Flight design and dynamics analysis of a new water-air UAV

Yan Zhang¹*, Xu Chen², Jie Zhou³

¹School of Logistics Engineering Wuhan University of Technology, Wuhan, China
²School of Logistics Engineering Wuhan University of Technology, Wuhan, China
³School of Logistics Engineering Wuhan University of Technology, Wuhan, China
*Corresponding author’s e-mail: 287767@whut.edu.cn

Abstract: In the field of UAV research, water-air amphibious is an important direction. If water-air amphibious is realized, the UAV will no longer be restricted by the space field, and can realize various functions in the three domains of water, land and air more flexibly and freely to complete various flight and exploration missions. Therefore, this paper designs the model and flight algorithm of a new type of water-air amphibious variable wing UAV, and verifies the dynamic analysis of the relevant flight components of the UAV.

1. Research Introduction

In the design stage, this paper studies the multi rotor UAV, fixed wing UAV, unmanned helicopter and other UAVs, and carefully analyzes the structure, flight principle, advantages and disadvantages and application fields of various UAVs. Among them, the project team focuses on the "Osprey", which combines the characteristics of fixed wing aircraft and helicopter, with vertical take-off and landing and short-range take-off and landing capabilities. Based on the above research, this paper designs a water-air amphibious variable wing UAV which can quickly switch between water and air. (as shown in Figure 1) the UAV combines the advantages of two axis UAV, four axis UAV and tilt rotor UAV, and improves and perfects the fuselage and rotor to complete the water air conversion.

Figure 1 Model diagram of water air UAV

The principle of four axis UAV is adopted when lifting from the water. The auxiliary propeller of culvert turns to the vertical axis, and the whole machine is driven to rise by the propeller. Because of the obvious height difference between the main propeller and the culvert auxiliary propeller, the main propeller can come out of the water first. When the main propeller comes out of the water, the main propeller gradually increases the speed, thus driving the whole machine to leave the water surface. There is a height difference between the main and auxiliary propellers to ensure continuous power and reduce the power Water entry impact and ensure water outlet. (as shown in Figure 2).
2. **Algorithm Introduction**

In this paper, the attitude angle of water-air amphibious UAV is detected by inertial sensor, and the flight attitude of UAV is accurately controlled by using two-stage series PID algorithm, so as to ensure the stable flight of underwater and air-water amphibious UAV. When the UAV is disturbed by external disturbance, the two-stage series PID controller can respond to the disturbance automatically and quickly adjust the output of main propeller motor and steering gear to resist external interference and ensure the stability of UAV in the air. In order to resist the interference of water impact and ensure the stability of underwater navigation, the double stage series PID controller can quickly calculate and adjust the output of the auxiliary propeller motor of the underwater amphibious UAV.

3. **Coordinate system**

When studying the kinematics and dynamics of UAV, the relative coordinate system of UAV should be determined first. In the field of UAV, two kinds of coordinate systems are often used: navigation coordinate system and airframe coordinate system. Navigation coordinate system: also known as geographical coordinate system, its origin is on the earth's surface, Z axis is along the direction of local geographical vertical line, X, Y axis is along the tangent direction of local longitude and latitude line. The body coordinate system of this design: the body coordinate system takes the center of mass of the UAV as the origin, and generally forms the coordinate system according to the structure direction of the UAV. The origin of the body coordinate system is located at the center point of the water-air amphibious UAV. The definition of x-axis points to the nose direction, Y-axis points to the right side of the body, and z-axis is perpendicular to the plane composed of x-axis and Y-axis and points downward. Figure 3 shows the navigation coordinate system and the body coordinate system.
3.1 Accelerometer calibration

According to the principle characteristics of accelerometer, its mathematical error model can be expressed by the following formula:

\[ a_m = R_s S_s (a_m + b_m') \]

Among them, \( a_m \) is the original measurement value before calibration. Due to the factors of chip production and assembly, the value will have zero offset error; Zero offset compensation is represented by \( b_m' \); In addition, scale factor \( S_s = \begin{bmatrix} S_{xx} & 0 & 0 \\ 0 & S_{yy} & 0 \\ 0 & 0 & S_{zz} \end{bmatrix} \) is used to compensate for the scale accuracy caused by scale scaling; Finally, a rotation factor matrix \( R_s = \begin{bmatrix} 1 & \Delta \phi & -\Delta \theta \\ -\Delta \phi & 1 & \Delta \phi \\ \Delta \theta & -\Delta \phi & 1 \end{bmatrix} \) is needed to compensate for the installation error and the distortion of the inductor axis inside the chip.

In this paper, the accelerometer is calibrated by arithmetic average method: The water-air amphibious UAV is placed on the horizontal ground, and the gravity acceleration component is removed from the first 200 original sampling data of the accelerometer after starting up, it is taken as the zero offset value of the accelerometer. And then the actual three-axis acceleration value of the UAV position can be obtained by the difference between the measured accelerometer data and the zero offset value. Part of the implementation code is as follows:

```c
void icm20602_acc_cal(void)
{
    int16_t acc_cal[3][200];
    int32_t acc_cal_add[3] = {0,0,0};
    for(uint16_t i=0;i < 200; i++)
    {
        icm20602_seven_data(icm20602_data);
        acc_cal[0][i] = icm20602_data[0];
        acc_cal[1][i] = icm20602_data[1];
        acc_cal[2][i] = icm20602_data[2];
        acc_cal_add[0] += acc_cal[0][i];
        acc_cal_add[1] += acc_cal[1][i];
        acc_cal_add[2] += (acc_cal[2][i] - 2048);
        Delay_ms(2);
    }
    acc_offset_Cal.x = (int16_t)(acc_cal_add[0]/200.0f);
    acc_offset_Cal.y = (int16_t)(acc_cal_add[1]/200.0f);
    acc_offset_Cal.z = (int16_t)(acc_cal_add[2]/200.0f);
}
```

3.2 Gyroscope calibration

The factors of triaxial deviation and zero deviation will be introduced into the three axis gyroscope in production and practical application. It is necessary to calibrate the gyroscope sensor accurately. The mathematical error model of three axis gyroscope can be expressed by the following formula:

\[ \omega_m = R_s S_s (\omega_m + b_m') \]

Where \( \omega_m \) is the original measurement before calibration.
Due to the factors of chip production and assembly, \( b'_{ax} \) is used to represent zero offset compensation; scale factor \( S_a = \begin{pmatrix} S_{ax} & 0 & 0 \\ 0 & S_{ay} & 0 \\ 0 & 0 & S_{az} \end{pmatrix} \) is used to compensate the scale accuracy caused by scale scaling; rotation factor matrix \( R_a = \begin{pmatrix} 1 & \Delta\phi & -\Delta\theta \\ -\Delta\phi & 1 & \Delta\theta \\ \Delta\theta & -\Delta\phi & 1 \end{pmatrix} \) is needed to compensate for installation error and distortion of the axis of the inductor inside the chip.

4. Design of Mahony quaternion complementary filtering algorithm

In this paper, Mahony quaternion complementary filtering algorithm is used to calculate the Euler angle (roll angle, pitch angle, yaw angle) of the water-air amphibious UAV, and the UAV attitude angle is updated every 5ms.

4.1. Dynamic analysis verification

Referring to the structures of fixed wing UAV, Quad rotor UAV and tilt rotor UAV, the project team designed and created the first generation model structure. After determining the parameters of the aircraft, the viscous flow field of fuselage was simulated by CFD technology, and the estimated results of potential flow theory were modified, which can be applied to obtain the initial dynamic parameters of UAV more accurately and quickly. Then, according to the existing model, the modification and correction are carried out to obtain the fuselage shell whose shape is more in line with the theory of fluid mechanics and structural strength. The fluid field resistance of UAV shell is analyzed by combining computational fluid dynamics (CFD) with vortex lattice method (VLM) and VBS script language. According to the parameters of the fuselage shell obtained by VLM method, the installation of its structure and parts position is adjusted, and the geometric model is modified. Then, the viscous flow field of the whole aircraft is simulated by CFD technology, and a more comprehensive modified estimation model of fuselage shell shape involving water and air is obtained. Figure 4 is partial simulation diagram.
5. Innovation

5.1 Blade structure of height difference
Due to the obvious height difference between the main propeller and the auxiliary propeller in the culvert, the main propeller can come out of the water first. When the main propeller comes out of the water, the speed of the main propeller gradually increases, thus driving the whole machine to leave the water surface. There is a height difference between the main and auxiliary impellers to ensure continuous power, reduce the impact of water inflow and ensure the water outlet.

5.2 Low resistance operation
At normal temperature, the viscosity of water is about 55 times that of air. At the same speed, the resistance in water is significantly greater than that in air. However, in water, the speed of water-air amphibious UAV is small, which leads to the resistance in water similar to that in air. Therefore, the obstruction to the operation of amphibious UAV in water does not affect the change of flight attitude.

5.3 Precise control
The UAV flight control system adopts open source flight control for secondary development, which can realize the precise control of various flight states and flight modes of UAV in this project. Using inertial sensor correction algorithm, quaternion attitude fusion algorithm, PID closed-loop control algorithm and other algorithms to accurately obtain and control the flight attitude of UAV, it has strong anti-interference ability and good stability.

Acknowledgment
National innovation and entrepreneurship training program for college students S202010497202

References
[1] Wenyan Yu, Kunlin Yang. Design of cascade fuzzy adaptive PID control system for quadrotor UAV [J]. Mechanical design and manufacturing, 2019 (01).
[2] Li Zhang. Design and implementation of control system for quadrotor UAV Based on intelligent optimization algorithm [D]. North China University of water resources and hydropower, 2018.
[3] Zhijun Liu, Qiang Lv, Donglai Wang. Modeling and simulation control of small quadrotor UAV [J]. Computer simulation, 2010.
[4] Jian Luo, Yang Chen, Hui Yi, Shuangjin Wu. Wind tunnel test of hybrid UAV [J / OL]. Electronic technology and software engineering, 2019 (08).
[5] Zhaoxiong He, Zhenshan Zheng, Dongli Ma. Development history and Enlightenment of foreign cross medium aircraft [J]. Ship science and technology, 2016.
[6] Ke Huang. Research on flight stability control of UAV [D]. Guizhou University, 2018.
[7] Jiaxian Chen. Bo Liang. Mode transition control of tilt rotor UAV [M]. Beijing University of Aeronautics and Astronautics, Beijing Institute of Aerospace Automatic Control, 2015.
[8] Le Ma. Analysis of key technologies of UAV aerial remote sensing system [J]. China Equipment Engineering, 2020 (17): 195-197.
[9] Siqi An, Xiaofeng Liu, Kuanxin Hou, Xingchen Xu. Establishment of dynamic model of electric power system for light UAV [J]. Journal of Harbin University of science and technology, 2020,25 (03): 33-39.
[10] Wei Wang, Tianyu Zhu, Zhigang Huang, Meng Wang, Shuai Zhang. UAV Ground Monitoring System [J]. Computer knowledge and technology, 2020,16 (19): 26-27+32.
[11] Dengfeng Chen, Jianqin Geng, Wen Zhang, Guo Liu. Dynamic modeling and Simulation of flapping wing UAV [J]. Computer measurement and control, 2020,28 (06): 202-206.