Design of Autonomous Flight Control System for Small-Scale UAV

Shuo WANG, Ziyang ZHEN*, Fengying ZHENG, Xinhua WANG

Abstract—**The aim of this paper is to develop a design of autonomous flight control system for a small-scale unmanned aerial vehicle (UAV). The hardware of autopilot is based on ATmega 2560, which is one of the best low-power MCU. High accuracy sensors including MPU6000, HMC5883l, MS5611 are integrated into the autonomous flight control system. Laser distance sensor is used in measuring the altitude in auto landing, because of the zero drift of barometer. Flight control laws of lateral and longitudinal loops are designed. Finally, flight tests are carried out to verify the designed autonomous flight control system, the results of which indicate that the aircraft can fly stable with acceptable precision.**

I. INTRODUCTION

With the development of technology, the application of small-scale UAV becomes wider [1, 2]. In the military field, small-scale UAV can be target drone, reconnaissance plane, in the civilian field, it can be used in providing disaster relief in earthquake[3], forest fire, also can be used in surveying[4] and mapping, etc. In a word, small-scale UAV acts an important part of our lives. As the key component of this aircraft, autonomous flight control system needs a lot of research.

A number of research studies have designed kinds of autopilots. Researchers such as Weigang Pan have designed an autopilot for small vessel based on ARM [5]. Wang Fu and Xian Bin have designed an autopilot for quadrotor unmanned aerial vehicle based on DSP [6].

The purpose of this study was to design a low-power, small-size autopilot for small-scale UAV. Most autopilots use barometer as the altitude sensor, but barometer is sensitive to temperature and air flow, so it can't provide accurate height of aircraft, leading to inaccuracy of landing point in auto landing. Laser distance sensor was used to achieve more accurate altitude for automatic take-off and landing. In the end, flight tests were implemented to verified the stability and reliable of the autopilot.

II. AUTOPILOT SYSTEM DESIGN

The autonomous flight control system of small-scale UAV is shown in Figure 1.

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The system generally contains sensor part, microprocessor and output part, as shown in Figure 1. Autopilot system can communicate with the ground control station (GCS) through a couple of wireless data transmitter. Navigation commands and other types of command can be saved in the memory of autopilot. Besides, commands can be transmitted to the autopilot by GCS, and the status of aircraft can be viewed by GCS in real-time. The actuator of autopilot includes DC motor, servo, etc.

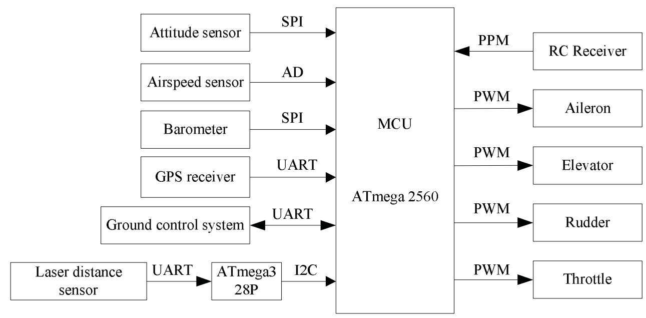

Figure 1. Autopilot system structure

Figure 2 shows the aircraft intended to be controlled by the autopilot we designed. This plane weighted 16Kg, and the wingspan is 3.8m, powered by gasoline engine.

Figure 2. Aircraft photo

The design of controller of the autopilot is based on cascade control method. The outer loop is trajectory controller; the inner loop is attitude controller. Among them, the role of the trajectory controller is to calculate the desired attitude and throttle, based on the desired trajectory and current UAV position and height. While, the attitude controller controls the size of aileron, elevator and rudder, in order to controls the attitude of UAV consistent with the attitude calculated by the trajectory controller.

Figure 3 shows the controller structure of the autopilot.

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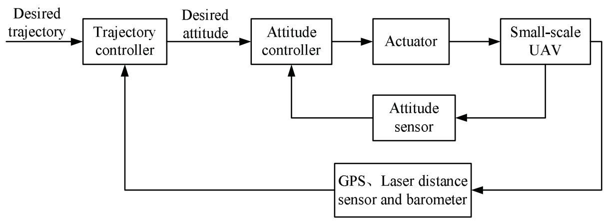

Figure 3. Controller structure of the autopilot

III. HARDWARE DESIGN

A. MCU Selection

There are some limitations on weight and power consumption of the autonomous flight control system, because of the carrying capacity of small-scale UAV is light. We chose ATmega 2560 as the MCU, the Clock Speed of it is 16MHz, and the amount of RAM is 8KB, satisfied the needs of autopilot .

There are kinds of sensors in the autonomous flight control system, such as attitude sensor, altitude sensor, airspeed sensor, heading sensor, and GPS position sensor. With these sensors, the autopilot can know the attitude, altitude, flight airspeed, flight heading, and GPS position.

We take barometer and laser distance sensor as the altitude sensor of autopilot. Most autopilot measure the altitude by the barometer, the principle of it is that air pressure will reduce with the rise of altitude. The relationship between air pressure and altitude is approximating linear in the bottom of atmosphere, so barometer can be used to measure the altitude. But barometer is sensitive to temperature and air flow which is generated by the propeller. The temperature effect can generate up to 15 meters deviation. Laser distance sensor can measure the distance between the UAV and the ground. Its high accuracy and measure frequency make it be an appropriate altitude sensor of autopilot.

B. Sensors Selection

The attitude sensor used in the autonomous flight control system is MPU6000, in which there are a three-axis gyroscope and a three-axis accelerometer. It can be driven through SPI or I2C interface. The communication speed can reach up to 1MHz, fast enough to get accurate, real -time attitude.

The barometer we choose is MS5611, which is one high accuracy air pressure sensor. Although it can be affected by temperature and air flow, the accuracy in short time(less than 1 mi) is reliable. The laser distance sensor used in the autopilot is YF-YJ50, one product of Ya Fei An Zhi Company in Beijing. Its range is 0.05-50 m, precision is 1.5mm, and measurement frequency is up to 10Hz. Although the maximum range is only 50m, it is large enough for controlling of automatic takeoff and automatic land.

The heading sensor used in this autopilot is HMC5883L, which is an inexpensive chip. It can output the angle between current heading and magnetic north pole. With the magnetic declination of the current position, we can get the heading angle relative to the true North Pole.

We select a differential pressure sensor to measure the airspeed, the model is MPX7002DP produced by Freescale Company. Pressure difference between the dynamic pressure and the static pressure of pitot tube can be measured by the differential pressure sensor, according to the following formula, we can get the airspeed of UAV.

$$v = \sqrt{\frac{2(P_0 - P)}{\rho}}$$

Where P_0 is the dynamic pressure, P is the static pressure, ρ is the air density. The density of air decreases with increasing altitude, increased by approximately 1000m, the air density is reduced by about 10%.

The GPS receiver we select is Ublox's LEA-6H, the horizontal positioning accuracy is 2.5m, and the speed accuracy is 0.1m /s. When the UAV is flying faster, GPS heading data can be cross-checking with electronic compass.

C. Co-processor Design

ATmega328P, as a co-processor, is used in the autopilot, in order to compensate for the inadequate of serial ports of MCU. The two processors via the I2C interface. ATmega328P and the MCU belong to AVR 8 bit microcontroller. ATmega328P contains 2 SPI interface, 1 I2C interface, 4 serial ports. This co-processor can read some sensors, transit useful information to the MCU through the I2C interface. Another advantage of using the co-processor is to increase the expansibility of autopilot. For example, differential GPS can be driven by the co-processor, it can improve the position accuracy of small-scale UAVs, AHRS sensor can be extended through the co-processor, it can increase the redundancy of attitude, improve the robustness of autopilot.

IV. FLIGHT CONTROL LAW DESIGN

Trajectory controller contains two parts: lateral controller and longitudinal controller. The lateral controller's role is to reduce, eliminate cross track error, making the UAV flight along the desired trajectory as far as possible. While, the longitudinal controller tries to eliminate the altitude error, in the meantime, the airspeed of UAV remains within a safety range, avoiding underspeed.

A. Lateral Control Law Design

Lateral control includes of roll controller and yaw controller. The function of roll controller is to eliminate cross track error, and makes the UAV roll in coordinated turn. Yaw controller plays an important role in automatic takeoff and automatic land. Because in these stage, the UAV remain heading only based on the control of rudder and front wheel. Besides, in the cruise phase of flight, yaw controller coordinate with roll controller; speed up eliminating the cross track error.

There are several methods can be used in roll controller. Among them, classical PID control method is common. It aims at calculating desired roll angle according to the cross crack error and heading deviation by PID operation. This method is simple and easy to implement, but the speed of UAV affect the control accuracy, besides, if the desired trajectory is not a straight line, the UAV cannot track the desired trajectory well.

Except for PID control method, many other methods are designed by researchers in recent years. Take the L1 control method as an example, which is used in our autopilot. It was presented by Sanghyuk Park and John Deyst and others in 2004 [1]. It is a new nonlinear guidance method for trajectory tracking, especially suited in the situation where the desired trajectory is not a straight line, rather than a complex curved path. Firstly, select a reference point, the reference point is on the desired path, and the distance between this reference point and the UAV is L1， as shown in Figure 4.

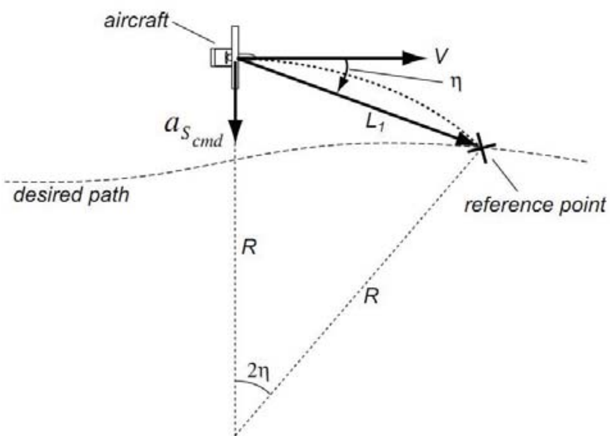

Figure 4. Diagram for L1 control method

Secondly, compute the desired lateral acceleration. The formula used in this computation is:

$$a = 2\frac{V^2}{L_1}\sin\eta$$

Where V is the airspeed of the UAV, η is the angle between the airspeed heading and the line from the UAV to reference point, as shown in Figure 3. According to the desired lateral acceleration, we can archive the desired roll angle by the following formula:

$$Roll_D = \tan^{-1}\left(\frac{a}{g}\right)$$

With the desired roll angle, autopilot can eliminate the cross track error.

B. Longitudinal Control Law Design

The control of altitude and airspeed of small-scale UAV is difficult, because there is strong coupling between the airspeed and altitude of the UAV, which is in low dynamic pressure flight state, particularly during the landing approach phase.

Traditional control methods are airspeed control in altitude maintained mode, or altitude control in airspeed maintained mode. But due to lack of coordination between elevator and throttle, the aircraft altitude and airspeed control results are often unsatisfactory.

Total energy control system (TECS) is a theory about altitude and airspeed control by coordinating the throttle and desired pitch angle of the UAV [12]. It is presented by the Boeing Company when worked for the NASA. According to the theoretical mechanics, the total mechanical energy of aircraft is:

$$E_T = GV^2 / 2g + Gh$$

Where E_T is the total amount of mechanical energy of the aircraft, it consists of kinetic energy and potential energy. G is the weight of the aircraft, g is the gravitational acceleration, V is the airspeed, h is the altitude, $GV^2/2g$ and Gh represent the kinetic and gravitational potential energy of the aircraft. The kinetic energy is directly related to the airspeed, while, the gravitational potential energy is directly related to the altitude. The desired altitude and real altitude, desired airspeed and real airspeed, these 4 parts are the input of TECS, we can get the desired kinetic energy, potential energy and total energy, as well as the real kinetic energy, potential energy and total energy of the aircraft. Desired throttle can be calculated according to the error between the desired total energy and real total energy, so we have done the control of total energy; desired pitch angle can be calculated, according to the error between desired kinetic energy and real kinetic energy, and the error between desired potential energy and real potential energy, thus we have completed the distribution of kinetic energy and potential energy.

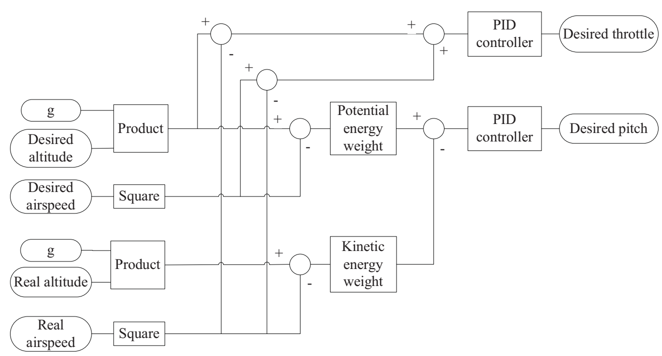

Figure 5. Structure chart of TECS

V. Experiments Results

Many flight tests have been done about the autonomous flight control system designed in this article on a small-scale UAV. With approximate parameters, the small-scale UAV flight well, the accuracy of trajectory control is about 1.5m; the altitude error is no more than 0.5m.

Figure 6 shows the flight trajectory of one test, the aircraft is expected to flight along with a rectangle at the altitude 100m. We can see that different trajectories were not coincident, because of the influence by wind. Figure 7 shows the altitude measured by laser distance sensor in auto landing. At the end of this curve, the altitude value isn't equal to 0, because there is an undercarriage between the aircraft and ground.

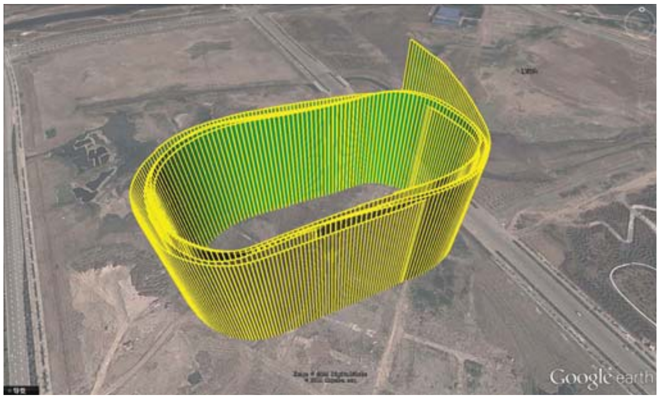

Figure 6 Flight trajectory

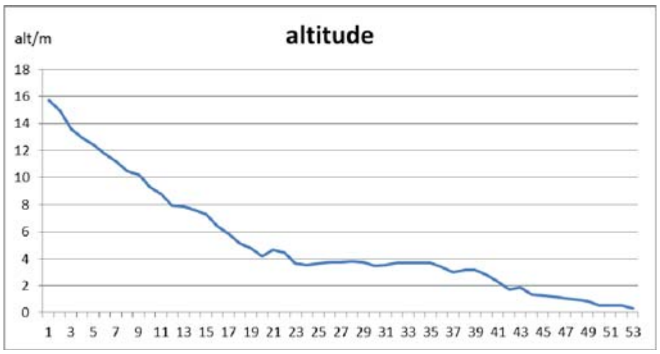

Figure 7 Altitude in auto landing

VI. CONCLUSION

The design of the autonomous flight control system in this paper is reasonable, suitable and stable, works well for small-scale UAV. L1 control method and TECS used in the autopilot works well. In order to get the best performance, more flight tests need to be done. Laser distance sensor is appropriate for measuring altitude during take-off and landing. The measurement range of laser distance sensor is generally no more than 100m, so it is necessary to combine barometer and laser sensor.

REFERENCES

[1] Park, Sanghyuk, Deyst, John, and How, Jonathan P., “A new nonlinear guidance logic for trajectory tracking,” *AIAA Guidance, Navigation, and Control Conference,* 2004

[2] Yoon, Seungho, Park, Sanghyuk and Kim, Youdan, “Circular motion guidance law for coordinated standoff tracking of a moving target,” *IEEE Transactions on Aerospace and Electronic Systems,* 2013

[3] Kruijff, G.-J.M. ; Tretyakov, V. ; Linder, T. “Rescue robots at earthquake-hit Mirandola, Italy: A field report,” *Digital Object Identifier,*2012

[4] Haiyang Chao ; Yu Gu ; Napolitano, M., “A survey of optical flow techniques for UAV navigation applications,” *Unmanned Aircraft Systems (ICUAS),* 2013

[5] Weigang Pan ; Hairong Xiao ; Yaozhen Han ; Changshun Wang, “Design and realization of autopilot system based on ARM for small vessel,” *Intelligent Control and Automation (WCICA)*, 2010

[6] Wang Fu ; Xian Bin ; Huang Guoping ; Zhao Bo, “Autonomous hovering control for a quadrotor unmanned aerial vehicle,” *Control Conference (CCC)*, 2013

[7] Sufendi,Trilaksono, B.R., Nasution, S.H., and Purwanto, E.B. “Design and implementation of hardware-in-the-loop-simulation for uav using pid control method,” *Instrumentation, Communications, Information Technology, and Biomedical Engineering (ICICI-BME)*, IEEE, 2013

[8] Peng Kemao, Dong Miaobo ; Chen Ben, M. ; Cai Guowei ; Lum Kai Yew ; Lee, T.H. “Design and Implementation of a Fully Autonomous Flight Control System for a UAV Helicopter,” *Control Conference,* 2007.

[9] Zhiyang Zhang ; Fei Hu ; Jian Li, “Autonomous flight control system designed for small-scale helicopter based on approximate dynamic inversion,” *Advanced Computer Control (ICACC),* 2011

[10] Triputra, F.R. ; Trilaksono, B.R. ; Sasongko, R.A. ; Dahsyat, M. “Longitudinal dynamic system modeling of a fixed-wing UAV towards autonomous flight control system development: A case study of BPPT wulung UAV platform, ”*System Engineering and Technology (ICSET),* 2012

[11] Ueno, H. ; Ohtake, H. ; Tanaka, K. “Autonomous flight control of flapping-of-wings robot using GPS,” *SICE Annual Conference*, 2008

[12] Voth, Christopher ; Ly, U.-L. “Total Energy Control System Autopilot Design with Constrained Parameter Optimization, ”*American Control Conference,* 1990

[13] Akmeliawati, R. ; Mareels, I.M.Y. “Included in Your Digital Subscription Nonlinear Energy-Based Control Method for Aircraft Automatic Landing Systems, ”*Control Systems Technology, IEEE Transactions*, 2010

[14] Oda, N. ; Ito, M. “Motion stabilization using laser distance sensor for biped robots with flexible joint,” *Intelligent Robots and Systems*, 2009