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YingLong-Hel: Design and Implementation of a Hybrid Aerial Underwater Vehicle with Integrated Adaptive Rotor Module

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***Abstract*—Hybrid Aerial Underwater Vehicle (HAUV), capable of aerial flight, underwater navigation, and seamless air-water medium transition, hold significant potential for cross-domain missions. However, current HAUV still encounter significant challenges regarding cross-medium stability, transition success rates, and integrated air-water propulsion. To address these limitations, a novel HAUV, YingLong-Hel, featuring a coaxial dual-rotor architecture and an integrated adaptive rotor module, is proposed. The prototype, which has dimensions of 445 $\times$ 240 $\times$ 485 mm and a total mass of 2.6 kg, achieves a thrust-to-weight ratio of 2:1, enabling high-efficiency propulsion across both aquatic and aerial environments through the integrated adaptive rotor module. Through field experiments, the aerial flight, underwater navigation, and cross-medium capabilities of YingLong-Hel are validated. YingLong-Hel presents a practical solution for HAUV applications and offers a platform for future collaborative research in this domain.**

***Index Terms*—Hybrid Aerial Underwater Vehicle(HAUV), Integrated Air-Water Propulsion, Coxial Dual-Rotor.**

I. Introduction

The hybrid aerial underwater vehicle (HAUV) is a novel vehicle capable of aerial flight, underwater navigation, and seamless transition across the air-water interface, offering significant potential for both military and civilian applications. Due to the refraction and scattering of light in water, which reduces visibility, and the shielding of electromagnetic signals, the HAUV leverages underwater navigation strategies to achieve superior stealth capabilities [1], [2]. Additionally, underwater navigation consumes less energy, making it suitable for long-distance and long-duration missions [3]. In contrast, the low density and resistance of air enable the HAUV to utilize aerial flight strategies to achieve higher speeds, longer travel distances, and the ability to overcome terrestrial obstacles.

The multi-rotor HAUV is currently the most developed type with the advantages of simple structure, vertical takeoff and landing, aerial hovering, strong maneuverability, and flexible operation. However, there are also some drawbacks, such as irregular shapes leading to high underwater drag, instability of single-layer propellers when crossing the air-water interface, lack of compact design, low payload capacity, and high energy consumption. To address the aforementioned shortcomings, various solutions have been proposed. To reduce water resistance, a foldable-arm HAUV named Nezha-F, based on a piston variable buoyancy system (PVBS), was also proposed in [4]. In [5], the "Nezha-mini" HAUV was introduced, showcasing a highly compact and lightweight design with a weight of only 953 grams and dimensions comparable to an A4 sheet. In [6], a bone-shaped HAUV, named Nezha-B, was introduced, utilizing a double-layered and staggered quadrotor configuration to minimize the vehicle's size. However, the above miniaturization measures were achieved at the expense of some payload capacity and roll control performance. As proposed in [7], a ducted fan is utilized instead of a conventional aerial propeller to enhance underwater propulsion performance.

Addressing high energy use and slow speed in multi-rotor HAUVs, hybrid multi-rotor/fixed-wing designs have emerged. Notable examples include the Nezha-SeaDart from Shanghai Jiao Tong University [8], the HAUV with tunable tilting motors and a delta wing from Zhejiang University [9], and the Diving Hawk from Sun Yat-sen University, which integrates a tilt-rotor unmanned aerial vehicle (UAV) and a hybrid underwater glider (HUG) [10]. This inevitably increases the size of the HAUV. Additionally, in the case of the latter two solutions, the large contact area between the wings and the water surface leads to increased adhesion, which weakens the cross-medium water-exit performance.

Compared to multi-rotor AUVs, coaxial rotor systems offer advantages such as a larger rotor area for improved flight efficiency and payload capacity [11], reduced energy loss during control, lower noise due to lower rotor speeds, and a more compact design enhancing maneuverability [12]. While

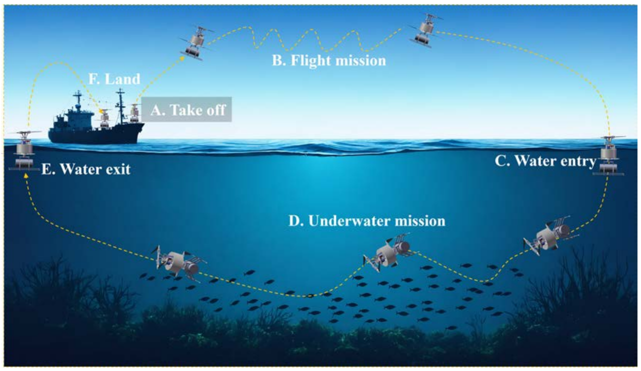

Fig. 1. Overview of the complete operational cycle in air and underwater.

researchers have explored coaxial HAUV [13], [14], limitations persist, including untested prototypes, complex independent drive systems hindering direct takeoff/landing, and inadequate cross-medium performance with slow transition times. These limitations in current coaxial dual-rotor HAUV research necessitate a novel design, as presented in this paper.

HAUV propulsion typically involves propellers, with performance significantly impacted by using inappropriate propellers for the medium [15]. Current drive solutions are broadly categorized as air-water independent or integrated systems. Air-water independent systems, as seen in [14], [16], [17], offer optimal performance in each medium but increase robot weight, size, and complexity, impacting payload and reliability. Integrated drive systems, such as direct motor drive with a gearbox for underwater operation [18], can compromise underwater propulsion efficiency due to the use of aerial propellers and complex gearbox structures. Another approach involves modifying aerial propellers for underwater folding [19], which maintains motor efficiency but yields suboptimal underwater performance.

This paper introduces a novel HAUV, YingLong-Hel (overview in Fig. 1), with the following key contributions: 1) a coaxial counter-rotating rotor system aimed at enhanced thrust efficiency and maneuverability, overcoming limitations of conventional designs; 2) an integrated adaptive rotor module featuring unified aerial and underwater blades for efficient propulsion in both mediums, reducing system volume, weight, and complexity compared to independent systems; and 3) an attitude control module based on the direct flight control (DFC) rotor head assembly, with simplified pitch control on the upper rotor for more agile control and improved power efficiency.

II. Design of Vehicle Structure and Electronics

A. Configuration Overview

As illustrated in Fig. 2, YingLong-Hel is primarily composed of several key subsystems: a Integrated Adaptive Rotor Module, a DFC (Direct Flight Control, assuming DFC stands for this, otherwise leave as DFC) Rotor Head Module, a Drive Module, an Electronics Compartment, Integrated Landing Gear, and a Buoyancy Adjustment Compartment. The Integrated Adaptive Rotor Module interfaces with both the DFC Rotor Head Module and the Propulsion Module. The DFC Rotor Head Module, connected to the upper section of the Propulsion Module, governs the vehicle's pitch, roll, and vertical motion. The lower section of the Propulsion Module links to the Integrated Landing Gear. It is responsible for driving the integrated adaptive rotors and controlling the tilt angle and vertical displacement of the swashplate. Mounted on the Integrated Landing Gear, the Electronics Compartment supplies power and facilitates vehicle control functions. Finally, the Buoyancy Adjustment Compartment, connected to the main structural frame, regulates the vehicle's attitude when submerged.

The YingLong-Hel prototype exhibits dimensions of 445 x 240 x 485 mm (Length x Width x Height). The adaptive rotor module has a wingspan of 600 mm when deployed. In its folded configuration, the rotor module measures 278 mm in length. The prototype has a mass of 2.6 kg.

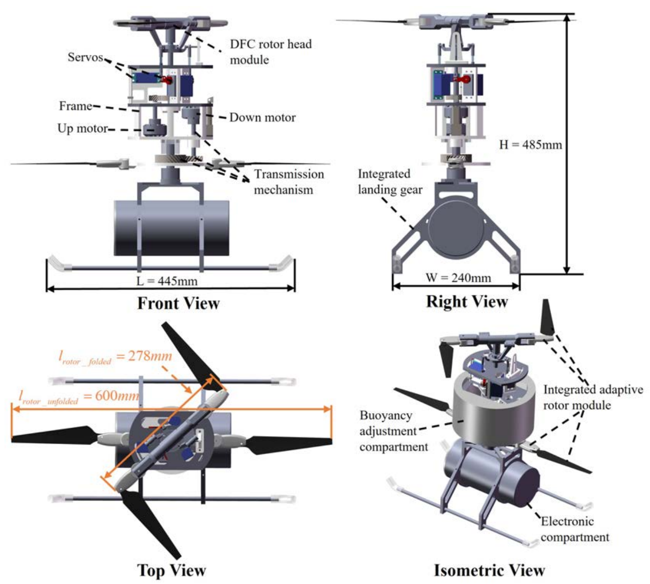

Fig. 2. Schematic diagram of YingLong-Hel, illustrating different views and labeled with key component names and dimensions.

B. Integrated Adaptive Rotor Module

The differences in density and viscosity between water and air are significant. Under the same conditions, water is approximately 800 times denser than air and about 50 times more viscous. Therefore, different mediums require specially designed propellers to achieve optimal propulsion efficiency.

Informed by the methodology detailed in [19] by Li et al., an integrated adaptive rotor module is proposed herein to improve underwater propulsive efficiency. The integrated adaptive rotor module comprises four identical units, each consisting of a underwater propeller and an aerial propeller as shown in Fig. 3. Due to variations in the upper and lower drive connection structures, different underwater propeller designs were implemented, as illustrated in Fig. 3(a) and (b). Notably, while the blade geometry of these underwater propellers remained consistent, only their connection structures differed. Mechanically, one end of the underwater propeller is coupled to the actuation system, while the opposing end is connected to the aerial propeller. Notably, the aerial propeller is designed to rotate relative to the underwater propeller, enabling unfold state during aerial locomotion(Fig. 3 d) and a folded state for underwater operation(Fig. 3 c). The four units are arranged in two pairs: the upper and the lower pairs. Within each pair, the aerial propellers exhibit an opposing folding direction when in the folded state.

The integrated adaptive rotor operates based on the following principles: During the transition from underwater to aerial locomotion, the aerial propeller autonomously rotates relative to the water propeller to a unfolded configuration under the influence of centrifugal forces. This deployment generates sufficient lift for sustained aerial flight. Conversely, upon transitioning from aerial to underwater operation, the hydrodynamic drag forces exerted by the water cause the aerial propeller to automatically rotate relative to the submerged propeller into a folded configuration. In this state, propulsion is primarily provided by the submerged propeller, allowing the drive unit to maintain a relatively high rotational speed, thereby ensuring efficient power output. Furthermore, the folded aerial propeller minimizes hydrodynamic drag during submerged navigation.

This design facilitates a more compact vehicle layout and enables a shared drive unit for both aerial and underwater propulsion. The direct and efficient power transmission pathway minimizes energy losses typically associated with additional transmission mechanisms. Consequently, this integrated adaptive rotor facilitates high-speed cruising in both aerial and underwater environments while simultaneously reducing the overall volume, weight, and control complexity of the propulsion system.

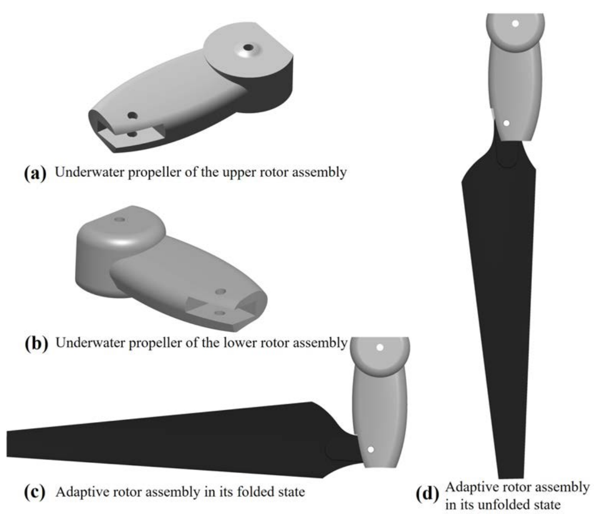

Fig. 3. Schematic diagram of the integrated adaptive rotor module, including the specially designed underwater propeller and different states of the rotor assembly.

C. Altitude Control Module

For attitude control, this research employed a Direct Flight Control (DFC) rotor head assembly, a mature and widely adopted system in the field of model helicopters. The DFC rotor head was selected for its responsiveness, precision, and integrated design, offering effective control over the vehicle's pitch, roll, and lift. As illustrated in Fig. 4, the principal components encompass the main rotor grip, main motor hub, linkage arms, swashplate, ball links, spinning shaft and servos.

The DFC rotor head assembly governs aircraft attitude and lift by adjusting rotor blade pitch through swashplate manipulation. Tilting the swashplate cyclically alters blade pitch during rotation, generating differential lift across the rotor disk, which induces roll and pitch moments. Vertical movement of the swashplate simultaneously adjusts the collective pitch of all blades, thereby controlling the overall lift for ascent or descent.

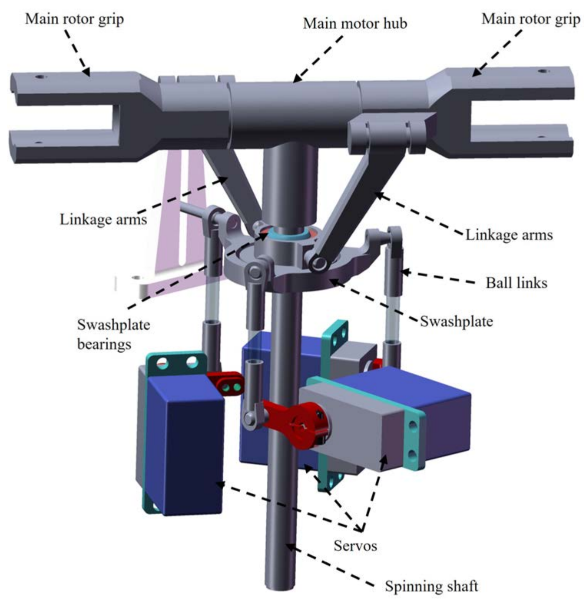

Fig. 4. Schematic diagram of the attitude control module based on the DFC rotor head assembly.

D. Drive Module

Due to the coaxial dual-rotor design, if the lower electronic cabin is used to power the motors, the issue of routing the upper motor's wiring through the lower motor's working area inevitably arises. If the motor has a central through-hole, the wiring of the upper motor can pass through it. However, commercially available brushless motors with a central through-hole that are suitable for aerial flight are extremely rare, making it difficult to find a suitable model. To address the wiring challenge for the upper motor and attitude control servos, we designed the drive module shown in Fig. 5. This module consists of a frame, a hollow fixed shaft, two brushless motors, a transmission shaft and positioning bearings, a gear set, and a rotating disk. The wiring from the electronic cabin passes through the hollow fixed shaft to connect the motors and servos. The upper motor drives the spinning shaft through a transmission shaft and a gear set with a module of 1 and a gear ratio of 15:26, thereby powering the upper rotor assembly. The lower motor drives the rotating disk via a transmission shaft and a gear set with a module of 1.5 and a gear ratio of 15:26, ultimately driving the lower rotor assembly.

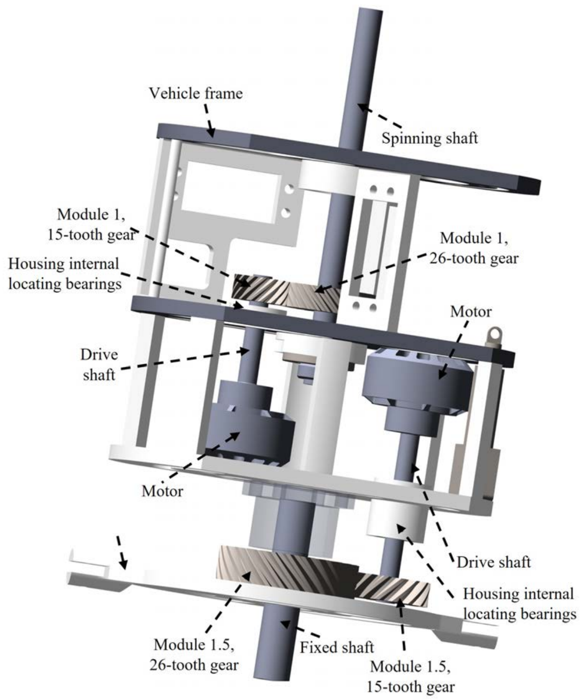

Fig. 5. Design diagram of the drive module, illustrating component names and their connections.

E. Avionics

YingLong-Hel employs a Pixhawk 6C Mini flight controller with custom ArduPilot Copter firmware, powered by a 6S lithium battery regulated by a Holybro PM02D power module, which also monitors power consumption. A 24V-to-5V BEC powers the servos. The buoyancy adjustment chamber is controlled by a linear actuator via relays. Electronic speed controllers (ESCs) manage the brushless motors. The system integrates a GPS module, a depth sensor, and a water immersion sensor for navigation and cross-medium transitions. Wireless communication is established through a 2.4 GHz transmitter and receiver. Detailed component composition and wiring are illustrated in Fig. 6, and device specifications are summarized in Table I.

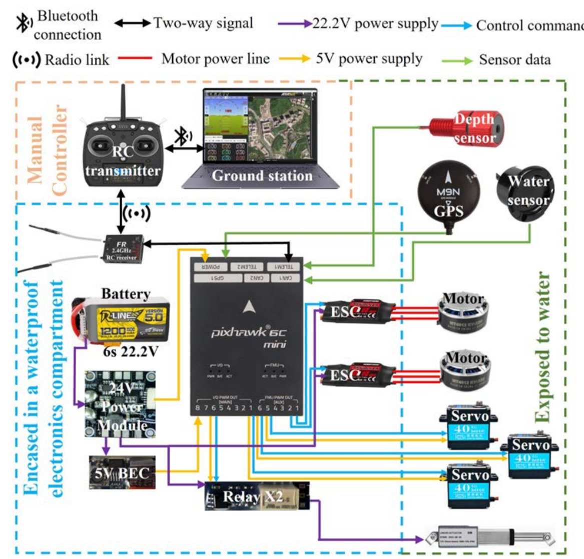

Fig. 6. Electronic layout of YingLong-Hel, illustrating onboard and offboard components and their connections.

TABLE I
YINGLONG-HEL COMPONENT SELECTION

Component Name	Type
Flight Controller	Pixhawk 6C Mini
Battery	Grepow R-Line5.0 LiPo 6S 150C 1200mAh
Power Module	Hoybro PM02D
BEC	5V5A
PWM Relay	XingXing 30V2A
Linear Actuater	24V 50mm
Servo	RS1040 40Kg
ESC	HOBBYWING Skywalker-V2 60A
Motor	TAROT-RC MT4012 320KV
Aerial Propeller	TAROT-RC 18X6.5J
GPS	Holybro M9N
Water Sensor	KLT-SJBSQ
Depth Sensor	MS5837
Transmitter	SIYI FT24 2.4GHz
Receiver	SIYI FR 2.4GHz

III. CONTROL STRATEGY

A. PID-based Motion Control

YingLong-Hel employs a Proportional-Integral-Derivative (PID) control strategy adapted for its coaxial dual-rotor architecture and integrated adaptive rotor module, enabling unified aerial and underwater operations.

In aerial flight, the PID controller regulates the vehicle's attitude (pitch, roll) by manipulating the pitch of the upper rotor via the DFC rotor head assembly. Yaw control is achieved through differential thrust between the counter-rotating coaxial rotors. The PID loops are implemented to minimize the error between the desired attitude and the measured attitude, ensuring stable and responsive flight characteristics.

For underwater navigation, the PID control strategy is adapted to manage depth and attitude. Depth control is achieved by an electric actuator that adjusts the position of a buoyancy chamber, thereby modulating the vehicle's pitch angle. This mechanism is coupled with thrust adjustments to control the vehicle's vertical motion. Attitude control (roll and yaw) underwater utilizes similar principles as in aerial flight, albeit with potentially different PID parameters to account for the higher density and viscosity of water. During underwater operation, the aerial blades of the adaptive rotor module are folded to minimize drag and optimize hydrodynamic efficiency. The PID controller works to maintain the desired depth and orientation, enabling stable underwater trajectory tracking.

The PID control parameters for both aerial and underwater modes were empirically tuned through a series of field experiments to achieve optimal performance in terms of stability, responsiveness, and minimal overshoot.

B. Cross-Domain Transition Control

The YingLong-Hel is designed with a slight negative buoyancy, and its center of gravity and center of buoyancy are positioned approximately along the same vertical axis. This configuration facilitates stable transitions between aerial and aquatic environments.

Water Entry Procedure: Upon approaching the water surface to within a 1-meter range, the propellers are commanded to cease rotation. The vehicle then undergoes a freefall splashdown, typically maintaining a near-vertical orientation due to its design. Immediately upon water contact, the electric actuator adjusts the position of the buoyancy chamber. This action shifts the center of buoyancy downwards, positioning it below the center of gravity. Consequently, the vehicle's attitude is passively adjusted from vertical to a horizontal orientation, with the nose pointing downwards, facilitating controlled submersion into the water.

Water Exit Procedure: Initiating the water exit, the electric actuator repositions the buoyancy chamber to elevate the center of buoyancy above the center of gravity. This shift in forces reorients the vehicle from a horizontal to a vertical attitude. Subsequently, both the upper and lower propellers simultaneously increase their rotational speed, generating upward thrust to propel the vehicle towards the water surface. As the upper propeller reaches the water surface, detected by the co-planar water immersion sensor, its rotation is immediately halted. This temporary cessation prevents the propeller from experiencing uneven lift forces caused by the complex water-air interface, which could destabilize the vehicle's attitude. Once the upper propeller has completely cleared the water surface, its rotation is immediately resumed to generate upward lift. A similar strategy is employed as the lower propeller reaches the water surface: its rotation is temporarily stopped until it fully emerges from the water, whereupon it is restarted. With both propellers now operating in air, they collectively provide the necessary lift to fully extract the YingLong-Hel from the water, completing the transition from the aquatic to the aerial domain. The precise timing of propeller cessation and restart is governed by the signals from the water immersion sensors integrated at the propeller plane.

IV. Experiments Results

A. Underwater Rotor Thrust Experiment

To evaluate the performance of the underwater propeller within the integrated adaptive rotor module, aerial and underwater thrust tests were conducted, as depicted in Fig. 7. The aerial thrust test, performed with a 24V power supply, yielded a thrust of only 0.03N at 60% throttle and 8400 rpm. This result indicates that the underwater propeller generates negligible thrust during aerial flight, with lift primarily attributed to the aerial propeller. Conversely, the measured data presented in Fig. 7(b) demonstrates that the designed underwater propeller provides sufficient thrust to easily propel the vehicle underwater, thus meeting the aquatic propulsion requirements.

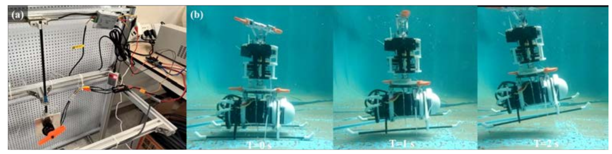

Fig. 7. Thrust performance testing of the underwater propeller in air and water. (a) Experimental setup for aerial thrust test (b) Measured underwater thrust

B. Integrated Adaptive Rotor Module Experiment

The adaptive deployment and folding experiment of the aerial blades in the integrated adaptive rotor module is illustrated in Fig. 8. For clarity, the corresponding blades are highlighted with red dashed boxes. The experimental results demonstrate rapid transitions: during the aerial flight phase, the aerial blades fully deploy from the folded state within 0.05 seconds, while during the underwater navigation phase, they complete folding within 0.1 seconds, indicating near-instantaneous actuation. This integrated adaptive rotor module effectively enables a single power system to drive both aerial and underwater propellers, ensuring efficient propulsion across different mediums.

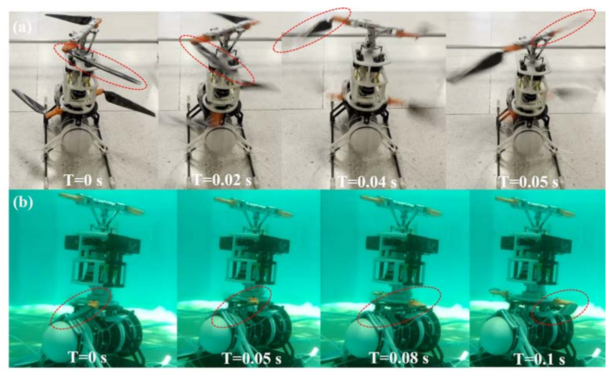

Fig. 8. Deployment and folding experiment of the integrated adaptive rotor module. (a) Aerial blade deployment during flight. (b) Aerial blade folding during underwater navigation.

C. Experimental Validation of Cross-Domain Locomotion

The core capabilities of YingLong-Hel in aerial flight, underwater navigation, and cross-domain locomotion have been demonstrated. In terms of performance, the vehicle achieves an aerial altitude of 20 m, an average flight speed of 5 m/s, and an aerial endurance of 8 minutes. Underwater, it reaches a maximum cruising speed of 1.5 m/s with an endurance of

30 minutes. To optimize propulsion efficiency, YingLong-Hel maintains a vertical orientation during aerial flight and transitions to a horizontal orientation for underwater navigation. Fig. 9 illustrates representative keyframe sequences of its aerial flight and underwater motion, showcasing the fundamental maneuvering capabilities that enable cross-domain transition.

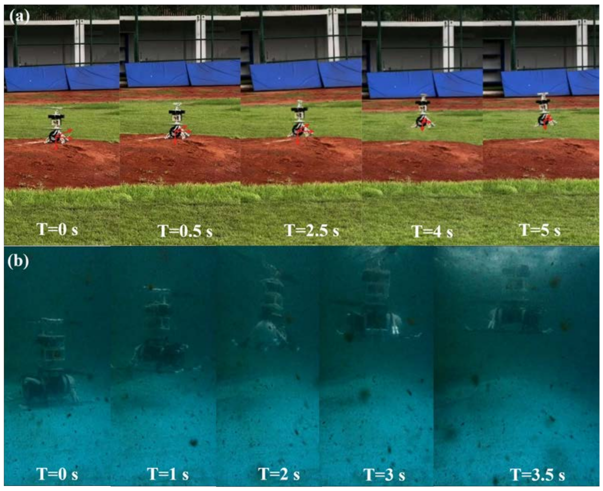

Fig. 9. Keyframes of YingLong-Hel's aerial flight and cross-medium water exit process. (a) Aerial flight phase. (b) Water exit and underwater motion phase.

V. Conclusion

A novel HAUV named YingLong-Hel was presented in this paper, which is designed to overcome limitations in cross-medium stability, transition success, and integrated propulsion. The key innovations of YingLong-Hel, including a coaxial counter-rotating rotor system for enhanced thrust efficiency and maneuverability, an integrated adaptive rotor module for efficient air-water propulsion, and a simplified direct flight control system for agile attitude control, are highlighted. YingLong-Hel's aerial flight (reaching 20m altitude, 5m/s speed, and 8 minutes endurance), underwater navigation (achieving 1.5m/s speed and 30 minutes endurance), and rapid cross-medium transition capabilities were successfully demonstrated through experimental validation. It is confirmed by these results that a practical and efficient solution for HAUV applications is offered by YingLong-Hel, thus providing a valuable platform for future research and development in this rapidly evolving field.

Future work will primarily focus on optimizing the HAUV's configuration, including designing a variable geometry for reduced underwater drag and easier land operations.

Acknowledgment

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