Design of Attitude Control System for Quadrotor

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Abstract

Quadrotor is a widely used aircraft now and be with the nonlinear, uncertain characteristics. Because of requirement on high attitude stability the attitude control system of quadrotor needs to be well designed. Firstly the movement pattern and working principle of the quadrotor are analyzed. Then the hardware schematic diagram of attitude control system is designed which includes several sensors, the master controller, power supply module and so on. Sensors communicate with the master controller mainly through the I^2C interfaces. Thirdly the application of Kalman filter is studied as the attitude solving algorithm for the quadrotor. Kalman filter is used to realize data fusion and the effectiveness of this algorithm is verified. Then Based on a dynamic model the classic PID algorithm is verified. At last outdoor flight tests are conducted several times. The results show the quadrotor can realize basic functions of hovering and vertical take-off and landing.

Keywords: *Quadrotor, Attitude Control System, PID, STM32, Kalman Filter.*

1. Introduction

Quadrotor has a simple structure, flexible and small size, light weight. It is a good experiment platform for aircraft technology, sensor technology, robot technology, path planning, image recognition and other research fields. Now it is becoming a new hotspot in the field of unmanned aerial vehicles. The quadrotor can play an important role in disaster evaluation and rescue, environmental protection, power line inspection, aerial imaging and mapping, military missions, communications relay, forest fire monitoring, agricultural pest and disease control, so it has very broad application prospects for the military and civilian uses. There has been much research work on the quadrotor.

GTMARS[1] was an unmanned aircraft system designed by Georgia Institute of Technology for mars exploration. It can expand the rotors automatically, take off or landing vertically autonomously, return to the Lander to supply energy when lack of energy. OS4[2] project initiated by the Autonomous Systems Laboratory was focused on the institutional design method and autonomous flight control algorithms and its long term goal is to make full autonomy in indoor and outdoor environments using a variety of attitude stability control algorithms. HMX4[3] was designed by University of Pennsylvania. Five colored blobs were attached to the bottom of the quadrotor and the camera on the ground tracked and measured the location and area of blobs to determine three attitude angles and location of the quadrotor. DraganFlyer X4[4] was a super remote camera aircraft of Draganfly Innovation Company. It can achieve self-balancing and fixed-point hovering. After losing the control the automatic landing system will work to make the aircraft land safely. MIT Quadrotor[5] was an autonomous flight system with a Hokuyo Laser Rangefinder and a monocular camera that is developed by Robust Robotics Group. It used simultaneous localization and mapping(SLAM) algorithms to build a map of the environment around the vehicle and estimate the vehicle’s position. This made it possible to achieve autonomous flight in small indoor environments and GPS-denied environments with high-level security and stability.

Here we design a quadrotor that can be applied to forest measurement and forest resources inventory. As a MIMO nonlinear system, coupling between the input and output variables, time-varying nonlinear dynamics characteristics, the uncertainty of the system itself and the external interference introduced make it complicated to solve control problem[6]. The structure and principle of quadrotor are introduced in Section 2, the hardware circuits of the quadrotor are designed in Section 3. We then discuss Kalman filter-based attitude estimation algorithm and PID control algorithm employed by our system in Section 4 and Section 5. Finally we demonstrate this attitude control system in the outdoor environment successfully.

2. Structure and principle of quadrotor

The structure of quadrotor[7] is shown in Figure 1. Four rotors and motors are set to the end of the frame arms, the rotors have the same radius. Rotor 1 and Rotor 3 spin counterclockwise, while Rotor 2 and Rotor 4 spin clockwise to balance counter rotating torque of the rotors. The attitude control system and external devices are placed in the middle board.

As showed in Figure 1, Rotor 1 and Rotor 3 are in one group, Rotor 2 and Rotor 4 are in another group. The four rotors maintain the same speed to offset the gyroscopic effects and aerodynamic torques[8]. The pitch movement is obtained by increasing/reducing the speed of one group rotors while keeping the speed of another group rotors. The roll movement is obtained similarly with the pitch movement. The yaw movement is obtained by increasing/decreasing the speed of one group rotors while decreasing/increasing the same speed of another group rotors.

3. Hardware design of quadrotor controller

Taking reliability, feasibility, advancement, real-time and high integration degree as a quadrotor hardware design specifications, the block diagram of the overall design for the quadrotor control system is shown in Figure 2, the controller schematic is shown in Figure 3.

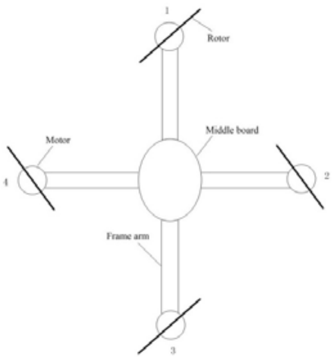

Figure 1. The structure of the quadrotor

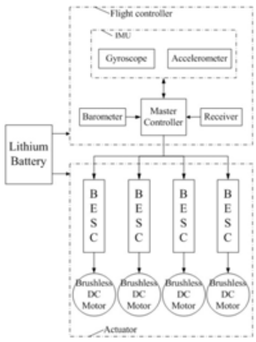

Figure 2. Overall design diagram of attitude control system

3.1. General structure of hardware

Figure 2 shows that the attitude control system consists of flight controller and actuator. The flight controller includes three sensors, a master controller, a receiver, etc. The actuator includes four brushless electronic speed controllers(BESCs), four brushless DC motor and rotors. Inertial measurement unit(IMU) provides parameters of the device to flight attitude control system. The receiver is responsible for receiving radio control signal. In each of the control period the master controller firstly processes the data collected by the IMU and gets attitude information in time. Then according to the control information of the receiver it calculates the control variables. At last it transfers these control signals to BESCs which will adjust motors speed to achieve the desired flying state of the quadrotor.

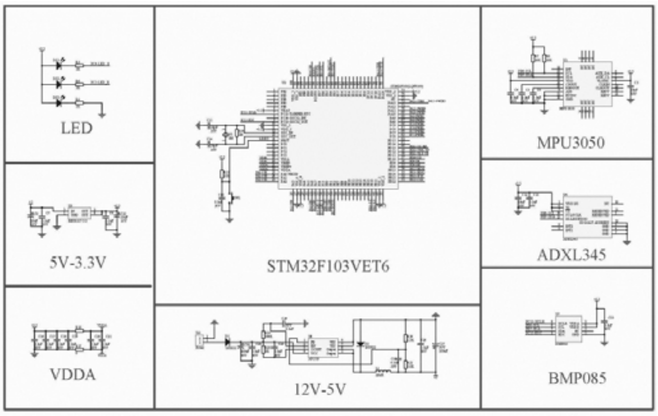

Figure 3. Circuit schematic of attitude control system

3.2. The master controller

We select the STM32F103VET6 as attitude control system processor[9]. It is a STM32 family of 32-bit ARM processor with Cortex-M3 core operating at a 72MHz that includes four general-purpose timers, two advanced-control timers, 3 SPI interfaces, 2 I^2C interfaces, 3 USART interfaces, up to 80 general-purpose I/O, 512K bytes of Flash and 20K bytes of SRAM. STM32F103VET6 costs low power with sleep, stop and standby modes.

3.3. IMU

IMU consists of a three-axis accelerometer and a three-axis gyroscope. The accelerometer measures the acceleration of the carrier, speed, flying distance and position are calculated by the flight controller at the initial conditions of the given motion vector. The gyroscope measures the angular velocity of the carrier then transfer to the master controller to converse, process and calculate the attitude and heading[10]. Because of gyro zero bias drift error and random drift error, the result of the integration will drift, and integrated error will accumulate, so the error will be growing. The accelerometer error is time-independent so we can use it to correct the error of gyroscope[11][12].

(1) Three-axis accelerometer

The acceleration measurement accuracy directly affects the accuracy of the attitude control system, we select MEMS three-axis digital accelerometer of Analog Devices Inc that has small size, low power consumption, and high resolution(3.9 mg/LSB), SPI(3- and 4-wire) and I^2C digital interfaces. Its supply voltage ranges from 2.0V to 3.6V.

(2) Three-axis gyroscope

The purpose of using the gyroscope is to create a reference coordinate system and measure the angular velocity of the moving object[13]. We select MEMS three-axis digital gyroscope MPU3050 of InvenSense Inc.. The MPU3050 integrates 16-bit analog-to-digital converters(ADCs) and I2C interface, supply voltage range of 2.1V to 3.6V, resolution is 16.4LSB/(°/sec).

3.4. Digital barometer

The function of the digital barometer is depending on the atmospheric pressure to measure the height of the quadrotor flight. We select digital barometer BMP 085 of Bosch Sensortec GmbH that has high precision and low power consumption. It provides AD converter and I2C interface, measuring the height range from -500m to 9000m, supply voltage range of 1.8 to 3.6V.

3.5. Power supply

The quadrotor that we designed is powered by a lithium battery, the voltage of 11.1V, but the each part of hardware system needs different voltage: motors and BESCS need 11.1V power supply, receiver needs 5V power supply, sensors and master controller need 3.3V power supply. So we design 11.1V-5V-3.3V power supply circuits.

We select AP1510 of Diodes Inc to convert 11.1V into 5V. The drive current up to 3A, an over current protect function and a short circuit protect function are built inside. We select REG1117-3.3 of Texas Instruments Inc to convert 5V into 3.3V. The maximum output current is 800mA, an internal current limit function and a thermal overload protection function are built inside.

4. Attitude estimation algorithm

The key of the quadrotor attitude control is to get an accurate flight attitude angles, the classic method is using the Kalman filter for multi-sensor data fusion compensating and correcting the attitude deviation to obtain accurate attitude angles[14]. The role of the Kalman filter is to verify the system state by estimate the quantity of system state and acceleration measurement value to obtain the optimal system state, and update the parameters of the system in real-time.

Figure 4 shows the workings of Kalman filter. Kalman filter estimates process state by feedback control method: the filter estimates a process state of a certain moment, and then obtains the feedback through the measured variables (including noise). Therefore, the Kalman filter can be divided into two parts: time update and measurement update. Time update calculates the estimated value of the current system state variable and error covariance to provide priori estimate of next state variable. Measurement update combines priori estimate and new measurement variables to obtain improved posteriori estimate. It makes the estimation algorithm becoming a prediction – correction algorithm with numerical solutions[15][16].

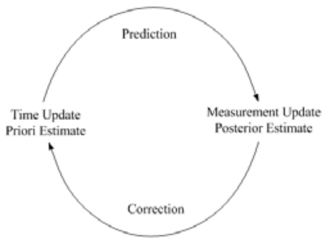

Figure 4. Function diagram of Kalman filter cycling update

The attitude estimation algorithm first obtains an angular velocity of the attitude angle by gyro outputs as the attitude angle control value $\boldsymbol{u}$, then obtains an attitude angle by the accelerometer outputs as measured value $\boldsymbol{y}$, at last obtains the updated attitude angle by Kalman gain. The working procedure of attitude estimation algorithm is as follow:

(1) Obtain a control value

$$\boldsymbol{u} = \boldsymbol{gyro\_rate} \tag{1}$$

(2) Update the estimation of system state

$$\boldsymbol{x} = \boldsymbol{A} \cdot \boldsymbol{x} + \boldsymbol{B} \cdot \boldsymbol{u} \tag{2}$$

(3) Obtain measured value

$$\boldsymbol{y} = \boldsymbol{acc\_angle} \tag{3}$$

(4) Calculate the difference between measured value and predicted value

$$\boldsymbol{Var} = \boldsymbol{y} - \boldsymbol{H} \cdot \boldsymbol{u} \tag{4}$$

(5) Calculate the covariance

$$\boldsymbol{S} = \boldsymbol{H} \cdot \boldsymbol{P} \cdot \boldsymbol{H}^T + \boldsymbol{R} \tag{5}$$

(6) Calculate the Kalman gain

$$\boldsymbol{K} = \boldsymbol{P} \cdot \boldsymbol{H}^T \cdot \boldsymbol{S}^{-1} \tag{6}$$

(7) Obtain corrected system state variable

$$\boldsymbol{x} = \boldsymbol{x} + \boldsymbol{K} \cdot \boldsymbol{Var} \tag{7}$$

(8) Calculate error covariance matrix

$$\boldsymbol{P} = \boldsymbol{A} \cdot \boldsymbol{P} \cdot \boldsymbol{A}^T - \boldsymbol{K} \cdot \boldsymbol{H} \cdot \boldsymbol{A} \cdot \boldsymbol{P} \cdot \boldsymbol{A}^T + \boldsymbol{S}_W \tag{8}$$

In order to verify the effectiveness of the algorithm, the system every 20ms gathers gyroscope and accelerometer outputs to conduct attitude estimation, and the results are shown by the upper computer, and the red line shows the outputs of gyroscope, the blue line shows the outputs of accelerometer, the cyan line shows the outputs of Kalman filter. The experimental results are shown below:

Figure 5 shows the waveforms on upper computer when system remains stationary and level. We can see the output waveforms of gyroscope, accelerometer and Kalman filter are coincident with only minor fluctuations, the value of each output is zero.

Figure 6 shows the waveforms on upper computer when system maintains a certain angle. We can see the accumulated errors of gyroscope have become more apparent, but the output waveforms of accelerometer and Kalman filter are coincident with only minor fluctuations, and both of them have the same output value.

Figure 7 shows the waveforms on upper computer when system introducing artificial interference. We can see the outputs of gyroscope are not affected by artificial interference, but the output waveform of accelerometer has serious fluctuation, while the output waveform of Kalman filter can properly track the accelerometer outputs, and the fluctuation has significantly reduced.

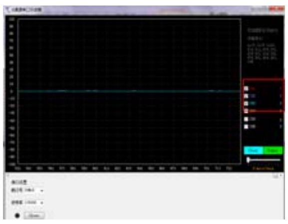

Figure 5. Display of upper computer when system remains stationary and level

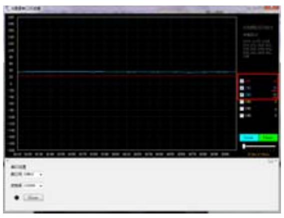

Figure 6. Display of upper computer when system maintains a certain angle

Figure 7. Display of upper computer when system has artificial interference

In summary the static drift has been suppressed effectively, the Kalman filter-based attitude estimation algorithm has high static accuracy and good dynamic performance and is able to meet the requirements of the quadrotor attitude measurement.

5. Attitude stabilization control strategy

We need appropriate control strategy to implement the quadrotor attitude stabilization control after precise attitude information is available. Based on a dynamic model of the quadrotor[17], the attitude stability control strategy is studied and verified through digital simulation in Simulink.

We select proportional-integral-derivative (PID) control as the attitude stabilization control strategy. PID control algorithm has a simple structure, easy to implement, good robustness, applicable to a wide range and the other advantages[18], it is most widely used in industrial control field and most familiar to technicians. PID control has a simple structure and a stable nature for the establishment of the error and the perturbation model.

Figure 8 shows Function block diagram of PID control system. $r(t)$ is set expectation. $u(t)$ is control variable, that is the linear combination of Proportional, integral and derivative. y is actual output value. $e(t)$ is control error $(e(t)=r(t)-y(t))$, that is the deviation between the set output and the actual output. The expression is

$$u(t)=K_p[e(t)+\frac{1}{T_i}\int_0^t e(t)dt+T_d\frac{de(t)}{dt}] \tag{9}$$

In Formula 9 K_p is the proportional coefficient, T_i is the integration time constant, T_d is the derivative time constant. Formula 10 is the transfer function form of Formula 9.

$$G(s)=\frac{U(s)}{E(s)}=K_p+K_I\frac{1}{S}+K_DS \tag{10}$$

In Formula 10 K_p is he proportional coefficient, K_I is the integral coefficient, K_D is the derivative coefficient.

The key of the design and application of the PID controller is the parameter tuning, the parameters K_p, K_I and K_D will affect the quality of the PID control effect[19][20]. We use the parameterized optimization method[21] to adjust these parameters.

We can obtain the transfer function of the pitch angle according to Formula 11:

$$\frac{\Delta\theta(s)}{u_1(s)}=\frac{72s+7815.454}{s^3+166.226s^2+3106.8s+5618.0} \tag{11}$$

Figure 9 shows unit step response of quadrotor attitude loop without PID in Simulink. Longitudinal axis shows pitch angle, unit is the degree. Transverse axis shows Time, unit is the second.

Figure 9 shows the attitude loop has good dynamic characteristics, but there is a steady-state error. The integral control can eliminate the steady-state error with dynamic performance degradation, so we use a proportional-integral (PI) control for attitude loop. The Structure block diagram of quadrotor attitude loop with PI control is shown in Figure 10.

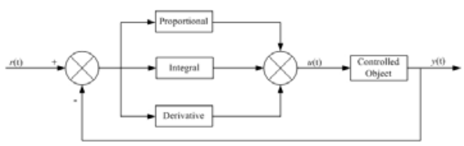

Figure 8. Function block diagram of PID control system

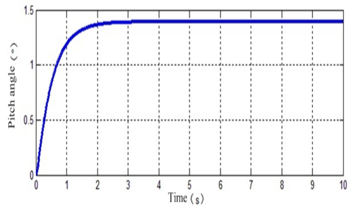

Figure 9. Unit step response of quadrotor attitude loop without PID

We use the parameter optimization method to get the optimal parameters for example $K_P=5.8$ and $K_I=9.2$. By substitution the parameters into Figure 10 we can see the unit step response of quadrotor attitude loop with PI control in Figure 11.

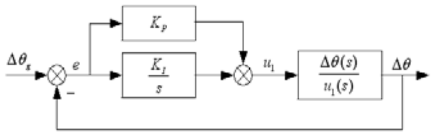

Figure 10. Structure block diagram of quadrotor attitude loop with PI control

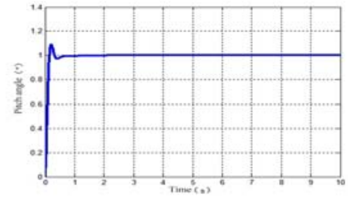

Figure 11. Unit step response of quadrotor attitude loop with PI control

The performance index with unit step signal input of attitude control loop is: $\sigma\% = 9\%$, $t_s = 0.3s$, $e_{ss} = 0$. Figure 11 shows the PI control is able to guarantee the stability and the fast response speed of the system, the steady-state error is zero. The system performance is effectively improved by PI control.

6. Flight Experiment

We fulfilled the attitude estimation algorithm and attitude stabilization control strategy on the designed STM32 controller. The aim of flight test is to verify the design specifications, airworthiness, and operational performance of the attitude control system. Both flight venue and meteorological condition can affect the flight state of the quadrotor, flight failure causes harm to the quadrotor and testers. Therefore the software and hardware should be carefully debugged at the beginning test.

Figure 12 shows the actual quadrotor we brought about. We conducted a series of flight tests mainly about hovering and VTOL(Vertical Take-off and Landing) with this quadrotor. We focus on the performance of the software, verify the effectiveness of the Kalman filter and PID control algorithm for attitude control system. Figure 13 shows that this quadrotor is in a VTOL state. The maximum flying height is 10m in outdoor environment and the quadrotor also can land smoothly. Figure 14 shows the hovering of quadrotor. During the 10s test period, the inclination angle of the quadrotor is less than 15 degrees.

The result from the flight test shows the performance of the attitude control system has good performance during the process of hovering and VTOL.

Figure 12. Actual quadrotor

Figure 13. Test for VTOL

Figure 14. Test for hovering

7. Conclusion

Quadrotor is one of the most important research spots currently because not only it can be used in the industry, agriculture, power and other industries but also it is with the serious nonlinear and time-varying characteristics. Considering the quadrotor requirement for the VTOL and hovering abilities its structure and working principal are summed up firstly. Then a ARM-based schematic diagram for the attitude control function is designed in detail. The attitude estimation algorithm and the attitude stabilization control strategy are research cores of this paper. At last the experiment result demonstrates that the proposed attitude control system is effective.

8. Acknowledge

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9. References

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