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Design and Preliminary Validation of A Multi-mode Quadrotor Aerial-Aquatic Vehicle with Tilting Mechanism

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***Abstract*— This paper presents the development of a quadrotor vehicle capable of movement between air and water environments. The design challenges, including torque matching in the propulsion system, balance maintenance in different mediums, and waterproofing requirements, are discussed. A prototype is constructed to demonstrate the feasibility of the proposed design. Through the tilting mechanism in four rotors, the vehicle can not only fly in air like a normal quadrotor vehicle, but also propel in water with two configured rear thrusters. Moreover, the four tilted rotors cooperate in aligning the center of gravity and buoyancy, addressing limitations observed in traditional aerial-aquatic vehicles. The prototype has been verified through experiments in both air and water.**

***Index Terms*— Aerial-aquatic vehicle, quadroter, mechanism design, reconfiguration.**

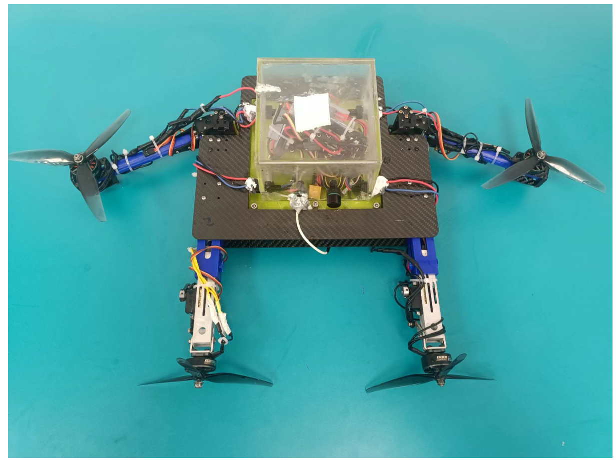

Fig. 1: Proposed multi-mode aerial-aquatic quadrotor vehicle with tilting mechanism.

I. Introduction

With the development of robotics technology, the operation of multi-mode robots in different environments has increasingly become a research focus. This has been demonstrated in the development of wheeled robots that possess additional mechanisms that allow jumping [1], [2], or flying [3], [4]. While these designs can enhance a robot's capability to overcome various terrestrial obstacles, expanding the scope of terrain navigation would be further facilitated if it could operate in entirely different media, such as both air and water. However, these media differ from terrestrial locomotion as they constitute three-dimensional fluid spaces, with water posing the greatest challenge due to its properties as a medium. Apart from the fundamental requirement for waterproofing, an efficient propulsion system compliant with underwater dynamics is essential.

Compared with land-water hybrid robots [5], air-water hybrids encounter even greater design challenges. In both air and water, maintaining position requires the robot to counteract the effects of gravity and buoyancy. Although the gravitational weight of the robot remains constant in both air and water, the disparity in fluid density results in significantly greater buoyancy when submerged. This additional phenomenon impacts vehicle stability and locomotion efficiency, necessitating specialized designs to maintain level orientation.

Additionally, the propulsion system must be capable of accommodating the distinct fluid properties to propel the vehicle effectively. Due to the more stringent requirement for generating sufficient lift, existing air-water hybrid robots typically employ aerial vehicles adapted for underwater operations. These often take the form of aerial platforms such as fixed-wing [6]–[8], multirotors [9]–[12], or a combination of both [13], [14]. While these examples demonstrate various kinds of hybrid locomotion, their operation in both media primarily relies on similar configurations and principles.

Given the requirement variation between air and water, employing a morphable mechanical structure adaptable to current conditions would better meet the demands of both environments [15], [16]. However, the vehicle described in reference [15], due to its fixed-arm structure, is only capable of achieving submersion and forward propulsion underwater separately and cannot actively adjust the position of the thrusters relative to the center of buoyancy. The vehicle described in reference [16], a foldable and self-deployable arm mechanism linked to and driven by a piston variable buoyancy system (PVBS) is proposed to reduce the excessive underwater drag caused by aerial structures. The piston-type VBS commonly used on floats has the advantages of small size, simple structure, and low power consumption [17]. However, in terms of flexibility and controllability, it

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is inferior to thruster propulsion.

In this paper, our aim is to comprehensively analyze the various challenges faced by air-water hybrid vehicles and propose a unique mechanical and control solution best suited for this purpose. By rotating the rear thrusters and front arms, the standard layout of an aerial quadrotor can be transformed into a propulsion layout highly suitable for underwater navigation (see Fig. 1). This not only makes underwater movement more efficient compared to relying solely on attitude control, but also enables active adjustment of the thrusters' relative position to the center of buoyancy.

The paper is structured as follows: Section II introduces the vehicle's design principles, Section III and IV present the prototype and the control methods of the vehicle, respectively. Experimental results are illustrated in Section V, and Section VI concludes the whole paper.

II. Design Principle

To achieve a vehicle capable of seamless transition between air and water, we need to address the following challenges:

1. Dual-environment propulsion system: We need to design a propulsion system capable of generating sufficient thrust in both air and water. This requires constructing a system that can adapt to the differences in these two mediums.

2. Buoyancy and balance control: To cope with the difficulties of operating in environments with significant differences in fluid density, the vehicle must have an active buoyancy control system. Whether it is positive or negative buoyancy, an active force is needed to counteract the net buoyancy or effective weight to ensure the vehicle maintains the desired depth underwater. Unlike other fixed-position quadrotors that maintain stability underwater through speed and torque distribution, our designed vehicle can align the center of gravity and buoyancy by mechanical structural changes, which provides advantages in both stability and energy efficiency.

3. Waterproofing: Due to the challenging underwater environment, the vehicle requires a robust waterproof design. The casing must be both compact and lightweight to strike a delicate balance between protection and functionality.

The first two challenges encapsulate the complexity of navigating in air and water. Differences in fluid density significantly affect the propulsion efficiency and the balance of the vehicle. This density disparity demands that the propulsion system can provide higher torque at lower speeds underwater. Thus, torque matching between the motor and propeller becomes a critical factor, determining the performance of the system under both operational conditions.

It is conceivable to employ separate propulsion systems tailored for each medium. However, the constraints of small-scale systems, particularly the limited weight budget, render this approach impractical. On the other hand, a unified propulsion system can result in inevitable trade-offs, especially when transitioning between very different mediums. We have chosen a quadrotor-type configuration as the base for the vehicle design. This choice stems from the platform's inherent versatility. We have developed a tilting mechanism to realize different locomotion modes for air-water transition. It offers a promising solution to address the multifaceted challenges stated before. The following sections will delve into specific strategies for overcoming these challenges and optimizing the vehicle's performance in both air and water. We will focus on propulsion system design, buoyancy control, and waterproofing techniques to construct a lightweight yet robust air-to-water transition vehicle.

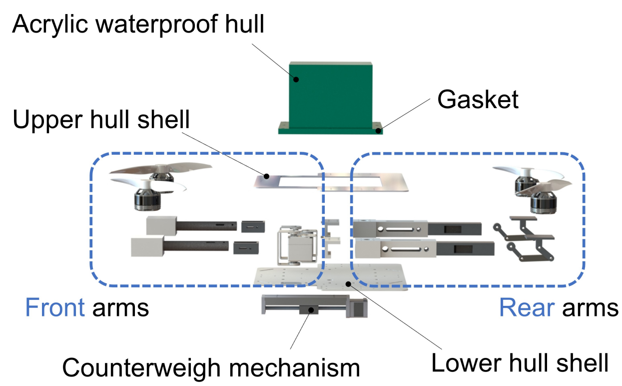

Fig. 2: Exploded view of the prototype design.

III. Prototyping

We have constructed a quadrotor vehicle prototype demonstrating the ability of maneuvering in both aerial and aquatic environment through special mechanism and control methods. The exploded view of the prototype is depicted in Fig. 2, which primarily consists of three main subcomponents: the front two arms, the rear two arms and the hull.

A. Tilting Mechanism

As shown in Fig. 3, the tilting mechanism allows the vehicle to realize two different configurations for propulsion in both air and water. The details of the mechanism are shown in Fig. 4. Two servo motors are used to actuate the front two arms rotate around the vertical z-axis at an angle of α. The other two motors actuate the rear two thrusters rotate around the horizontal y-axis through a four-bar linkage at an angle of β. The waterproof compartment is housed within a framework, forming the primary structure of the vehicle along with the aforementioned tilting mechanisms.

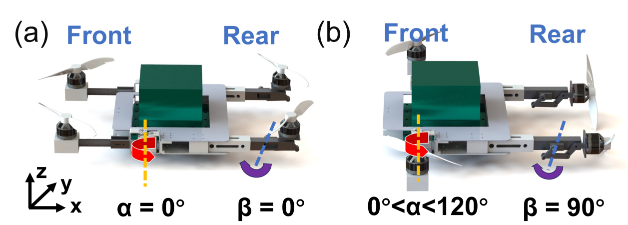

Fig. 3: Modes and corresponding joint angles of the vehicle for different environment propulsion. (a) Air mode; (b) water mode.

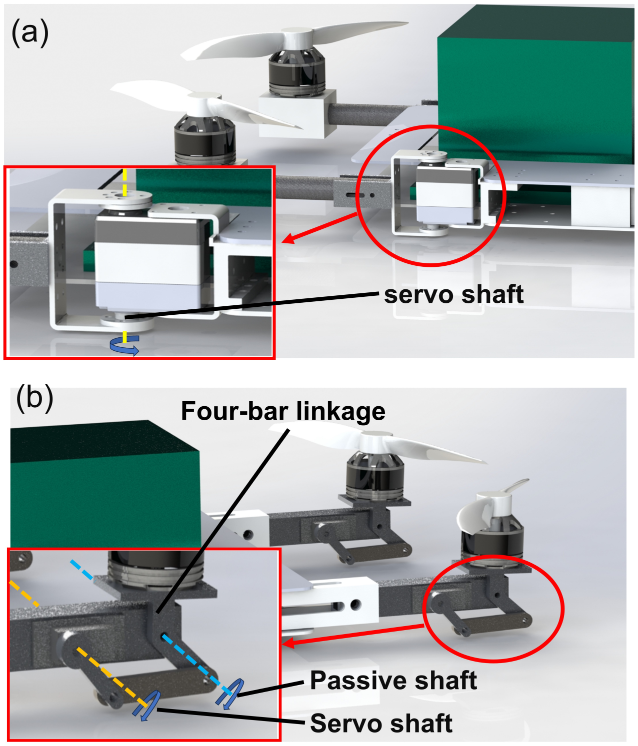

Fig. 4: Tilting mechanism. (a) Front tilting mechanism for arm rotation; (b) rear tilting mechanism for propeller rotation.

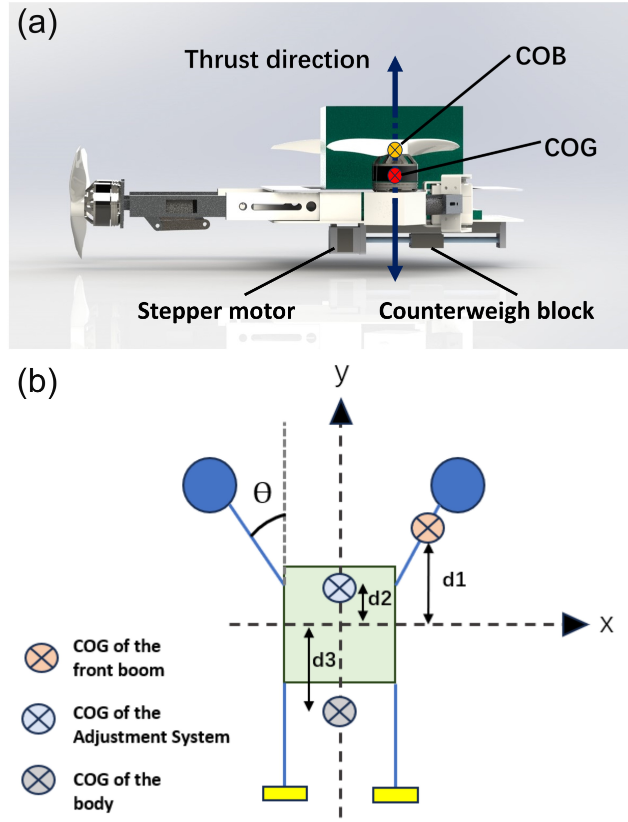

Fig. 5: Principle of center of gravity adjustment. (a) COG, COB, and thrust direction collinear; (b) the schematic diagram of gravity adjustment.

Compared to conventional quadrotors where the four arms with motors are typically rigid structures, the front cantilever arm here requires rotation. To achieve this rotation while maintaining structural rigidity, the vehicle frame is designed with support points extending from the center to support the tilting mechanisms. When the tilting mechanism is activated, it does not obstruct the propellers since the design allows rotation in only one direction.

B. Vertical Thrusters and COB Adjustment Mechanism

To avoid the additional weight and volume that would come with carrying an active buoyancy control system, we opted to compactly package the vehicle components to achieve a design close to neutral buoyancy.

When transitioning to underwater mode, the front tilting mechanism allows the front thrusters connected to the front arm to rotate around the z-axis by a certain angle α ($0^\circ < \alpha < 120^\circ$). This ensures that the vertical thrusters responsible for buoyancy control in the x-z plane remain aligned with the center of buoyancy and center of gravity on the same line, enhancing adaptability to the underwater environment, as shown in Fig. 5. The rear tilting mechanism rotates the rear propellers by 90° (β =90°) to become horizontal thrusters.

This design provides more efficient underwater propulsion and balance, while avoiding the attitude calibration issues that may arise during the transition from surface to underwater. With this innovative tilting mechanism, the vehicle can maneuver more flexibly in both mediums and ensure sufficient stability underwater. The design also allows for flexible adjustment of the thruster positions by changing the tilt angle of the longitudinal vertical thrusters based on the current position of the center of buoyancy. Additionally, by adding a center of gravity adjustment device composed of a screw, a stepper motor, and a counterweight block the center of mass position can be adjusted by adding ballast blocks to ensure that the thrust direction remains aligned with the center of buoyancy and center of gravity on the same line (see Fig. 5.(b)), adapting to various underwater environments, which can alternatively be expressed in the following formula:

$$M_F d_3 g = (2M_f d_1 + M_A d_2)g \tag{1}$$

$$d_1 = L_f \cos\theta \tag{2}$$

where M_F is the mass of the frame excluding the front boom, M_f is the mass of the front boom, M_A is the mass of the gravity adjustment device and L_f is the length of the front boom.

C. Hardware

The target design for the distance or wheelbase between the propeller motors is 250 millimeters. Based on the performance scores of various combinations of potential engines and propellers in the database [18], the selected system consists of the T-MOTOR F100-1350KV motor paired with T8045×3 propellers, powered by a 6S lithium high-voltage battery. To evaluate the performance of the propulsion unit in underwater motion, the propulsion ability is to be assessed through static output characteristics. The ESC limit is set to 30A. Based on the size, weight, and aviation requirements of the ESC, the safe operating range underwater can be restricted by air-break switch within 30A to avoid damage.

The avionics equipment consists of Pixracer flight control hardware running on PX4. A micro-USB is used for manual control, capable of communication in freshwater up to a depth of 5 meters. Table I provides a summary of the hardware components used in the prototype.

TABLE I: Summary of the hardware

Motor	T-MOTOR F100-1350KV
Propeller	T8045×3
Electronic Speed Controller (ESC)	Multistar 30 A
Battery	BOLT LiHV 6S 2200mAh
Flight Controller	Pixracer R15
Radio System	model1
Air-break switch	30A
Front servo	DSSERVO 30kg
Rear servo	KMI703

D. Hull design

The components that need to be installed inside the hull include the flight controller, power distribution board (PDB), battery, receiver, and ESC. Ideally, these should be packaged as compactly as possible to minimize the vehicle's volume while ensuring that the center of gravity remains below the center of buoyancy.

Within the main hull, the heaviest component is the battery, which is placed at the bottom. The PDB and flight controller are mounted in a stack above the battery, utilizing brackets extending from the top of the hull. The complete vehicle, including the enclosed hull, has a center of buoyancy (COB) located 20 millimeters vertically above the center of gravity (COG) when fully submerged, as shown in the diagram.

The design of the sealed compartment is intended to maintain waterproof sealing while facilitating the connection between the ESC and flight controller. Four openings are provided on the sides of the sealed compartment to pass through cables connecting the ESC to the motors, including three motor plug connections for each motor (totaling twelve) and two receiver connections for tilt servos and receiver signal lines. The wires of motors and servos are routed out of the waterproof hull through feedthrough bolts and sealed with epoxy resin to ensure waterproofing.

IV. Control Methods

A. Control Structure

The control structure of quadrotors is shown in Fig. 6. The central power source consists of a battery unit, which provides electrical energy to the entire system. This is facilitated through a Universal Battery Elimination Circuit (UBEC) that steps down the voltage to a suitable level for the avionics. The system's core avionics include an autopilot module, which integrates an accelerometer/gyroscope and a barometer to facilitate stable flight dynamics and altitude control, a depth sensor is employed.

The propulsion mechanism comprises electronic speed controllers (ESCs), which modulate the electrical supply to the propellers, thereby controlling the thrust output. The ESCs receive their commands from the autopilot, which adjusts the vehicle's thrust in response to navigational inputs. Servomechanisms for both forward and rear alignment are included, indicating a vectored thrust capability or control surface adjustments for navigation. The system also features a tilting mechanism, potentially for varying the propulsion vector to enable transitions between flight modes.

B. Dynamic Model

To achieve motion control of the vehicle underwater, we meticulously referred to prior work documented in [19]. Utilizing the conventional northeast-down position framework outlined in [20], the dynamic behavior of our system was modeled. By adhering to established principles and methodologies, we developed a robust model that accurately captures the intricacies of the system's dynamics. Through this framework, we delved into the intricate dynamics governing the motion of the vehicle. The system's dynamics modeling can be represented as:

$$\boldsymbol{M}\ddot{\eta} + \boldsymbol{C}(\eta)\dot{\eta} + \boldsymbol{D}(\eta)\dot{\eta} + \boldsymbol{g}(\eta) = \tau \tag{3}$$

$$\begin{bmatrix} \boldsymbol{M} & 0 \\ 0 & \boldsymbol{I} \end{bmatrix} \begin{bmatrix} \ddot{\eta} \\ \dot{\eta} \end{bmatrix} = \begin{bmatrix} \mathbf{F_b} \\ \mathbf{M_b} \end{bmatrix} + \begin{bmatrix} 0 \\ \tau_\eta \end{bmatrix} \tag{4}$$

$$\mathbf{F_b} = \begin{bmatrix} \cos(\psi)(T_1+T_2) \\ \sin(\psi)(T_1-T_2) \\ 0 \end{bmatrix} + (mg-U) \begin{bmatrix} -\sin(\theta) \\ \sin(\phi)\cos(\theta) \\ \cos(\phi)\cos(\theta) \end{bmatrix} \tag{5}$$

$$\mathbf{M_b} = \begin{bmatrix} l_1(T_3-T_4) \\ 0 \\ l_2(T_1-T_2) \end{bmatrix} + \sum_{i=1}^{4} \begin{bmatrix} M_{iX} \\ M_{iY} \\ M_{iZ} \end{bmatrix} \tag{6}$$

The indications of the parameters in the formula are as follows:

- $\boldsymbol{M}$: Mass matrix.
- η: The underwater vehicle's position and orientation.
- $\boldsymbol{C}(\eta)$: Matrix containing Coriolis and centrifugal forces.
- $\boldsymbol{D}(\eta)$: Matrix describing hydrodynamic damping and restoring forces, accounting for the damping and restoring effects due to hydrodynamic forces.
- $\boldsymbol{g}(\eta)$: Resultant force and moment caused by gravity and buoyancy.
- τ: Total applied external control force and control moment.
- T_i: Thrust produced by the motor i.
- M_i: Moment in the X, Y, Z axis.

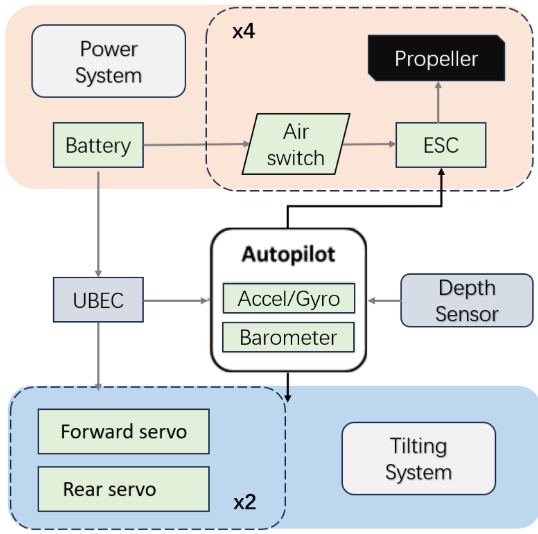

Fig. 6: Control structure of the designed quadrotor.

V. Experimental Verification

A. Propeller Test

As shown in Fig. 7(a), the propulsion test stand is developed to examine the propulsion unit's actual performance. The motor, along with the propeller, is fixed on a thrust test stand capable of displaying tension, current, and power.During the tests, the propeller is submerged in water and the motor speed is controlled through the flight control board. Data for tension and power are measured. The tension equals the thrust generated by the propeller. Fig. 7(b) displays the power, the tension and the specific thrust data obtained for different propeller speeds of the motor (0-600 RPM). The specific thrust is the ratio of the tension to the power, which indicates the efficiency the propeller. It can be observed that both the power and the tension almost increase linearly along with the increase of the motor speed, while the specific thrust achieves maximum at 200 RPM.

B. Motion Tests

The fully assembled prototype, as shown in Fig. 1, has an all-up weight (AUW) of 2025g. Testing was conducted on the prototype to validate the following primary objectives: ensuring that the designed framework and added tilt components do not compromise structural rigidity and have no adverse effects on aerial flight; ensuring that the hull design possesses sufficient waterproofing capabilities while achieving ideal buoyancy dynamics and underwater stability.

The aerial flight tests confirmed that the designed tilting structure provided sufficient rigidity to maintain the tiltable arm in a fixed aerial configuration, and the aircraft flew like a standard quadrotor. The current configuration allows for a hover flight time of 7 minutes, limited by battery capacity. However, the prototype is capable of generating a maximum thrust-to-weight ratio (T/W) of 4.4, indicating that larger capacity batteries could easily extend the endurance.

As in water mode, the prototype was capable of executing water entry, and movement on the water surface. Fig. 8(a) and (b) show the vehicle ascend from diving at the bottom to floating on the water surface. Once the thrusters have breached the water surface, the vehicle realized transition from the water mode (Fig. 8(c)) to the air mode (Fig. 8(d)), so as to aerial flight (Fig. 8(e)). After experimental validation, the aircraft designed in this paper, utilizing a tilting mechanism, achieved satisfactory attitude control compared to traditional centrally symmetrical quadrotor aircraft. As shown in Fig. 9, we also conducted tests to observe the vehicle's actual attitudes as the set values were varied, showing good stability, responsiveness, and tracking ability.

VI. Conclusion

Developing an aerial-aquatic vehicle continues to pose significant challenges. In this paper, We have constructed a quadrotor prototype to demonstrate the feasibility of our proposed design. Through the tilting mechanisms, the prototype can flexibly transition underwater into a configuration with two lateral vertical thrusters and two rear thrusters. This design achieves good balance and efficiency in both aerial and aquatic movement. Furthermore, it aligns the center of gravity and the center of buoyancy through mechanical structure changes, addressing the drawbacks of traditional air-water vehicles that can only passively adjust the center of gravity and buoyancy. This alignment provides advantages

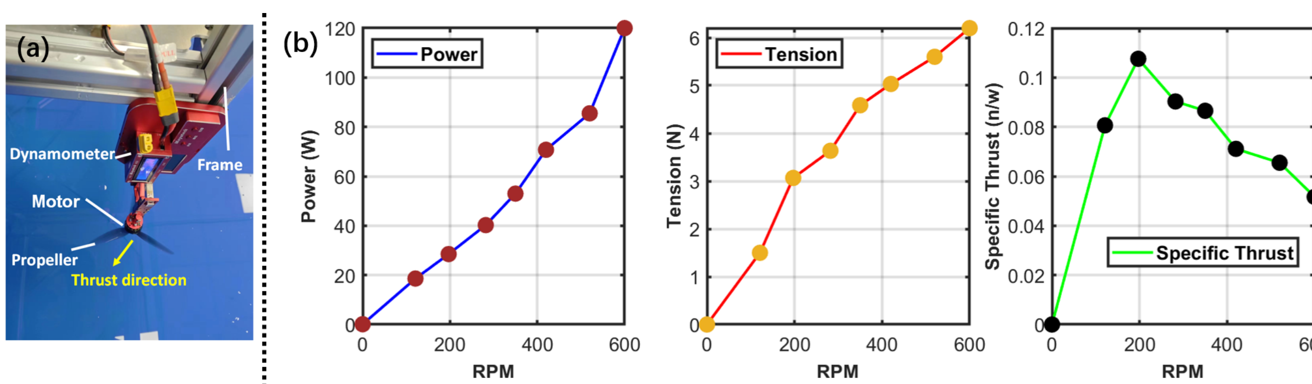

Fig. 7: The performance test of the propeller when actuated underwater. (a) Measurement setup; (b) results.

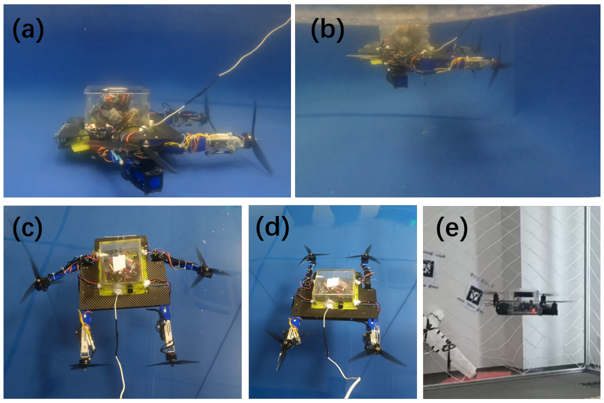

Fig. 8: Testing of the prototype from (a) diving to (b) floating, and transitting on the water surface from (c) water mode to (d) air mode, and (e) aerial flight.

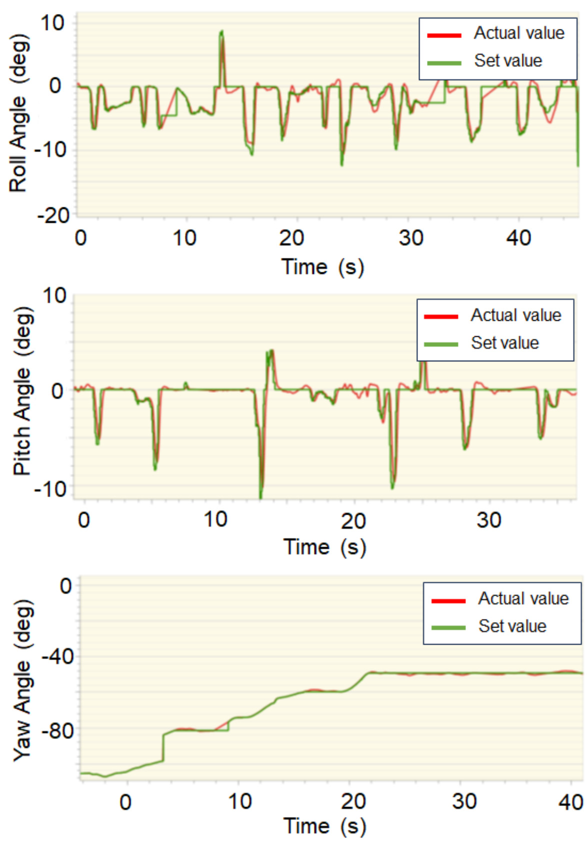

Fig. 9: Euler angles and respective set point angles of the vehicle over time as it conducts a flying maneuver in the field.

in terms of stability, energy efficiency, and adaptation to load changes.

Future work will encompass precise motion control in both air and water, as well as optimization of the vehicle through enhancements such as wireless capabilities and improved mechanical design.

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