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Design and Performance Analysis of a Triphibious Robot With Tilting-Rotor Structure

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ABSTRACT Triphibious robots can move in more complex environment compared with common mobile robots, which makes the triphibious robots have a wider movement space and better environmental adaptability. This paper proposes an innovative design solution of a triphibious robot with the tilting-rotor structure (TR-TRS), which can change its motion mode to perform smoothly transition between different media, such as land, water, and air. First, the mechanical structure of the triphibious robot is described with design diagrams. Two tilting-rotors are mounted on the left and right side of a quadrotor-like aerial platform, in which four legs with passive wheel are integrated to make the triphibious robot move on land. Tilting-rotor structure is used to change the orientation of the rotors on both sides of the robot's fuselage, thus, through adjusting the orientation of these two rotors they can drive the triphibious robot to move on land and underwater. Next, according to the mechanical design, the motion modes in different environmental media are given, and the transition methods between different motion modes are explained in detail. Finally, the influence of tilting-rotor structure on the performance of the designed triphibious robot is analyzed and discussed by the results of virtual simulation. The superior performance of tilting-rotor structure in triphibious robots is demonstrated through the comparison of existing robots.

INDEX TERMS Triphibious robots, structure design, tilting-rotor, performance analysis.

I. INTRODUCTION

Triphibious robots can move in multiple environments, such as walking on land, flying in the air and maneuvering underwater. So triphibious robots have a wider movement space, better environmental adaptability and greater potential compared with common mobile robots, and can be applied in civil and military field, such as monitoring, exploring, rescue, repair and mapping of remote region in complex environment. Therefore, triphibious robots have been a research hotspot in the domain of mobile robots. According to the design inspiration of robots, multi-field robots can be mainly divided into two types: bionic design robots [1]–[3] and functional bionic robots with hybrid propulsive mechanism [4], [5]. According to the movement space, multi-field robots can be divided into four types: water-land amphibious robots [6], water-air amphibious robots [7], land-air amphibious robots [8], and water-land-air triphibious robots [9].

Because amphibians are widespread in nature, researchers initially design amphibious robots by learning and imitating biologic characteristics of amphibians, such as snake-like amphibious robots and legged robots [10]. Hirose and Yamada [1] designed snake-like robot called ACM-R5, which can swim underwater and move on land depended on specially designed propulsive mechanism installed on each joint. Crespi *et.al* [11]–[15] developed the AmphiBot series and Salamander series of snake-like amphibious robots, which adopt modular design for easy maintenance. Besides these snake-like amphibious robots mentioned above, some researchers designed a number of hybrid propulsive mechanism by combining the bionic structure with modern actuators. Zhang *et.al* [16]–[18] proposed an amphibious robot called AmphiHex-I with novel transformable flipper-leg hybrid propulsive mechanisms, which can transform by cable

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to adapt to different environment. Yu *et.al* [19] presented a hybrid propulsive mechanism coupled with wheel-propeller-fin movements and developed an amphibious robot called AmphiRobot-II. However, the mechanism is rigid while the physiological structure of amphibians is soft, so these bionic mechanisms are unusually complex. Furthermore, since these amphibians can not fly, these designed amphibious robots are also unable to fly, which limits the development of bionic multi-field robots.

Over the past decades, more and more researchers focus on unmanned aerial vehicle (UAV), expecting to advance the study of amphibious robots through further investigation and improvement of existing unmanned aerial vehicles, such as quadrotor, fixed-wing robot and helicopter [20], [21]. Among them, quadrotor have the advantages of simple structure, excellent environmental adaptability and superior scalability, so that it attracts more attention and interest from the researchers [22]. But quadrotor can not move underwater, which limits the workspace of robots, especially in some specific applications. In addition, due to the heterogeneity in the physical properties of water and air, the external environment of multi-field robots when moving in the air and underwater is different, which brings some difficulties to the smooth transition of robot's motion modes between two media and also poses a potential challenge of the triphibious robot development. To realize the amphibious function of robots, Drews-Jr *et.al* [7] presented an amphibious robot based on quadrotor equipped with a propeller under each aerial rotor for underwater propulsion. Maia *et.al* [23] developed a double layer coaxial eight-rotor robot, and proposed a seamless transition method between the air and water media. Nevertheless, the above mentioned two robots require more energy consumption due to eight motors installed on the robot. Alzu'bi *et.al* [24] presented a quadrotor robot utilizing a ballast system under the body of quadrotor to control robot buoyancy and depth underwater and change the attitude of robot to perform seamless air-to-water and water-to-air transition. However, it may cost long time to perform transition, and the change of robot's attitude reduces the stability of the robot underwater. In addition, these robots successfully perform transition smoothly between water and air, but the lack of movement mechanisms on land makes them can only move in the air and water.

Although current amphibious robots based on quadrotor have some problems and disadvantage, quadrotor has become the first choice of multi-field robot development. The main challenge is how to control the robot to successfully and stably perform transition between air and water, and make the robot can move on land. This paper presents a novel triphibious robot with tilting-rotor structure (TR-TRS) based on quadrotor, which can achieve the performance of movement that can move underwater, on land and in the air. The main contributions of this paper can be stated as follows.

(1) The design of a triphibious robot with tilting-rotor structure based on quadrotor that can walk on land, maneuver underwater and fly in the air is proposed.

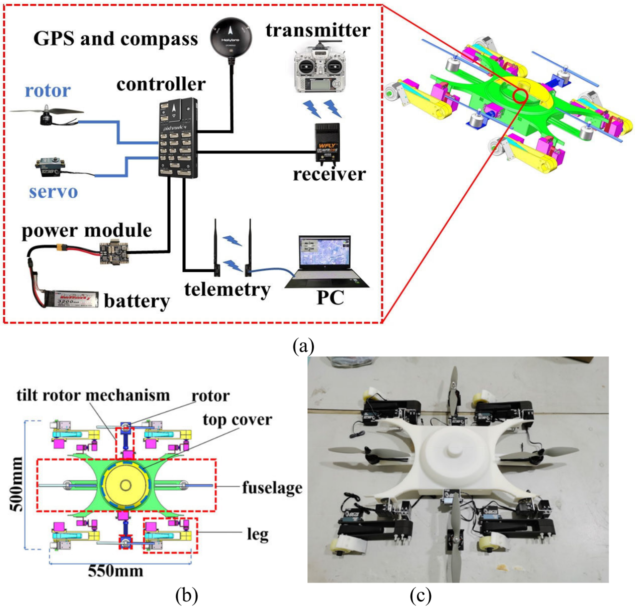

FIGURE 1. **(a) Diagram of system architecture of TR-TRS. (b) Virtual prototype in SolidWorks. (c) Physical prototype of TR-TRS.**

(2) Various motion modes in different environmental media are analyzed, and the smooth transition methods between different media are proposed.

(3) The superior performance of tilting-rotor structure in the proposed triphibious robot is demonstrated through comparison of some existing robots.

II. SYSTEM DESIGN OF TR-TRS

A. SYSTEM ARCHITECTURE

Fig. 1(a) shows the system architecture diagram of TR-TRS. The appearance of TR-TRS is shown in the right part of Fig. 1(a), and the dotted box in the left part of Fig. 1(a) represents the electronic system, which is placed in the interior of the fuselage. Especially, in TR-TRS four legs are attached to the fuselage of a conventional quadrotor drone, and most electronic component is placed in the interior of fuselage except rotors and servos. The controller is Pixhawk 4(PX4), which is a powerful open source autopilot flight stack, and other electronic components are listed in the Table 1.

There are two ways to control TR-TRS, namely, the radio control system consisting of a receiver on the robot and a transmitter on the ground, and the telemetry radios. TR-TRS can be manually controlled using a handheld transmitter or connect to a ground control station like QGroundControl via wireless MAVLink connection using telemetry so that the robot can perform or change a mission in real-time

B. MECHANICAL DESIGN

The TR-TRS appears to have added four legs to the fuselage of an ordinary quadrotor drone, but there are still many differences. Fig. 1(b) shows the virtual prototype in SolidWorks. The TR-TRS is composed of five parts: body, top cover, leg,

TABLE 1. Devices used in TR-TRS.

Devices	Model
Controller	Pixhawk 4
Receiver and Transmitter	WFT09SII
Battery	3200mah 70C 4s1p
Telemetry	RADIO V5
Rotor	Jfrc U2810
Servo	KKPIT HV-CLS-1238

TABLE 2. Devices Used in TR-TRS.

Device	**Model**
Controller	Pixhawk 4
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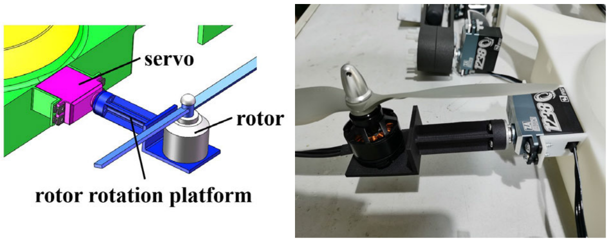


(a) (b)

FIGURE 2. (a) Virtual prototype of tilting-rotor structure in SolidWorks. (b) Physical prototype of tilting-rotor structure.

rotor and rotor tilting-rotor structure. Fig. 1(c) shows the physical prototype of TR-TRS. The overall dimension of TR-TRS is 550mm × 500mm, and its total weight is about 4kg.

In order to improve the motion performance of TR-TRS, the tilting-rotor structure shown in Fig. 2 is applied, which enables the orientation of rotors on both sides of the fuselage to be controlled. Fig. 2(a) shows the virtual prototype of tilting-rotor structure in SolidWorks while Fig. 2(b) shows its physical prototype installed in the fuselage. The tilting-rotor structure is composed of a servo and a rotor rotation platform. The servo is fixed on the fuselage, one end of the rotor rotation platform is mounted on the steering wheel of the servo, and the other end is used for mounting the rotor motor. In this way, when the servo works, it can drive the rotor motor to rotate together so as to adjust the orientation of the rotor. This design makes full use of the rotors on both sides of the fuselage, the two rotors are not only used for flying in the air, but also maneuvering underwater and moving on land, the details will be introduced later.

In further, to enable TR-TRS to move on land, four legs with passive wheel are integrated into the robot base on our previous research [25], [26]. Figs. 3(a)–(c) show the details of designed mechanical leg, which has three degree of freedoms (DOFs) with three joints and two limbs (Limb1 is 150mm and Limb2 is 100mm), and the passive wheel whose diameter is 50mm is installed in the third joint. TR-TRS also can walk on land like quadruped using its four 3-DOF legs. Moreover, when the Limb 2 rotates to the interior of the Limb 1, the passive wheel could touch the ground and TR-TRS can move rapidly using the passive wheels together with the tilting-rotor structure, which is used to provide propulsion by changing the orientation of rotors on both sides of the fuselage. In addition, a brake mechanism is designed on the leg, as shown in Figs. 3(b) and 3(c), the brake mechanism is consisted of a flexible sheet, a brake ring and a putter on the Limb 2. First, when TR-TRS is not in wheel mode, the putter on the Limb 2 does not touch the flexible sheet, so the brake ring is tightly attached to the wheel, which makes the passive wheel can not turn. Then, when TR-TRS transforms into wheel mode, the putter would lift the flexible sheet, so the brake ring is separated from the passive wheel and the wheel can turn freely. Once the brake is needed, the Limb 2 will turn a small angle, which makes the putter separate from the flexible sheet, and the brake ring will tightly attach to the wheel and force the wheel to stop.

Considering the condition that the TR-TRS moves underwater, the watertightness is necessary. The external rotor motors and servos of TR-TRS are in direct contact with water, so the selected rotor motors and servos are waterproof. The electronic system is placed inside the fuselage, where an airtight space is formed by the top cover and fuselage. As shown in Fig. 3(d), a screw thread mechanism is applied in the top cover and fuselage to make the interior is sealed.

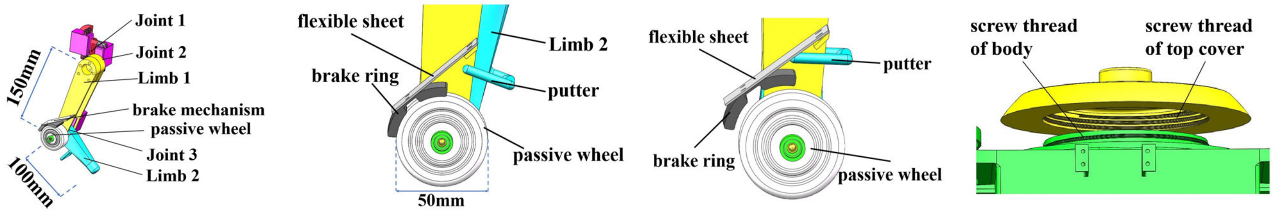
III. MOTION MODES OF TR-TRS

The proposed TR-TRS has four motion modes for better adapting to different environments, i.e., aerial quadrotor mode, underwater mode, quadruped mode and wheel mode. TR-TRS would determine appropriate motion mode depending on the movement environments. Fig. 4 shows the various attitude of TR-TRS in different motion mode, in which the above diagram is the virtual prototype while the below one is the physical prototype.

Fig. 4(a) shows the attitude of TR-TRS in aerial quadrotor mode. It looks like a conventional quadrotor drone which use four rotors for flying. The legs installed in the fuselage would be folded up and stayed still to avoid interfering with the rotor and reducing the stability of robot.

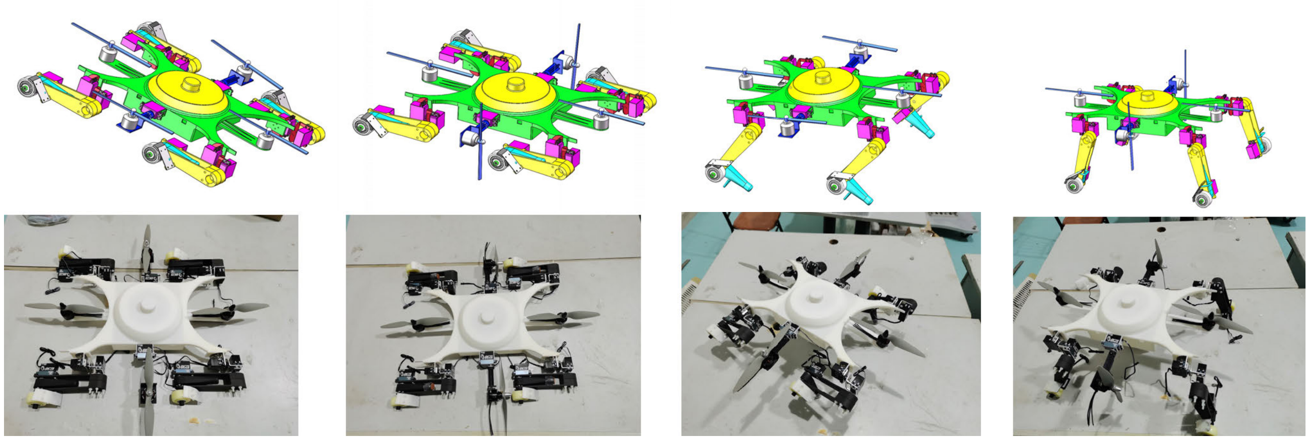
The attitude of TR-TRS in underwater mode is shown in Fig. 4(b), which is similar to what the TR-TRS looks like in aerial quadrotor mode. The main difference between these two modes is the orientation of two rotors on the left and right sides of the fuselage. When the TR-TRS is in the underwater mode, the orientation of rotors on both sides of the fuselage is forward, which can provide propulsive force for maneuvering underwater. While the rotors at the front and rear of TR-TRS are used to control the depth that it in the water.

When TR-TRS needs to move on land, there are two different modes can be chosen, i.e., quadruped mode and wheel mode. Fig. 4(c) shows the attitude of TR-TRS in quadruped mode, in which it can walk on the ground using four 3-DOF legs even if the terrain is rugged, because the legs enable



(a) (b) (c) (d)

FIGURE 3. (a) Leg mechanism. (b) Braking state. (c) Moving state. (d) Waterproof mechanism using screw thread.



(a) (b) (c) (d)

FIGURE 4. (a) Aerial quadrotor mode. (b) Underwater mode. (c) Quadruped mode. (d) Wheel mode.

TR-TRS to have good terrain adaptability. If the road is flat and suitable for vehicles to drive, the Limb 2 rotates to the interior of the Limb 1 shown in Fig. 3. In this case, the passive wheel could touch the ground, then, the rotors on both sides of the fuselage rotate 90 degrees so that the propulsive force generated by the two rotors is directed towards the front of TR-TRS, which can drive TR-TRS to move forward. This motion mode looks like a taxiing plane before takeoff and the two rotors on both sides of the fuselage can be seen as the aeroengine, so that the TR-TRS can move rapidly on the road. Once it needs to slow down or stop, the brake mechanism mentioned above will work.

IV. TRANSITION BETWEEN TWO ENVIRONMENTAL MEDIA

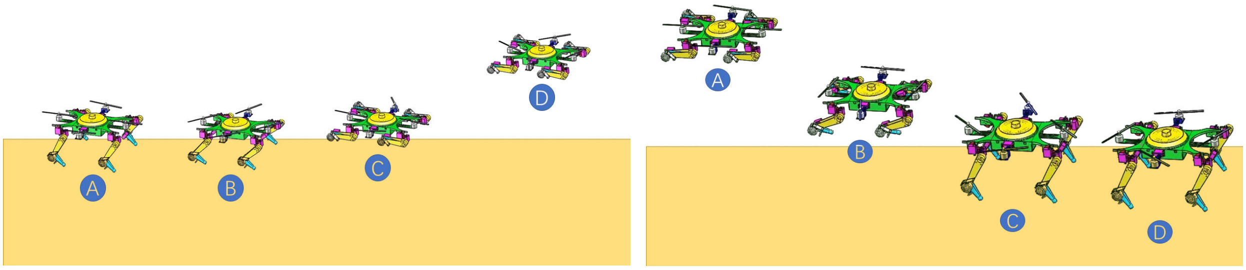
The smooth transition between two environmental media is the challenge of study of amphibious and triphibious robots. The proposed TR-TRS can move on land, maneuver underwater and fly in the air, therefore, there are three motion transitions, i.e., land-air transition, water-air transition and land-water transition. Thereinto, water-air transition is the critical issue of motion transition investigation because of the water and air are fluid media and their physical properties are different. This section will introduce three methods of motion transitions in detail.

A. LAND-AIR TRANSITION

The TR-TRS flies in the air in aerial quadrotor mode while moves on land in quadruped mode or wheel mode. In this case, the land-to-air transition could be viewed as the takeoff of helicopter, and the air-to-land transition could be considered as the landing of helicopter. In this transition process, the legs of TR-TRS can be viewed as the landing gear whether the robot is in quadruped mode or wheel mode. Therefore, for more easier to understand, the quadruped mode is taken as an example to illustrate the land-air transition in this paper.

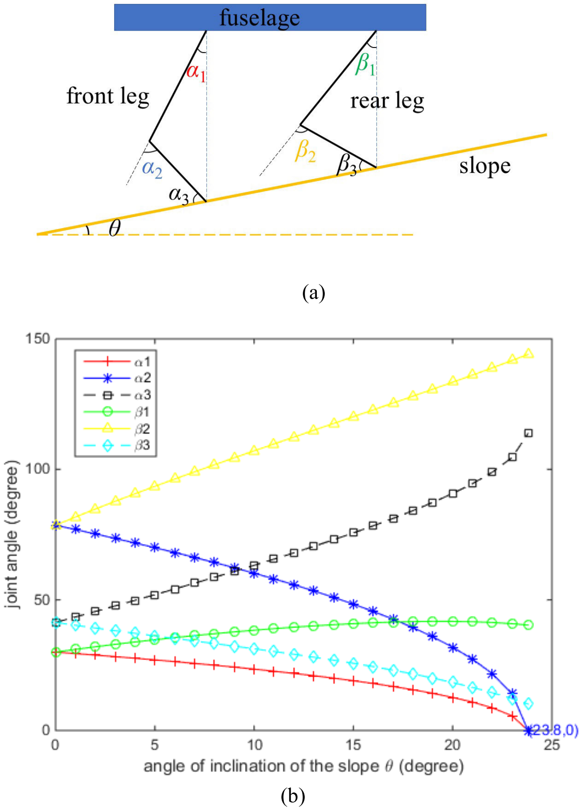
Fig. 5(a) shows the process of land-to-air transition, which can be divided into four stages. State A shows that the TR-TRS is in quadruped mode. Then four rotors work and generate the lift force, which pull TR-TRS to fly upward, namely State B. After the robot leaves the ground, four legs will be folded up slowly and stayed still, so as not to influence the stability of TR-TRS, namely State C. As the TR-TRS continues to rise, it switches to the State D, i.e., aerial quadrotor mode.

The TR-TRS performs air-to-land transition in the reverse sequence of land-to-air transition, as shown in Fig. 5(b). The TR-TRS extends its legs so that it descends slowly, namely State A and State B. To ensure a stable landing, four legs should be deployed in a predetermined attitude before the ends of legs touch the ground, namely State C. Finally, four



(a) (b)

FIGURE 5. **(a) Land-to-air transition. (b) Air-to-land transition.**



(a)

(b)

FIGURE 6. **(a) Schematic diagram of simulation model. (b) Changes of the angle of inclination for the slope and the joint angles of legs.**

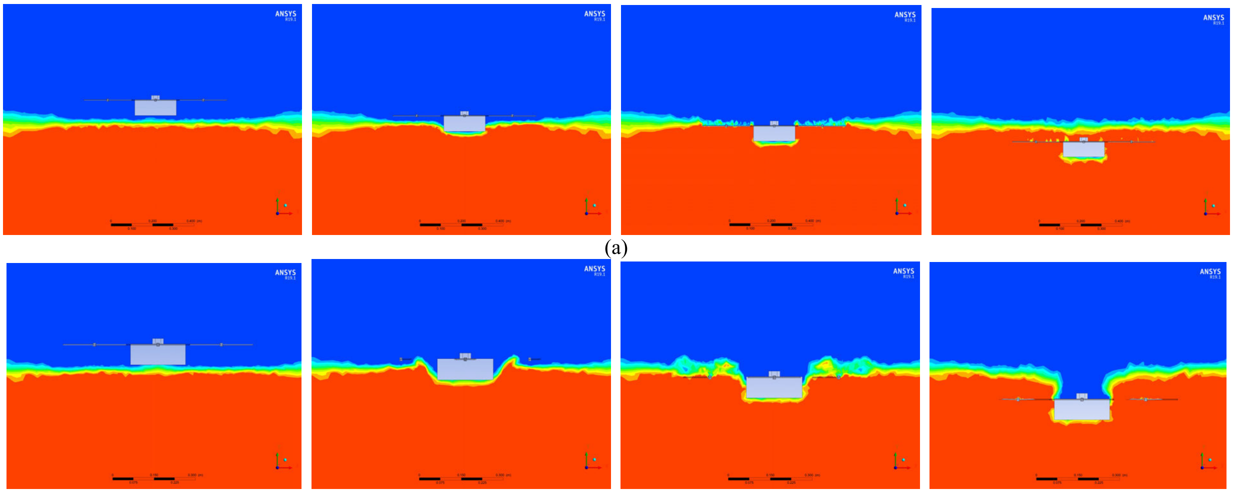
rotors stop working after TR-TRS lands, and TR-TRS transforms into the quadruped mode, namely State D.

In addition, compared to the takeoff and landing of a conventional quadrotor UAV, the proposed TR-TRS has a better environment adaption. For the conventional quadrotor UAV, flat ground is indispensable for smooth takeoff and landing, because all four rotors of a conventional quadrotor UAV need to be on the same level, while TR-TRS can take off and land on slope or uneven ground using four legs to keep the fuselage horizontal. To demonstrate this, a simulation is conducted in MATLAB about the angle of inclination of the slope and the joint angle of legs, Fig. 6(a) shows the simplified model of TR-TRS, and the result is shown in Fig. 6(b), where $\alpha 1$, $\alpha 2$ and $\beta 1$, $\beta 2$ are the first and second joint angles of the front leg and the rear leg, respectively, and $\alpha 3$ and $\beta 3$ are the intersection angles between the ends of front and rear legs and the ground, respectively. To ensure the stability of TR-TRS when it takes off, the ends of legs are placed on the projection point of the first joint of leg on the ground, so that the center of gravity of robot is always within its footholds, which can enable the TR-TRS keeping stable.

From Fig.6(b), as the angle of inclination of the slope (i.e., θ) increases, the joint angles of the front legs (i.e., $\alpha 1$ and $\alpha 2$) decrease because the increase in height of the first joints of front legs from the ground makes the front legs must be straightened to touch the ground. While the joint angles of rear legs (i.e., $\beta 1$ and $\beta 2$) increase because the decrease in height of the first joint of rear legs from the ground makes the rear legs must be folded up. At the same time, the intersection angles between the ends of front and rear legs and the ground (i.e., $\alpha 3$ and $\beta 3$) are always greater than zero, which means the second joints of the front and rear legs do not touch the ground in quadruped mode. Therefore, when the joint angles of the front legs decrease to zero, which means the front legs are straightened fully. In this case, the angle of inclination of the slope is 23.8 degrees, which is the maximum angle of inclination of the slope that TR-TRS can take off and land smoothly. Thus, it is obvious that TR-TRS can keep the fuselage horizontal to take off and land smoothly from a slope, which the conventional quadrotor UAV can not.

B. WATER-AIR TRANSITION

Our proposed triphibious robot needs to move in two environmental media during the water-air transition process, i.e., water and air, which have different effects on the TR-TRS. Although they are both fluid form, the physical properties difference of water and air makes the parameters of the movement environment for TR-TRS change sharply in water-air transition. This results in a great impact force that TR-TRS suffers in the air-to-water transition and a tensile force when the robot moves to air from water. Therefore, how to keep robots stable in the water-air transition process is one of the


(a)

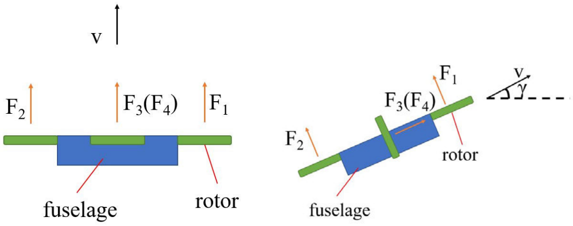
(b)

FIGURE 7. **(a) Result of air-to-water transition with a slower velocity. (b) Result of air-to-water transition with a higher velocity.**

critical issues. For TR-TRS, the environmental media that it moves in and its attitude are two main factors, which affect the stability in this transition process.

Regarding the movement environment, TR-TRS flies in the air using aerial quadrotor mode and maneuvers underwater using underwater mode, and it can respectively keep stable in two motion modes because the movement environments are steady. However, as mentioned above, when TR-TRS passes through the water surface, it would suffer the impact force or tensile force which are mainly derive from water surface. Moreover, the waves resulting from the motion of robot would also affect the its stability. Therefore, the faster TR-TRS passes through the water surface, the greater impact force or tensile force is generated, which can produce bigger waves. Besides, the faster rotors rotate, the bigger the waves are produced. Therefore, reducing the velocity of the robot passing through water surface and slowing the rotors can reduce the external interferences so that TR-TRS can perform water-air transition stably.

In order to examine and verify the above analysis results, the virtual prototype technology and process simulation technology are used in Fluent software. First, we set the velocity of robot passing through the water surface is 0.2m/s and the rotors do not rotate. The simulation result of this condition is shown in Fig. 7(a), the blue part represents the air and the red part represents the water. Form Fig. 7(a), it is observed that the waves produced are small, which means the effect on TR-TRS is not great so that TR-TRS can keep stable during the transition process. For comparison, another virtual simulation is conducted with higher velocity of robot, in which the velocity of robot is 1m/s and the rotation velocity of four rotors are all 300rmp. Fig. 7(b) shows the simulation result of this condition. Apparently, the waves produced by TR-TRS are bigger due to higher velocity of the robot and the rotors. Moreover, after TR-TRS passes through the water surface from air a cavity is generated above the fuselage, which is bound to produce larger waves and further affect the stability of TR-TRS underwater. Through the comparison of these two results under different conditions, it can be concluded that lower velocity of TR-TRS passing through the water surface can reduce waves produced by the robot, which can better ensure the stability of TR-TRS underwater.

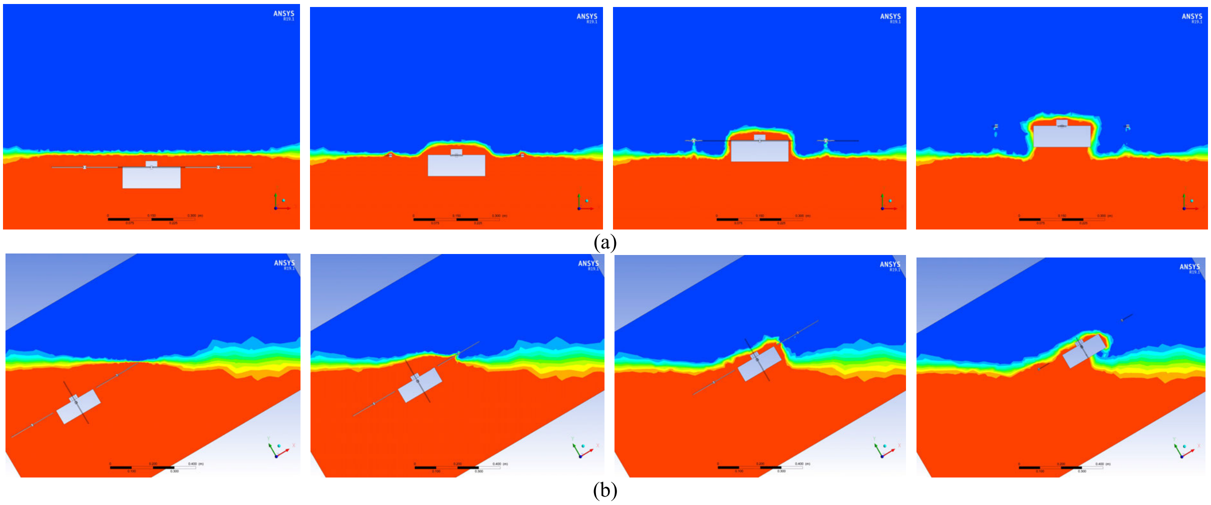


(a)

(b)

FIGURE 8. **(a) Horizontal attitude. (b) Tilted attitude.**

The attitude of robot passing through the water surface also can affect the stability of robot, particularly in the water-to-air transition. Considering the structure design of TR-TRS, there are two different attitudes for water-to-air transition, i.e., the horizontal attitude and the tilted attitude, which are shown in Fig. 8. When TR-TRS in the horizontal attitude it rises vertically and the fuselage keep horizontal, while in the tilted attitude means it moves tilted upward with the fuselage sloping, and the orientation of two rotors on both sides is changed perpendicular to the fuselage. For water-to-air transition, after TR-TRS passes through the water surface, it is needed to transform into the aerial quadrotor mode as soon as possible. As shown in Fig. (8), the horizontal attitude is similar to what the robot looks like in aerial quadrotor mode, while TR-TRS in tilted attitude need to adjust its attitude to transform into the aerial quadrotor mode. For this reason, the horizontal attitude

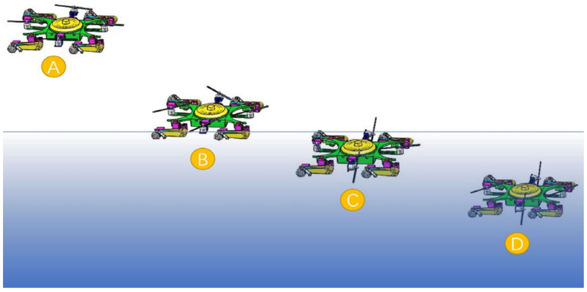

(a)

(b)

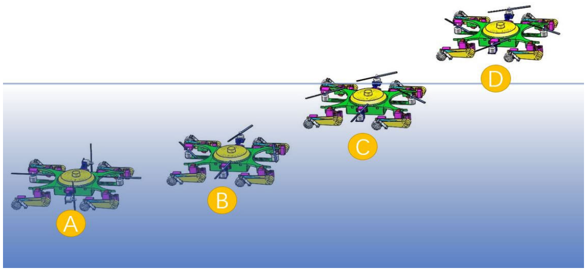
FIGURE 9. **(a) Result of water-to-air transition using the horizontal attitude. (b) Result of water-to-air transition using the tilted attitude.**

has an advantage over the tilted attitude when robot performs water-to-air transition. In further, to illustrate it graphically two virtual simulations of these two attitudes for TR-TRS performing water-to-air transition are conducted in Fluent software, in which the velocity of robot in vertical direction, which is the direction of Y axis, are 1m/s and the rotation velocity of four rotors are all 300rmp. The angle of inclination of robot (i.e., γ) in the tilted attitude is 30 degrees. The results are shown in Figs. 9(a) and 9(b). It is clear that the tilted attitude of TR-TRS affects more area of water surface than the horizontal attitude during its water-to-air transition process, which means TR-TRS adopts the horizontal attitude when it passes through water surface to air can improve the stability comparing to other attitudes.

In conclusion, slower velocity of the robot passing through water surface can reduce the impact/tensile forces and the waves produced by the cavity, which can enhance the stability of TR-TRS. In addition, the horizontal attitude has an advantage over the tilted attitude when the robot performs water-to-air transition. Take these into account, the methods of water-to-air and air-to water transitions are shown in Fig. 10. Fig. 10(a) is the schematic diagram of the proposed method in air-to-water transition. State A means TR-TRS is in aerial quadrotor mode and descents slowly. When TR-TRS approaches the water surface, the four rotors stop working and TR-TRS will slowly sink due to its own gravity, which can reduce the interaction effect between the water and robot so that the TR-TRS can keep stable, namely state B. Then, two rotors on both sides of the fuselage will rotate 90 degrees in state C. Finally, TR-TRS transforms into the underwater mode, i.e., state D, and the air-to-water transition is completed smoothly. The water-to-air transition is in reverse order with air-to-water transition. Firstly, two rotors on both sides of the fuselage of TR-TRS rotate 90 degrees to make their orientation is upward vertically, namely state A to state B. Next, TR-TRS rises and passes through the water surface depending on the forces from four rotors, namely state C. When TR-TRS bursts to the water surface, four rotors rotate faster to transform into the aerial quadrotor mode rapidly and smoothly without any change of attitude, and the water-to-air transition is accomplished.



(a)



(b)

FIGURE 10. **(a) Air-to-water transition. (b) Water-to-air transition.**

C. LAND-WATER TRANSITION

Due to the topography, some terrain does not allow the robot to pass directly using foot or wheel between land and water, such as port, artificial lake and so on. Therefore, the air environment is considered as a relay station in land-water

TABLE 3. The performance comparison of TR-TRS with other multi-field robots.

	TR-TRS	**Loon Copter** [21]	**Naviator1,2** [20]	**HUAUV** [7]
Actuators	Four rotors	Four rotors	Double layer coaxial eight-rotor	Four aerial rotor and four underwater propellers
Complexity of water-air transition	Simple	Complex	Simple	Simple
Stability in water-air transition	Better. The change of robot attitude is small.	General. The change of robot attitude is large.	Good. The change of robot attitude is small.	Good. The change of robot attitude is small.
Mobility on land	Yes	No	No	No
Take off and land on slope	Yes	No	No	No
Energy consumption	Low	Low	High	High

transition. For example, the water-to-land transition can be divided into two steps, which are water-to-air transition and air-to-land transition, and the land-to-water transition can be divided into land-to-air transition and air-to-water transition, which are introduced above, so it will not be explained here.

V. PERFORMANCE ANALYSIS OF TR-TRS

Tilting-rotor structure is proposed combining the functional characteristics of helicopters and fixed-wing aircrafts. Therefore, it can hover in the air like a helicopter or fly at high speed like a fixed-wing aircraft. This paper uses a tilting-rotor structure to connect the fuselage of TR-TRS with the rotors on its both sides, which allows TR-TRS to adjust the orientation of the rotors while the fuselage stays still. Thereby, the direction of propulsive force generated by the rotors on both sides of the fuselage can be changed to obtain various motion modes for adapting different environments. This function is used in the underwater motion and wheel motion modes. It can be seen from the above analysis that the tilting-rotor structure plays an important role in the design of TR-TRS. It is because of the tilting-rotor structure that the proposed motion modes and transition processes can be realized. In further, a comparison of TR-TRS with other multi-field robots is shown in Table 2 detailedly.

Loon copter utilizes a ballast system consisting of a water pump, a two-way valve, a movable piston, a water cylinder, and the vehicular hull to control buoyancy and depth of robot underwater and achieve a seamless water-air transition. However, the robot needs to flip 90 degrees to maneuver underwater. The change of robot attitude is large, which affects the stability of robot underwater. The Naviator1 and Naviator2 are similar to Loon Copter, they can operate underwater in ‘‘horizontal’’ mode. These robots are also needed to flip 90 degrees by control the equipped eight rotors, which not only affects the stability of robot, but also increases the energy consumption. While the HUAUV uses four aerial rotors and four underwater propellers, so its energy consumption is high too. Besides, all this multi-field robots are amphibious that means they can not move on land. With the help of tilting-rotor structure, our proposed TR-TRS can control the orientation of rotors on both sides of the fuselage, which allows TR-TRS to maneuver underwater while the attitude of robot does not change. Moreover, it also can move on land and take off or land on a slope with a certain angle. Comparing with other robots listed in Table 2, not only the stability of TR-TRS is improved, but also the movement space is expanded, at the same time, the energy consumption does not increase. It is obvious that the tilting-rotor structure has great potential in the field of multi-field robots such as triphibious robots.

VI. CONCLUSION

In this paper, a novel triphibious robot called TR-TRS is developed, which is based on a quadrotor. The tilting-rotor structure is introduced and utilized to change the orientation of the rotors on both sides of the fuselage. Thanks to the tilting-rotor structure, the designed TR-TRS allows rotors on each side of its fuselage not only to be used to fly in the air, but also maneuver underwater and move on land. In addition, the various motion modes of TR-TRS in three different environments and the methods of motion transition when TR-TRS moves between two different environmental media are presented. Especially, the land-air and water-air transition processes of the TR-TRS are analyzed emphatically. With the help of the 3-DOF legs, TR-TRS can take off and land on a slope or rough road. According to the virtual simulation in Fluent software, it is found that reducing the velocity of TR-TRS and the rotors when robot passes through the water surface can weaken the impact/tensile forces and waves, and the horizontal attitude is more stable for TR-TRS than the tilted attitude during water-to-air transition process. Finally, by comparing the performance of TR-TRS and other three multi-field robots, the superiority of tilting-rotor structure in TR-TRS is discussed. It can not only simplify the design of multi-field robots, but also improve the motion performance of the robots. In future work, we will conduct experiments about the motion control and motion mode transition to further verify the validity of the design methods proposed in this paper.

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