dot{\gamma}(I_x - I_z)\right]/I_x \\ \left[M_y + \dot{\beta}\dot{\gamma}(I_z - I_x)\right]/I_y \\ \left[M_z + \dot{\alpha}\dot{\beta}(I_x - I_y)\right]/I_z \end{bmatrix} \tag{10}$$

Supposed four state control variables as $(U_1, U_2, U_3 U_4)$ according to the four motion states of the UAV. The coupled nonlinearity models are divided into four relatively independent control systems by the four state control variables:

$$\begin{cases} U_1 = F_{l1} + F_{l2} + F_{l3} + F_{l4} \\ U_2 = F_{l4} - F_{l2} \\ U_3 = F_{l3} - F_{l1} \\ U_4 = F_{l2} + F_{l4} - F_{l1} - F_{l3} \end{cases} \tag{11}$$

Introduced the four state variables into Eqs. (6) and (10), the system mathematical model of the aircraft is following:

$$\begin{cases} \ddot{x} = U_1(\cos\alpha \sin\beta \cos\gamma + \sin\alpha \sin\gamma)/m \\ \ddot{y} = U_1(\cos\alpha \sin\beta \sin\gamma - \sin\alpha \cos\gamma)/m \\ \ddot{z} = U_1(\cos\alpha \cos\beta)/m - g \\ \ddot{\alpha} = \left[lU_2 + \dot{\beta}\dot{\gamma}(I_x - I_z)\right]/I_x \\ \ddot{\beta} = \left[lU_3 + \dot{\beta}\dot{\gamma}(I_z - I_x)\right]/I_y \\ \ddot{\gamma} = \left[U_4 + \dot{\alpha}\dot{\beta}\left(I_x - I_y\right)\right]/I_z \end{cases} \tag{12}$$

3 Hardware Design of the Quadrotor UAV

In order to be able to mount the camera or video camera for low-altitude aerial or reconnaissance missions, the aircraft need to ensure adequate load and life time, the specific design indicators of quadrotor UAV are as follows:

(1) Rack size does not exceed 50 cm * 50 cm, height is not more than 30 cm;
(2) No-load weight is not more than 1000 g;
(3) Full load weight does not exceed 3000 g;
(4) Life time is not less than 10 min;
(5) The maximum flight speed is not less than 10 m/s;
(6) Automatic flight radius is 1800 m, remote control flight radius is 600 m;
(7) Wind resistance level 3;
(8) Control mode: automatic/remote control;

The overall structure of the miniature quadrotor UAV is shown in Fig. 1, which is divided into six parts: aircraft frame, power system, main control board of aircraft, GPS navigation module, wireless communication module and remote control receiver.

(1) The frame of the aircraft is the support structure of the UAV. The standard cross-shaped frame, the middle flight control board and the battery mounting board are sandwiched by four motor arms with a cross shape. The wheelbase of the symmetrical motor is 450 mm. The landing gear with the high of bottom 16 mm and the wide 26.5 mm, can effectively ensure that the aircraft take-off and landing is not reflected by the ground reflection of airflow.
(2) The power system of the aircraft is composed of a lithium battery, a BDCM, a driver of BDCM and four propellers. The BDCM is mounted vertically at the end of the four motor arms. The four propellers paralleling to the body four

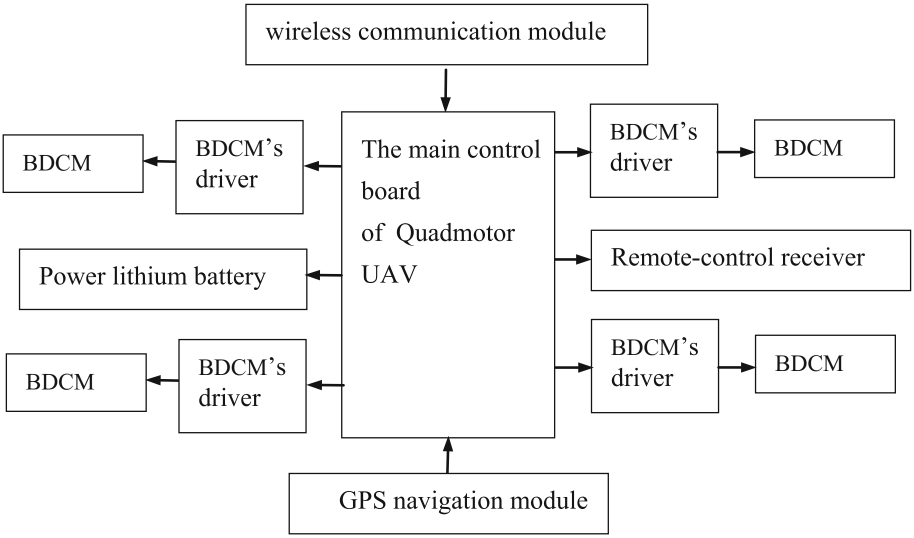

Fig. 1. Design of the aircraft structure

symmetrical positions provide lift perpendicular to the plane's plane. Power lithium battery with high-capacity and high-magnification provides the explosive force to guarantee life time and flight attitude adjustment.

(3) As the core of the whole system the main control board of the aircraft is integrated accelerometer, gyroscope and geomagnetism sensor, and adopts high-precision air pressure sensor to feedback current height information, and provides GPS navigation module, wireless communication module communication interface of the remote control receiver. The main control chip drives the integrated sensor and the external module, obtains the digital data of the sensor data in parallel and then calculates the current flight attitude and height. According to the current flight condition the flight control algorithm adjusts the lift caused by the four BDCM to achieve self-flight by controlling the flight attitude and Height.

(4) Connected to the main control board through the serial port, GPS navigation module searches signal of the measured satellite which is strong enough, and the protocol is consistent with it, then continue to track these signal. Adopting the positioning algorithm, the current location of the module's latitude and longitude, altitude, real-time speed, current time and other information are calculated by amplifying, transforming and processing the satellite signal obtained. Comparing with the local sensor data, these positioning information is sent to the main control panel through the serial to achieve long-distance flight path navigation.

(5) Wireless communication module for a pair, using 433 M frequency band communication, using single-chip and dedicated RF transceiver chip. Built-in single-chip drive RF chip to achieve wireless communication protocol, FM algorithm and software error correction algorithm, The interface of external and wireless communication module is provided by the USART serial port of the

microcontroller, and the same wireless communication module can be used to achieve complete transparent data transmission with the ground station.

(6) Using the FuSi FS-T6 matching receiver of the model remote controller as remote control receiver, remote controller can Interfere with the quadrotor UAC, especially in the take-off and landing stage when the UAV are susceptible to interference from the environment and other unfavorable factors. The 2.4G frequency band communication is used between the remote controller and receiver, and the automatic frequency modulation digital system (ADHDS) protocol can effectively reduce communication interference, improve communication distance, and effectively reduce power consumption.

4 Control Algorithm of the UAV'S Attitude

The aircraft can only obtain the current flight attitude through the attitude algorithm. In order to obtain smooth flight and make a variety of flight movements according to the given attitude change, it is also need to control the current flight attitude. When the angle occurs between the aircraft and the horizontal, the body of UAV will be affected by the component force in the horizontal direction and produce displacement, so the angular motion of the UAV must have an effect on the linear motion, and the autonomous route flight of the aircraft needs to control the line motion. In order to solve the problems above, the attitude control algorithm uses cascade PID to control the attitude angle and linear displacement at the same time. The actuator controls the four motion states of yaw, pitch, vertical and roll, and requires independent control of at least four control input variables, while ensuring low coupling of the control channels under the conditions used. Supposed our state control variables as $(U_1, U_2, U_3 U_4)$ according to the four motion states of the UAV, the coupled nonlinear model of the aircraft is divided into four relatively independent control systems. Using a linear motion and angular motion control subsystem to describe the two states(pitch and yaw movement), the linear motion subsystem is affected by the angular motion subsystem, but the angular motion subsystem is not directly affected by the linear motion subsystem. So consider the control of the attitude movement firstly, followed by the position control.

In the X-axis direction of the ground coordinate system and the pitch angle control are showed in Fig. 2. The outer loop controls the displacement of the quadrotor UAV in the X axis direction, and the inner loop controls the pitch angle of the OXZ plane of the quadrotor UAV. Because the pitch angle response fast, modal frequency band is wide, so the inner loop is pitch angle control loop; But the displacement response of the X axis direction is slow, the modal frequency band is narrow, so the outer loop is the displacement control loop in the X axis direction. The displacement control commands in the X-axis direction can be set remotely or generated in real time by the GPS navigation control system. The displacement control loop in the X-axis direction acts to keep the quadrotor UAV in the X-axis direction or in accordance with the reference trajectory. The pitch angle control loop enables the quadrotor UAV to keep horizontal on the X axis or to generate the acceleration on the X axis by the pitch angle. Through the joint action of the two loops, the output control signal is used to adjust the four motor, and the quadrotor UAV can complete the control of the displacement and angle in the X axis direction according to the control requirements.

Figure 2 Cascade PID control chart of aircraft pitch angle and X-axis displacement

The Y-axis displacement and roll angle control are similar to those in the X-axis direction, as shown in Figs. 3, 4 and 5. Since the yaw angle does not affect the displacement (height) of the UAV on the Z-axis, only the single-stage PID controller can be used to meet the control requirements. The PID control charts of the Z-axis and the heading angle of the aircraft is shown in Figs. 4 and 5.

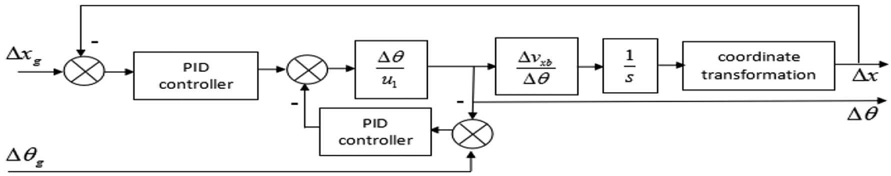

Fig. 2. Cascade PID control of aircraft pitch angle and X-axis displacement

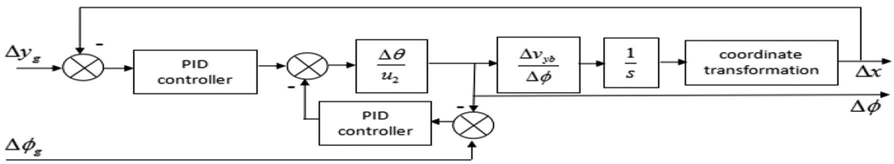

Fig. 3. Cascade PID control chart of aircraft roll angle and Y-axis displacement

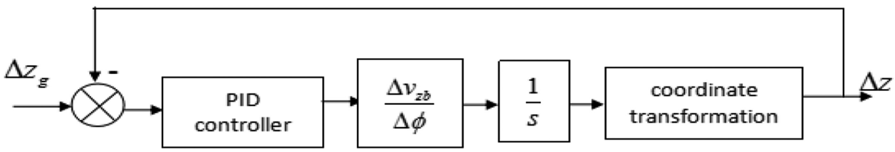

Fig. 4. PID control chart of aircraft Z axis displacement

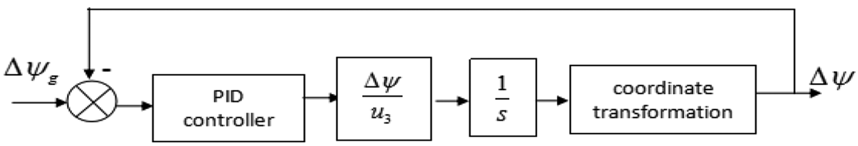

Fig. 5. PID control chart of aircraft yaw angle

5 Assembly and Debugging of the Quadmotor UAV

In order to avoid unnecessary damage during the flight test due to hardware failure, it is necessary to be careful in the assembly stage. Firstly, take the rack and install the motor and fix it with screws. Then connect the motor, the ESC and the power splitter with 18AWG cable and fix it with solder. Use a 12AWG silicone cable to connect the manifold and lithium battery, and the XT60 high-power connector to turn off the power when it is turned off. The main control board is installed in the middle of the aircraft. It should be noted that the x-axis of the sensor direction is consistent with the flight direction. Then connect the GPS module, the wireless communication module, the remote control receiver and the ESC cable to the corresponding port of the main control board. And the GPS antenna should be faced up and surrounded away from the wireless communication module antenna and remote control receiver antenna to prevent mutual Interferences. Finally, by changing the location of the battery, fine-tune the center of gravity of the aircraft to make it be centered as much as possible. With the tie and double-sided adhesive on all facilities to re-fixed, the prototype will be completed, as shown in Fig. 6.

Fig. 6. A Quadrotor UAV prototype

Flight attitude calculation test uses the ground station data display software as the host computer software to realize the wireless monitoring of the quadrotor UAV status, real-time display aircraft attitude curve. In order to remove the blade safely, it is necessary to hand up the aircraft to change the attitude of the aircraft after power on. Flight attitude control test need to install the paddle, then adjust the throttle so that the aircraft will be off the ground, and then hold the aircraft by hand. First change the flying posture by hand, at this time, the hand will feel the strength of lift generated by four blades, then adjust the PID parameters for each change posture corresponding to the lift variation. Then use the remote control to change the flight attitude, with the gradual increase in control efforts, it is significantly to feel the adjustment force of the attitude growing at this time. The corresponding action attitude angle curve through the posture calculation can be seen in the host computer. As shown in Figs. 7, 8, 9, and 10,

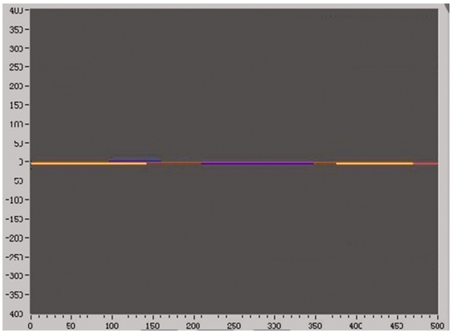

Fig. 7. The attitude angle curve of the quadrotor UAV at rest

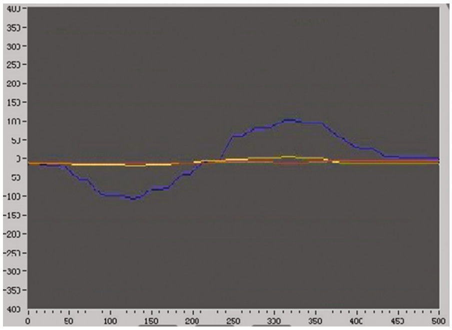

Fig. 8. The attitude angle curve of the quadrotor UAV in pitching motion

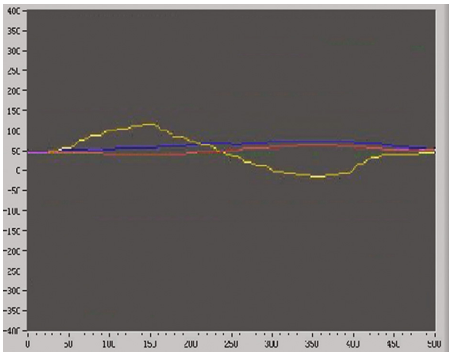

Fig. 9. The attitude angle curve of the quadrotor UAV in roll motion

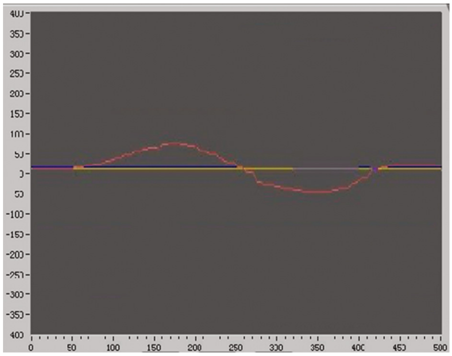

Fig. 10. The attitude angle curve of the quadrotor UAV in yaw motion

the attitude angle response curve can fully reflect the current attitude changes obviously. Where the blue curve shows the pitch angle σ, the yellow curve shows the roll angle β, and the red curve shows the yaw angle γ. The ordinate represents the magnitude of the angle (°), and the abscissa indicates the time of flight(s).

6 Conclusion

The design of the quadrotor UAV can meet the design requirements, and it has certain value in the research of automatic control algorithm and autonomous navigation algorithm. However, due to the limitation of R&D funding and the shallow knowledge of aircraft-related expertise, there is a huge room for improvement. There are some prominent aspects need to be improved:

(1) The UAV need higher development costs. Due to the lack of protecting function, if high drop occurred during the test, hardware replacement will increase research

and development costs. So it is necessary to increase the anti-drop system from software and hardware to reduce the damage caused by falling.

(2) The height data of the UAV is complemented by the air pressure sensor and GPS navigation module, but the detection accuracy of two methods above is limited and get the altitude. Low-precision high-value feedback will cause the UAV to take off and landing on the impact of excessive resulting in damaging to the landing gear. Hitting the raised ground when flying at a high altitude in terms of altitude probably, so it is necessary to increase the sensor to measure the height of the ground, such as ultrasonic or infrared.

(3) Although the quadrotor UAV designed is characterized by long-distance over-the-horizon autonomous flight, the GPS/SINS integrated navigation algorithm is not mature enough, so it is necessary to introduce the higher precision navigation method to correct. For example, install a digital camera in the bottom of the body to take terrain photos, after identification processing and stored route map comparison to correct the course to achieve a higher navigation accuracy.

References

1. Bo-wen, N., Hong-xian, M., Wang, J., et al.: Research status and key technology of micro-four rotorcraft. Electro-Optic Control **14**, 113–117 (2007)
2. Ji, J., Feifei, H., He, Z.: Application of quadrotor micro-aircraft in farmland information acquisition. J. Agric. Mechanization Res. **2**, 1–4 (2013)
3. Hamel, T., Mahony, R., Lonano, R., et al.: Dynamic modeling and configuration stabilization for an X4-Flyer. In: Proceedings of the IFAC World Congress, Barcelona, Spain, pp. 336–384 (2002)
4. Jiang, B.: Small quadrotor low-altitude unmanned aerial vehicle integrated design. Zhejiang University (2013)
5. Yang, Y., Xian, B., Yin, Q.: Four rotor unmanned aerial vehicle architecture and flight control research status. China Automation Society of Control Theory Professional Committee. China Automation Society Control Theory Professional Committee C roll. China Automation Society Control Theory Professional Committee, p. 6 (2011)
6. Li, J., Li, Y.: Dynamic modeling and PID control of four rotorcraft. J. Liaoning Tech. Univ. **31**, 114–117 (2012)
7. Zhou, Q., Huang, X.: Experimental study on attitude stabilization control of quadrotor micro flight platform. J. Sens. Microsyst. **28**(5), 72–79 (2009)
8. Liu, W.: Design and experimental study of four rotor unmanned aerial vehicles. Harbin Engineering University (2011)
9. Wang, L.: Four rotor unmanned aerial vehicle control technology research. Harbin Engineering University (2012)