Flight Control System Simulation for Quadcopter Unmanned Aerial Vehicle (UAV) based on Matlab Simulink

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Flight Control System Simulation for Quadcopter Unmanned Aerial Vehicle (UAV) based on Matlab Simulink

Yunxin Fan [1]

[1] School of Mechatronic Engineering and Automation ,Shanghai University, Shanghai, China

*Corresponding author's e-mail: fanyunxin@shu.edu.cn

Abstract. Unmanned aerial vehicle (UAV) are widely used in military and civilian applications due to its advantages of strong maneuverability. Flight control system simulation of a UAV is always a research focus. At present, there are three major algorithms for a UAV flight control: strapdown inertial navigation system, Kalman filter algorithm, flight control Proportional-Integral-Derivative (PID) algorithm. In this study, UAV flight control system and quadcopter drone flight control principle are discussed. In addition, this research developed a dynamic model based on a thorough examination of the quadcopter drone's frame construction and features. This dynamic model describes the transformation matrix of UAV coordinate system to ground coordinate system. Matlab Simulink was used to simulate a flight control system. A quadcopter drone's vertical movement, yaw motion, pitching motion, and roll motion, as well as its flight attitude, were simulated and described. Dynamic modeling is developed based on the drone's flight principle and force relationship in different motion states, as well as the Newton-Eulerian model. Matlab Simulink was used to simulate the trajectory of a quadcopter drone. The red line denotes the trajectory, while the black x markings denote a change in trajectory or a specific position. Blue lines that reflect the waypoint's heading accompany specific poses. The results of this study could provide a good reference for the simulation of a UAV flight control system.

1. Introduction

Unmanned aerial vehicle (UAV) have been widely used in military and civilian applications due to its advantages of strong maneuverability and convenient operation. UAVs can be classified into three major categories: fixed-wing UAVs, unmanned helicopters, and multirotor UAVs [1]. Other small types of UAV platforms include parachute UAVs, flapping-wing UAVs and unmanned airships. Fixed-wing UAVs are the mainstream platforms for military drones. Most of the civilian drones are also Fixed-wing UAVs.

Flight control system simulation and the attitude control of a UAV is always a research focus. At present, there are three major algorithms for a UAV flight control: strapdown inertial navigation system, Kalman filter algorithm, flight control Proportional-Integral-Derivative (PID) algorithm [2]. The principle of strapdown inertial navigation system is to use the two inertial foresights of the accelerometer and gyroscope on the carrier to separately measure the angular motion information and line motion information of the UAV. Strapdown inertial navigation systems are divided into platform-type inertial navigation and strap-down inertial navigation. Inertial navigation systems are originally platform-type. Platform-type inertial navigation system has a physical platform. Gyroscopes and accelerometers are placed on the platform. The platform can track the navigation coordinate system to calculate speed and attitude data [3]. Another type of strapdown inertial navigation system directly installs the inertial measurement components on the main body of the UAV that converts navigation information such as attitude, speed, and the measurement signals into navigation parameters [4]. The Kalman filter algorithm uses the state space model of signal and noise, uses the estimated value at the previous moment and the observed value at the current moment to update the estimation of the state variable, thereby obtaining the estimated value at the present moment. The Kalman filter algorithm has been widely used for robot navigation, sensor data fusion, military radar systems, and missile tracking for more than 30 years. Flight control PID algorithm is a closed-loop control system, which returns a linear combination of deviation according to the given value (input value) and the actual output value and uses the deviation to give a reasonable control amount [5]. For the multirotor UAV, the signal is directly used to drive the motor to drive the propeller to rotate to generate control force. However, the dynamic response will be too fast, or too slow, or the phenomenon of overshoot or insufficient control will occur in the absence of a control system. In order to solve these problems, it is necessary to add the PID controller algorithm to control the parameters of each link to establish the relationship between attitude information and propeller speed.

Literatures proposed to use the PID controller algorithm to achieve vertical movement, yaw motion, pitching motion, roll motion of a quadcopter drone. In the literature, the linear expansion state observer is usually used to estimate the internal uncertain disturbance and external disturbance of the quadcopter drone in real time. The linear state feedback control then is used to compensate the estimated value of the disturbance online to accomplish the attitude control of a quadcopter drone. At present, the research on the control technology of a quadcopter drone mainly focuses on the following two aspects: one is the autonomous control based on inertial navigation system, and the other is the autonomous flight control based on vision. The aim of this paper is to: 1) present the current knowledge and perspectives of the UAV flight control system research; 2) discuss to use the Matlab/Simulink simulation platform to use the PID control system to control the quadcopter drone.

2. The classification of UAV

According to different flight platform configurations, UAVs can be classified into three major categories: fixed-wing UAVs, unmanned helicopters, and multirotor UAVs. Other small types of UAV platforms include parachute UAVs, flapping-wing UAVs and unmanned airships. Fixed-wing UAVs are the mainstream platforms for military drones. Most of the civilian drones are also Fixed-wing UAVs. The biggest advantage of Fixed-wing UAVs is their fast flight speed. Unmanned helicopters are the most flexible UAV platforms, which can take off and hover vertically in situ. Multirotor UAVs are the platform of choice for consumer and some civilian use, with intermediate flexibility between fixed-wing and helicopters (thrust is required for takeoff and landing).

3. Quadcopter drone

The existing quadcopter drones can be divided into three categories. One is a radio-controlled quadcopter. The other is an autonomously controlled small and medium-sized quadcopter. The other is an autonomously controlled micro quadcopter. All these quadcopter drones belong to small unmanned aerial vehicles. Compared with fixed-wing drones, multirotor drones have the advantages of vertical take-off and landing, hovering in the air, etc. Quadcopter drone is one of the typical representative multirotor drones. It not only has a simple structure, but also have good load-carrying capacity and easy to use. It has a wide range of applications in the military and civilian fields, including aerospace photography, disaster relief, material transportation.

The structure of a quadcopter drone is a symmetrical cross-shaped rigid body structure (Figure 1)[6]. The flying power for the aircraft is generated from a rotor composed of two blades where are installed at the four ends of the cross-shaped. Each rotor is installed in a motor. The speed of each rotor is controlled by controlling the rotational state of the motor to provide different lift forces to achieve various attitudes. Each motor is connected to the motor drive components and the flight control unit which is used to control signal to adjust the speed. The rotors located on the same diagonal line of the quadcopter drone are grouped as one group. The front and rear rotors rotate clockwise to generate clockwise torque, while the left and right rotors rotate to generate counterclockwise torque. In this way, the torque generated by the rotation of the four rotors can cancel each other out. It can be seen that the attitude and position control of a quadcopter drone are realized by adjusting the speed of the four drive motors.

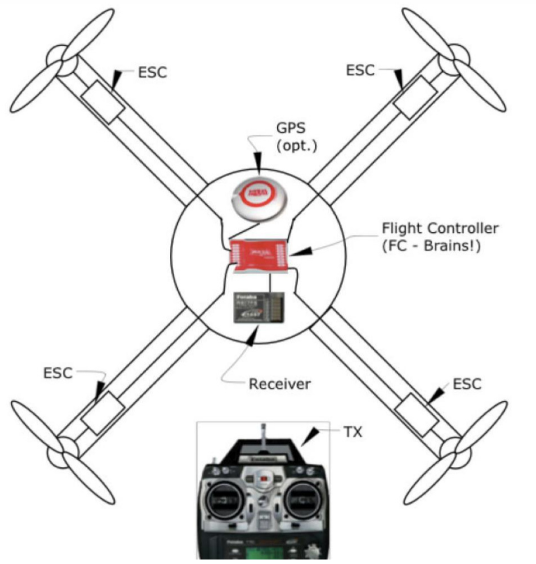

Figure 1. Structure of a quadcopter UAV

4. UAV flight control systemc

The flight control system of a UAV is a complex system which is a systematic concept integrating flight navigation, flight dynamics, and flight guidance [7]. The flight control system is usually including two parts: sensors and airborne computers. It can achieve UAV attitude stabilization and control, mission management, and emergency management. The flight control system can compute and analyze the flight data collected from gyroscopes, accelerometers, magnetometers, barometers, ultrasonic sensors, optical flow sensors and GPS to in control the flight attitude of the UAV. Figure 2 shows a typical flight control system schematic of a quadcopter drone [8].

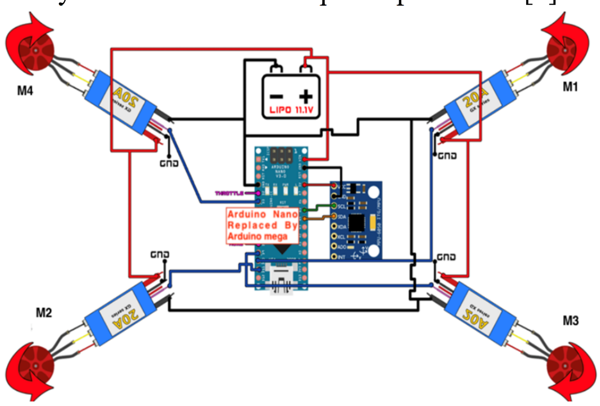

Figure 2. Flight control system schematic of a quadcopter drone

Various sensors assembled in a UAV are the basis of the flight control system. They are mainly including gyroscopes, accelerometers, magnetometers, barometers, ultrasonic sensors, optical flow sensors and GPS modules[9]. Sensors such as gyroscopes and magnetometers can be used to calculate orientation and velocity thereby providing different information for the UAV. More specifically, the gyroscope and accelerometer can measure the rotational angular velocity and linear acceleration of the

UAV during flight and perceive the flight attitude of the UAV. The magnetometer estimates the flight attitude by measuring the geomagnetic field vector. The barometer can measure the altitude of the UAV by sensing the altitude of the barometric pressure, making a rough estimate of the hovering altitude. Ultrasonic sensors can control the low altitude of the UAV or avoid obstacles. Optical flow sensors accurately determine the hovering position of the UAV. The GPS module can measure the speed and position of the UAV, which plays an important role in the positioning and navigation of the UAV.

The airborne computer is the core computational unit installed on the UAV. It can achieve the intelligent control and autonomous decision-making of the UAV and make up for the shortcomings of the flight control that cannot be advanced in development. The airborne computer is responsible for the calculation and judgment of the UAV attitude. It also contains communication interfaces for the high-performance computer hardware resources. At present, the mainstream airborne computers are Raspberry Pi and Jetson Nano with Ubuntu system and other frameworks such as Robot Operating System (ROS) [10].

5. Flight control principle of quadcopter drone

The real-time attitude and real-time position of a quadcopter drone is by adjusting the speed of the four motors. Quadcopter drones have 4 different flight modes based on the speed and positions of rotors.

1) Vertical movement: When the speed of the four motors is increasing the same at the same time, the rotors generate the lift force. If the total lift force is greater than the gravity of the drone, the drone will rise. On the contrary, when the speed of motors is decreasing at the same time and the total lift is less than the gravity of the drone, the drone will fall vertically. If the total lift generated by the drone is equal to the gravity, then the quadcopter drone is hovering horizontally.

2) Yaw motion: the quadcopter drone uses 2 forward propellers and 2 reverse propellers to offset the torque generated by the rotor during the rotation process and keep stable flying. The adjacent rotor propellers are different, and the direction of rotation of the motors on the diagonal is also different. When the rotation speed of the four motors is the same, the torque generated by the four rotors cancels each other out and the quadcopter drone does not rotate. When the rotation speeds of the four motors are different, the unbalanced torque will cause the quadcopter to turn. The reaction torque of rotor 2 and rotor 4 is greater than the reaction torque of rotor 1 and rotor 3, when the rotational speed of motor 2 and motor 4 increases and the rotational speed of motor 1 and motor 3 decreases (Figure 3). The drone will rotate around the z-axis under the action of the surplus anti-torque to achieve yaw motion.

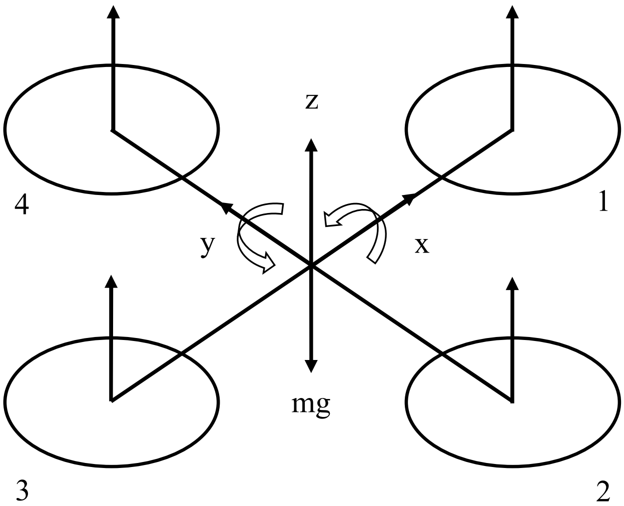

Figure 3. Force analysis of a quadcopter drone

3) Pitching motion: when the speed of motor 1 decreases or the speed of motor 3 increases. As the lift force of rotor 3 increases (or decreases) and the lift force of rotor 1 decreases (or increases), the drone will rotate around the lateral axis (y axis).

4) Roll motion: the principle of roll motion is similar to the pitching motion. When the speed of motor 2 decreases and the speed of motor 4 increases, the drone will rotate around another lateral axis (x axis) as the lift force of rotor 4 increases and the lift force of rotor 2 decreases.

In aircraft flight dynamics, the angle describing the relationship between the ground coordinate system and the UAV coordinate system can be determined by three Euler angles defined as follows:

Yaw angle ψ: The angle between a line in the direction of a plane through the longitudinal and vertical axes of an aircraft;

Pitch angle θ: the angle between the longitudinal axis and the horizon;

Roll angle φ: the angle rotation around the UAV longitudinal axis.

So, transformation matrix of UAV coordinate system for each axis to ground coordinate system can be constructed as following:

$$Rx = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\Phi & sin\Phi \\ 0 & sin\Phi & cos\Phi \end{bmatrix}$$

$$Ry = \begin{bmatrix} cos\theta & 0 & sin\theta \\ 0 & 1 & 0 \\ -sin\theta & 0 & cos\varphi \end{bmatrix}$$

$$Rz = \begin{bmatrix} cos\psi & -sin\psi & 0 \\ sin\psi & cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Transformation matrix of UAV coordinate system to ground coordinate system can be constructed as following:

$$R = RxRyRz = \begin{bmatrix} cos\psi cos\Phi & cos\psi sin\theta sin\Phi & cos\psi sin\theta cos\Phi + sin\psi sin\Phi \\ sin\psi\cos\theta & sin\psi\sin\theta sin\Phi & sin\psi sin\theta cos\Phi - \cos\psi\sin\Phi \\ -sin\theta & cos\theta sin\Phi & cos\theta cos\Phi \end{bmatrix}$$

6. Drone flight simulation and control by using Matlab Simulink

Each figure should have a brief caption describing it and, if necessary, a key to interpret the various lines and symbols on the figure. In this study, Simulink is used to model flight simulation and control of a quadcopter drone. The attitude of a quadcopter drone is estimated by using a complementary filter. In addition, Kalman filters is used to estimate the position and velocity. A PID controller is used for pitch and roll motions. A proportional derivative (PD) controller is used for yaw motion. The variables relevant to the controller are recorded in the controllerVars file. The variables relevant to the estimator can be found in the estimatorVars file. The controller and estimators are implemented as model subsystems in this simulation, which allows multiple combinations of estimators and controllers to be examined for the simulation design. To measure angular rates and translational accelerations, the simulation uses an inertial measurement unit (IMU) to determine the model's status. The variables of the quadcopter drone in the simulation can be visualized by using simulation data inspector. Trajectory generator is used to generate a series of navigational waypoints by using the Dubin method. This method uses a series of poses defined by position, heading, turn curvature, and turn direction to build a route with a set of waypoints. The interface of asbTrajectoryTool in

Matlab Simulink is shown as Figure 4. The default data includes postures for particular areas where the simulated quadcopter's cameras are used to estimate the height of the snow on the roof by the pilot on the ground[11]. Three no-fly zones were established for each of the auxiliary power generators, ensuring that if the quadcopter fails, the campus infrastructure is not harmed. The trajectory for the default data is shown as Figure 5. The trajectory is highlighted by the red line, while the black x markings indicate either a change in trajectory or a specific position. Specific poses are accompanied by blue lines that reflect the waypoint's heading. Green circles are used to denote no-fly zones.

Figure 4. The interface panel of asbTrajectoryTool in Matlab Simulink

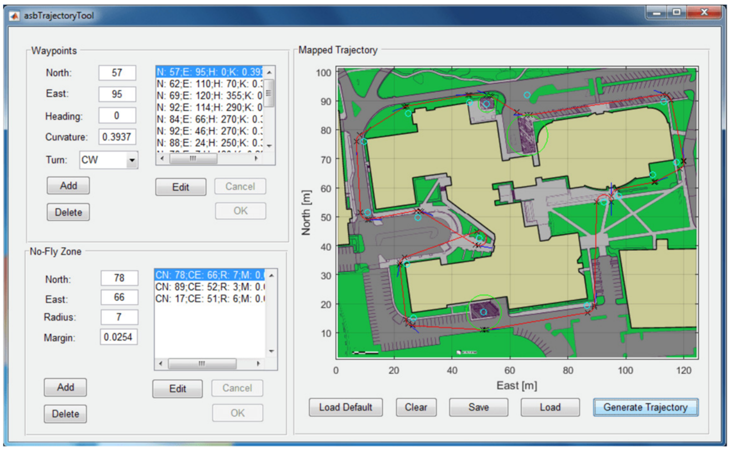

Figure 5. The simulated trajectory of a quadcopter drone in asbTrajectoryTool (Quadcopter Project, 2022).

7. Conclusion

Drone technology is being developed at an exponential rate. Regarding the research of UAV flight control system in China, only the National Defense Science and Technology University, Harbin Institute of Technology, and Shanghai Jiaotong University Institute of Micro-Nano Science and Technology have some progresses. The UAV flight control system and flight control principle of quadcopter drone has been discussed in this paper. In addition, this study established a dynamic model based on the detailed analysis on the frame structure and characteristics of the quadcopter drone. A flight control system was simulated by using Matlab Simulink. Various flight status such as vertical movement, yaw motion, pitching motion, and roll motion and the flight attitude of a quadcopter drone were described. Dynamic modeling is a simulation model established by the flight principle of the drone and the force relationship under various motion states and by referring to the Newton-Eulerian model. The trajectory of a quadcopter drone could be well simulated by using Matlab Simulink. The trajectory is highlighted by the red line, while the black x markings indicate either a change in trajectory or a specific position. Specific poses are accompanied by blue lines that reflect the waypoint's heading. The results could provide a good reference for the simulation of UAV flight control system.

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