Fault-Tolerant Design and Implementation of Tiltable Quadcopter Aerial-Aquatic Vehicle

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***Abstract*—The failure rate of aerial-aquatic vehicles (AAVs) is higher compared to unmanned devices operating in a single medium. To ensure the reliable and stable completion of tasks by AAVs, this paper proposed a tiltable quadcopter AAV to address the potential issue of rotor failure leading to high-speed spinning or damage during cross-media transitions. Experimental validation demonstrates that this tiltable quadcopter AAV can transform into a dual-rotor or tiltable triple-rotor AAV after losing one or two rotors, enabling it to perform cross-domain movements with good stability and the capability to continue task completion. This enhancement effectively improves its fault tolerance and task reliability to a certain extent.**

Keywords—aerial-aquatic vehicle, tiltable quadcopter, fault-tolerance, cross-media operation

I. Introduction

In recent years, AAVs with the capability to operate across both aerial and underwater domains have gradually become a research hotspot and have made some progress, bringing new solutions for further exploration of the skies and ocean development [1-3]. Nevertheless, at the current stage, during the process of multiple consecutive cross-domain movements, factors such as motor sealing or significant cross-domain impacts may lead to rotor failures and subsequent risks of high-speed spinning or even direct damage. Therefore, it is crucial to study how AAVs can continue to operate stably and maintain the ability to reliably complete tasks even after rotor failures occur during cross-domain operations.

Through the continuous efforts of researchers, the types of AAVs have gradually diversified, with rotor-type AAVs and foldable fixed-wing AAVs being the main types. Among these, rotor-type unmanned aerial vehicles(UAVs), with their excellent stability, precise hovering capabilities, and high maneuverability, have been improved by a considerable number of scholars to have trans-media capabilities[4-8]. This has greatly promoted the practical application of trans-media aerial vehicles. However, due to the complex marine environment, rotor failures in rotor-type AAVs are inevitable. Current research has made some progress in fault-tolerant control issues for rotor-type UAVs, especially quadcopters[9]. Nonetheless, there have been no attempts or in-depth studies on trans-media AAVs. Guzmán et al.[10] designed a robust linear parameter-varying observer to address the issue of partial or complete rotor failure in quadcopters and verified its effectiveness through numerical analysis. When a rotor completely fails, the system faces greater risks and becomes more challenging to control. In such cases, the quadcopter becomes underactuated, leading to difficulties in controlling its attitude [11]. To ensure the UAV's safety, researchers such as Lanzon [12], Sun [13], and Ke at al. [14] have designed flight controllers sacrificing controllability of yaw angle. While these proposed flight control strategies can still achieve trajectory tracking for quadcopters, the method of sacrificing yaw angle control for trajectory tracking or safe landing results in continuous rotation around the vertical axis, limiting its ability to perform tasks such as observation and inspection. Moreover, for AAVs, due to their unique working environment and the need to complete cross-domain tasks in both water and air mediums, studying their fault tolerance capabilities is of greater significance. However, there have been few attempts or in-depth research on the fault tolerance issues of AAVs so far.

Therefore, it is necessary to further explore fault-tolerant methods to ensure that a tiltable quadcopter AAV can continue its mission even in the event of complete failure of one or even two rotors. This study introduces tiltable actuating mechanisms to the quadcopter AAV, transforming it into a controllable tiltable tri-rotor or dual-rotor AAV after the failure of a rotor or two rotors. This modification enables the AAV to maintain stability in attitude control and continue to fulfill its original mission even after a failure, providing it with the capability to remain controllable and accomplish tasks post failure.

The remaining sections of this article are as follows, Section 2 discusses the overall design of the tiltable quadrotor AAV, the production of the prototype, and the establishment of relevant mathematical models; Section 3 covers the actual cross-domain motion of the tiltable quadrotor AAV, as well as fault-tolerant experimental verification following the occurrence of failures; Section 4 presents the conclusions of this paper.

II. Overall Design of Tiltable Quadcopter AAV

A. Configuration Overview

The tiltable quadcopter AAV features a carbon fiber structure, connected by aluminum columns of varying lengths. Each of the four arms includes a tilting mechanism, consisting of a waterproof servo and a 3D-printed rotating component. The motor is mounted on the tilting mechanism base to enable motor tilting. The top carbon fiber plate houses the flight control system and a four-in-one electronic speed controller,

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both sealed with epoxy resin for airtightness. A detachable buoyant shell is placed on top, with the GPS mounted on it. The electronic components underneath the AAV are sealed for protection. A 90mm aluminum column connects to the body, forming a mounting rack for the battery and camera. The produced prototype is shown in Fig. 1 (a), clearly displaying the layout of each component. The AAV has a total mass of 1485g, with the mass distribution of each component shown in Fig. 1 (b).

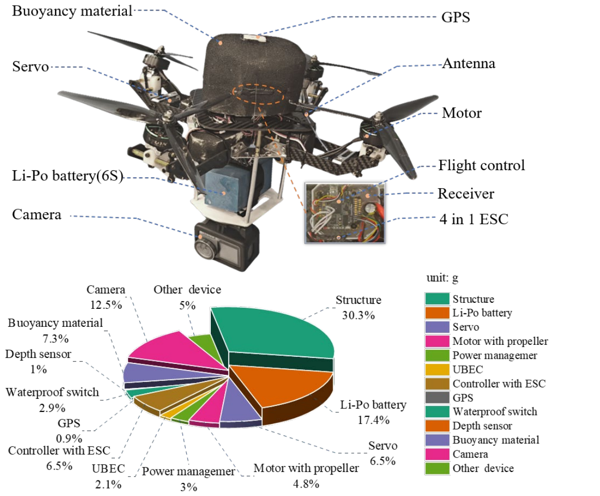

Fig. 1. Overview of the AAV system composition and mass distribution

The dimensions of the designed tiltable quadcopter AAV are illustrated in the Fig. 6 below. The Fig. 2 shows that the AAV has a wheelbase of approximately 225mm ($L_w = 225mm$), a diagonal motor distance of about 300mm ($L_d = 300mm$), and a total height of 280mm ($H_A = 280mm$). Without a camera, the UAV's height is 195mm ($H_{AAV} = 195mm$). The AAV uses a single power system for both aerial and underwater operations, featuring a 7-inch propeller blade with an actual diameter of approximately 190mm ($D_P = 190mm$). The buoyancy material height is 80mm ($H_B = 80mm$), positioning the buoyancy center above the center of gravity, ensuring vertical posture in the water.

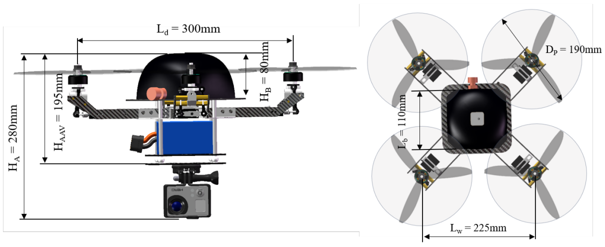

Fig. 2. 3D model and dimensioning of the AAV

B. Avionics

The electronic system includes a flight control module, servo actuator, motor drive (ESC), depth sensor, communication receiver, and power supply system. tiltable quadcopter AAV employs a microcontroller-based open-source flight control system that outputs 8 PWM signals to control 4 brushless motors and 4 servos, enabling multi-medium motion control. The AAV equipped with an 868MHz receiver connected to the flight control module by USART, allowing remote control through ground equipment for easy operation and demonstration. The flight control module integrates an inertial measurement unit with flight data storage and export capabilities. Sufficient peripheral pin interfaces are reserved for the flight control module, facilitating secondary development and expansion. The GPS includes a magnetic compass and communicates with the controller by I2C and USART . The servos operate at 6V, with a UBEC module added to meet power supply demands and provide adequate voltage. The brushless motors are driven by a 4-in-1 ESC with a rated current of 50A, powered by a 6S (25.2V) battery. The depth sensor communicates with the controller by I2C, detecting water depth to ensure effective communication within range. The electronic system composition of the AAV is shown in Fig. 3.

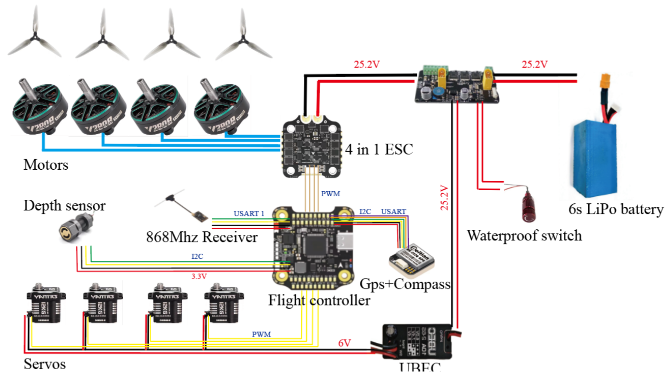

Fig. 3. Overview of the avionics and hardware framework of the AAV

C. Mathematical models

As shown in Fig. 4, The body coordinate system of the tiltable quadcopter AAV is defined as $O_b - X_bY_bZ_b$, O_b is at the center of mass of the tiltable quadcopter AAV, X_b points to motor No. 4., Z_b points perpendicular to the bottom of the fuselage of the tiltable quadcopter AAV, and Y_b conforms to the right-hand rule. define the inertial coordinate system as $O_e - X_eY_eZ_e$, the origin O_e is taken from the starting position of the tiltable quadcopter AAV, the O_eX_e axis is located in the horizontal plane and points to the initial heading direction, Z_e axis is perpendicular to the large ground and points in the direction of the center of the earth, and Y_e conforms to the right-hand rule.

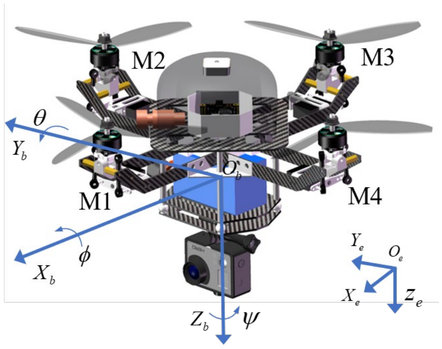

Fig. 4. Model of the AAV with the marks on the coordinate systems

According to the Newton-Euler equation, the mathematical model for the tiltable quadcopter AAV is as follows:

$$\begin{aligned}\dot{\xi}_1 &= R_b^e \boldsymbol{v_1}\\ \dot{\xi}_2 &= W_b^e \boldsymbol{v_2}\\ \dot{\boldsymbol{v}} &= \boldsymbol{v_1} \times \boldsymbol{v_2} + \boldsymbol{F} / \boldsymbol{m}\\ \boldsymbol{v_2} &= \boldsymbol{I}^{-1}\boldsymbol{\tau} + \boldsymbol{I}^{-1}\left(\left(\boldsymbol{I}\boldsymbol{v_2}\right) \times \boldsymbol{v_2}\right)\end{aligned} \tag{1}$$

To describe the motion of the tiltable quadcopter AAV, the position and orientation of the vehicle with respect to the inertial frame are denoted as $\xi_1 = \begin{bmatrix} x & y & z \end{bmatrix}^T$ and $\xi_2 = \begin{bmatrix} \phi & \theta & \psi \end{bmatrix}^T$, while the linear velocity and angular velocity can be represented as the vectors $\boldsymbol{v_1} = \begin{bmatrix} u & v & w \end{bmatrix}^T$ and $\boldsymbol{v_2} = [p \quad q \quad r]^T$. $\boldsymbol{F} = [F_{bx}\ F_{by}\ F_{bz}]^T$ and $\boldsymbol{\tau} = [\tau_x\ \tau_y\ \tau_z]^T$ are, respectively, the total force and moment exerting on the tiltable quadcopter AAV. m is the quality of the tiltable quadcopter AAV. $\boldsymbol{I} = diag[I_x\ I_y\ I_z]$ is the matrix of the tandem twin-rotor AAV moment of inertia. The velocity and angular rate in the two coordinate systems can be transformed using matrices R_b^e and W_b^e, respectively.

The conversion matrix of linear speed from the airframe coordinate system to the inertial coordinate system:

$$R_b^e = \begin{bmatrix} \mathrm{c}\psi\,\mathrm{c}\theta & -\mathrm{s}\psi\,\mathrm{c}\phi + \mathrm{s}\theta\,\mathrm{s}\phi\,\mathrm{c}\psi & \mathrm{s}\psi\,\mathrm{s}\phi + \mathrm{s}\theta\,\mathrm{c}\psi\,\mathrm{c}\phi \\ \mathrm{s}\psi\,\mathrm{c}\theta & \mathrm{c}\psi\,\mathrm{c}\phi + \mathrm{s}\psi\,\mathrm{s}\theta\,\mathrm{s}\phi & \mathrm{s}\psi\,\mathrm{s}\theta\,\mathrm{c}\phi - \mathrm{s}\phi\,\mathrm{c}\psi \\ -\mathrm{s}\theta & \mathrm{s}\phi\,\mathrm{c}\theta & \mathrm{c}\theta\,\mathrm{c}\phi \end{bmatrix} \tag{2}$$

$$W_b^e = \begin{bmatrix} 1 & \mathrm{t}\theta\,\mathrm{s}\phi & \mathrm{t}\theta\,\mathrm{c}\phi \\ 0 & \mathrm{c}\phi & -\mathrm{s}\phi \\ 0 & \mathrm{s}\phi / \mathrm{c}\theta & \mathrm{c}\phi / \mathrm{c}\theta \end{bmatrix} \tag{3}$$

where $s\theta = \sin\theta$, $c\theta = \cos\theta$, $t\theta = \tan\theta$, $s\phi = \sin\phi$ $c\phi = \cos\phi$, $t\phi = \tan\phi$, $s\psi = \sin\psi$, $c\psi = \cos\psi$.

The forces acting on the tiltable quadcopter AAV during cross-domain movement can be represented as:

$$\boldsymbol{F} = \boldsymbol{F_C} + \boldsymbol{F_R} + \boldsymbol{F}_A + \boldsymbol{F}_D + \boldsymbol{F_{df}} \tag{4}$$

where $\boldsymbol{F}$ represents the total resultant force acting on the tiltable quadcopter AAV during cross medium motion. $\boldsymbol{F_C}$ represents the forces generated by the corresponding rotors. $\boldsymbol{F_R}$ represents the restoring force consisting of buoyancy and gravity. $\boldsymbol{F}_A$ represents added mass force. $\boldsymbol{F}_D$ represents the fluid damping force. $\boldsymbol{F_{df}}$ represents errors and disturbances such as resistance, buoyancy, and other linearized errors and random disturbances like wind and waves that are difficult to measure.

The moment acting on the tiltable quadcopter AAV during cross-domain movement can be represented as:

$$\boldsymbol{\tau} = \boldsymbol{\tau_C} + \boldsymbol{\tau_R} + \boldsymbol{\tau}_A + \boldsymbol{\tau}_D + \boldsymbol{\tau_{df}} \tag{5}$$

where $\boldsymbol{\tau}$ represents the total resultant moment acting on the tiltable quadcopter AAV during cross-medium motion. $\boldsymbol{\tau_C}$ represents the moments generated by the corresponding rotors. $\boldsymbol{\tau_R}$ represents the restoring moment consisting of buoyancy and gravity. $\boldsymbol{\tau}_A$ added mass moment. $\boldsymbol{\tau}_D$ fluid damping moment. $\boldsymbol{\tau_{df}}$ represents the moments generated by errors and disturbances such as resistance, buoyancy, and other linearized errors and random disturbances that are difficult to measure.

The restoring force and moment of the tiltable quadcopter AAV can be expressed as follows:

$$F_R = \begin{bmatrix} -\left(F_B - mg\right)\sin\theta \\ \left(F_B - mg\right)\cos\theta\sin\phi \\ \left(F_B - mg\right)\cos\theta\cos\phi \end{bmatrix} \tag{6}$$

$$\tau_R = F_B \begin{bmatrix} -y_B\cos\theta\cos\phi + z_B\cos\theta\sin\phi \\ z_B\sin\theta + x_B\cos\theta\cos\phi \\ -x_B\cos\theta\sin\phi - y_B\sin\theta \end{bmatrix} \tag{7}$$

where V is the volume of the tiltable quadcopter AAV immersed in water, and $\boldsymbol{r} = \left(x_B, y_B, z_B\right)^T$ is the buoyancy center of immersed part of the tiltable quadcopter AAV.

When the tiltable quadcopter AAV is in motion, the fluid exerts a reactive force on it, which is an inertial-type fluid dynamic force (added mass force). This can be represented by the following added mass matrix:

$$\boldsymbol{M} = \mathrm{d}iag(m - X_{\dot{u}}, m - Y_{\dot{v}}, m - Z_{\dot{w}}, I_{xx} - K_{\dot{p}}, I_{yy} - M_{\dot{q}}, I_{zz} - N_{\dot{r}}) \tag{8}$$

where, $X_{\{\bullet\}}, Y_{\{\bullet\}}, Z_{\{\bullet\}}, K_{\{\bullet\}}, M_{\{\bullet\}}, N_{\{\bullet\}}$ are all represent hydrodynamic parameters.

The added mass force F_A and moment τ_A are as follow:

$$\begin{bmatrix} F_A \\ \tau_A \end{bmatrix} = -M\left(v\right)\begin{bmatrix} \dot{v}_1 \\ \dot{v}_2 \end{bmatrix} - C\left(v\right)\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} \tag{9}$$

where the $\boldsymbol{C}(\boldsymbol{v})$ is the Coriolis force matrix:

$$\begin{aligned}\boldsymbol{C}(\boldsymbol{v}) &= \begin{bmatrix} \boldsymbol{O}_{3\times3} & \boldsymbol{S}_1 \\ \boldsymbol{S}_2 & \boldsymbol{S}_3 \end{bmatrix}\\ \boldsymbol{S}_1 &= \begin{bmatrix} 0 & (m - Z_{\dot{w}})w & -(m - Y_{\dot{v}})v \\ -(m - Z_{\dot{w}})w & 0 & (m - X_{\dot{u}})u \\ -(m - Y_{\dot{v}})v & -(m - X_{\dot{u}})u & 0 \end{bmatrix}\\ \boldsymbol{S}_2 &= \begin{bmatrix} 0 & (m - Z_{\dot{w}})w & (m - Y_{\dot{v}})v \\ -(m - Z_{\dot{w}})w & 0 & (m - X_{\dot{u}})u \\ (m - Y_{\dot{v}})v & -(m - X_{\dot{u}})u & 0 \end{bmatrix}\\ \boldsymbol{S}_3 &= \begin{bmatrix} 0 & (I_z - N_{\dot{r}})r & -(I_y - M_{\dot{q}})v \\ -(I_z - N_{\dot{r}})r & 0 & 0 \\ (I_y - M_{\dot{q}})q & 0 & 0 \end{bmatrix}\end{aligned} \tag{10}$$

The fluid damping force F_D and moment τ_D are as follow:

$$\begin{bmatrix} F_D \\ \tau_D \end{bmatrix} = -D(v)\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} \tag{11}$$

where the $D(\boldsymbol{v})$ is the state-correlated damping coefficient matrix:

$$\boldsymbol{D}(\boldsymbol{v}) = \begin{bmatrix} X_u u_r + X_{u|u|} u_r \left|u_r\right| \\ Y_v v_r + Y_{v|v|} v_r \left|v_r\right| \\ Z_w w_r + Z_{w|w|} w_r \left|w_r\right| \\ 0 \\ M_q q_r + M_w w_r + M_{w|w|} w_r \left|w_r\right| \\ N_r r_r + N_v v_r + N_{v|v|} v_r \left|v_r\right| \end{bmatrix} \tag{12}$$

Since this paper discusses the fault tolerance issue of the tiltable quadrotor AAV in the event of random rotor failures, there are several different scenarios for its actuators. Below, we will primarily categorize them into three main cases for discussion.

Case1. Actuators of the quadcopter AAV

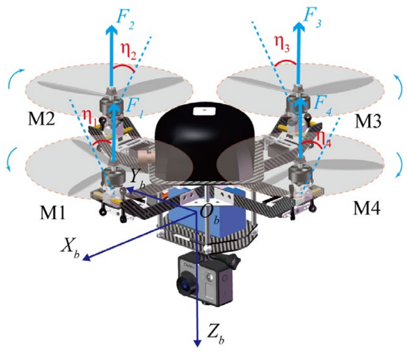

Fig. 5. The force generated by the actuators of the quadrotor AAV.

Under normal working conditions, the tiltable quadcopter AAV can use the servo to achieve the flight in tilt mode, or it can use the four rotors at different speeds to achieve stable control like the ordinary quadrotor. This paper mainly discusses the ordinary quadcopter state based on the speed difference, and the four servos only keep the four motors from tilting. The tensile force generated by its rotor can be expressed as:

$$F_{Ci} = K\omega_i^2, (i = 1,2,3,4) \tag{13}$$

In the inertial coordinate system, it can be expressed as:

$$F_C = R_b^e F_{Cb} \tag{14}$$

The lift of the quadcopter in the fuselage coordinate system is combined as:

$$\begin{bmatrix} F_{Cbx} \\ F_{Cby} \\ F_{Cbz} \end{bmatrix} = \begin{bmatrix} -\boldsymbol{F}_{C2}\sin\eta_2 - \boldsymbol{F}_{C4}\sin\eta_4 \\ \boldsymbol{F}_{C1}\sin\eta_1 + \boldsymbol{F}_{C3}\sin\eta_3 \\ -\boldsymbol{F}_{C1}\cos\eta_1 - \boldsymbol{F}_{C2}\cos\eta_2 - \boldsymbol{F}_{C3}\cos\eta_3 - \boldsymbol{F}_{C4}\cos\eta_4 \end{bmatrix} \tag{15}$$

The rotor moment can be expressed as:

$$\begin{bmatrix} \tau_{Cbx} \\ \tau_{Cby} \\ \tau_{Cbz} \end{bmatrix} = \begin{bmatrix} (\boldsymbol{F}_{C4}\cos\eta_4 - \boldsymbol{F}_{C2}\cos\eta_2)l + (\boldsymbol{F}_{C1}\sin\eta_1 + \boldsymbol{F}_{C3}\sin\eta_3)h \\ (\boldsymbol{F}_{C1}\cos\eta_1 - \boldsymbol{F}_{C3}\cos\eta_3)l + (\boldsymbol{F}_{C2}\sin\eta_2 + \boldsymbol{F}_{C4}\sin\eta_4)h \\ (\boldsymbol{F}_{C1}\sin\eta_1 + \boldsymbol{F}_{C2}\sin\eta_2 - \boldsymbol{F}_{C3}\sin\eta_3 - \boldsymbol{F}_{C4}\sin\eta_4)l \end{bmatrix} \tag{16}$$

where $\eta_i, i = 1,2,3,4$ are the tilt angle of each servo separately; l is the distance from the center of each rotor of the quadrotor to its center of mass.

Case2. Actuators of the tiltable quadrotor AAV with one rotor failure

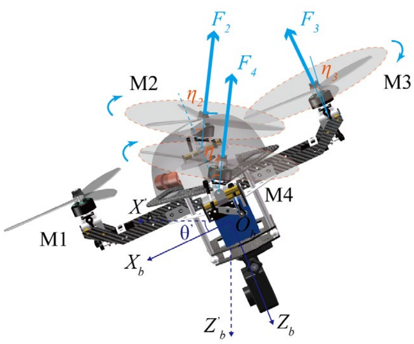

Fig. 6. The force generated by the actuators of the tiltable tri-rotor AAV.

When any rotor completely fails, for the sake of description, rotor No.1 is selected as the faulty rotor, and the tiltable quadrotor AAV will transform into a tiltable tri-rotor configuration. Since the two rotors on the same side of the quadrotor drone rotate in the same direction, when rotor 1 fails, the torque generated by rotor 3 is insufficient to counteract the torque produced by rotors 2 and 4 , causing the AAV to spin around the Z_b axis. Additionally, as rotor 1 no longer generates lift, this will lead to the fuselage tilting, which could result in the AAV overturning and sustaining damage. However, it is important to note that all rotors in this paper can be deflected under the drive of servos. When the deflection is in the opposite direction of the rotation, the generated forces and torques will balance out the forces and torques that cause the rotation. Although the AAV will tilt towards the side of the failed rotor due to the influence of the remaining three rotors, this tri-rotor AAV is still capable of achieving stable and reliable flight in a constant attitude. The forces acting on the tiltable tri-rotor AAV are as follows:

$$\begin{bmatrix} F_{Cbx} \\ F_{Cby} \\ F_{Cbz} \end{bmatrix} = \begin{bmatrix} -\boldsymbol{F}_{C2}\sin\eta_2 - \boldsymbol{F}_{C4}\sin\eta_4 \\ \boldsymbol{F}_{C3}\sin\eta_3 \\ -\boldsymbol{F}_{C2}\cos\eta_2 - \boldsymbol{F}_{C3}\cos\eta_3 - \boldsymbol{F}_{C4}\cos\eta_4 \end{bmatrix} \tag{17}$$

$$\begin{bmatrix} \tau_{Cbx} \\ \tau_{Cby} \\ \tau_{Cbz} \end{bmatrix} = \begin{bmatrix} (\boldsymbol{F}_{C4}\cos\eta_4 - \boldsymbol{F}_{C2}\cos\eta_2)l + \boldsymbol{F}_{C3}\sin\eta_3 h \\ (\boldsymbol{F}_{C2}\sin\eta_2 + \boldsymbol{F}_{C4}\sin\eta_4)h - \boldsymbol{F}_{C3}\cos\eta_3 l \\ (\boldsymbol{F}_{C2}\sin\eta_2 - \boldsymbol{F}_{C3}\sin\eta_3 - \boldsymbol{F}_{C4}\sin\eta_4)l \end{bmatrix} \tag{18}$$

Case3. Actuators of the tiltable quadrotor AAV with two diagonal rotors failure

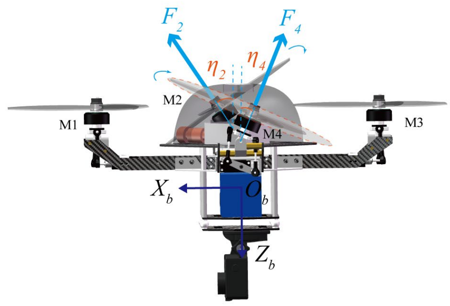

Fig. 7. The force generated by the actuators of the tiltable dual-rotor AAV.

Due to the rotor configuration of the quadrotor, when the tiltable quadrotor AAV switches to using the two rotors with relative directional rotation, the rotation direction of this dual rotor setup will be the same. This will result in spinning. To counteract the spinning in the yaw direction, the servos need to tilt the rotors to induce reverse yaw in the two rotors, thereby canceling out the spinning of the airframe. As shown in the fig. 7, when the AAV has only rotors 2 and 4 operating normally, it is necessary to generate a yaw force opposite to the direction of the spin in order to counteract the torque produced by these two rotors that rotate in the same direction. This can be achieved under the action of the tilt servo, allowing the AAV to offset the spin and maintain stability.

The forces acting on the tiltable tri-rotor AAV are as follows:

$$\begin{bmatrix} F_{Cbx} \\ F_{Cby} \\ F_{Cbz} \end{bmatrix} = \begin{bmatrix} -\boldsymbol{F}_{C2}\sin\eta_2 - \boldsymbol{F}_{C4}\sin\eta_4 \\ 0 \\ -\boldsymbol{F}_{C2}\cos\eta_2 - \boldsymbol{F}_{C4}\cos\eta_4 \end{bmatrix} \tag{19}$$

$$
\begin{bmatrix} \tau_{Cbx} \\ \tau_{Cby} \\ \tau_{Cbz} \end{bmatrix} = \begin{bmatrix} (\boldsymbol{F}_{C4}\cos\eta_4 - \boldsymbol{F}_{C2}\cos\eta_2)l \\ (\boldsymbol{F}_{C2}\sin\eta_2 + \boldsymbol{F}_{C4}\sin\eta_4)h \\ (\boldsymbol{F}_{C2}\sin\eta_2 - \boldsymbol{F}_{C4}\sin\eta_4)l \end{bmatrix} \tag{20}
$$

III. Experiment Results

In order to evaluate the performance of the designed tiltable quadrotor AAV in water-air cross-domain movement and its fault tolerance capability after failures, we first conducted outdoor aerial flight, water entry and exit, and underwater navigation experiments with the tiltable quadrotor AAV. Following that, we performed fault tolerance experiments by assuming that the tiltable quadrotor AAV had completed a phase of underwater navigation. However, at the moment of takeoff from the water, one or two rotors completely failed. The experiments verified whether it could maintain stability and whether it had the capability to continue executing its mission, thus assessing the fault tolerance performance of the tiltable quadrotor AAV after rotor failures.

A. *Cross-Domain Motion Performance Testing*

To verify the flight and underwater motion capabilities of the designed tiltable quadrotor AAV, we conducted tests in an indoor swimming pool. The objective was to demonstrate the AAV's ability to quickly transition between air and water. As shown in Fig.8, the tiltable quadrotor AAV takes off from a shelf beside the pool, flies briefly through the air, and then enters the water, turning off its motors upon submersion. Since the AAV's weight slightly exceeds its buoyancy, it becomes fully submerged after entering the water. Upon reaching a certain depth, the motors are reactivated, causing the propellers to rotate at low speed. By varying the motor speeds, the AAV can achieve rapid inclined and vertical movements underwater, as well as execute steering maneuvers. Finally, the AAV ascends vertically, emerging from the water to complete the cross-domain transition. This experiment confirms the tiltable quadrotor's capability for effective motion both underwater and in the air, demonstrating its robust cross-domain operational abilities.

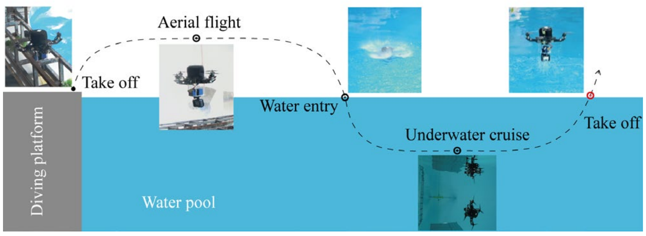

Fig. 8. Cross-domain motion process of the tiltable quadrotor AAV

We utilized the gyroscope integrated within the flight control module to capture the attitude data and monitor the water emergence process of the tilting quadrotor under normal operational conditions. As illustrated in Fig. 9, the attitude data of the fault-free AAV demonstrates that during vertical motion underwater, the attitude remains stable, with the pitch and roll angles confined within ±4 degrees. At the moment of leaving the water surface, the yaw Angle changes greatly due to the viscous force of the water and the fact that the four rotors do not leave the water at the same time.

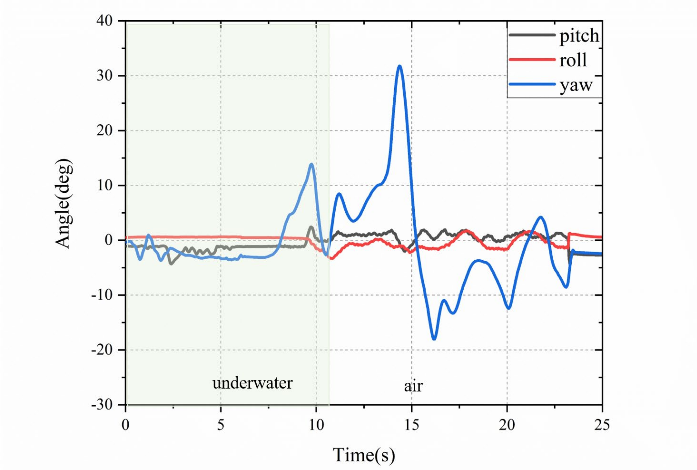

Fig. 9. Attitude change during the water-exit process

B. *Fault Tolerance Performance Testing*

1) *The tiltable quadrotor AAV with one rotor failure*

When a rotor of the quadcopter AAV fails underwater, it results in significant rotation and tilt, compromising the vehicle's ability to fly effectively. We conducted in-water flight tests in indoor swimming pools, both with and without tilting mechanisms, to assess the fault-tolerant control capabilities of the AAV upon water entry.

In the absence of a tilting mechanism, as demonstrated in Fig.10, a rotor failure leads to irregular tilting and spinning as soon as the AAV emerges from the water. The attitude data indicates that, underwater, the AAV drifts in the direction of the failed rotor. Due to the failure of the rotor, which prevents it from exiting the water, the AAV exhibits uncontrollable tilting and is unable to complete the intended water maneuvers.

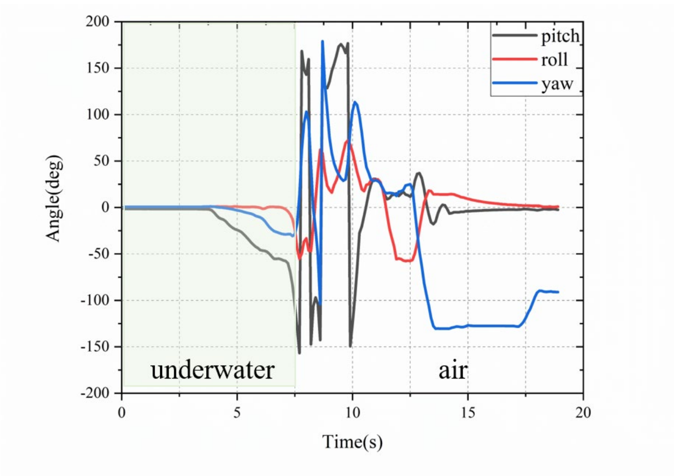

Fig. 10. Attitude data when a rotor fails without fault-tolerant control

However, for tiltable quadrotor AAVs equipped with tilting mechanisms, the adverse spin can be mitigated by adjusting the motor deflection on the side opposite the failed rotor. The two diagonally positioned motors are tilted towards the direction of the operational rotor to counterbalance the instability caused by the rotor failure. Experimental results demonstrate that the tiltable tri-rotor AAV can exit the water despite a single rotor failure, maintain stable flight at a specific tilt angle, and re-enter the water effectively.

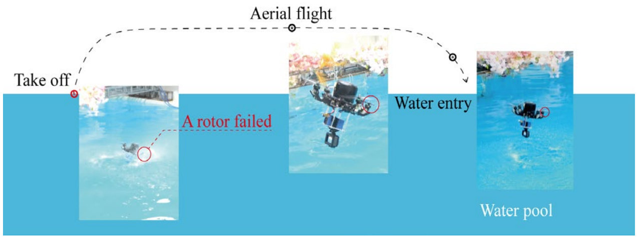

Fig. 11. Cross-domain motion of tiltable quadrotor AAV after one rotor failure

As shown in Fig.12, it presents the flight attitude data of the tilting rotor AAV under conditions where a rotor is lost. The data reveals that, upon exiting the water, the AAV tilts towards the direction of the missing rotor. However, due to the tilting capability of the remaining rotors, the yaw and roll angles are effectively controlled. Notably, the AAV maintains stable flight at an approximate tilt angle of 37 degrees during the flight, and successfully completes the landing. This underscores the reliability of the tiltable quadcopter AAV in the event of rotor loss.

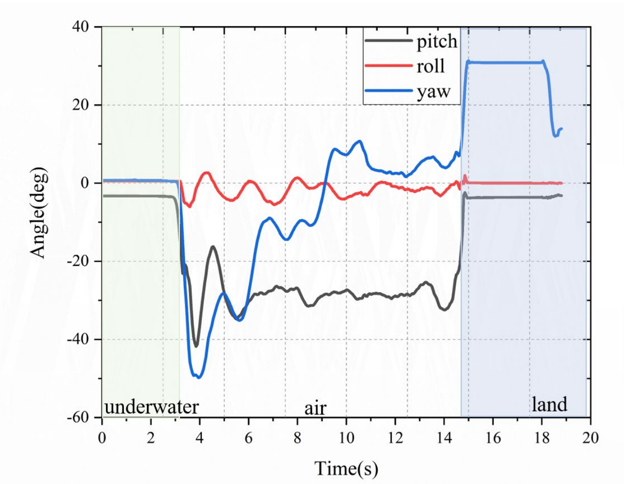

Fig. 12. Attitude data when a rotor fails under fault-tolerant control

2) The tiltable quadrotor AAV with two diagonal rotors failure

When the two diagonal rotors of the tiltable quadrotor AAV fail underwater, the remaining rotors' synchronized rotation causes the vehicle to spin. To investigate this, we conducted motion tests of the tiltable dual-rotor AAV under these failure conditions in an indoor swimming pool environment.

When the AAV lacks tilting capability, failure of two diagonal rotors causes the remaining two diagonal propellers, which rotate in the same direction, to generate torque, resulting in uncontrolled spinning at the moment of failure. Fig.13 illustrates the attitude data when the two diagonal rotors fail underwater. The data clearly shows that such a failure induces rotation, preventing the AAV from achieving stable controlled flight.

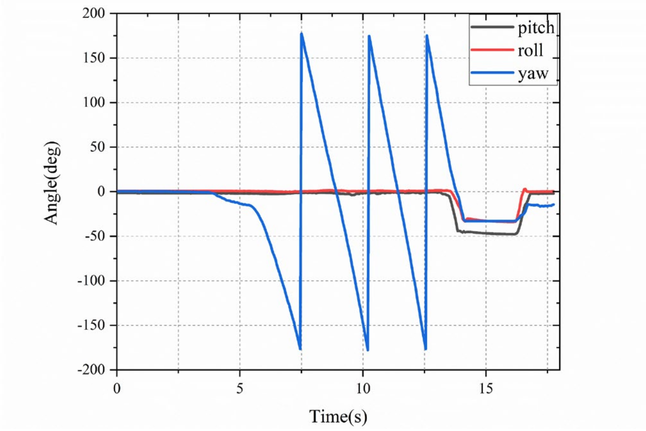

Fig. 13. Attitude data when two rotors fails without fault-tolerant control

As depicted in Fig.14, when the two diagonal rotors fail, the AAV begins to spin upon emerging from the water. Due to the tilting capability of the tiltable dual-rotor AAV, this spin can be counteracted by angling the two functional rotors in the opposite direction. The torque required to offset the tilt is relatively small, allowing sufficient tilt margin to maintain motion control in the dual-rotor state. Experimental results indicate that the tiltable dual-rotor AAV can maintain stable flight after normal water exit and has the ability to re-enter the water.

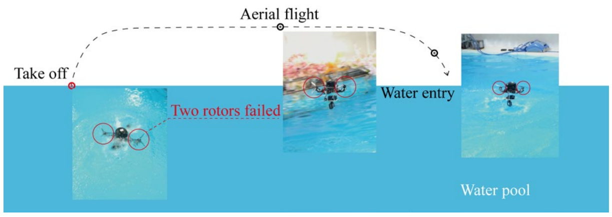

Fig. 14. Cross-domain motion of tiltable quadrotor AAV after two rotors failure

When both diagonal rotors fail, as shown in Fig.15, a significant yaw angle is observed at the moment of emergence from the water, which then returns to the initial state. This data confirms that even with the loss of two diagonal rotors, the quadrotor can still achieve flight. This experiment verifies the cross-domain operational capability of the tiltable quadrotor AAV, even with the simultaneous failure of two diagonal rotors.

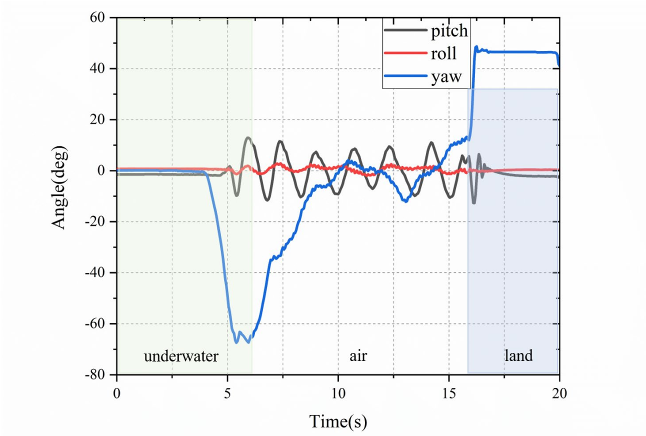

Fig. 15. Attitude data when two rotors fails under fault-tolerant control

IV. Conclusion

This paper proposes a tiltable quadrotor AAV to address potential issues such as high-speed rotation or damage caused by rotor failure during the transition across different media. Experimental validations have shown that the designed tiltable quadrotor AAV possesses excellent capabilities for water-air cross-domain movement. This tiltable quadrotor AAV can transform into a tiltable tri-rotor AAV after losing one rotor; furthermore, it can convert into a tiltable dual-rotor AAV after losing two rotors with relative directional alignment, achieving stable and reliable cross-domain movement while also maintaining the ability to continue executing its mission. This enhanced capability effectively reduces the risk of spinning and overturning damage after rotor failure to some extent, thereby significantly improving its fault tolerance and task execution reliability.

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