

# Waterwing: An Aerial-Underwater Quadcopter Drone for Underwater Purposes

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**Abstract:** *Amphibious drones are in high demand for underwater search and rescue as well as environmental monitoring missions. Conventional devices such as submarines and professional divers are cumbersome to transport, complicated to operate, and accompanied by notable safety hazards, leaving room for improved alternatives. This study presents Waterwing, a self-developed amphibious quadcopter capable of aerial flight, underwater locomotion and real-time video recording. The drone can navigate autonomously to designated sites and fully submerge without manual control. It is integrated with rotatable waterproof servos, a fully sealed electronic compartment and a wireless camera for real-time environmental observation. A PID control system and complete electromechanical modules are also adopted to guarantee stable and consistent operation. The prototype was firstly modeled in SolidWorks, then manufactured and assembled, with repeated iterative modifications to optimize its overall performance. Indoor and outdoor testing results verified that the refined prototype operates stably in both aerial and underwater scenarios, fully fulfilling the design requirements for practical underwater application scenarios.*

**Keywords:** *Amphibious drone, Rotatable servo, PID control, Test and experiment*

## 1. Introduction

With the rapid advancement of science and technology, unmanned aerial vehicles (UAVs) have been widely used in emergency rescue, scientific research, filmmaking, and other fields due to their easy operation and high flexibility, making them the preferred equipment in relevant scenarios. In recent years, various UAV development projects have continued to increase, and related research on technology and applications has become a current hotspot<sup>[1,2,3,4]</sup>. The main reason they're so widely used is how easy they are to operate. But there's one big problem we noticed: none of the drones you can buy right now can do two things at once-fly in the air and navigate under water. That gap means we're still a long way from making the most of what amphibious drones could really do.

Waterwing is an amphibious quadcopter with three core capabilities: it can fly through the air, move underwater, and capture live video as it operates. We designed it to fly on its own to whatever location it's set for, and it can fully submerge without anyone having to control it manually. It works really well for underwater search and rescue jobs and environmental monitoring tasks-way better than the usual equipment we rely on, things like submarines and professional divers. Those traditional tools are a hassle to transport, take a lot of work to operate correctly, and come with pretty serious safety risks that we wanted to avoid.

To make sure it functions properly in both air and water, we outfitted the drone with rotatable waterproof servos, a fully sealed electronic cabin, and a wireless camera that lets us keep an eye on the environment in real time. We also added a PID control system and a complete set of electromechanical hardware; these parts work together to make sure the drone runs steadily and reliably every time we use it.

## 2. Related Works

### 2.1. Waterproof Drones

As drones and underwater videography grow increasingly mainstream, a number of manufacturers have rolled out waterproof drone models to meet market demand. One notable example is SwellPro, which has launched several drone lines engineered to withstand water exposure. These devices keep all internal electronic parts fully sealed inside the fuselage, with a built-in camera mounted on the bottom to

record clear underwater scenery and environmental footage.

The PowerEgg drone is another comparable waterproof option, designed to operate normally even in rainy and humid conditions. It features a dedicated enclosed compartment to house core electronic components, effectively isolating them from water damage. Even so, while both drones can come into contact with water safely, neither is capable of independent underwater movement. They cannot withstand deep-water pressure, nor can they automatically transition from flight mode to underwater cruising without manual operation. As the drone's propellers does not have the capability of rotating, for the drone to submerge in water, it has to be placed upside-down. This is not possible to achieve by the drone itself, as it is only able to land on top of the water. Surely, these drones are able to take videos and photographs underwater, but it is only to a small extent as they are unable to dive underwater and make further observations.

## 2.2. Underwater Drones

Contrasting to waterproof drones, there are underwater drones which are essentially small submarines. They are suitable for swimming underwater and capturing footage of deeper waters as it can completely submerge itself. As an example, the Powerray is an underwater drone designed to take videos and photographs of the underwater environment through including a high quality waterproof camera that can take defined pictures. It can be released into oceans, lakes, rivers, and other bodies of water. However, this drone is unable to withstand strong currents, so it can only be used in calm waters. More importantly, it is not an amphibious drone that has the ability to swim and fly. When faced with strong or unstable currents, something that the drone struggles to resist, it cannot be used as it faces the risk of getting damaged. Compared to the Powerray underwater drone, a drone like the Waterwing that is capable of both flying and swimming can be more beneficial as it can fly to the desired location rather than swimming underwater, reducing the risk of getting damaged due to travelling against the currents.

## 3. Structural Design

### 3.1. Overall Design

Quadrotor drones generally have two layouts: “+” shape and “X” shape. The “+” shape uses only a single motor to control tilting, while the “X” shape uses two motors, providing stronger force and faster adjustment. Therefore, the Waterwing drone adopts the X-shaped layout for better stability and balance. Meanwhile, to ensure stable movement in the air, the diagonal propellers of the drone rotate in the same direction, and adjacent propellers rotate in opposite directions.

As shown in Figure 1, the Waterwing drone is mainly composed of two modules: the main body and the waterproof compartment. The main body is located at the upper part of the drone, including the driving unit and the arm unit. The driving unit fixes the servos and the arm unit through a top plate and arm support rods. The arm unit is equipped with four motors and propellers. The waterproof compartment is located at the lower part, which is a large-diameter cylindrical structure with openable and closable waterproof covers at both ends, and it houses all electronic components and the control system.

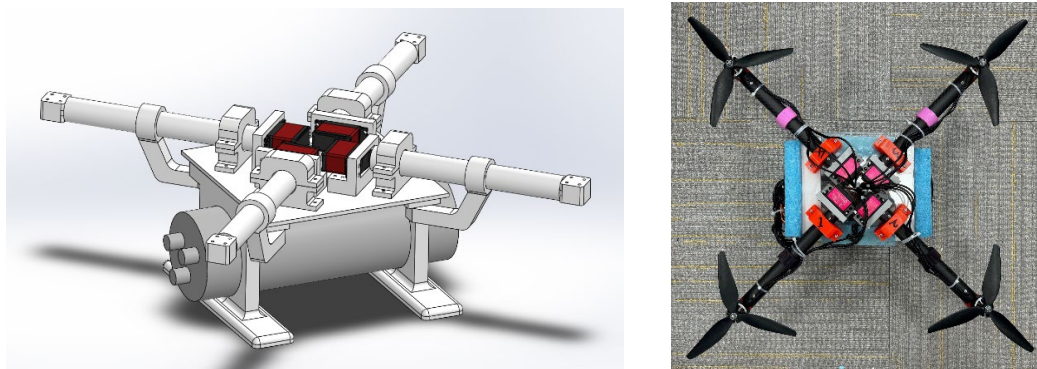


Figure 1: 3D model of the waterwing drone and physical prototype.

### 3.2. Specific Components

The Waterwing drone relies on three core components for aerial flight and underwater movement: DS3218 waterproof rotatable servos, ceramic bearings, and Avenger 2812 V3 brushless motors, all mounted on its four arms. For underwater applications, this project selects the DS3218 servo for its excellent waterproof performance, ceramic bearings to prevent rust, and brushless motors for higher efficiency and longer service life. The servos drive the arms to rotate, swinging the propellers from vertical to lateral positions for underwater swimming. In this state, the servos orient the propellers toward the moving direction to push water backward, enabling stable omnidirectional movement underwater. The speed of the brushless motors can be adjusted via the remote controller to achieve flight, ascent, descent, and directional movement.

In addition, as illustrated in Figure 2, eight types of 3D-printed parts or laser-cut parts are designed to support and stabilize the overall structure, including motor supporters, bearing supporters, servo supporters, arm supporters, control board supporters, connecting pieces, and main sustaining pieces. These parts firmly secure the motors, bearings, servos, and control board, protect the arms, and fix the cylindrical waterproof compartment. These components and structures work together to guarantee the water-wing UAV operates reliably and maintains structural stability, whether it is flying in the air or working underwater.

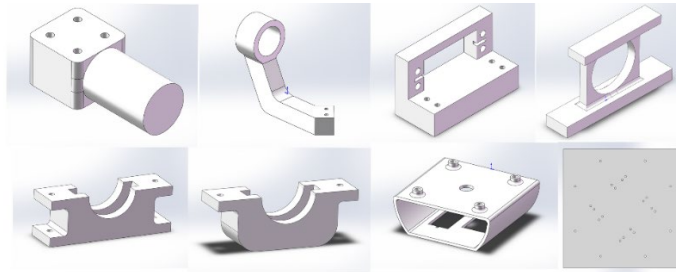


Figure 2: Partial parts drawing.

## 4. Control System Design

### 4.1. PID Control

A PID control system is critical for the stable and accurate flight of the water-wing UAV. It comprises three key parts: proportional, integral, and derivative terms. These three terms work together to adjust the drone's control inputs and outputs, ensuring it stays on the desired flight path<sup>[5,6]</sup>. They collect data on the drone's pitch, roll, and yaw, then make targeted adjustments: the proportional term responds to the deviation between the current position and set-point, the integral term corrects long-term deviations, and the derivative term enables quick response to sudden changes to avoid overshooting. These PID output signals are fed into the motor mixing algorithm. This algorithm translates pitch, roll and yaw correction signals into four independent PWM commands, with each command assigned to a single rotor. Proper tuning of the PID control system enables the UAV to adapt to complex flight environments, execute delicate attitude maneuvers, and complete assigned tasks with better stability and control accuracy. The mathematical expression of the PID algorithm is given in Equation (1).

$$PID_{out}(t) = K_p e(t) + K_i \int_0^t e(t) dt + K_d \frac{d}{dt} e(t) \quad (1)$$

$K_p = Proportional\ value$

$K_i = Integral\ value$

$K_d = Derivative\ value$

$e = Error\ value$

$t = Time$

#### 4.2. PWM Control

Pulse Width Modulation (PWM) is the core technology for motor control of the hydrofoil UAV. Its core control logic achieves precise regulation of motor output power, speed and thrust by adjusting the duty cycle (the proportion of power-on time within a signal cycle)—the duty cycle is positively correlated with motor power, speed and thrust, and dynamic adjustment of the duty cycle can meet the UAV's different attitude control requirements<sup>[7,8,9]</sup>.

The UAV flight control system independently regulates each motor through separate PWM signals, and achieves precise attitude control by means of differential adjustment of the duty cycle: increasing the duty cycle of motors on one side while decreasing that on the opposite side can complete the rolling and tilting action; adjusting the duty cycle of front and rear motors can realize precise control of the pitch attitude as well as forward and backward movement.

For this hydrofoil UAV, the motor power range is set to 0-1000, where 0 corresponds to zero throttle and motor stop, 1000 corresponds to full throttle and full rated speed of the motor (continuous power supply throughout the cycle, PWM maintains a constant high level), and the other values correspond to different PWM duty cycles in proportion, forming a hierarchical control system.

The dynamic changes of PWM signals and their duty cycles are the core support for the UAV's stable hovering in the air and command-based movement<sup>[10]</sup>. By receiving the speed adjustment commands output by the PID control system, it adjusts the duty cycle of each signal in real time to ensure the aircraft's balance and control accuracy. The relevant control codes are as follows.

```
motor_step[m1] = mc.ct_val_thr +mc.ct_val_yaw -mc.ct_val_rol +mc.ct_val_pit;  
motor_step[m2] = mc.ct_val_thr -mc.ct_val_yaw +mc.ct_val_rol +mc.ct_val_pit;  
motor_step[m3] = mc.ct_val_thr +mc.ct_val_yaw +mc.ct_val_rol -mc.ct_val_pit;  
motor_step[m4] = mc.ct_val_thr -mc.ct_val_yaw -mc.ct_val_rol -mc.ct_val_pit;
```

#### 4.3. Flight Control Components

The flight control unit is composed of an IMU module, a magnetometer, a barometer, flash memory and an optical flow sensor. As shown in Figure 3, the inertial measurement unit (IMU) serves as the core hardware of this water-wing UAV and most conventional unmanned aerial vehicles. It undertakes the measurement and real-time tracking of vehicle attitude, acceleration and angular velocity, and fuses data from multiple sensors to output precise motion and spatial state information.

The IMU mainly contains two key sensors. The accelerometer captures linear acceleration along the X, Y and Z three axes corresponding to pitch, roll and yaw. It monitors speed variations, calculates the real-time acceleration of the UAV, and solves its tilt angle relative to the gravitational direction — a key basis for maintaining flight stability and achieving position closed-loop control. The gyroscope is used to collect three-axis angular velocity and rotational rate signals, perceive real-time attitude changes, and reflect the UAV's rotating speed and motion state. Through angular velocity integration, it can further realize high-precision estimation of three-dimensional attitude. Subsequently, the flight controller processes the raw data output by the IMU and feeds the processed results into classic control algorithms including PID. By dynamically adjusting the rotational speed of each motor, the whole system can maintain stable flight status all the time.

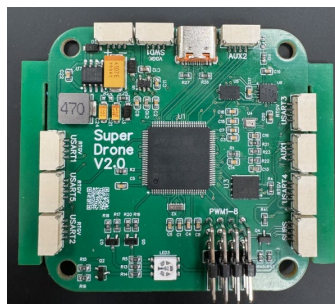


Figure 3: Flight control board.

The magnetometer gauges the strength and orientation of the Earth's magnetic field to offer heading

reference for the UAV. It allows the aircraft to navigate and orient itself with respect to magnetic north, and meanwhile compensates the long-term drift error inherent in the IMU gyroscope. The barometer relies on atmospheric pressure readings to measure the UAV's altitude. It helps the drone maintain a preset flight height and calculate vertical displacement, which not only supports steady flight and reliable return-to-home performance but also optimizes its vertical flight capability. Flash memory acts as the onboard storage unit. It saves and runs the UAV's built-in program codes, covering control algorithms, communication protocols and sensor data records. Upon power-on, these programs are loaded into the CPU, enabling the UAV to run in accordance with preset logic. In addition, firmware updates, debugging records and flight log data are all stored in this module, which plays an indispensable role in guaranteeing the overall performance and normal operation of the UAV system. The optical flow sensor is primarily deployed to assist steady flight, altitude hold and position locking. Equipped with a high-definition camera, it captures and analyzes ground optical flow information to judge the UAV's real-time flight condition and location, thereby achieving high-precision fixed-point and constant-altitude hovering. By detecting relative ground movement, it further assists altitude maintenance. Combined with data fusion from accelerometers and gyroscopes, it enables fine flight tuning, greatly enhancing the UAV's stability and maneuverability, and laying a solid foundation for accurate navigation and smooth flight.

#### 4.4. Electrical Circuits

As shown in Figure 4, the circuit system mainly consists of electronic speed controllers (ESCs) and buck converters. The electronic speed controller serves as the key device for driving and regulating the UAV motors, and is directly connected to the main battery power supply of the aircraft. It receives PWM control commands transmitted from the flight controller, which define the motor rotational speed needed for steady hovering and attitude maneuvering. After decoding these incoming signals, the ESC dynamically adjusts the working current and supply voltage of each motor, so as to regulate the UAV's flying speed, moving direction and flight altitude.

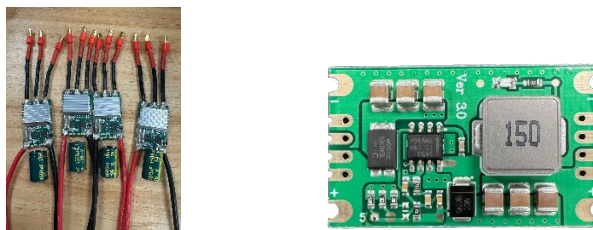


Figure 4: Electronic speed controllers(left) and step-down converter(right).

Inside each ESC lies a set of essential hardware, including a microcontroller, power MOSFETs and matching capacitors. The onboard microcontroller takes charge of processing incoming control commands, and modulates motor power output by switching the MOSFETs. Most ESCs come with built-in protection mechanisms against overcurrent, overheating and undervoltage, which effectively protects both the motor and the ESC itself from burnout and permanent damage.

On the Waterwing drone, every ESC paired with a single motor is wrapped with insulating tape. This simple measure helps shield the circuit from external signal interference and lowers the risk of short circuits during operation. As for the buck converter, it mainly supplies power to core modules like the flight control board. Its core function is to step down battery voltage and limit input current. Many low-power onboard components cannot withstand the raw voltage from the drone battery; direct connection would easily trigger short-circuit faults and cause permanent hardware damage, making the buck converter an essential part of the overall power supply design.

#### 4.5. Filters

The Waterwing UAV adopts two types of filters: low-pass filters and complementary filters. The low-pass filter is used to filter out abnormal acceleration signals caused by the UAV's vibration and collision, eliminate abnormal values, output stable data, and only allow low-frequency signals from 0Hz to the cut-off frequency to pass through, providing accurate data for PID calculation; the complementary filter is used for sensor fusion to accurately characterize the UAV's motion and attitude. The data of the accelerometer (good at long-term attitude measurement but susceptible to noise and vibration) and gyroscope (good at short-term attitude measurement but prone to drift) output by the IMU, after being fused by the complementary filter, can combine the advantages of both to output a more accurate and stable attitude estimation.

#### 4.6. Flow Diagram

The electrical flow diagram of this UAV is shown in Figure 5.

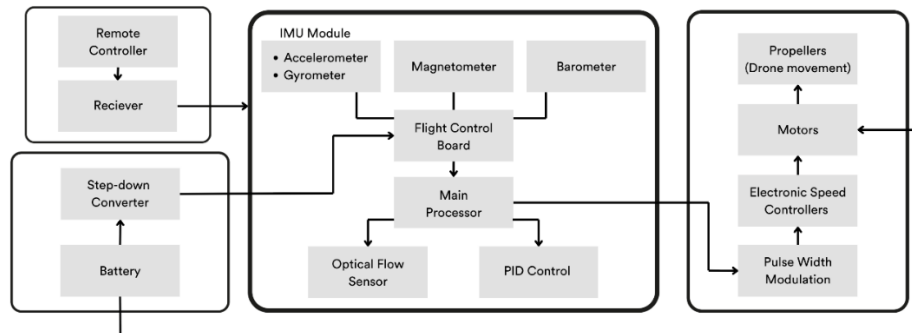


Figure 5: Electrical flow diagram.

### 5. Experiments

#### 5.1. Flight Test

To verify the flight performance of the Waterwing UAV, three sets of test experiments were set up in this project, as shown in Figure 6. The upper, middle, and lower groups are the take-off and landing test, lateral acceleration test, and forward-backward acceleration test respectively, while the horizontal direction shows the test process of the three sets of experiments.



Figure 6: Flight test process.

In conclusion, from the three experiments conducted to test the Waterwing's aerial performance, it is clear that the drone is capable of completing regular maneuvers such as taking off or landing and accelerating in various directions.

#### 5.2. Underwater Test

To test the underwater performance of the Waterwing UAV, two sets of tests were set up in this project. As shown in Figure 7, the upper and lower groups correspond to the acceleration test and the rotation test respectively, and the horizontal direction shows the test process. Meanwhile, the experimental data of the underwater pitch angle and roll angle of the UAV were recorded to reflect the stability of the UAV during underwater movement. Among them, the experimental processes of the acceleration test and the rotation test, as well as the underwater pitch angle and roll angle data, are shown in Figure 8.



Figure 7: Underwater test process.

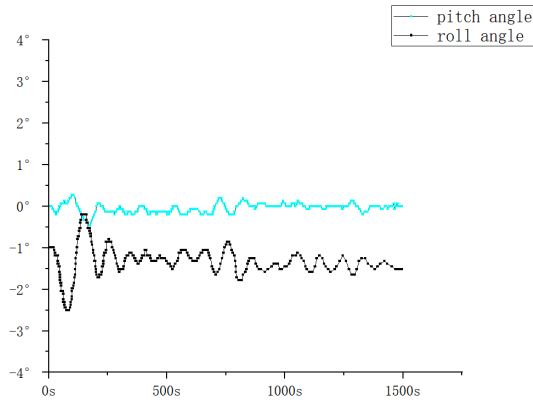


Figure 8: Underwater pitch and roll axis data.

After the above tests, the Waterwing UAV can complete acceleration and rotation movements underwater. At the same time, the pitch and roll data show that the pitch and roll angles remain relatively stable during the entire underwater acceleration and rotation process, proving that the parameters of the control system (PID) are set reasonably.

### 5.3. Air-Water Mode Conversion Test

#### 5.3.1. Air-Water Mode Conversion Test Process.

To test the reliability and stability of the water-air mode conversion of the hydrofoil UAV, two sets of experiments were set up in this project, as shown in Figure 9. The upper and lower groups correspond to the water entry test and water exit test respectively, and the horizontal direction represents the test process.



Figure 9: Air-Water mode conversion test process.

#### 5.3.2. Air-Water Mode Test Data

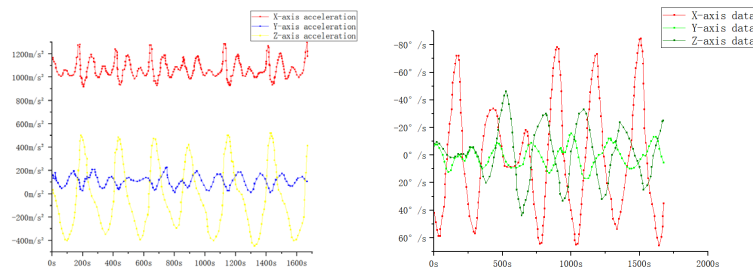


Figure 10: Accelerometer data(left) and gyroscope data (right).

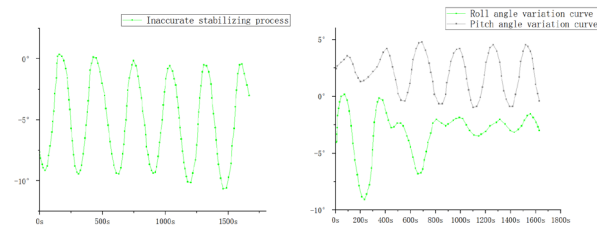


Figure 11: Inaccurate stabilizing process(left) and slow stabilizing process(right).

As shown in Figure 10 and Figure 11, from the acceleration and angular velocity data measured using the accelerometer and gyroscope within the IMU, we can calculate the drone's precise angle (pitch, roll, yaw), which is used to make adjustments on the drone's position and orientation (through the PID control system) and maintain stability throughout its flight. From the experiments with the PID control system's Proportional value, we can see that when the value is too large, the adjustments constantly overshoot, causing the drone to constantly fluctuate without maintaining stability. On the other hand, when the value is too small, adjustments are very gradual, causing the drone to take a long time before being able to remain stable.

## 6. Conclusion

This paper addresses the technical limitation that conventional drones cannot achieve both aerial flight and underwater maneuvering. It focuses on the design, development, testing, and optimization of the Waterwing hydrofoil amphibious quadcopter for practical applications such as underwater search and rescue and environmental monitoring, establishing a complete research and development system.

Structurally, the drone adopts an X-shaped quadrotor layout and consists of a main body and a fully sealed waterproof compartment. It is equipped with DS3218 waterproof rotatable servos, ceramic bearings, 2812 V3 brushless motors, and customized 3D-printed and laser-cut components to ensure structural stability and reliable underwater performance.

The control system is centered on PID and PWM regulation. The PID controller adjusts the drone's attitude and generates four independent PWM signals to control motor speed. The flight control unit integrates multiple sensors, and stable data processing is realized through complementary filtering and low-pass filtering algorithms. The electrical system includes electronic speed controllers (ESCs) and a buck converter with insulation protection to ensure continuous and safe power supply.

Flight, underwater, and air-water transition experiments show that the drone can perform stable maneuvers and achieve smooth mode switching. Its core innovation lies in the one-key air-water dual-domain operation capability. Future improvements will focus on enhancing environmental adaptability and adding functions such as GPS positioning and water quality monitoring.

## References

- [1] Balaguer C , Laschi C ,Monje A C .2018 *IEEE/RSJ International Conference on Intelligent Robots and Systems, Madrid, Spain [Society News][J].IEEE Robotics & Automation Magazine*,2019,26(2):111-113. 4.
- [2] *IEEE/RSJ International Conference on Intelligent Robots and Systems Award Recipients Announced [Society News][J].IEEE Robotics & Automation Magazine*,2020,27(1):128-130.
- [3] Ding L ,Zhu G ,Li Y , et al. *Cable-Driven Unmanned Aerial Manipulator Systems for Water Sampling: Design, Modeling, and Control[J].Drones*,2023,7(7).
- [4] Pahlke K ,Gardner A ,Jones M , et al. *Special issue on advances in rotorcraft research and technology: 49th European Rotorcraft Forum[J].CEAS Aeronautical Journal*,2025,16(4):1-2.
- [5] Xin C , Xiaozhou Z ,Wen Y .*FTESSO-adaptive neural network based safety control for a quadrotor UAV under multiple disturbances: algorithm and experiments[J]. Industrial Robot: the international journal of robotics research and application*,2024,51(1):20-33.
- [6] Lee D .*A Linear Acceleration Control for Precise Trajectory Tracking Flights of a Quadrotor UAV Under High-wind Environments[J]. International Journal of Aeronautical and Space Sciences*, 2021,22(4):1-13.
- [7] Kim T ,Chung J ,Kim Y , et al. *A Experimental Study of Aerodynamic Interference on Quad-Tilt Propeller UAV Wings in Forward Flight Condition[J]. Journal of the Korean Society for Aeronautical & Space Sciences*,2019,47(2):81-89.
- [8] Muluaem L Y ,Jin G G ,Kwon J , et al. *Backstepping Sliding Mode Control of Quadrotor UAV Trajectory[J]. Mathematics*,2025,13(19):3205-3205.
- [9] Tavoulareas T ,Cescon M .*Safety Assurance for Quadrotor Kinodynamic Motion Planning[J]. IFAC PapersOnLine*, pp.689-694, Jan. 2025.
- [10] Hernández N D ,Barrios M F C .*Modeling and control of an interactive tilt-rotor MAV. A robust delay-based strategy[J].Mathematics and Computers in Simulation*,2025,2(30):256-277.