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Design of Clutch Units of the Propulsion System for the Three-Dimension Triphibian Robot

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***Abstract*- Robots capable of traversing various environments have stringent design requirements for their drive structures. To add flight capabilities to the existing amphibious spherical quadruped robot, enhance its mobility space, and optimize its propulsion strategies, this paper designs a clutch units for the propulsion system of the three-dimension triphibian robot (3DTR). The article first introduces the concept of the 3DTR and its significant importance, and explains the critical role of the clutch units for the propulsion system of the 3DTR. Then, according to the design requirements for functionality upgrade, the types of clutches and motors are selected, and the mechanical model of the clutch units is designed. Subsequently, performance tests and function verification of the clutch units were conducted, demonstrating the effectiveness of the clutch units design, laying the foundation for the subsequent overall design and experiment of the 3DTR propulsion system.**

Index Terms - Three-dimension triphibian robot, Propulsion system optimization, Clutch units, Function verification.

I. INTRODUCTION

Movement across environments has always been a frontier topic in the field of biomimetic robot design. In recent years, with the in-depth study of amphibious biomimetic robots, robots that can move efficiently in different environments and save energy have gradually become the focus of researchers. Unlike the previous multi-drive structure amphibious robots, the current design of amphibious robots is more inclined to use simple drive structures to achieve multi-environment mobility [1]. This approach not only effectively reduces energy consumption, enhances the endurance of the robot, but also lowers the overall weight of the robot, simplifying the control difficulty of the robot.

There are many research topics on amphibious robots, mainly adopting the design concept of using a single drive structure to achieve multi-environmental mobility. For example, Yale University developed the ART amphibious biomimetic robot with a single drive device based on the movement characteristics of sea turtles and land turtles [2]. Its drive device is only its limbs. Through the pneumatic device, the limbs generate deformation, thereby achieving the flapping and paddling movements of sea turtles in the ocean and also the crawling movements of land turtles on land. Tongji University's "TJ Flying Fish" robot is based on the traditional quadrotor [2] and increases the rotation torque of the motor through the gear structure. Therefore, its drive device is only a combination of the flight motor and the flight rotor, and the rotor during flight serves as the propeller for underwater movement, realizing the robot's air and underwater movement under the condition of a single drive device.

Under such a design concept, our research group developed a multifunctional amphibious spherical quadruped robot (ASR) [3-8]. Taking the crawling motion of land turtles as a biomimetic reference, it completed multi-modal movements on land and underwater, achieving good results. However, the existing robot still has significant shortcomings in movement, such as low obstacle avoidance efficiency and stringent requirements for ocean landing. Therefore, we plan to upgrade and optimize the existing robot, add flight capabilities, and make it a new type of three-dimension triphibian robot (3DTR). The next section will unfold the concept of the 3DTR and propose the design of the clutch units for the 3DTR based on this concept.

The structure of this article is arranged as follows. The first part is an introduction to the article, mainly introducing the research background of this paper, explaining the urgent need for research on multi-habitat robots, and proposing a design structure to solve the problem of drive devices. The second part describes the principle and scheme design of the clutch units based on electromagnetic clutches. The third part explains the design prototype of the clutch units and conducts experimental calculations. Finally, the fourth part summarizes the content of the article and looks forward to future work.

II. CONCEPTS OF MULTI- ENVIRONMENT ROBOT

The 3DTR evolves from the existing robot ASR in our lab. Therefore, it is essential to first analyze the advantages and disadvantages of the ASR, due to its good mobility characteristics in unstructured environments, including zero turning radius and cross-environment movement, has significant application value in fields such as pollution detection and oceanographic surveying. This robot uses cylindrical devices as its leg structure, completing terrestrial biomimetic crawling movement. Meanwhile, the cylindrical legs contain motors and propellers. When the robot enters the water, the leg propellers start rotating, and at this point, the

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cylindrical legs act as water jet propulsors, driving the robot to move underwater.

Although the single propulsion system's application in various environments has been achieved, ASR still has obvious deficiencies [9-13]. For instance, in terms of ocean landing, ASR can only land in shallow beach areas at the current stage. It cannot effectively land in the face of reefs or cliffs, limiting its movement space. Moreover, in the vast terrestrial environment, the traditional crawling movement's efficiency and obstacle avoidance efficiency are relatively low, causing certain obstacles to the robot's practical application. Therefore, expanding the amphibious robot's movement space, making it capable of moving in three environments - sea, land, and air - has become an urgent need for studying cross-environment biomimetic robots.

Based on such requirements, we plan to upgrade and optimize ASR by redesigning the propulsion system to enable the original ASR's flight function. Once the flight function is implemented, the original robot is no longer merely an amphibious robot that can move on land and in water. Instead, it becomes a robot that can crawl on land, propel underwater, and fly in the air. We refer to this brand-new robot as the three-dimension triphibian robot (3DTR).

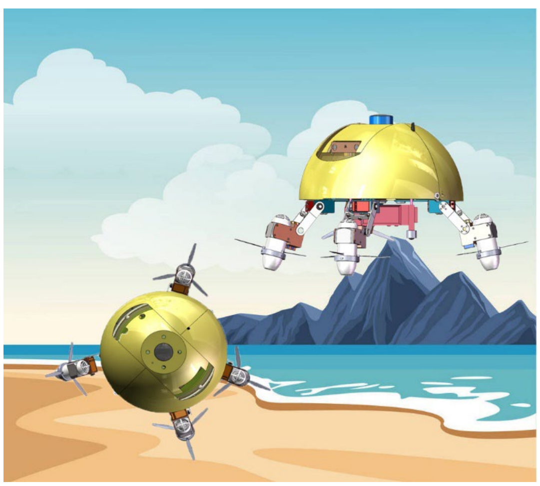

Fig. 1 Multi-environment Robot

For the upgraded 3DTR, the most important aspect is to enhance its propulsion system. While maintaining the original amphibious motion function and the single-drive structure design concept, the key problem is how to add a flight function and complete the transition between different movement states. To solve this core problem, this paper innovatively proposes a clutch units based on electromagnetic clutches to realize the switching between different movement functions.

III. Design of Clutch Units for Propulsion System

A. Design Methodology

At present, most sea-air amphibious robots are mostly designed based on the structure of the rotor UAV [14], that is, their air and underwater movements use the flying rotor as an important component to generate lift and thrust. Although such a structure greatly simplifies the design of the robot, the rotor needs strict size design to avoid damage from strong resistance when moving underwater. Not only that, the main way to solve the huge difference in resistance in the air and water at this stage is to increase the torque of the brushless motor, including adding a reduction gear box, increasing the power of the motor, and so on. However, increasing the torque will inevitably reduce the motor speed, thereby sacrificing the performance of the robot in the air.

Therefore, although the amphibious robot designed based on the structure of the rotor UAV realizes the multifunctional movement of the single motor drive structure, it is obvious that the size of the rotor is strictly constrained in different environments, which makes the robot have obvious load limitations and More stringent design constraints have a greater impact on the practical application of amphibious robots. In order to solve the inappropriate problem of the underwater movement of the flying rotor, while retaining the design idea of single motor drive to achieve multifunctional movement, the design principle of this paper is based on the leg drive structure of the multifunctional ASR. While maintaining the original design of the propeller, the flying rotor is added, and the switch between the propeller and the flying rotor in different environments is realized through the clutch units based on the electromagnetic clutch. This can not only reduce the dimensional constraints of the rotor, but also ensure the load requirements of the robot during flight, without sacrificing the underwater movement of the robot. Therefore, the design of the clutch units plays a crucial role in the locomotion efficiency of the 3DTR.

B. The Part of Clutch Units

The design of the clutch units is related to the motion function of the whole robot [15]. Considering the continuous change of the working environment of the robot and the high-speed rotation during flight, the entire clutch units must not only be effective in various environments, but also ensure that the clutch can effectively transmit power at high speeds to avoid failure. In addition, due to the limited leg space of the robot, the size of the entire clutch units needs to be as small as possible, and in order to cooperate with the various motion functions of the robot, the clutch units needs to respond quickly, so as to realize the rapid motion switching of the 3DTR in different environments. To sum up, for the entire clutch units, the first step in the design is the selection of the clutch, which is also crucial. Most of the existing clutches can be classified into four categories, namely mechanical clutches, hydraulic clutches, pneumatic clutches, friction clutches and electromagnetic clutches.

The working principle of the mechanical clutch is to realize the transmission of power through a mechanical connection device composed of mechanical structures such as levers, friction plates, and gears. The connection or separation of the driving end and the driven end of the clutch is realized by operating a device such as a lever, and then the clutch effect of the overall transmission is realized. For mechanical clutches, its advantages are simple structure and easy maintenance, and it does not require external power supply, and it also has a large torque range. However, mechanical clutches also have major disadvantages, such as limited operation methods, low degree of automation, slow response speed of the clutch, and relatively serious mechanical wear.

The principle of the hydraulic clutch is suitable for using a liquid medium such as oil to transmit pressure, so as to realize the effective transmission of power. The commonly used method is to push the displacement of the piston through the hydraulic pump, so that the driving end and the driven end of the clutch are engaged or separated. The advantage of the hydraulic clutch is that the power transmission is relatively smooth, and at the same time it can realize effective automatic control. But its shortcomings are also very obvious. The structure of the hydraulic clutch is often very complicated, and the weight is relatively large. It is prone to leakage when moving underwater, polluting the environment, and its response speed is relatively slow.

The principle of the pneumatic clutch is similar to that of the hydraulic clutch, the difference is that the pneumatic clutch uses air to transmit pressure to drive the piston. Its advantages are simple structure, small weight and fast response. But the disadvantage is that it requires air source equipment, and has high requirements for air tightness of the gas. It is difficult for the clutch to work effectively in an underwater environment, and the torque range is limited.

The principle of the electromagnetic clutch is to realize power transmission through the magnetic force generated by the electromagnet. Under the energized condition, the electromagnet generates a strong magnetic field through the electromagnetic principle, and the driving end and the driven end of the clutch are closely attached to realize power transmission. After the power is cut off, the magnetic field disappears, and the driving end and the driven end are separated, thereby realizing the clutch function. The advantages of the electromagnetic clutch are fast response, the clutch effect can be realized quickly through the control of an external circuit, and its structure is very simple, easy to install and maintain later, and the service life of the electromagnetic clutch is very long, and the reliability of the clutch function is also high. Its disadvantages are mainly that electromagnetic radiation may interfere with surrounding equipment, and the torque range of the electromagnetic clutch is relatively limited.

Based on the characteristics of various clutches, this paper decides to use the electromagnetic clutch as the device of the clutch units based on the advantages of small weight, fast response and convenient control. After the clutch is fixed, when the motor rotates and the clutch units is disengaged, the driving end of the electromagnetic clutch rotates while the driven end does not move. When the clutch units is in the connected state, with the rotation of the motor, the driving end and the driven end of the electromagnetic clutch will rotate at the same time, thereby realizing the clutch function of the clutch units.

Fig. 2 Electromagnetic Clutch

Next is the selection of the motor, which is also the hardest part of the entire design process. Due to the complexity of the changing working environment and the different requirements for the motor under different motion functions, the clutch units has relatively strict indicators for the motor speed, torque, size, and shaft output mode. For flight sports, because it needs to drive the rapid rotation of the flying propeller, the motor needs to have the characteristics of high speed [16]. For underwater sports, the motor needs to drive the water jet propeller to rotate in a liquid environment with high resistance to generate thrust, so the motor needs to have a large torque [17]. For land crawling, the overall leg size should not be too large, otherwise it will greatly affect the efficiency of crawling, so the size and weight of the motor need to be controlled within a certain range. For the entire clutch units, the shaft output mode of the motor is very critical, and different shaft output modes directly determine the design structure of the entire clutch units.

At present, the motors used for rotor drones and marine propellers are mainly brushless motors [18]. A brushless motor (BLDC) is a type of DC motor that uses electronic commutation instead of traditional carbon brush commutation. It has the characteristics of low heat generation, high speed, long life, etc., and can realize precise control of the speed and position of the brushless motor with the controller, and is widely used. The structure types of commonly used brushless motors include outer rotor brushless motors and inner rotor brushless motors. The main difference is mainly reflected in the relative positions of the stator and rotor. The stator of the outer rotor brushless electronics is located inside the motor, and the rotor is surrounded by the outside of the stator. This design makes the diameter of the rotor larger, so that the motor has a larger torque and good heat dissipation performance, but the disadvantage is slow response and waterproof performance. poor. Inner rotor brushless motors have the stator inside the motor and the rotor inside the stator. It has the advantages of high speed, fast response, simple structure, and good sealing, but the disadvantage is that the torque of the motor is small.

In addition to considering the performance of the motor, it is more important to consider the shaft structure of the motor. There are two types of motor output shaft structures, namely single output shaft and front and rear double output shafts. When considering the way of shaft output, it is more important to consider the design of the overall separation system. In view of the fact that we have two power machines, the propeller and the flying rotor, but there is only one drive motor, considering the complex fixing method of the electromagnetic clutch under the single-outlet shaft mode, and the very serious off-axis movement, the front and rear double-outlet motors will be used the shaft brushless motor is used as the output shaft structure of the motor. Such a structure can not only simplify the leg size, but also effectively fix the electromagnetic clutch. Based on the above, our team finally adopted the front and rear dual-shaft inner rotor brushless motor with good waterproof performance, high speed and more simplified structure as shown in the figure below as the drive motor for the clutch units.

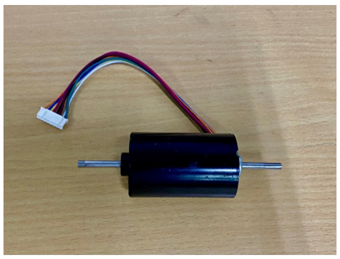

Fig. 3 Dual-Shaft Inner Rotor Brushless DC Motor

IV. Experimental verification of clutch units

A. Design Prototype

In order to realize the various functions of the clutch units, it is necessary to design and model the whole system, and to carry out experimental verification of the clutch units. In the clutch units, the two electromagnetic clutches are fixed to the front and rear shaft ends of the double-outlet shaft motor by means of shaft end fixing. The shaft end fixation has high stability, even under high-speed rotation, it will not easily loosen or appear off-axis movement. In addition, the shaft end fixing method can ensure good cooperation between the motor output shaft and the load parts, reduce energy loss, and its centering performance is relatively outstanding, which can well ensure the position of the axis and axial direction, and is very convenient for installation and installation. repair. The design prototype of the integral clutch units is shown in the figure below.

Fig. 4 Design Prototype of Clutch units

To reflect the function of the clutch units, a water jet propeller and a flying propeller are installed on the driven ends of the two electromagnetic clutches. The flying propeller adopts a three-rotor structure to increase lift and flight stability. The propeller still uses the original ASR robot propeller system, which reduces repeated parameter tests and simplifies the model.

B. Experimental Principle

Whether the clutch units is effective depends on whether it can achieve the separation, connection function between the motor and the propeller hub, as well as the braking function of the propeller hub itself. Therefore, the tests for the clutch units mainly involve functional experiments, that is, by testing the physical entity to determine whether the clutch units can achieve the three functions of connection, separation, and braking.

Fig. 5 Experimental Principle Flowchart

C. Clutch Units Assembly and Performance Testing

The assembly of the physical entity is done first, as shown in the figure below. A double-output shaft motor is used, connecting the motor to the clutch unit. The clutch unit consists of an electromagnetic clutch, propeller hub, and electromagnetic brake. There are two rough-surfaced permanent magnet pieces fixed on both sides of the propeller hub. When the clutch or brake is powered, the hub will connect with them through magnetic force to realize the clutch units function. For the convenience of experimental testing, we first adopt a one-end fixed method for testing.

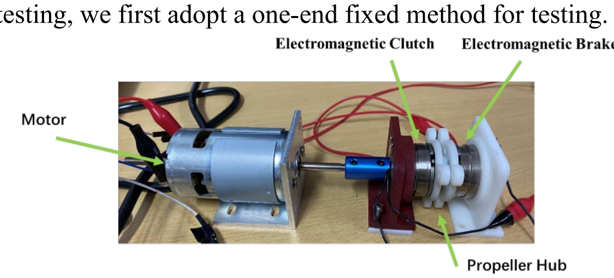

Fig. 6 Clutch Units Assembly

Next, we perform load performance testing on the motor. The key indicator of brushless motor performance is the KV value. It is a parameter and representation method for fluid flow characteristics. This index indicates the increase in the speed of the brushless motor for each additional volt of input voltage. By measuring the voltage at different speeds, we can get the KV value of the brushless motor under load as a clutch units. Since the thrust generated by the rotation of the propeller is related to its speed, measuring the load KV value of the motor can not only compare with the idle speed but also primarily calculate the thrust of the propulsion system in the air and underwater in subsequent steps.

We use the DLY-2301 tachometer to test the motor speed. The tachometer uses laser and reflective stickers for non-contact testing, making the speed measurement range wider and the resolution higher.

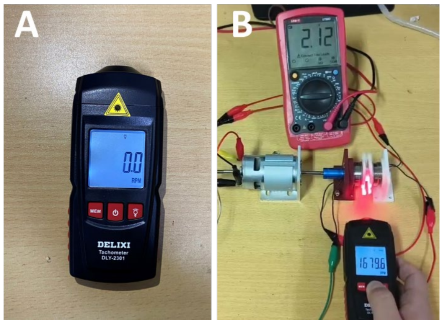

Fig. 7 Tachometers and Performance Test

After several sets of tests, we obtain the motor speed under different voltages. Within the range of 1V to 7V, we measure the corresponding speed for each selected voltage with an interval of 0.2V, and take the average of three sets of data to get the relationship graph between the load motor speed and voltage.

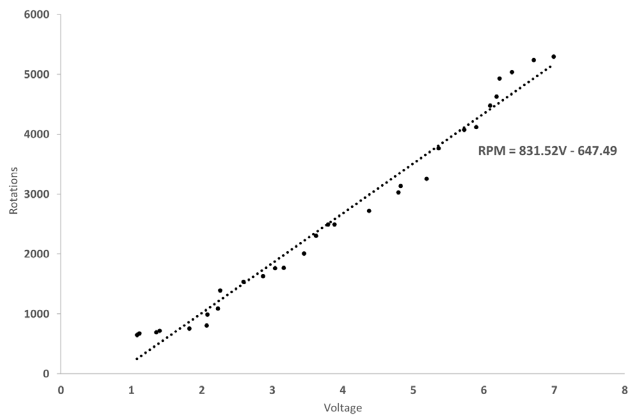

Fig. 8 Performance Testing Result

The load KV value of the motor is the slope of the fitted curve in the table above, approximately 831.52KV. The KV value of this motor without load is about 840 KV. Compared with it, the performance loss is small, which meets our requirements for the motor after loading. We have also completed the performance testing of the loaded motor.

D. Clutch units Functional Verification

The functional test is the most crucial part of the verification process, directly reflecting whether the designed clutch units can realize its functions. We conducted verification through the above-mentioned device, mainly verifying three functions: connection, separation, and braking. These three functions correspond to three control logics.

The first function is the separation function. In the initial state, the propeller hub is connected to the electromagnetic brake. At this time, the motor is started, and the motor will drive the rotor of the electromagnetic clutch to rotate. However, because the propeller hub is connected to the electromagnetic brake and separated from the electromagnetic clutch, when the motor starts at this time, the propeller hub does not rotate, as shown in the figure. This realizes the separation function of the clutch units.

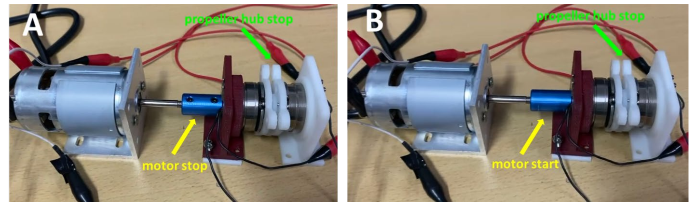

Fig. 8 Separation Function

The second function is the connection function. In the initial state, the propeller hub is connected to the electromagnetic brake. At this time, the motor is started, and the motor will drive the rotor of the electromagnetic clutch to rotate, but the propeller hub and the motor remain in a separate state. Then turn off the electromagnetic brake and start the electromagnetic clutch. Due to the magnetic attraction, the propeller hub quickly and tightly adheres to the rotor of the electromagnetic clutch at this time and rotates with the motor shaft under the action of static friction, as shown in the figure. This realizes the connection function of the clutch units.

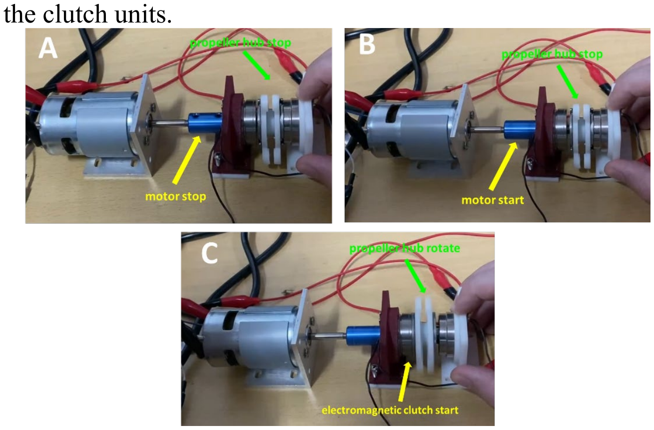

Fig. 9 Connection Function

The third function is the braking function. In the initial state, the propeller hub is connected to the electromagnetic clutch. At this time, the motor is started, and the motor will drive the rotor of the electromagnetic clutch to rotate. Because the propeller hub is connected to the electromagnetic clutch at this time, the propeller hub will rotate. Then turn off the electromagnetic clutch, start the electromagnetic brake, and the propeller hub stops rotating instantly, as shown in the figure. This realizes the braking function of the clutch units.

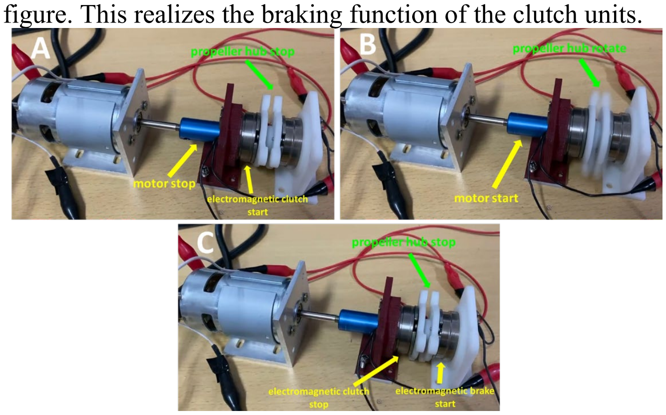

Fig. 10 Braking Function

In summary, both the motor speed test under load in the clutch units and the function test of the clutch units meet the design requirements. This indicates that the design of the clutch units is effective and can serve as the functional system of the propulsion system of the subsequent 3DTR.

V. Conclusion

This paper introduces the design and verification of a propeller clutch units based on an electromagnetic clutch in the propulsion system of a three-dimension triphibian robot (3DTR). First, the concept of 3DTR is proposed, and an analysis is made of the existing multifunctional amphibious spherical quadruped robot (ASR), to further optimize the mobility of the robot, we plan to upgrade the existing ASR by adding flight capabilities, and according to the concept of being able to operate in water, land, and air environments, the new robot is named as 3DTR.

Then, the paper analyzes and explains an important structure in the 3DTR, which is the clutch units in its propulsion system, and proposes a design plan for a propeller clutch units based on an electromagnetic clutch. Finally, the selected components are assembled physically, and performance tests are carried out on the motor under load, and a comprehensive functional verification of the clutch units is conducted. This indicates that the designed clutch units can achieve the functions of connecting, separating, and braking the motor and the propeller hub.

In the future, we need to further coordinate verification with the flight rotor system and the water jet propeller system. In order to better control the clutch units, the power system of the original robot also needs to be optimized. In summary, for the entire propulsion system of the 3DTR, the design of the clutch units is the first step, and further optimization needs to be carried out according to the movement function requirements of the 3DTR in the future.

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