
Design and Simulation of Amphibious Wheel-Foot Composite Mechanism

Abstract: With the continuous development of society and the deepening of the level of science and technology, the fields explored by human beings are becoming more and more extensive, and the requirements for exploration are becoming more and more detailed. However, due to the limitation of mobility, most of the existing amphibious robots still can't be used to complete the specified tasks in complex environments. In order to meet the reliability of motion in complex environments, referring to ePaddle mechanism can enhance the mobility of amphibious robots. Based on the new movement mechanism of eccentric paddle mechanism (ePaddle), according to its principle and prototype, this paper proposes a compound wheeled amphibious robot, which realizes the movement of the robot through an improved eccentric lever mechanism. This mechanism includes multiple gaits, and can adapt to various complex terrains by actively changing the position of the paddle shaft to follow the alternate movement of the wheel foot and the paddle shaft. The key feature of the improved mechanism is to design the rotation of the planet carrier to drive the blades to expand and contract to realize underwater movement. This paper mainly introduces the kinematics analysis and prototype design, and simulates various gait movements through simulation software to verify the feasibility of the new design.

Key words: amphibious robot; Compound wheel foot; Eccentric lever mechanism; ePaddle

1 Introduction

Recently, autonomous amphibious robots are being studied all over the world, and are becoming an increasingly popular topic in the field of robotics. Because of its mobility on land and water, autonomous amphibious robots can assist human beings to perform various high-risk tasks. Whether the tasks such as mine clearance, topographic mapping, search and rescue after tsunami and flood can adapt to various complex terrains is an important assessment standard for amphibious robots, so high environmental adaptability is an important feature for amphibious robots to complete these advanced and intelligent tasks, and the existing amphibious robots have achieved outstanding sports ability in amphibious environment.

Bionic amphibious robot and hybrid amphibious robot are the main types of amphibious robot at present. The design of mechanism and system of bionic amphibious robot is based on the characteristics and principles of biological movement. The froot robot frog designed by Yang et al. [1] reproduces the frog's swimming style by swinging a pair of flippers. The snake-shaped amphibious robot ACM-R5 designed by Yanmada et al. [2] uses the propeller-type propulsion mechanism as the joint module, which can zig zag in water and land. The turtle robot developed by Low et al. [3] designed similar propulsion structure by imitating the shape and movement mode of turtle flippers, and realized amphibious operation in waterway. Jun et al. [4] developed the robot crab CR200; which uses hexapod mechanism to walk on the beach or seabed. Hybrid amphibious robot realizes the maneuverability of amphibious robot by integrating or switching various propulsion mechanisms. The Aqua robot developed by Georgiades and others [5] realizes two movements by replacing rigid legs and flexible paddles. The robot Amphibot-ii developed by Yu et al. [6] of Chinese Academy of Sciences is an

original wheel-paddle-fin hybrid propulsion mechanism; However, due to the limitation of the ability of movement and load, these two kinds of robots are difficult to be used in practical tasks. For example, a series of rescue tasks such as search and rescue monitoring after tsunami and flood attacks, after such disasters, in order to carry out amphibious rescue tasks, robots must be able to travel in complex terrain and underwater. Based on this problem, this paper puts forward a compound mechanism which combines planetary gear mechanism and eccentric (ePaddle) [1] mechanism, which combines wheel gait, leg gait and paddle gait into a single mechanism, and follows various gait of alternating motion by changing the position of blade shaft. This paper mainly studies a kind of amphibious robot with wheel-paddle integration based on the combination of blade and wheel-foot. Focusing on the characteristics of various motion modes of amphibious robot, the design of amphibious robot with wheel-foot mechanism as the main body is carried out, and its motion characteristics and how to coordinate control are studied and analyzed. A three-dimensional model of amphibious robot is built by Solidworks to verify its gait on land **Error! Reference source not found.** And floating gait in water [7]**Error! Reference source not found.** Based on the comprehensive motion performance, we hope to realize various motion modes of amphibious robot, which forms the theoretical basis of amphibious robot based on wheeled foot mechanism, and provides effective strategies and methods for multi-mode motion of amphibious robot. The research methods of this paper are as follows:

- (1) Calculate the transmission ratio between gears of each part of the gear train through kinematic analysis.
- (2) Build the virtual prototype model of the robot by Solidworks, and build the motion simulation animation, and analyze whether the model is qualified or not through the model and animation.
- (3) Simulate the motion of the 3D model by Solidworks, and observe the motion of the amphibious robot under multiple gaits.

2 Structural design and analysis of amphibious robot

The amphibious robot studied in this paper is based on ePaddle mechanism. The design of planetary gear mechanism, ePaddle mechanism was first developed by Sun et al. [11] Put forward. The key feature of this mechanism is that all joints are rotary joints, and there is dynamic coupling between the joints, which enables it to perform various gait movements.

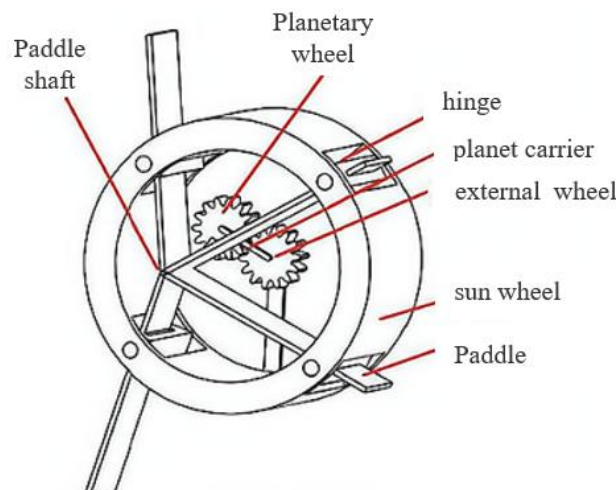


Fig. 1. schematic diagram of epaddle structure

The structural diagram of ePaddle is shown in Fig.1, which includes a movable paddle shaft, four paddles, an actively driven wheel housing and four passive paddle hinges, which constitute the mechanical module of ePaddle. The paddle shaft is driven by a linear sliding screw and a rotating base through two DC motors (one for the screw base and one for the sliding screw). The DC motor drives the housing to rotate around the axis of the fixed housing. Because the paddle shaft is located inside the housing through two brakes, the movement modes of the paddle end points can be alternated. By changing the position of the paddle shaft, the movement modes of the paddle in the plane can be changed, so that the movement gait of the robot based on epaddle can realize the advantage of versatility. This design can carry out four main gaits, including wheel-type rolling, leg walking and wheel-leg integrated gait, and paddle gait in water environment. The end of each paddle protrudes from the shell, which serves as the control surface when swimming and the leg when walking. In wheeled movement, the shell acts as a wheel, and its gait is shown in Fig.2.

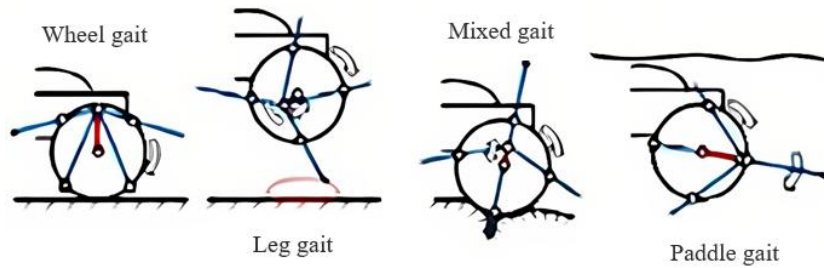


Fig. 2. ePaddle running gait

Through a series of experiments, this mechanism has verified the multi-gait of the ePaddle mechanism. However, there are some problems that limit the performance of ePaddle in practical tasks.

1) Eccentricity and eccentricity angle are respectively controlled by two independent joints in the original prototype. In order to cope with extreme situations in harsh environment, it is necessary to configure high-power DC motors for two joints. This will increase the weight of the robot and consume more energy.

2) It is difficult to ensure the waterproof work of the mechanism in underwater environment because of the need to use linear sliding screw to adjust the eccentricity. In addition, the linear sliding screw is also prone to failure in muddy and sand environment, and the eccentricity adjustment method of the linear sliding screw will limit the performance of the mechanism in harsh underwater and land environment.

3) In order to transmit enough torque, the reverse timing belt is used in the ePaddle mechanism. However, it also causes relative sliding between the belt and the inner gear of the rotator and between the belt and the driving pulley, which will adversely affect the motion stability of the belt mechanism.

Considering these problems, this paper puts forward the conceptual design of an improved wheel-foot mechanism (eccentric lever mechanism based on planetary gear mechanism), as shown in Fig.3. This mechanism actively changes the position of paddle shaft to follow the pattern of alternate movement of wheel foot and paddle blade, and uses planetary gear mechanism instead of linear sliding screw with rotating base to change the position of paddle shaft.

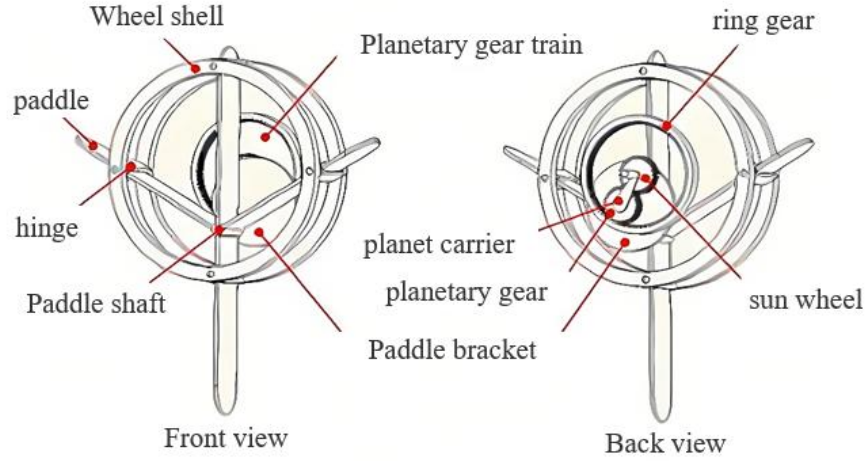


Fig. 3. Schematic diagram of wheel foot structure

The wheel mechanism consists of four main components:

- 1) a movable paddle shaft driven by a planetary gear mechanism;
- 2) a group of four paddles that can freely rotate around the paddle shaft;
- 3) a ring gear which can rotate around the axis of the fixed shell;
- 4) Four passive paddle hinges located in the shell. Rely on the edge of the shell and let the blades slide over them.

The planetary gear mechanism used in this wheel foot mechanism consists of four basic components: sun gear, planetary gear, planetary gear carrier and ring gear. As shown in Fig.4, the centers of the sun gear and the ring gear coincide with the center of the housing O . The sun gear and the ring gear are inputs and driven by two DC servo motors to rotate around the fixed housing axis. The angular displacement of the sun gear and the ring gear are expressed by θ_1 and θ_3 respectively. Planetary gears and planetary carrier are outputs. The angular displacement of the planet gear and the planet carrier are represented by θ_2 and θ_4 respectively.

Planetary gears are fixed by disks with larger diameters. The center of the planetary gear indicated by O_c coincides with the center of the wheel disc. The disc is named paddle shaft bracket because the paddle shaft and the disc are fixed in an eccentric position. The fixed eccentricity is expressed by R_e . Using the angular displacement of sun gear and ring gear θ_1 and θ_3 , two actively rotating joint variables, the position of paddle shaft in the shell can be determined. Another active actuator in the wheel is a DC servo motor that drives the housing to rotate around the fixed housing axis. The angular displacement of the shell is indicated by θ_w . When the shell rotates around the shell axis, the hinge forces the blade to rotate around the blade axis.

This mechanism has the following two advantages. First of all, the planetary gear mechanism of this wheel foot is a two-input and two-output system, and there is dynamic coupling in the system. By changing the torque and speed of the two inputs, the mode of output torque and power in the system can be adjusted, so the efficiency of each movement gait can be optimized. Secondly, it is convenient to design the whole waterproof structure by using three rotary joints. In addition, without linear sliding screw, the failure probability in sediment environment is reduced, and the new design can improve the maneuverability in underwater and harsh environment.

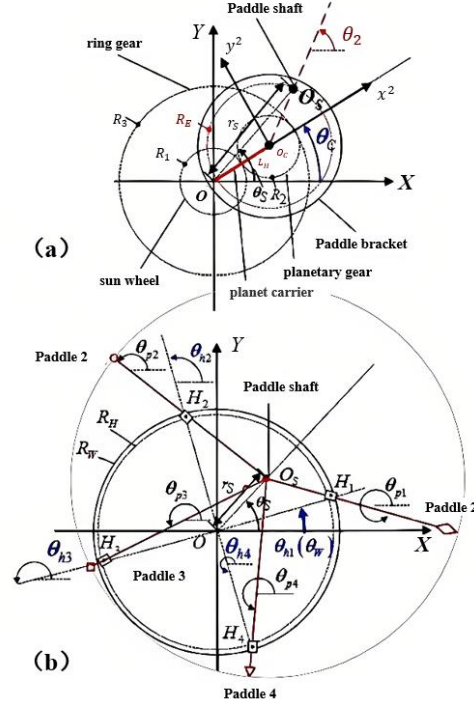


Fig. 4. Schematic diagram of wheel foot movement

3 Robot kinematics theory analysis

Three independent actuators are used in the wheel compound mechanism. Therefore, the forward kinematics equations of θ_1 , θ_3 and θ_w can be used to calculate the position of each blade tip. In order to clearly express the geometric characteristics of the wheel foot, the mechanism principle is divided into two parts. The planetary gear mechanism and the lever shaft bracket are shown in Fig.4(a), and the rest of the wheel foot is shown in Fig.4(b). In the figure, the position of shell axis is O point, and the position of paddle axis is O_s point.

By calculating the transmission ratio between the gears of the planetary gear, the angular displacement between the planetary gear (θ_2) and the gear carrier (θ_c) can be obtained as follows

$$\begin{bmatrix} \theta_c \\ \theta_2 \end{bmatrix} = A \begin{bmatrix} \theta_1 \\ \theta_3 \end{bmatrix} = \begin{bmatrix} \frac{1}{1+n_2} & \frac{n_2}{1+n_2} \\ \frac{1-n_2}{1+n_2} & \frac{n_2+n_1n_2}{1+n_2} \end{bmatrix} \begin{bmatrix} \theta_1 \\ \theta_3 \end{bmatrix} \quad (1)$$

In formula (1), n_1 and n_2 are the tooth ratios of the planetary gear mechanism, that is

$$n_1 = \frac{Z_1}{Z_2}, n_2 = \frac{Z_3}{Z_1} \quad (2)$$

In formula (2), Z_1 , Z_2 and Z_3 are the tooth numbers of the sun gear, the planet gear and the ring gear respectively. The position of the blade shaft is obtained by geometric transformation, which can be expressed as

$$O_s = \begin{bmatrix} X_{os} \\ Y_{os} \end{bmatrix} = \begin{bmatrix} R_E \cos \theta_2 + L_H \cos \theta_c \\ R_E \sin \theta_2 + L_H \sin \theta_c \end{bmatrix} \quad (3)$$

In formula (3), L_H is the length of the planetary carrier. Pay attention to positioning the blade shaft in the circular area of the shell shaft O center, and the eccentric distance of the blade shaft bracket and

the length of the planetary gear carrier should meet the requirements.

$$L_H = R_E = R_1 + R_2 \quad (4)$$

In equation (4), R_1 and R_2 are the pitch circle radii of the sun gear and the planet gear. The eccentricity r_s and eccentricity angle θ_s of the propeller away from the wheel center can be expressed as

$$\begin{aligned} r_s &= L_H \sqrt{2[1 + \cos(\theta_2 - \theta_c)]} \\ \theta_s &= \frac{1}{2} (\theta_2 + \theta_c) \end{aligned} \quad (5)$$

It can be seen from equation (5) that the maximum eccentricity in the wheel foot is

$$r_{s_mx} = 2L_H \quad (6)$$

Then, according to equation (7), the position of the i paddle hinge in equation (6) is obtained.

$$H_i = \begin{bmatrix} x_H \\ y_H \end{bmatrix} = \begin{bmatrix} R_H \cos \theta_{hi} \\ R_H \sin \theta_{hi} \end{bmatrix} \quad (7)$$

Where R_H represents the radius of the circle where the hinge is located, and θ_{hi} is the angular position of the i hinge, which can be expressed as

$$H_i = \begin{bmatrix} x_H \\ y_H \end{bmatrix} = \begin{bmatrix} R_H \cos \theta_{hi} \\ R_H \sin \theta_{hi} \end{bmatrix} \quad (8)$$

Then, the attitude angle of the i paddle θ_{pi} ($i = 1, 2, 3, 4$) in equation (8) can be obtained by equation (9):

$$\theta_{pi} = \arctan 2[y_H - y_o, x_H - x_o] \quad (9)$$

Therefore, the tip position P_i of the i paddle can be obtained by equation (10).

$$P_i = \begin{bmatrix} x_{pi} \\ y_{pi} \end{bmatrix} = \begin{bmatrix} L \cos \theta_{pi} + L_H (\cos \theta_2 + \cos \theta_c) \\ L \sin \theta_{pi} + L_H (\sin \theta_2 + \sin \theta_c) \end{bmatrix} \quad (10)$$

Among them, L is the length of each paddle. By coordinating the three actuators, the tip position of each paddle can be actively positioned on the plane of the shell to realize various gait. Due to the structural size limitation, the tip position of each blade should meet the formula (11):

$$\sqrt{(x_{pi} - x_o)^2 + (y_{pi} - y_o)^2} \leq R_E + L_H + L \quad (11)$$

4 3D modeling and motion simulation

4.1 Model building

Table 1 Main data of robot

Name	Unit	Data
Paddle length	mm	265
Shell radius	mm	145
Radius of pitch circle of sun gear	mm	25
Paddle board	mm	50

Radius of pitch circle of planetary	mm	25
Pitch radius of ring gear	mm	75
Sun gear tooth number		25
Planetary gear tooth number		25
Ring gear tooth number		75
Hinge gear number		25
Paddle shaft eccentricity	mm	50

According to the above analysis of the robot structure, with the data in Table 1 as the main dimensions, the 3D model as shown in Fig.5 is established by Solidworks.

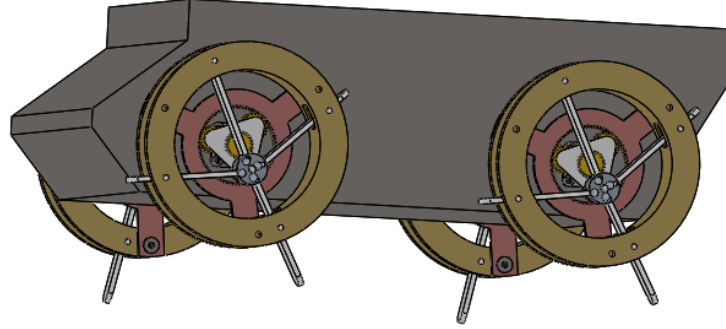


Fig. 5. 3D model of amphibious robot

4.2 Amphibious robot motion simulation

4.2.1 Analysis of Wheel Gait

In order to verify the motion ability of the robot, the 3D modeling software Solidworks is used to simulate its motion state based on the 3D model shown in Fig.5. From the kinematic point of view, water gait such as swinging paddle gait and rotating paddle gait are similar to wheeled gait. Therefore, the emphasis is placed on wheel gait and leg gait, and the gear toolbox of Solidworks is used to model the planetary gear mechanism. The contact type between teeth is 3D contact. In the simulation model, the mass and inertia characteristics of the electron beam assembly are extracted from the computer-aided design model, and the static friction coefficient between the robot and the ground is set to 0.8.

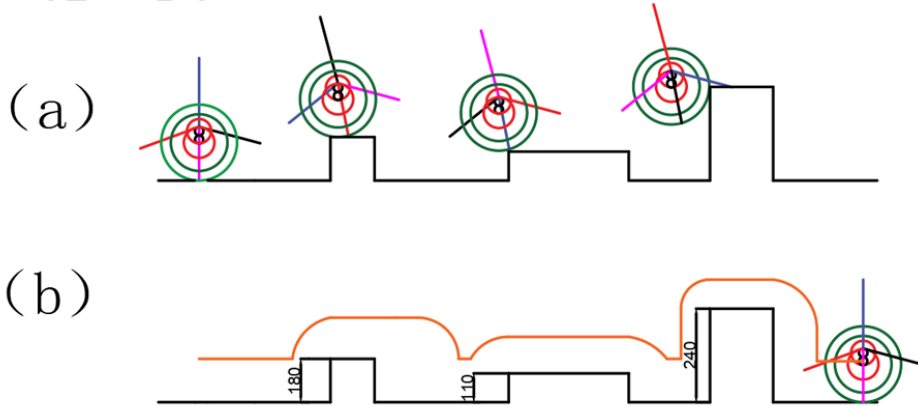


Fig. 6. Simulation results of wheel gait

Fig. 6 is the simulation result of wheel gait. Wheel gait is the most stable and effective gait based on epadle mechanism. In this gait, the position of the paddle shaft will be moved to the uppermost position, and the paddle near the ground will completely retract into the shell, and the outer surface of

the wheel shell is in contact with the ground to perform the required movement as a wheel. In the wheel gait, only the actuator of the shell is used, so it is obvious that the wheel gait is suitable for flat terrain. For the traditional wheeled robot, the maximum size of crossing obstacles is less than the wheel track. However, due to the adoption of freely retractable blades, the obstacle crossing ability of the wheel gait is improved. When the robot encounters a high obstacle, the blades in the forward direction provide additional supporting force by contacting with the obstacle, so the robot can overcome higher obstacles. To verify this hypothesis, the wheel gait simulation results are shown in Fig.6. In the simulation, the maximum height of the obstacle is 240mm, which is much higher than the radius of the wheel housing ($R_w=150\text{mm}$). Fig. 6 shows the posture of the module when climbing over different obstacles, and shows the traces of the axle.

4.2.2 Analysis of Leg Gait

As a discrete ground contact gait, leg gait is more maneuverable, but it consumes more energy. In order to perform leg gait, one of the paddles is selected as the leg first, and then the motion trajectories of three actuators are planned so that the tips of the legs are in discrete contact with the ground. Generally speaking, one-legged gait has two stages: supporting stage and swinging stage. In the supporting stage, the tip of the leg remains stationary and contacts with the ground, while changing the position of the paddle shaft and impeller to make the robot move forward; In the swing stage, the tip of the leg swings in a certain trajectory in the air; These two stages alternate, and the locus of leg vertices can be described as the combination of straight line segments and curves.

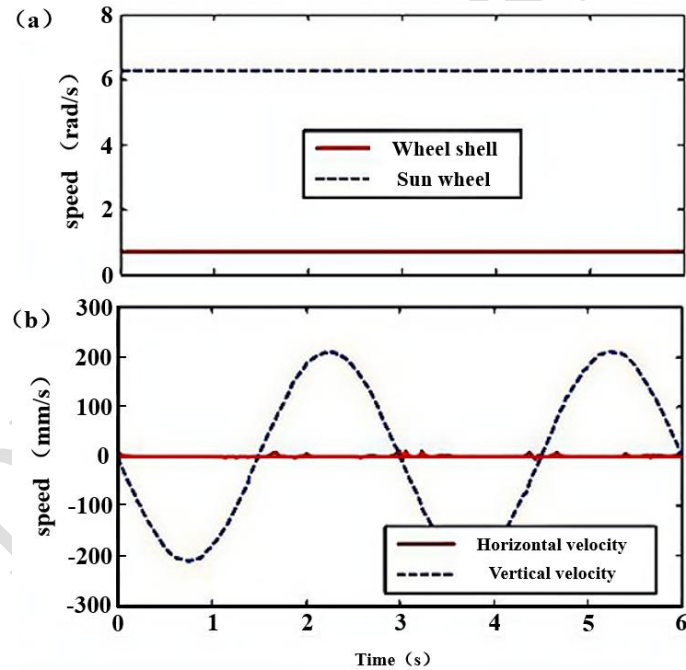


Fig. 7. Angular displacement of actuator

In order to verify the performance of the leg of the wheel foot in the swing stage, a simple arc is selected as the trajectory of the leg. The arc length and arc height are 400mm and 50mm respectively.

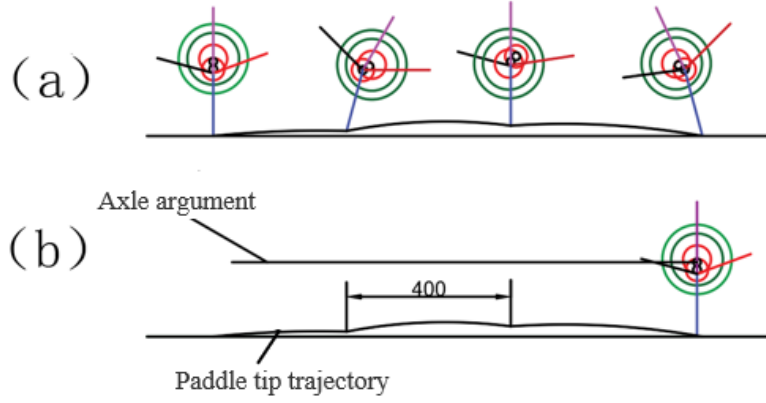


Fig. 8. Simulation results of leg gait

Through the analysis of inverse kinematics [12], a set of output data of three actuators is obtained. The angular displacement of the actuator is shown in Fig.7, which is the relative displacement of the initial posture of the leg gait. The results show that the displacement ratio of the sun gear to the ring gear is 9, which keeps the eccentricity angle θ_g unchanged. The simulation results are shown in Fig.8, and different postures of the module during gait are shown in Fig.8(a). The marks of the axle and the tip of the leg are shown in fig. 8(b). The trace of the axle is a straight line parallel to the ground. The trajectory of the leg tip is an arc curve with a length of 400mm and a height of 50 mm. As shown in Fig.9, the displacement of the paddle shaft (a) indicates the displacement in the X direction and (b) indicates the displacement in the Y direction. The yellow area indicates the swing stage. The red area indicates the support phase. In a cycle, the duration of the support phase is three times that of the swing phase. The simulation results verify the gait ability of the amphibious robot's legs.

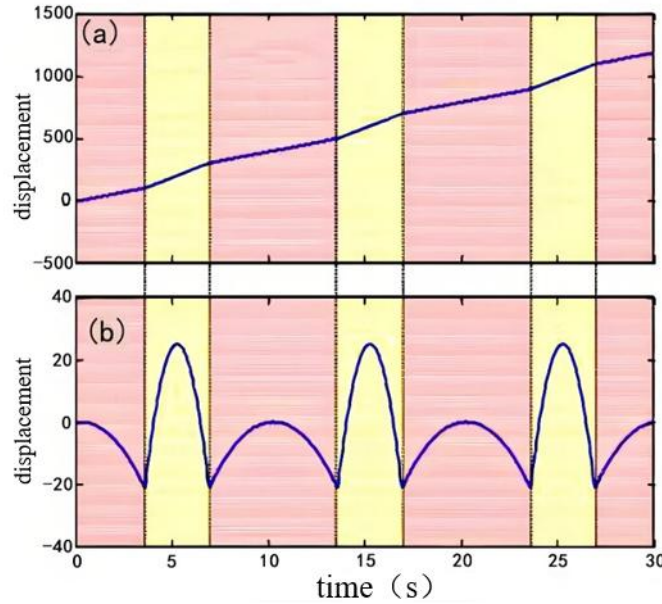


Fig. 9. Relative displacement of propeller shaft

4.2.3 Analysis of underwater floating

As shown in fig. 10(a). The first swimming gait is rotary paddling. In this gait, all paddles are driven by sun gear and rotate around the paddle axis, which is marked by the solid arrow in the figure. Because the blade shaft is located at the eccentric position, the protruding areas of the blades are different, thus producing different thrust. By changing the position of the central axis, we can change the magnitude and direction of the thrust. The second swimming gait, that is, swinging paddle gait, is

based on the swinging motion of blades, as shown in Fig.10(b). In this design, one of the four paddles is finally selected as the working paddle, which is marked with double lines in Fig.10(b). The paddle shaft is located at the eccentric distance R . The driving wheel-shaped housing rotates, but the direction of rotation is reversed periodically, as shown by the solid arrow in Fig.10(b), which will make the extended blades oscillate at the angle magnitude θ_{osc} at the average position A_{10} , and the direction and magnitude of thrust can be changed by changing A_{10} . Paddle gait is the first choice to drive floating in water, because the blades and the wheeled shell rotate in the same direction, so that when the wheel foot rotates and the blades move, the reaction force from water on the whole car body reaches the maximum, which makes the movement more stable and reliable. Moreover, there is no energy wasted on the swinging motion of the blade and the wheeled shell, which is the same as the swinging blade gait.

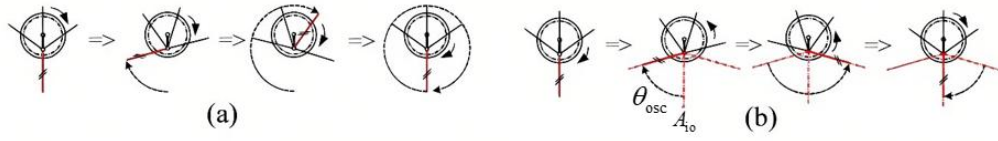


Fig. 10. Wheeled foot floating in water

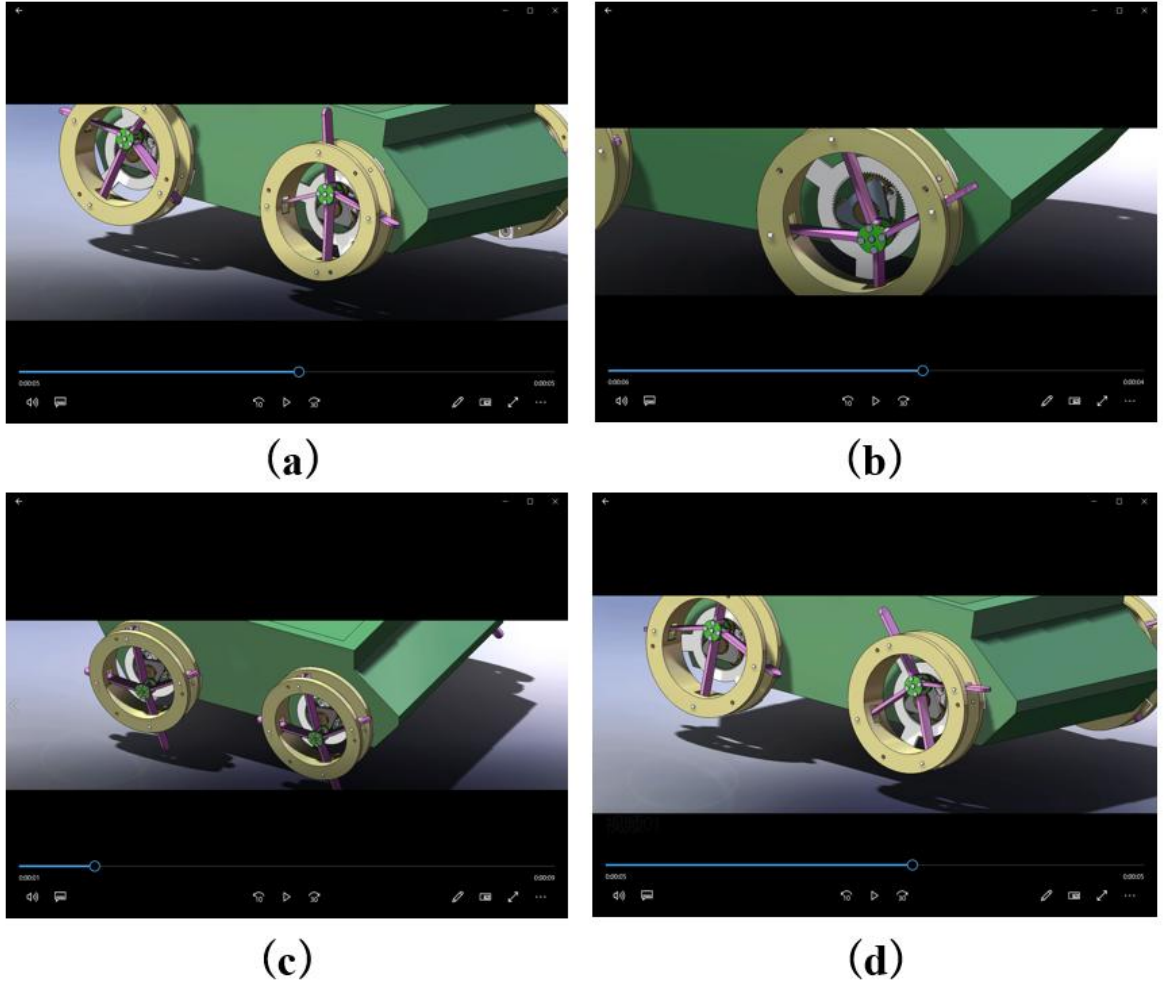


Fig. 11. animation demonstration of four gaits

In fig. 11, (a), (b), (c) and (d) are animation demonstrations of wheel gait, leg gait, mixed gait and paddle gait, respectively. Through the demonstration, it can be seen that each part of the wheel-foot

composite mechanism is reasonably designed, and each part does not interfere with each other and moves reliably.

4.3 Advantages of this design

In the design, the epicycloid gear mechanism is adopted [13]. To drive the plane motion of the blade shaft, which shows some advantages in reliability and maneuverability. First of all, the linear sliding screw is not used in this design, which improves the stability of the machine movement. Secondly, compared with the two independent inputs of eccentric displacement and eccentric angle of the previous gear, there is dynamic coupling between the two input ends of the planetary gear mechanism. This means that any plane motion of the propeller shaft can be realized by the combination of two inputs. For example, the input mode of leg gait is different from that of previous epaddle. When the previous epaddle prototype performed the leg gait, the paddle shaft was only driven by the linear sliding screw, which means that all the power came from the motor driving the linear sliding screw. In this design, two input terminals drive the movement of the paddle shaft, thus reducing the power requirement of each motor and ensuring the reliability of motor driving. Finally, the continuous rotation of the sun gear and the ring gear enables the paddle shaft to reciprocate in a certain direction. This mechanism is convenient to change the control mode of the leg gait in the future. At different stages, the direction of the paddle shaft needs to be changed in time. Therefore, this design has the potential to solve the problem of energy waste and extra wear caused by the constant change of motor direction in leg gait.

5 Conclusion

In this paper, the research methods and achievements of the wheel-foot composite mechanism of amphibious robot based on epaddle mechanism are mainly focused on the following aspects: (1) The robot can walk underwater and on land through the cooperation transmission between gears and the expansion and shifting of blades at specific positions, and the transmission ratio between gears can be calculated by gear train transmission ratio, and the running speed of the robot can be obtained according to the transmission ratio, which proves the rationality of the mechanism design. (2) According to the eccentric device, the position of the blade shaft will be fixed right above the whole wheel foot, and the blade near the ground will completely retract into the shell, thus achieving the movement of the wheel gait; Through the way of blade extension, the machine can realize the leg gait crossing obstacles. (3) The 3D model of the robot is established by Solidworks, a 3D software. The motion simulation of the wheel-foot composite mechanism is done by animation demonstration, and the motion pattern similar to the theoretical calculation in this paper is obtained, which proves the correctness of the theoretical analysis proposed in this paper. Through the above work, this paper puts forward the following optimization suggestions and research directions for this type of amphibious robot with wheel-foot composite mechanism: (1) Further optimize the transmission efficiency of planetary gear trains in the wheel-foot composite mechanism, reduce the power consumption of the system and increase the stability of the overall structure without affecting its transmission efficiency. (2) The prototype can be made according to the 3D model, the experimental platform can be built in the actual environment, and various gaits can be verified on the spot, so as to further improve the wheel-foot mechanism.

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