Design and Verification of a Novel Triphibian Platform

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Abstract—Multi-modal robots expand their operations from one working media to another, land to air for example. The majorities multi-modal robots mainly refer to platforms which operate in two different media. However, for all-terrain tasks, there are seldom researches to date in literature. In this paper, we proposed a triphibian robotic platform aiming at solving the challenges of different propulsion systems and greatly varied working media. In our design, three ducted fans are adopted to unify the propulsion system, and provide the robot with driving forces to perform all-terrain operations. A morphable mechanism is designed to enable the transition between different motion modes, and specifically a cylindrical body is implemented as the rolling mechanism in land mode. Detailed design principles of different mechanisms and the transition between various locomotion modes are analyzed in detail. Finally, a triphibian robot prototype is fabricated and tested in various working media with both mono-modal and multi-modal functionalities. Experiments have verified our platform, and the results show the promising adaptions in the future exploration tasks in various working scenarios.

Index Terms—design, triphibious vehicles

I. INTRODUCTION

Robotic platforms aid human beings in performing various tasks in different working environments, such as ground vehicles transporting in land, unmanned surface vehicles patrolling on water surface and aerial vehicles surveying in the air. Typically, the majorities of robots are mono-modal and focus on their specific tasks within one type of media (i.e. land, water or air) [1]. However, for the robots working in the field, the challenges come from different environments in different mediums, such as various land terrains, water surfaces and even obstacles to jump or go over, which requires more flexible robot designs [18] [9]. Therefore, multimodal robots with more than one locomotion method will enable themselves with greater adaptation to overcome the challenges in various working scenarios with different mediums, such as full perception with water and air media transition [6], and exploration tasks traversing or flying over high obstacles [10]-[12]. Thus, more recent research efforts have been put into the multimodal robotic platforms development, and the working environment properties expansion.

For the different locomotion modes, they can be decomposed broadly as three types: terrestrial (or land), aerial and aquatic modes [1]. Therefore, the multi-modal functionalities can be typically classified as the transition between different locomotion modes, i.e. aerial-aquatic locomotion, land-aerial, land-aquatic locomotion, and even triphibian modes with all the three locomotion modes. First, for the aerial-aquatic locomotion, the fluid density in air and water poses great variation and thus affects the locomotion mechanism design. For the aerial-aquatic robotic platforms, there are mainly wing-type designs and rotor-type designs (with multirotor device or morphable device). Flapping wing-type designs [3] [2] implemented versatile flapping propulsive strategies for the water entry and exit operation. Another wing-type multi-modal robots utilize air to enhance its flying [4]. Passive fixed wing-type designs [5] adjust its buoyancy by passively flooding or draining its wings. Another type of aerial-aquatic designs mainly take advantage of the multirotor platforms for operation ease [7], and control strategies form the multirotor unmanned aerial vehicles [6] [8]. Furthermore, rotor-type designs with morphable devices can further achieve an optimized aquatic operation by morphing its rotors/thrusters direction [18] [9]. For the land-aerial robotic platforms, typically they employ wheels (in land) and rotor-like devices (in the air) together with some transformation devices [10] [13]. For the land-aquatic designs, [14] proposed a snake-like robot by mimicking the gaits of a snake both in land and in water. [15] designed a wheel-propeller-fin mechanism for land and aquatic operations. Finally, for the triphibian platform designs, [16]...
and [17] both mixed the wheels, quadrotors and a buoyance mechanism (hollow body or vacuum tire) as a platform for all three different locomotion modes, which is functionally added for simplicity, and yet to optimize for fewer actuation units and better maneuver capabilities. Therefore, to achieve all-terrain locomotion modes, it is still a challenging design gap and a direction for unraveling a triphibian robot design.

Therefore, in this paper, we aim at designing a triphibian platform, which opt for all-terrain operation. As mentioned in [19], the same propulsion system in different media (air and water for example) leads to inefficiency for at least one of these media. Therefore, in our design, to improve the efficiency, we utilized the same propulsion system with a trirotor mechanism with ducted fans operating in the air to provide driving force in land, aquatic surface and air. A cylindrical body rolls as a wheel in land, and a morphable mechanism assists the robot to transit from land/aquatic surface mode to aerial mode, and vice versa. Section II introduced our platform design, Section III analyzed the different locomotion modes, and transitions between different modes are presented in Section IV. Experiment verification and validations are detailed in Section V and our contributions are summarized in the conclusion parts Section VI.

**TABLE I**

| Item                  | Specifications                  |
|-----------------------|---------------------------------|
| Diameter              | 41 cm                           |
| Height                | 12 cm (body height), 10 cm (deformation height) |
| Weight                | 3.88 kg                         |
| Controller            | Pixhawk autopilot               |
| Operation mode        | Automatic or manual control     |
| Modes                 | Land, surface, aerial mode      |
| Power                 | Lion Bat. (6S 5800mAh 75C), 100A ESCs |
| Actuation unit        | Ducted fans, 70 mm 12 blade     |

II. ROBOT DESIGN

In this section, we firstly introduced the proposed robot mechanical design, including the robot body and its actuation parts. Next, we detailed the robot power system with its electrical parts together with the actuation unit selection to provide propulsion system. Finally, the morphable device was presented with actuation unit expansion analysis.

A. Robot Mechanism Design

The robot axis is shown in Fig. 7. Our triphibian robot enables operations in land, water surface and air with proper mechanism design. As shown in Fig. 7 and Table I, the robot mechanical parts mainly consists of a cylindrical body and a morphable mechanism together with its actuation units. We first introduces the plastic cylindrical body with 10 cm in height and 30 cm in diameter. The robot body design mainly follows two principles: watertight (aquatic mode), and high efficiency (land mode). For aquatic mode, it provides room to house and secure all the electrical components including the flight controller, batteries, ESCs, and the wireless receiver with waterproof requirements. For land mode, it improves the efficiency by adopting the cylindrical body as a rolling mechanism on ground. For the land-aquatic mode transition, we further require the synergized cooperation with the morphable mechanism. Ideally, these should be packaged regularly to ensure that the center of gravity is concentrated at one end away from the ducted propellers, which is shown in Fig. 3.

B. Propulsion System

In this part, we detailed the robot propulsion system. First, as shown in Fig. 4, our system electrical parts consists of a Lion battery providing power for the whole system and ducted fans. Electrical parts specifications can be found in Table I. A Pixhawk suite is employed as the main controller with the ArduPilot autopilot system [23]. A receiver receives commands from the ground station for or wireless remoter. As mentioned in the mechanical design part, we implement a tri-motor configuration (MOTOR 1, 2, 3) for the aerial mode, since tri-rotor designs are more efficient in terms of compact size and power requirement [20]. Tail Servo is dynamically tilted to resist the imbalanced torque generated in the aerial mode for the tri-rotor setup design. Transition servo provides...
the driving force for the morphable mechanism to expand or retract its ducted fans. One thing to address is that the ducted fans are selected as the propulsion system actuation units for its higher hovering efficiency [22]. Compared with traditional propellers, ducted fans have high aerodynamic efficiency. Therefore, the robot could be more compact with its weight and area further reduced with reasonable thrust requirement. The ducted fans are arranged symmetrically with 120 degrees between. The weight of each ducted propeller is 77g, and its maximum thrust is 950g. Each ducted fan can only rotate anticlockwise. Another thing to illustrate is that the robot can perform operation in various locomotion modes, and therefore, in each mode, our allocation for each actuation ducted fan varied respectively. This allocation principle can improve the utilization rate of the whole propulsion system. The details of allocation methods will be illustrated in Section III.

For the wiring connection in our proposed robot, three ducted fans receive commands from Pixhawk PWM output channel 1, 2 and 4. The Pixhawk module is powered by D2627-4300KV-4S motors paired with 40A ESCs. Each ducted fan is powered independently by a BOLT LiHV 4S 1800 mAh 35C battery pack for its great power need. The tail servo and transition servo are connected to Pixhawk PWM output channel 7 and 8 respectively. Manual and automatic control can be switched by a wireless receiver linked to the Pixhawk.

![Fig. 4. Robot electrical schematic diagram and its wiring overview.](image)

![Fig. 5. Morphable mechanism from surface mode (ducted fans retracted within the robot body) to aerial mode (ducted fans expanded outside the robot body).](image)

C. Morphable Mechanism

Our robot employs one set propulsion system with a morphable mechanism for locomotion transitions. As shown in Fig. 5 in land or aquatic modes, the ducted fans is arranged within the robot body. For the aerial mode, the ducted fans is supposed to arrange outside of the body to provide lift forces to fly. In order to achieve the transition between the two different arrangements, a morphable mechanism is designed. The morphable mechanism includes a transition servo connected with a big control steering gear, three small gear wheels, three straight gear rack assembled in their slots, two guide grooves, and some rods for connections. For the modes transition, the morphable mechanism achieves two goals: (1) pushing the ducted fans outside the robot body. (2) adjusting the ducted fans thruster direction from the horizontal along to robot top surface to the perpendicular direction of the top surface.

For the morphable mechanism working procedures, as shown in Fig. 5 the transition servo controls steering wheel to rotate, and small gear wheels rotate along with the steering wheel. Then the straight gear rack expands along the sliding slots and, the two grooves starts to function. The cut-out guidance channel is composed of a straight part joined by a 90-degree circular change. Therefore, the ducted fans are firstly expanded outside the robot body, followed by a rotation operation to achieve the thruster forces direction adjustment. Besides, since ducted propellers are arranged in two different directions, to rotate all ducted propellers upwards, two opposite rotation directions are needed. Ducted propellers #2 and #3 should rotate anticlockwise, while ducted propeller #1 should rotate clockwise. In order to achieve this, two ways of rotation are used. The rotation of the #2 and #3 ducted propellers is realized by guide grooves, while the rotation of the green ducted propeller is controlled by the tail servo. To rotate the green ducted propeller by the tail control, we give two different pwm values, differed by 90, to the tail control. We use the tail control because the tail control is needed to control the robot in the aerial mode, and it is also capable of rotating a ducted propeller. Therefore, the tail control can not only be used in the aerial mode, but also can be used to realize the rotation of the green propeller during the expansion. This frees us from using another guide groove, which can further reduce the weight of the robot. It is worthwhile to note that the weight of the whole expansion joint is about 121 grams, which is about 7.1 percent of the weight of the whole robot. Compared to using two different actuation systems, which is much heavier, using this expansion joint is much more weight-effective. Therefore, this expansion joint helps integrate two different actuation systems and hence reduces the weight of the robot.

III. MODES OF LOCOMOTION

The triphibian robot has three locomotion modes, land mode, aquatic surface mode and aerial mode as shown in Fig. 6. In different locomotion modes, the robot adopt the propulsion system to cooperate with proper morphable mechanism state. In this section, we specify the three modes with their respective actuation allocation and morphable mechanism separately. One propulsion system with proper thruster allocation method for various locomotion modes improves the utilization
Fig. 6. Different proposed motion modes: land mode, surface mode and aerial mode from top to bottom.

TABLE II
ACTUATION UNITS IN VARIOUS LOCOMOTION MODES

| Locomotion modes | Operations    | Actuation units |
|------------------|---------------|-----------------|
| Land             | Forward       | 0 f2 f3 0 0     |
|                  | Backward      | f1 0 0 0 0      |
|                  | Counter-clockwise | f1 0 0 0 0    |
| Surface          | Forward       | f1 0 f3 0 0     |
|                  | Clockwise     | 0 0 f3 0 0      |
|                  | Counter-clockwise | f1 0 0 0 0   |
| Aerial           | Morphed       | 0 0 0 1 0       |
|                  | Take-off      | f1 f2 f3 0 1    |

rate of the whole system and reduce the weight of the whole system.

A. Land mode

In the land mode, similar to [13], the robot itself acts as a wheel by rolling motions. To ensure smooth rolling, the morphable mechanism retract, and the three actuation ducted fans inscribe within the robot body. The three actuators work together to generate the power of movement. As shown in Fig. 6, main difference between forward motion, backward motion and clockwise motion is caused by the allocation of the actuation units, i.e. the ducted fans. In forward motion, the two active wheels rotate in the same direction and the passive wheel stay still. The vehicle does not rotate around the y axis. As shown in Fig. 6, the two wheels provide two forces $F_1$ and $F_2$ and apply torques $T_1$ and $T_2$ to the vehicle to make the whole vehicle rotate in the same direction. The ground friction $f_1$ would provide a thrust in order to push the robot forward. When the third wheel rotate in the opposite direction, the third torque $T_3$ applied to the vehicle would make the spinning vehicle rotate in opposite direction. The ground would provide a friction $f_2$ in the opposite direction of motion to stop the robot. Assume that the vehicle is uniform, the weight of the whole vehicle is $M$, the radius of the vehicle is $R$, the rotational inertia is $I_{com}$, the angular acceleration of the vehicle $a_{com}$ in the pure rotation stage could be calculated:

$$F_1 R + F_2 R = I_{com} a_{com}$$  \hspace{1cm} (1)

In backward motion, the wheels are in the opposite state comparing with the forward mode. The passive wheel works and the two active wheels stay still. The torque applied by the passive wheel would make the vehicle rotate in the opposite direction and the friction would cause the vehicle to move backward.

In clockwise motion, the vehicle would rotate along Z-axis. As shown in Fig. 6, the center of gravity of the vehicle should be in the lower part to ensure that the robot can walk straight and turn in the land mode. As shown in Fig. 6, the flight controller is positioned xx mm from the center of the body. When the curved surface of the hull lands on the ground, the center of gravity is xx mm above the ground. According to the research from MIT, when the moment in the Z-axis direction is not large enough, the power would be dissipated in heating the plastic hull and no torque is applied to the Z-axis. Assume that force provided by the air and the ducted propeller is $F_3$, the angle between the force and Y-axis is $\theta$, the distance between the Z-axis and the force is $h$, the critical rotation moment along Z-axis is $M_x$:

$$F_3 \cos(\theta) d < M_x$$  \hspace{1cm} (2)

The vehicle would not go forward in clockwise motion. Moreover, the horizontal component of $F_3$ cancels out the static friction force, leaving the object with no displacement. The component in the vertical direction provides a torque $T_3$ in Y-axis, giving the vehicle a tendency to rotate.

Assume that the distance between the Y-axis and the force is $h$, the angle between the force and Y-axis is $\theta$, the rotational inertia is $I_{com}$, the angular acceleration of the vehicle $a_{com}$ in the pure rotation stage could be calculated:

$$F_3 \sin(\theta) h = I_{com} a_{com}$$  \hspace{1cm} (3)

B. Surface mode

In surface mode, two ducted propellers, #x1 and #x2, are used. First, ducted propeller #1 and #2 are used in forward motion. Second, ducted propeller #1 and #2 are used respectively in clockwise and anticlockwise rotation motion. In surface mode, the robot lie on its cushion side with its ducts stay upwards. By rotating in the air through the ducted propellers, the boat can go forward and rotate in anticlockwise and clockwise direction. As shown in figure 6, the main differences between forward motion, anticlockwise rotation motion, and clockwise rotation motion are caused by different cooperation of the two ducts.
In forward motion, the two rear ducts are both active. As shown in Fig. 9, duct A gives $F_1$ and B gives $F_2$. If $F_1 = F_2$, then their side forces $F_{x1}$ and $F_{x2}$ equal and will be canceled. Then, the sum of $F_1$’s and $F_2$’s remaining components $F_{y1}$ and $F_{y2}$, which is the $F_{yt}$ shown in Fig. 9, will push the air and enable the robot to move forward. Note that the robots tend to rotate when moving, where $F_{x1}$ and $F_{y1}$ are the horizontal and vertical components of $F_1$. The force $F_{x2}$ and $F_{y2}$ are the horizontal and vertical components of $F_2$. The dot A and B represent the location of two rear active ducts, where C is the center of the robot. The force $F_{yt}$ represents the total vertical force of the whole system.

\[
F_1 = F_3 \quad (4)
\]
\[
F_{x1} = F_{x3} \quad (5)
\]
\[
F_t = F_{ty} = F_{x1} + F_{x3} \quad (6)
\]

In clockwise and anticlockwise motions, only one duct operate. As shown in Fig. 9, duct A gives $F_1$, where $F_1$ is the force. The dot A represents the location of the duct. The radius of the vehicle is $r$. The rotational inertia is $I_{com}$. The angular acceleration of the vehicle $a_{com}$ in the pure rotation stage could be calculated:

\[
F_1r = I_{com}a_{com} \quad (7)
\]
C. Aerial mode

In aerial mode, three ducted propellers are all used, enabling the robot to fly as a triplane. As shown in Fig. 10, the robot needs to leave the water after the experiment. In this case, taking the robot out of the water manually is time-consuming and potentially dangerous. To solve the problem of the robot getting out of the water, the aerial mode is useful.

In aerial mode, our robot has a tri-rotor design. Compared with other multi-rotor UAVs, tri-rotor UAVs are smaller in size, lighter in weight, and have longer duration time and no site limitation. In addition, our robot itself has three motors, and the three-rotor design allows each motor of our robot to fully function. Manufacturing costs could be reduced. These advantages make tri-rotor design ideal for our robot.

Here’s how our robot works in aerial mode. In aerial mode, the robot performs as a tri-rotor unmanned aerial vehicles. It can take off, turn, and land on the ground by accepting commands from the remote control. As shown in figure 5, the linkages stretch out and the three engines would go beyond the diameters of the hull in the aerial mode. For flight control, we directly adopted the model of Ardupilot. As shown in figure 6, all three motors will rotate counterclockwise. The three rotating motors generate an angular momentum that spins the entire vehicle. To nullify the yawing moment provided by the three motors, a servo motor is installed on the rotor axes of the rear motor.

IV. Transition between modes

To achieve the all-terrain locomotion in different media, we proposed the transition methods between different modes as shown in Fig. 11. We detailed the different roles for propulsion system actuation units and the morphable mechanism.

A. Surface-aerial mode

From aerial to surface mode, the robot can land on water surface successfully just by leveraging the deducted fans, which is typically an ordinary operation. From surface to aerial mode, the robot first extends the deducted fans to the outer of the robot body with the morphable mechanism. In this case, the deducted fans could generate vertical lift forces to fly the robot. The vertical flying operation will be handled by autopilot system with Pixhawk hardware.

B. Land-surface mode

This part could succeed for the imbalance of center of gravity and center of the whole body. While switching from land mode to surface mode, we need to make sure that the object is flipped in the position we wish. The three ducted propellers should be put on the top in surface mode. According to Pettersen and Egeland (1996), if the center of buoyant of a lake and the center of gravity of a vehicle are not the same point, then the vehicle tends to overturn towards the center of gravity. As shown in the Fig. 3, when the robot move from land to water, it tends to turn to side 2. In this picture, A is the center of buoyant and B is the center of gravity. Since they are not at the same point, force F can be divided along direction A-B and the direction perpendicular to A-B, getting F1 and F2. If we treat B as the center of rotation, then F1 can be ignored and F2 acts as a torque making the robot rotate clockwise. Therefore, during the transition from land to water, after the robot rotates on the surface, it will overturn towards the center of gravity and reach the initial position of surface mode.

C. Land-aerial mode

Similar to the analysis of rotation in the land mode, the deducted fans generates thruster forces and therefore turns the robot direction along its centers. By the imbalance mass of the robot, it can land on the ground. Further, morphable mechanism can expand the ducted fans and aerial mode will come into play thereafter.

V. Experiments and Analysis

In this section, we present the results of the experiments conducted on the robot. First, we tested the robot with its land mode, surface mode and aerial mode. Next, we evaluated its ... (various functions, such as energy consumption, stability, distance, time, etc).

A. Experiments Setup

1) Indoor pool: First, we tested our robot in the indoor pool in Shenzhen Institute of Artificial Intelligence and Robotics for Society (AIRS).
2) **Outdoor lake:** Next, we tested our robot in the outdoor lake in The Chinese University of Hong Kong, Shenzhen, Guangdong, China.

**B. Analysis of each mode**

As shown in Fig. 13, our robot can achieve three modalities of motion very well.

**C. Verification of transitions between nodes**

As shown in Fig. 14, our expansion mechanism enables the conversion of three models. More details will be updated in the future.

VI. **Conclusions**

In this paper, we presented our novel robot that can ship on the water, travel on the ground, and fly using the same motors. More details will be updated in the future.

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