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Initial Development of a Novel Amphibious Robot with Transformable Fin-Leg Composite Propulsion Mechanisms

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Abstract

Amphibious robots are very attractive for their broad applications in resource exploration, disaster rescue, and reconnaissance. However, it is very challenging to develop the robots for their complex, amphibious working environments. In the complex amphibious environment, amphibious robots should possess multi-capabilities to walk on rough ground, maneuver underwater, and pass through transitional zones such as sandy and muddy terrain. These capabilities require a high-performance propulsion mechanism for the robots. To tackle a complex task, a novel amphibious robot (AmphiHex-I) with,transformable fin-leg composite propulsion mechanisms is developed. With the fin-leg composite propulsions, AmphiHex-I can walk on rough and soft substrates and swim in water with many maneuvers. This paper presents the structural design of the transformable fin-leg propulsion mechanism and its driving module. A hybrid model is used to explore the dynamics between the transformable legs and transitional environment such as granular medium. The locomotion performances of legs with various elliptical shapes are analyzed, which is verified by the coincidence between the model predictions and the simulation results. Further, an orthogonal experiment is conducted to study the locomotion performance of a two-legged platform walking with an asynchronous gait in the sandy and muddy terrain. Finally, initial experiments of AmphiHex-I walking on various lands and swimming in water are implemented. These results verify that the transformable fin-leg mechanisms enable the amphibious robot to pass through a complex, amphibious working environment.

Keywords: amphibious robot, transformable fin-leg, composite propulsion mechanism, amphibious environment

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1 Introduction

Amphibians are the earliest terrestrial vertebrates in the world that have evolved in nature over hundreds of millions of years. They possess great abilities to adapt to various environmental conditions and extensively distribute their numbers inland and in water. Inspired by amphibians, developing a bionic amphibious robot is a challenging task that has gained much attention from researchers worldwide. An amphibious robot is a robot that should be adapted to various environmental conditions such as rough land and underwater environments. Furthermore, it should have the capability of passing through the transitional zone between land and water frequently occupied by soft substrates such as sand and mud. An amphibious robot with a high adaptive capacity to amphibious environment can find broad applications in resource exploration, disaster rescue, and reconnaissance.

In recent years, some interesting bionic amphibious robots have been developed. Snake-like robots are typical amphibious robots, which undulate bodies to propel themselves on land and underwater[1–3]. ACM-R5 is an example of an amphibious snake-like robot with an impressive water proof body structure; it can perform propulsive motion at the same speed of 0.4 m/s both on ground and in water[1]. Some amphibious robots employ different propulsion methods to achieve locomotion in different environments. Whegs is a biologically-inspired amphibious robot with a combination of propellers and legs that allows it to navigate on rough terrain and underwater[4]. Salamander Robot is a salamander-inspired amphibious robot that utilizes body undulation and limb walking to mimic the ability of salamanders to transit

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from terrestrial to aquatic locomotion[5,6] or vice versa. AmphiRobot-II combines wheel and fin propulsion mechanisms to demonstrate fish-like swimming and wheeled crawling[7]. The most attractive ones among amphibious robots are the AQUA series robots that stem from RHex[8,9], a cockroach-inspired hexapod robot with outstanding terrestrial locomotion performance[10,11]. AQUA2 with replaceable flipper foots was developed to allow autonomous transition between locomotion modes[12]. However, the amphibious locomotion ability to cross obstacles declined significantly due to its straight, rigid appendages. There are also many other amphibious robots developed to locomote on terrain and underwater[13–19].

Although affected by many factors, there are two key facts to determine the practicability of an amphibious robot in a complex environment. The first one is the composition of propulsion modes on land and underwater. Wheeled robots are well-known to move fast on even ground, while tracked and legged robots have better mobility on rough terrain. In water, undulatory or oscillatory propulsion could achieve high efficiency, high maneuverability, and lower environmental disturbance compared to screw propellers[20–22]. Some researchers employed two sets of propulsion mechanisms to achieve terrestrial and aquatic locomotions. This set-up resulted in a bulky body and lower efficiency for redundant mechanisms. An optimal solution is to use composite propulsion that utilizes only one set of propulsion mechanism that can optimize the efficiency and simplify the structure. ACM-R5, Whegs, and AQUA2 all adopt composite propulsion mechanisms to locomote in amphibious environment. The second key fact is the capability and effectiveness of an amphibious robot locomoting in the transitional zone between water and land. This fact is very important for amphibious robots, but it has gained little attention in the past years. Amphibious robots cannot easily overcome various kinds of complex environments at the transitional zone. Soft substrates such as sandy and muddy terrains are more difficult for amphibious robots because they will definitely affect the locomotion performance[23]. Wheeled and tracked robots tend to slip for the lack of a tractive force, while straight-legged robots also tend to get stuck in soft substrates due to the lack of a supportive force.

We proposed a novel amphibious robot, AmphiHex-I, with transformable fin-leg composite propulsion mechanisms to overcome the limitation of the existing amphibious robots[24]. The transformable fin-leg composite propulsion mechanism is designed to switch between fin and leg. This allows AmphiHex-I to locomote underwater and on loose and muddy terrain with good performance. A study of the interaction between the leg and Granular Materials (GMs) is presented, and the dynamics of leg-GMs interaction is analyzed by the model and simulation methods. A two-legged walking experiment is performed to validate the analysis of the leg shapes. Finally, robot locomotion experiments indicate that the transform fin-leg mechanism enables the amphibious robot to pass through rough land, soft substrate and water, simultaneously.

The remainder of this paper is organized as follows. Section **2** describes the materials and methods of our research that includes the detailed design of AmphiHex-I, theoretical and simulation analysis of leg-GM interaction, and two-legged working experiments. In section **3**, the results and experiments of AmphiHex-I are summarized and analyzed. Finally, the conclusion and future work are given in section **4**.

2 Materials and methods

2.1 Design of AmphiHex-I

The design concept of AmphiHex-I is illustrated in Fig. 1. This robot is composed of six sets of propulsion mechanisms, each with a transformable fin-leg and a fin-leg driver. AmphiHex-I uses six elliptical legs to walk like a cockroach when performing terrestrial locomotion. For aquatic propulsion, the elliptical legs could be transformed to straight fins, and the robot could swim and perform various underwater maneuvers with the fins oscillating as vector propulsions.

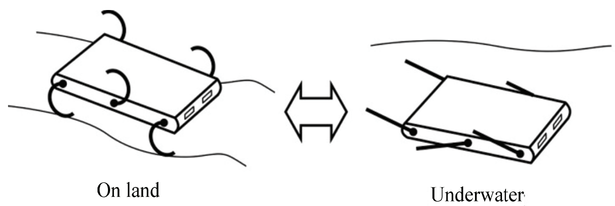


Fig. 1 Design concept of AmphiHex-I.

2.1.1 Transformable fin-leg module

The mechanical design of the fin-leg module is shown in Fig. 2. This module includes a transformable fin-leg and a driving unit. The fin-leg is composed of several segments including a head segment, an end segment, and middle segments. Adjacent segments are connected by a piece of thin elastic plate. A flexible cable runs continuously through all of the segments and is fixed to the end segment. When the flexible cable is dragged or loosened by the driving unit, the transformable fin-leg will switch between straight state (Fig. 2a) and bending state (Fig. 2b). In the former, the transformable fin-leg is suitable for underwater maneuver as a bionic fin and the robot is capable of various maneuvers with six fins as vectored thrusters. In the latter, the transformable fin-leg is appropriate for terrestrial locomotion as an elliptical leg by adopting rotating motions and this is especially suitable for locomotion in transitional environments such as sandy and muddy substrates. Angle, α, in the enlarged view is determined by the inclined planes of two adjacent segments that account for the shape of the elliptical leg when the flexible cable is pulled back. Cable driven transformation is a simple, reliable, and effective method that has been applied and verified in many soft robots[25,26].

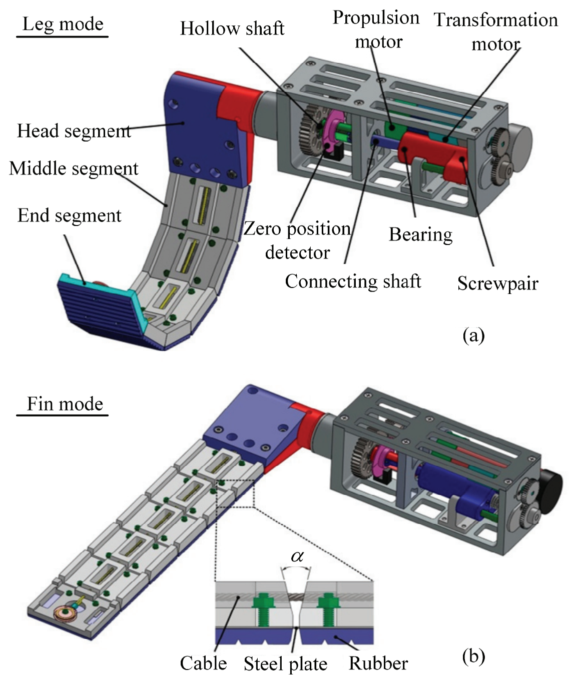


Fig. 2 Mechanical design of the transformable fin-leg. (a) Leg mode; (b) fin mode (enlarged view: the connection of two adjacent segments).

The fin-leg driving unit should realize the coupled motions without conflict to obtain the transformation between fin and leg modes. This includes the rotating motion of the fin-leg and the linear movement of the cable. In particular, the driving unit could avoid twining the cable when the leg rotates. In the current study, a cylindrical pair is adopted to achieve the coupled motion where the robot could switch between its fin and leg modes with different, simultaneous propulsion motions such as oscillation and rotation. A CAD model of the fin-leg driving unit is also presented in Fig. 2. A high-power propulsion motor accounts for the propulsion motion of the fin-leg. A low-power motor is utilized for fin-leg transformation. Thus, the amphibious robot could achieve terrestrial and aquatic locomotion by oscillating or rotating the leg-fins with the propulsion motors. It could simultaneously achieve the transforming motion by pulling or loosing the cable to transform the fin-legs.

2.1.2 Circuit and control method

AmphiHex-I comprises six leg-fin modules that involve the control of 12 motors. The control system of AmphiHex-I is illustrated in Fig. 3. A couple of propulsion units are controlled by a piece of DSP microprocessor communicating via the Controller Area Network bus. A PD controller is adopted to control the speed of the propulsion motors. The transformation motion is obtained by means of monitoring the current passing through the transformation motors. Furthermore, a central control unit is added to coordinate the motion of each propulsion unit and accounts for the propulsion gaits of AmphiHex-I.

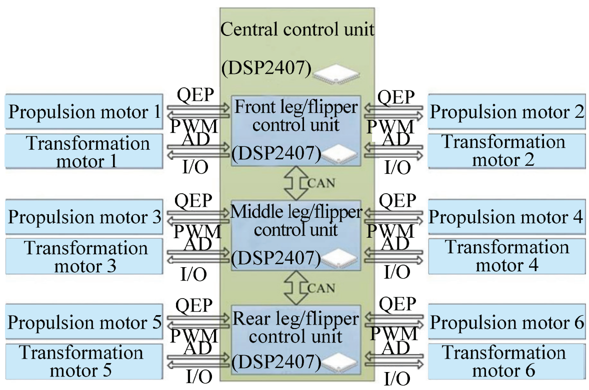


Fig. 3 Diagram of the control system of AmphiHex-I.

2.2 Theoretical analysis on leg-GM interaction

The locomotion performance of AmphiHex-I in an amphibious environment depends heavily on its interaction with the environment. An amphibious environment is frequently composed of sandy and muddy substrates. Sandy substrates can be viewed as a typical case of granular media whose rheological properties are still being explored by extensive researches[27,28]. The nature of such fascinating materials has not been understood as extensively as that of fluids and solids. Nevertheless, the combination of experimental and theoretical analyses can still be adopted to reveal the force behavior of the fin-leg locomotion in granular media such as dry sand[29]. This is relatively simple but significant for the studies of leg-GM interaction. It also leads to the optimal configuration design and motion control of fin-leg propulsions.

The leg-GM complex spatiotemporal interaction while AmphiHex-I walks on granular media can be approximately described by a hybrid model that incorporates an improved Resistive Force Theory (RFT) and a bar-drag experiment[29]. This is inspired by the RFT study of sandfish locomotion in GM[30–32]. The hybrid model displays most significant characteristics during the thrust period, but ignores other complex internal mechanisms. In the model, the elliptical leg is partitioned into infinitesimal elements, and the forces on all the elements represent the total force on the elliptical leg (Fig. 4a). However, the real situation is too complex for the leg-GM dynamics. In this study, we propose that the rotating shaft of the fin-leg should be fixed to simplify the analysis. The force generated in granular medium originating from internal friction has almost nothing to do with the speed of the object through the granular media[33]. Hence, the forward advancing force, F_f, and supportive force, F_s, that act on the elliptical leg are deduced as follows

$$F_f = W\int_{\psi_m}^{\psi_n} (F_\perp \cos\phi + F_\parallel \sin\phi) G \mathrm{d}l, \qquad (1)$$

$$F_s = W\int_{\psi_m}^{\psi_n} (F_\perp \sin\phi - F_\parallel \cos\phi) G \mathrm{d}l, \qquad (2)$$

where W denotes the width of the elliptical leg, and l denotes the length of the elliptical leg. ψ_m and ψ_n represent the two endpoints of the curved leg submerged in granular medium. $F_\perp$ and $F_\parallel$ are the local forces acting on a specified element. ϕ denotes the angle between the direction of $F_\perp$ and F_x, which means the force in the x-axis in the global coordinate system. G is the proportion coefficient that characterizes the nature of granular media. W, ψ_m, ψ_n and ϕ are all known or can be deduced. $F_\perp$, $F_\parallel$ and G can be obtained from the results of a bar-dragged experiment or simulation[29].

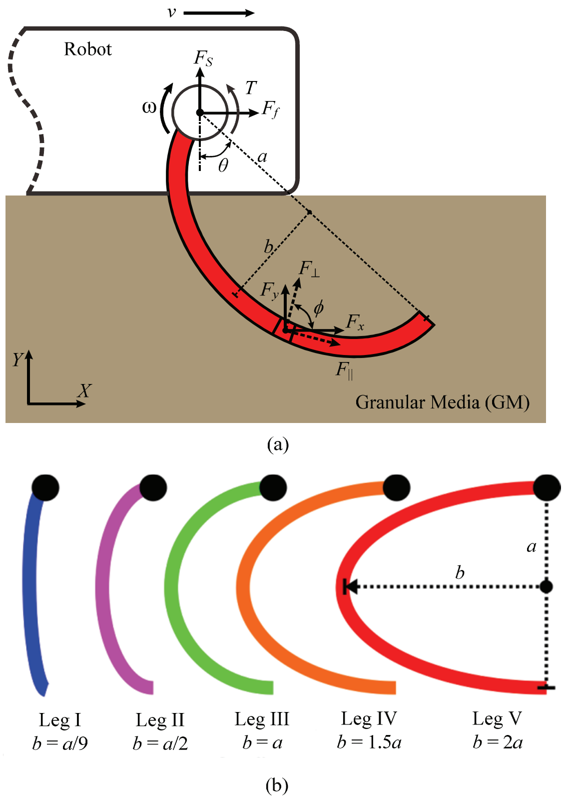


Fig. 4 Illustration of leg-GM interaction. (a) Force analysis of a Leg in GM; (b) five types of legs.

With the bar-dragged experiments and RFT theory, the dynamics of the forward advancing force and the supportive force of the elliptical legs exerted from the GM can be conveniently obtained. This allows us to conduct a further study on the influence of the shape of the elliptical leg on the performance of AmphiHex-I[24]. The shape of leg was also proved to affect the locomotion performance by recent study[34]. Here, five leg shapes were chosen to study the influence on the locomotion performance in granular material, as shown in Fig. 4b. As for the five types of legs, the height of the legs, a is kept constant, while the aspect ratio are variables because b is given different values. Generally, Leg I is similar to the limbs of animals for a small projective area in a horizontal plane. Leg V is more like a wheel because a relatively large projective area in a horizontal plane exists. This also leads to a different degree of subsidence when the robot walks on soft substrates.

2.3 Simulation analysis on leg-GM interaction

The leg-GM interaction could be simulated by a discrete particle simulation of granular media in 3D[35]. Maladen *et al*. utilized this simulation to study the locomotion of a sandfish in granular medium[30]. In this study, we used PFC2D (a commercial software of Particle Flow Code in two Dimensions) to simulate the interaction between the legs with different shapes and granular medium. This is a supplement and validation of the theoretical analysis. In the simulation, an elliptical leg is composed of several straight "walls" inscribed in the ellipse, while the "sand" consists of small particles. The characteristics of the particles are selected from the values recommended in the manual of PFC2D[36]. The forces between particles and the forces between the particles and the leg are shown as blue lines in Fig. 5. The width of each line is proportional to the magnitude of the contact force, and the distribution of the contact force is shown explicitly. With the simulation, the supportive force, F_S, the forward advancing force, F_f, and the torque of the fin-leg shaft, T, could be obtained during the elliptical legs' rotation in granular media.

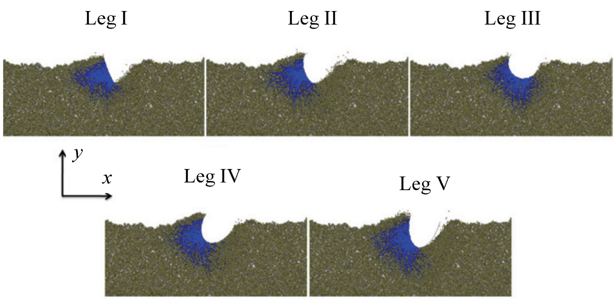


Fig. 5 Simulation of leg-GM interaction in PFC2D.

2.4 Orthogonal experiment on leg-terrain interaction

An experimental study was conducted to investigate the locomotion performance of the elliptical-legged platform walking in complex media such as wet sand and mud. In the experiment, the shapes of the elliptical legs, the water content of the sand and mud, and the rotating speed of the elliptical legs were considered as the factors that affect the locomotion performance.

2.4.1 Experimental platform set-up

In order to investigate the locomotion performance of the elliptical legs with various rotating speeds and shapes, an experimental platform was developed as shown in Fig. 6. The platform is similar to the wheel-terrain characterization test-bed in the lunar rover research[37]. A two-legged walking model was proposed to simulate a six-legged robot with various gaits. A tank measuring 850 mm × 800 mm × 500 mm in length × width × height was set to accommodate enough terrain materials such as sand and mud to simulate a real amphibious environment that amphibious robots usually encounter. The tank is also water-proof so that water can be added to granular media or muddy substrate to obtain certain water content. A strike-off plate was used to comb substrates and to flatten the surface horizontally. The two-legged walking model was installed in a horizontal guide rail to keep the walking direction unchanging. A synchronous belt co-rotating with a rotary encoder (resolution: 1000 P/R) was used to measure the forward speed of the two-legged walking model. A displacement sensor (range: 0 mm – 175 mm with linear accuracy: 0.05%) was utilized to monitor the displacement variation of the walking model along the vertical axis. A torque sensor (range: ±5 Nm; accuracy: 0.5% F.S) was also installed between the output shaft of the motors and rotating shaft of the elliptical legs to measure the output torque of the propulsion motors while the model walks. All of the selected design parameters, such as the motor power and reduction gear ratio, were the same as those of AmphiHex-I.

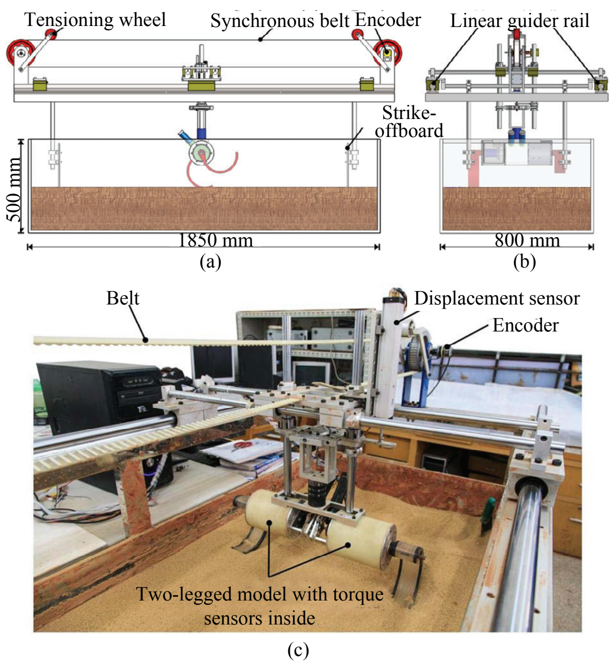


Fig. 6 Experimental platform of the leg-terrain interaction. (a) Front view for the platform; (b) left view for the platform; (c) photograph of the two-legged walking platform.

The proposed experimental platform in the current study could obtain more measurement results such as torque and height variation besides the forward speed, and it could also conduct a deeper analysis on locomotion performance[24,29,38].

2.4.2 Orthogonal experimental design

In the amphibious environment, many variables can affect the locomotion performance of the legged robots. The particle diameter and water content of the terrain medium are two important factors that mainly determine the terrain's physical properties. An orthogonal experiment is designed to investigate the locomotion performance of AmphiHex-I with various conditions, which could reduce the burden of the experiment because of too many parameters[39]. Two kinds of terrain (the sandy substrate and the muddy substrate) that are very common at the transitional zone between land and water were selected and prepared. In the experiment, the sands and the mud were dredged beside a river, and the diameters of the sand particles were varied. Three kinds of legs were selected to explore the influence of the leg's curve (Legs I and V were not taken into consideration because of the capacity of the propulsion motors). The rotating speed of the elliptical legs was also considered as a factor with three levels. All the variables in the experiment are listed in Table 1.

Table 1 Levels of factors

Level	Level 1		Level 2		Level 3	
Factor	Sand	Mud	Sand	Mud	Sand	Mud
Water content (W)	0 wt.%	23 wt.%	5 wt.%	25 wt.%	12 wt.%	27 wt.%
Leg shape (L)	II		III		IV	
Rotating speed of the leg (R)	0.15 rad·s^{-1}		0.18 rad·s^{-1}		0.21 rad·s^{-1}	

The two-legged walking model was driven to locomote 800 mm to record the torque, the forwarding speed, the height variation, and the angular velocity of the motors in real time. The water content of sandy medium was set to 0 wt.%, 5 wt.%, and 12 wt.%, representing dry sand, moist sand, and wet sand, respectively. When the water content exceeded 12 wt.%, the water also exceeded the top surface of the sand, thus was not considered in this trial. The water content of the muddy medium was set to 23 wt.%, 25 wt.%, and 27 wt.%. When the water content of the mud was lower than 23 wt.%, the characteristic of the mud became similar to solid ground that is easy to pass through. When the water content was higher than 27 wt.%, the mud became fluid-like that is not suitable for legged propulsion on the ground. After each test, the mud will be stirred and combed to keep homogeneity. The water content was measured by drying the samples taken from the tank immediately after each group of walking tests.

3 Results and discussion

3.1 Theoretical analysis of leg-GM interaction

The dynamics in the entire rotating period of the elliptical legs in granular media obtained from the RFT model is shown in Figs. 7a and 7b. In the figure, θ is the

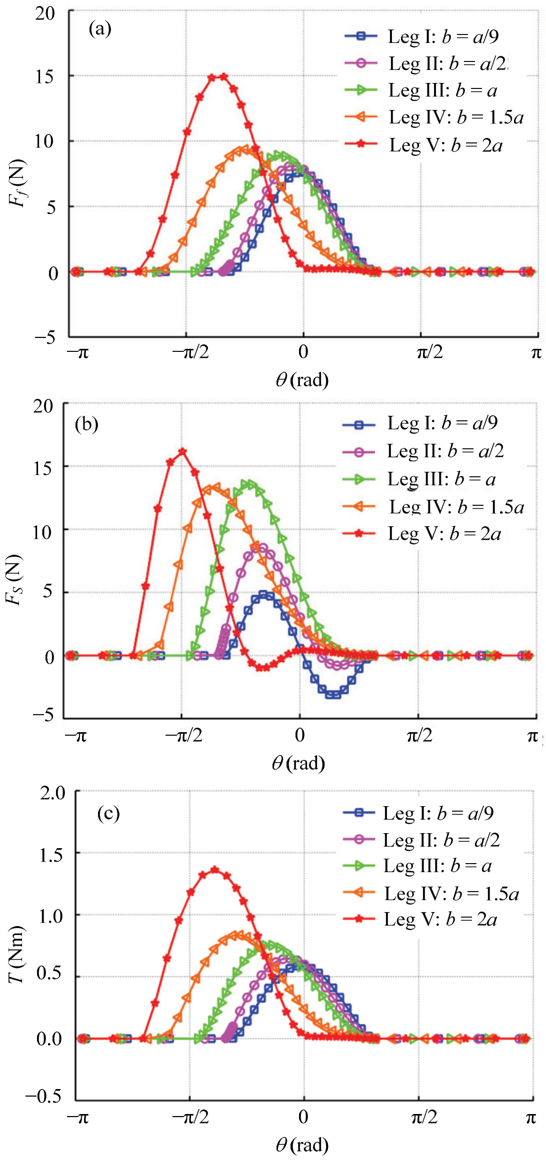


Fig. 7 Dynamics of the forces acting on the elliptical legs during an entire leg's rotating period (theoretical analysis). (a) Forward advancing force, F_f; (b) supporting force, F_S; (c) output torque, T.

angle between the long axis of the leg and the vertical direction shown in Fig. 4a. Utilizing the forces obtained above, the torque of the fixed shaft can be deduced as shown in Fig. 7c.

Fig. 7 shows the trend of the peaks of the forces. The peak positions of the supportive force, forward advancing force, and output torque arrive in the same order as Leg V to Leg I. However, the peaks of the supportive force, F_S, arrive earlier compared with those of the forward advancing force, F_f, with the same leg shapes. The shape of the forces predicted here are similar to the results in Ref. [40]. As b increases from below a to above a, larger peaks can be seen in F_S, F_f, and T. A larger supportive force, F_S, makes it possible to reduce subsidence in granular media, which is significant to energy saving and locomotion performance. Simultaneously, a larger F_f because of increasing b contributes to faster propulsion. A larger T denotes that the propulsion motor has to provide a larger torque to propel the elliptical leg in granular material. This is a negative factor in the locomotion performance, implying greater energy consumption. Thus, Legs III and IV lead to a relative large supportive force, a relative large forward advancing force, and a relative small torque compared with Leg I. The peak value of F_f for Leg V is 1.75 as much as that for Leg III, and the peak value of F_S for Leg V is 1.2 as much as that for Leg III. The peak burden of the propulsion motor is increased to almost twice by the negative effect of increasing T, which is not efficient for terrestrial locomotion. Without regard to the horizontal movement of the shaft of the elliptical legs, an amphibious robot with Legs II, III, or IV will be more effective in locomotion in granular media.

The forces and torque obtained here are different from those of Ref. [24]. For example, the duration of the forces and torque acting on Leg V cannot cover that of other legs. This also is verified by the simulation results in the next subsection.

3.2 Simulation of leg-GM interaction

The forward advancing force, F_f, supportive force, F_S, and output torque, T of the elliptical legs can also be obtained from the PFC simulation described in section **2.3**. The simulation result is shown in Fig. 8. When the legs come into contact with particles, the supportive forces increase fast because of the rapidly expanding contact area and the vertical compaction effort of sand. The forward advancing forces increase slower along with the leg penetrating deeper. The horizontal compaction also comes into effect as the legs rotate, and the forward advancing forces reach peak values afterwards.

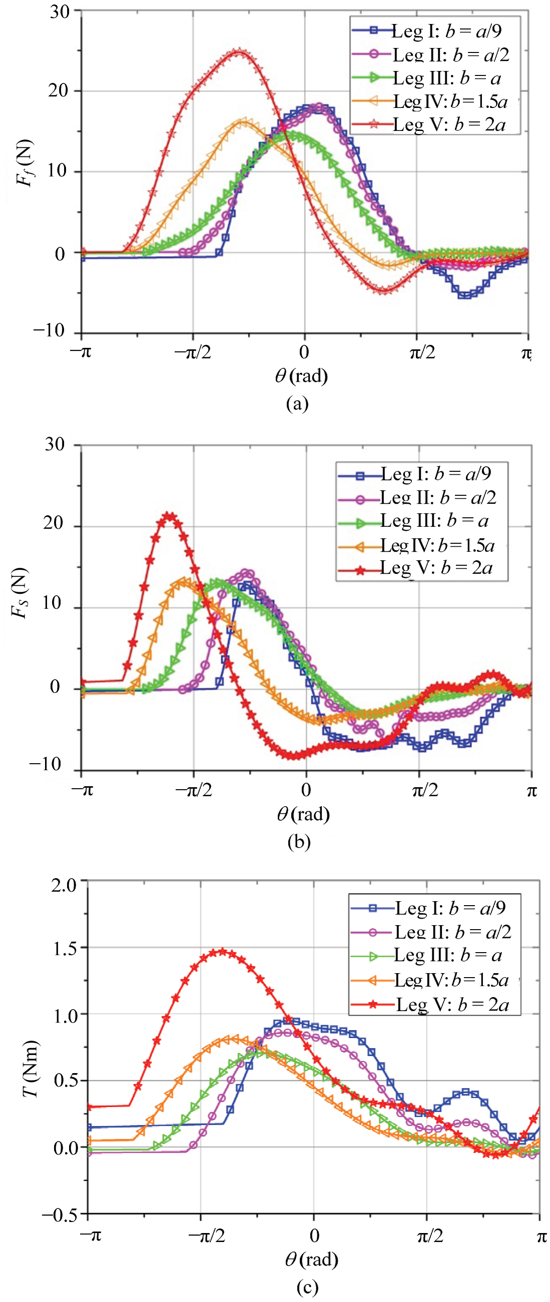


Fig. 8 Dynamic forces acting on the elliptical legs during an entire leg's rotating period (PFC simulation). (a) Forward advancing force, F_f; (b) supporting force, F_S; (c) output torque, T.

The dynamic forces obtained from PFC simulation were also found to share a similar trend with that of the theoretical analysis, including the sequence and the magnitude of the force peak. The absolute values of negative supportive forces and forward advancing forces in Fig. 8 are higher than that in Fig. 7. This is because that some particles are lifted by the elliptical legs from the granular media in the simulation. This fact is ignored in theoretical analysis. As shown in Fig. 8, the dependence of locomotion on b is recognizable. Except Leg V, the changes of peak supportive forces and forward advancing forces of other legs, $b < 2a$, are insignificant. The output torques of Legs III and IV are lower during the entire rotating period. However, the absolute values of the negative supportive forces and the forward advancing forces of Legs III and IV are lower than that of Legs I and II. As for Leg V, $b = 2a$, the large supportive force and forward advancing force lead to a higher output torque. This analysis implies that Legs III and IV are more effective in propelling an amphibious robot, which is similar to that of the theoretical analysis.

3.3 Orthogonal experiment of a two-legged walking model

We obtained the locomotion results shown in Fig. 9 by conducting a range analysis of the measured data in the orthogonal experiment of a two-legged walking model. The energy consumption is defined as the product of the output torque of the propulsion motors and the angular velocity of the corresponding elliptical legs.

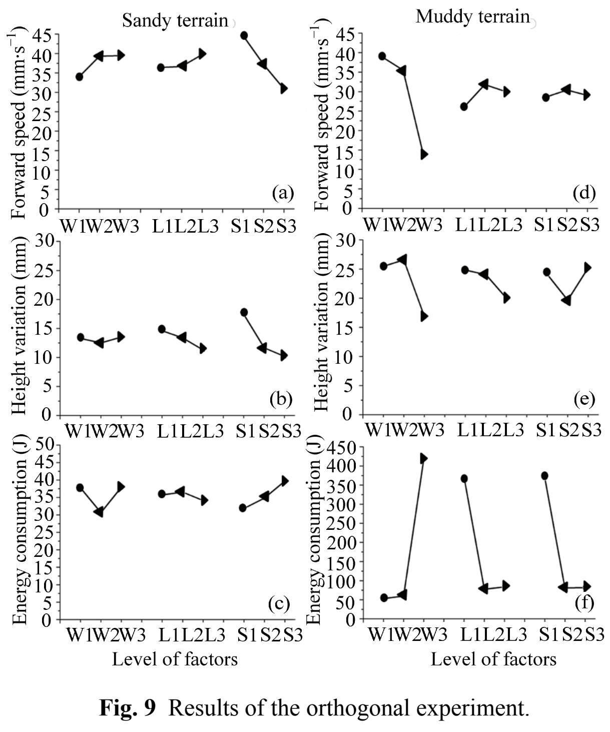


Fig. 9 Results of the orthogonal experiment.

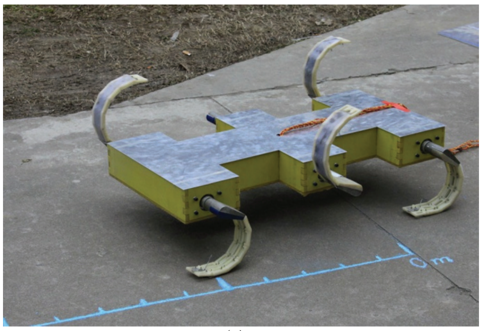
Figs. 9a, 9b, and 9c present the locomotion of the two-legged walking model in sandy terrain, which show that: (1) the sandy terrain with an appropriate water content is conducive for leg locomotion, especially at 25 wt.% water content; (2) the legs of shape IV has more advantages than the others because of its higher forward speed, a lower variation of height, and lower energy consumption; (3) the rotating speed plays a significant role in sandy terrain locomotion, which also indicates the rheological properties of the sandy terrain.

Figs. 9d, 9e, and 9f present the locomotion of the two-legged walking model in muddy terrain. As shown in the figure, we observed the following: (1) the wetter the muddy terrain, the lower locomotion performance the two legged walking model suffered; (2) the walking model with Leg III achieves a higher forward speed and lower energy consumption, while that of Leg IV has a lower height variation; (3) a suitable rotating speed contributes to better locomotion performance.

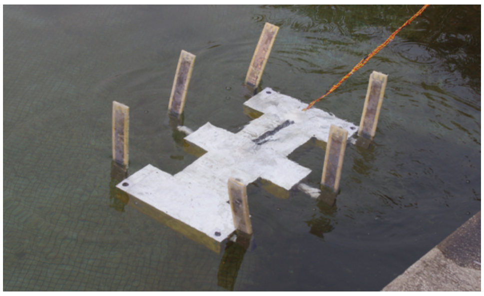
The result of the orthogonal experiment indicates that Legs III and IV are more suitable for propelling an amphibious robot in an amphibious environment, which are similar to the theoretical and simulation results of the fixed shaft propulsion cases. The rotating speed is the kinematic parameter of the fin-leg. It is also important for efficient locomotion in a transitional zone, especially for the rheological properties of sand and mud. The experimental result is of great importance to control AmphiHex-I across the transitional zone.

3.4 Experiments on AmphiHex-I's movement peformance

Fig. 10 shows the amphibious robot prototype, AmphiHex-I, developed using the previous design of a transformable fin-leg composite propulsion mechanism, and theoretical, simulation, and experimental studies. The main specifications are listed in Table 2. AmphiHex-I adopts Leg III to locomote on land. Considering the strength and rigidity of the case, the side and bottom surfaces of the body are formed by gluing 21 pieces of glass epoxy boards together. The top surface is a piece of composite aluminum board. The first prototype of the robot is powered by an external 24 V DC power to simplify the system design. We conducted the following experiments on terrain and in water to test the effectiveness of AmphiHex-I.



(a)



(b)

Fig. 10 The prototype of AmphiHex-I. (a) AmphiHex-I on land; (b) AmphiHex-I in water.

Table 2 Specifications of Amphihex-I

Parameters	Values
Total length	844 mm
Total width	669 mm
Total height	228 mm
Total weight	14.2 kg
Maximum ground clearance	179 mm
Length of a fin-leg	325 mm
Width of a fin-leg	60 mm
Weight of a fin-leg	0.324 kg
Length of the shell	795 mm
Width of the shell	388 mm
Height of the shell	90 mm
Weight of the shell	6.5 kg
Additional weight for suspension underwater	5 kg
Water displacement	0.0192 m^3

3.4.1 Locomotion on rough terrains

We conducted locomotion experiments for AmphiHex-I in different kinds of grounds to test its terrestrial locomotion capability, as shown in Fig. 11. Regardless of a flat or rugged terrain, the robot was found to have superior balance thanks to the curved legs and the bio-inspired tripod gaits. The successful locomotion of the robot on a natural sandy terrain (Fig. 11e) and a natural muddy terrain (Fig. 11f) also validates the effectiveness of the amphibious robot walking in a transitional zone between land and water. The maximum moving speed of Amphibious-I on even ground is currently about 0.55 m·s^{-1}. This figure could be raised by optimizing the structure and adopting a better gait in the future.

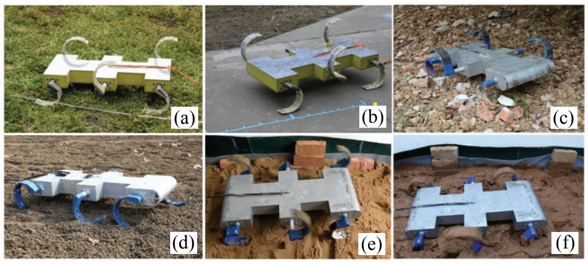


Fig. 11 Locomotion on terrain. (a) Grassland; (b)even ground; (c) rough land; (d) soft soil; (e) wet sand; (f) muddy substrate.

3.4.2 Maneuvering in water

AmphiHex-I also has high maneuverability in water if the six legs are transferred into oscillating fins, which are similar to vectored thrusters. Different combinations of the directions of the fin propulsion provide high maneuverability to the amphibious robot. Figs. 12 and 13 present a series of aquatic locomotion performed in a pool with depth of 0.8 m. AmphiHex-I could cruise forward or backward by the oscillation of its six fins at a speed of approximately two-third its body length per second (0.5 m·s^{-1}). It can also accomplish many maneuvers such as braking, rolling, pivot steering, diving, and ascending by switching and combining the thrust directions of its six fins. Fig. 13 presents a series of snapshots of the AmphiHex-I performing a turning maneuver.

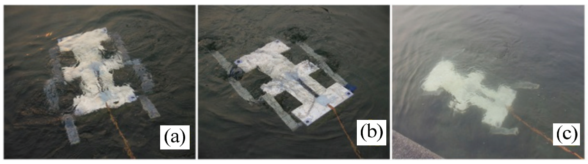


Fig. 12 Maneuvering in water. (a) Cruising; (b) backward swimming; (c) diving.

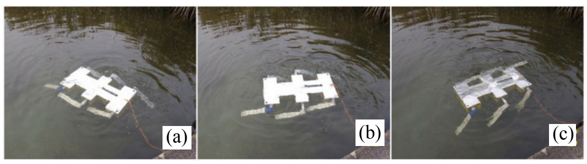


Fig. 13 Amphibious-I turning in water (anticlockwise).

3.4.3 Overcoming an obstacle

The AmphiHex-I robot can easily climb over some obstacles with a special gait based on the previous work of Johnson *et al*.[41]. With the gait, the robot can rotate its left and right legs at the same position as its body. However, we found that AmphiHex-I can climb over an outdoor stair more easily with a tripod gait. This means that the robot does not need to transit the gait when it encounters an obstacle. Fig. 14 shows that AmphiHex-I could climb over an obstacle that is higher than its body with a tripod gait.

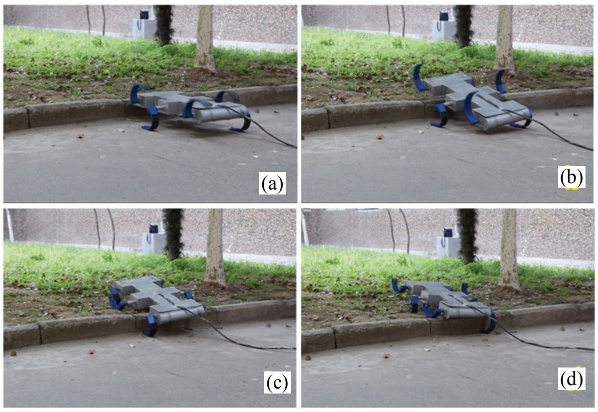


Fig. 14 AmphiHex-I climbing over obstacle.

The above experiments validate the effectiveness of the novel, transformable fin-leg module. With the developed composite propulsion module, the amphibious robot has multi-capabilities of passing through a rough terrain, a transitional zone between land and water, and a underwater environment.

4 Conclusion

An amphibious robot (AmphiHex-I) with novel, transformable fin-leg composite propulsions has been developed. A preliminary theoretical analysis, simulation experiment, and orthogonal experiment were carried out to explore the locomotion performance of transformable fin-legs. The fin-leg composite propulsion has great advantages in an amphibious robot: (1) the fin-leg could propel the robot both on land and in water; it also saves weight and further improves the efficiency of the robot; (2) the switch between fin and leg modes is very simple and effective, which can be accomplished with a transform motor: (3) we could even adopt one transform motor for the transformation of all the six fin-leg propulsions if the synchronous mechanism of the transformation is well-designed; (4) the locomotion performance of the fin-leg composite mechanism in a transitional zone such as sandy and muddy substrates could be optimized by changing the shape and the kinematic parameters of the legs. Basic propulsion experiments of AmphiHex-I achieved the anticipated objectives.

Future work mainly focuses on the following aspects: (1) the locomotion performance of the fin-leg composite propulsion mechanism working in various environments, including underwater, should be considered comprehensively; (2) the effect of the fin-leg's flexibility on the locomotion performance should also be studied and optimized.

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