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A review on the application of bionic underwater robots in different underwater environment

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Abstract. People have the spirit of constantly exploring the unknown areas of the world. The flow of fluid is ever-changing, and it can be simply divided into laminar flow and turbulent flow. In this context, the underwater robot was born. In order to cater to people's exploration of complex fluid flows such as lakes and oceans, bionic underwater robots with innate advantages have given full play to their role and become a certain trend. This paper mainly reviews the bionic underwater robots from three aspects, namely the prediction of the robot's trajectory in complex fluid, the rationality of its structural design, and the strength suitability of materials. Finally, the future of bionic underwater robots is analysed.

Keywords: Bionic underwater vehicle, Complex fluid, Smart material, Control and test, Fluid mechanics.

1. Introduction

Since the third scientific and technological revolution, the world has been gradually digitalized, and the progress brought by science and technology has made it more and more popular for people to pursue those unknown areas, such as the ocean. In recent years, the strategic position of the ocean is becoming more and more important, so the research on underwater robots has made considerable progress after undergoing a series of major changes. Traditional robots have the characteristics of loud noise, large volume, low safety factor, poor environmental adaptability, poor reliability, and low transmission efficiency. With the deepening of human exploration of complex waters, there is an urgent need to develop and deploy underwater robots that can perform dangerous or artificial tasks in a variety of complex water environment. Aquatic organisms have diverse body structures and excellent underwater motor skills, which enable them to survive in complex underwater environment. Therefore, it is possible to develop robots with underwater biological functions by combining the existing bionic structures, intelligent propulsion materials, and advanced control methods. Inspired by the swimming style of underwater animals, scientists have designed a series of underwater bionic robots using the newly developed software robotics technology [1].

In this paper, the application status of bionic underwater robots in different underwater environment is described comprehensively, so that people can be aware of the working efficiency problems of bionic underwater robots as well as understanding the importance of them as a future trend.

2. Trajectory prediction of bionic underwater robots in complex fluid

2.1. Current situation

As shown in Figure 1, the robot is called "Swimming Leaf" (hereinafter referred to as "Leaf"). It was developed by the research team of the Department of Mechanical Engineering of Seoul National University in South Korea. It can swim autonomously. When it swims downstream, it slowly falls or rises like a fallen leaf.

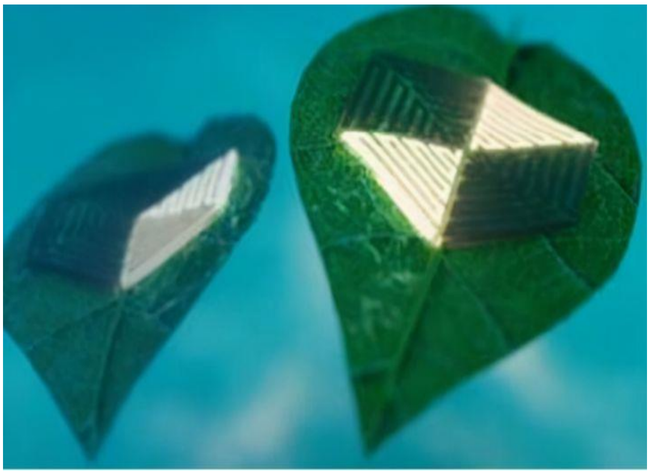

Figure 1. Cover of Science Robotics [2].

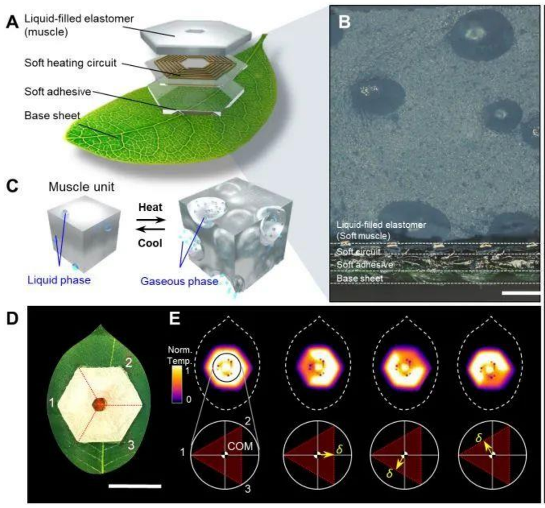

Figure 2. Schematic Diagram of "Leaf" Robot Movement [2].

The researchers involved found that there are nine significant points of mass on the leaf, each of which causes an offset between the center of mass and the buoyancy force, thus creating an internal torque coupled to the environment. This is usually seen when the leaf "swings". Therefore, changing the density distribution of the "leaves" is the key to the autonomous motion of the robot.

As shown in Figure 2, scientists made a thin layer of soft composite material into a blade and connected a "buoyant skin" actuator to the blade. The actuator consists of a liquid-filled elastomer (called "muscle") and a soft electronic circuit. When the loop is heated to a certain degree, the internal fluid produces a continuous and drastic volume change, which changes its density. If the density changes, so does the buoyancy [2].

But researchers say they have not yet solved the negative impact of turbulence on robots when they are swimming. The turbulence occurring naturally is also a necessary factor to consider the actual movement. In fact, it is impossible to accurately measure the general trajectory of the "leaves" under the turbulence. When the speed of the fluid changes, it is difficult for such robots to complete the corresponding tasks. Therefore, it is necessary to further study the motion control of this kind of robot in flowing water.

2.2. Current problems

In fact, in some complex places, such as the center of the vortex, it is difficult for particles to exist, because in the area where the boundary layer is close to the wall, there are centrifugal force, velocity gradient, pressure gradient and so on. The larger the particles are, the more difficult it is to do so. However, for PIV, not only the particles are required to be dispersed in the entire field, but also there is a requirement for the concentration of particles. It is not good for a concentration that is either too high or too low [3]. Therefore, considering the Laplace equation, the Lagrangian method, and the Euler method, it is absolutely not a simple matter to figure out the potential energy everywhere in the fluid and track the particles.

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Nowadays, direct numerical simulation (DNS) technology is also developing. The biggest disadvantage of DNS is that it has a very large amount of computation, which often requires a large parallel computer to achieve [4], and the cost and effort required are not controllable. The current level of science and technology can only predict the general trajectory of bionic underwater vehicles.There are great errors and technological cost constraints. As the main international trend of exploration and environmental protection, bionic underwater vehicles have the problem of predicting the general trajectory, where a new breakthrough can be made in the development of contemporary science and technology.

3. Rationality of underwater bionic structure design

3.1. Streamlined design of structure

The shear force in a fluid can be roughly regarded as friction. Water, as a Newtonian fluid, occupies a large part in lakes and seas, so other non-Newtonian fluids can be ignored for the time being. Newtonian fluids have the property of viscosity, which can be said to be the ratio of friction to velocity difference within liquid molecules. Moreover, the ratio is proportional to shear force. Therefore, the viscosity of Newtonian fluid can be regarded as a fixed value, and it is concluded that the shear force is proportional to the shear strain (the rate of change of velocity). Therefore, the problem is that how to intelligently reduce the shear force in turbulent flow, that is, under the condition of high fluid velocity. The answer to this problem is to design a reasonable structure that conforms to the fluid movement and present a streamlined structure that conforms to the trend of fluid velocity.

3.2. Stability design of structure

The complexity of the underwater environment brings not only special underwater topography, but also many different types of fish morphology. A large amount of literature indicates that in many marine organisms, fish driven by pectoral fin oscillations swim at low speeds, but are relatively efficient at low-speed propulsion. This kind of fish can maintain a relatively stable cruise mode, with flexible control and strong anti-jamming capability. It can generate forward thrust through the swinging movement of pectoral fins on both sides of its body and achieve operational turning movement through its slender tail. During the movement of the underwater observation robot, it is found that the flat object is very suitable for the target simulation of the underwater observation robot, since flat objects can remain static and have good stability [5].

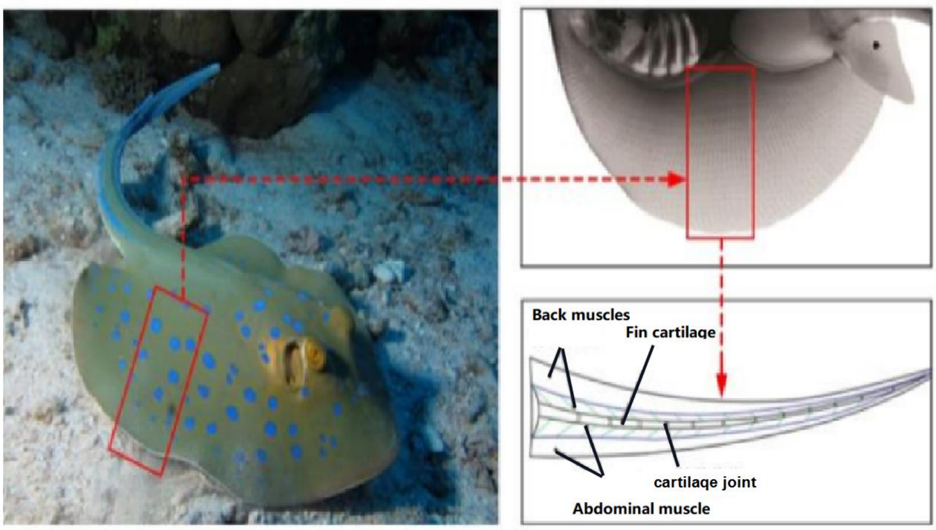

Figure 3. Blue spotted ribbon tail ray and pectoral fin skeletal structure [5].

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3.3. Fluid mechanics simulation design of the structure

Computational fluid dynamics (CFD) is mainly used to solve the governing equations, and simulate and analyze the basic problems of fluid mechanics by computer and numerical simulation. CFD numerical simulation combined with user-defined function (UDF) can be used to simulate the mechanics of the undulating fin, and the relevant parameters can be set. Fluent software can be used as a solver [6] to realize a realistic system combining structure and biological characteristics. By improving the self-control ability and self-perception ability of the bionic underwater vehicle, the bionic underwater vehicle can better integrate into the underwater environment, complete various tasks, and embark on the road of sustainable development.

4. Material classification and selection of underwater bionic robot

Engineers are constantly doing experiments, simulations, and practical tests, and now there are several kinds of materials for intelligent underwater bionic robots.

Shape memory alloy (SMA) is a kind of intelligent alloy material, which can restore its original shape when heated and eliminate the deformation at a low temperature.

Ionic Polymer-metal Composites (ICPF), also known as IPMC (Ionic Polymer-metal Composites), is an Electroactive Polymer (EAP) whose main body is a polymer film, such as Nafion. Both sides of the polymer film are plated with thin noble metal (e.g., platinum, gold) electrodes. They are called smart materials because of their dual functions of perception and driving.

According to the driving principle of nano-carbon composites, it can be divided into electrothermal actuation driving, light-induced actuation and humidity actuation driving. Because the driving frequency of the optical drive is very low, it is not suitable for the driving requirements of the underwater vehicle. In addition, the humidity drive is not applicable to the underwater environment. Therefore, the nano-carbon composite material is mainly driven by electrothermal actuation [7].

At present, with the development of society, the demand for intelligence and refinement in industry and life is growing, and the research and design of robots have become a research hot topic. The use of robots can facilitate people’s daily life and meet people's growing material needs. At the same time, it can also complete some complex and dangerous tasks in industrial production, such as mechanical assembly and on-site investigation.

The progress of underwater soft robots largely depends on the preparation of high-performance intelligent soft materials and structural molding. It is necessary to develop intelligent soft materials with high energy density, high efficiency, large deformation drive, wide frequency drive, and easy forming [8].

The underwater environment is complex, so the material requirements of the underwater bionic robot are very strict. At present, in addition to smart materials, the following are widely used materials and their important application characteristics:

(1) Polymer-metal composites. Its important feature is the combination of the advantages of polymer and metal materials. Polymers withstand some degree of deformation in most environments and adapt well to the effects of the external environment. At the same time, they are lightweight and the metal material is hard. The use of this composite material can make the robot more suitable for underwater environment. (2) Magnesium alloy materials. As a moderately priced material, its main feature is its light weight, which is very suitable for the external profile of robots. Meanwhile, the material is hard and not easy to damage. (3) Dielectric elastomer. This material is widely used in robotic actuators. As a material with good flexibility, it has some outstanding advantages, including its fast speed of adjustment after the change of shape, as well as its fast response, low energy consumption, and high electromechanical conversion efficiency. (4) Nanocarbon composite material driven by electric braking. The advantage of this material is that the driver made of this material has low driving voltage, low material stress, and long service life [9]. In combination with the central pattern generator control system, the method of central neural network control for the underwater bionic robot is to closely simulate the engineering of a central pattern generator (CPG) in an animal rhythmic motion control area in biology. Then, there is a need to apply the method to practical

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engineering, and form a control method which is more intuitive, flexible, and easy for computer programming, thus realizing the rhythmic motion of the robot and improving the working performance of robots in various practical unstructured working environments [10].

As shown in Table 1, the functions of the robot are normal under the experimental pressure of 3 MPa. Under the nominal pressure condition, the empty cabin and buoyancy material of the underwater robot do not produce residual deformation, and the underwater robot can still work normally after the test. The platform can realize the simulation of 650m underwater depth and real water temperature environment. It can also truly simulate the diving and floating speed of the special robot in water. The test function of the platform includes the underwater operation performance test of the robot, the underwater communication reliability test, the underwater sealing performance test of the robot, etc. At the same time, the underwater performance test method of the special robot is established [11].

Table 1. Pressure Value Record [11].

Number	Setting Pressure/MPa	Measured Pressure/MPa	Pressure Holding Time/min
1	1	1	5
2	2	2.1	5
3	2.5	2.6	5
4	3	3	30
5	2.5	2.4	5
6	2	2.1	5
7	1	0.9	5

But it is difficult to test the pressure in turbulent flow. How to accurately measure the average pressure in turbulent flow and select the appropriate material is the key point that engineers need to break through nowadays.

5. Future outlook and analysis

At present, the control methods of underwater bionic robot mainly include manual control, digital output control, program control and so on, but from the perspective of future development trend, researchers will pay more attention to the intelligent motion adaptation of underwater bionic robots, and will simulate the biological nervous system in a wider range.

With the rapid development of computer technology, especially the popularization of artificial intelligence and the optimization of machine learning methods, underwater bionic robots will have greater control autonomy in the future. They will be able to make reasonable judgment and timely correction according to the current environment. Additionally, they can better adapt to the environment, reduce the data feedback process and human behavior, and finally achieve the bionic control effect, so as to realize the application in complex fluid environment. For example, the effective transmission of data in turbulence and the achievement of more accurate calculation and simulation. Because of the complexity of the ocean environment, the bionic underwater vehicle is faced with many problems, such as the rapid change of flow velocity, the different pressure under different water depths, and the poor sealing. These problems bring great challenges to the structural design of the robot. Faced with these problems, the structure of the future underwater bionic robot must be more accurate and portable, and the application of materials must meet the requirements of the underwater environment.

Miniaturization is the trend of the development of robots today, because small structures are easier to adapt to the environment, reduce the contact area, and greatly mitigate the impact of underwater pressure on mechanical structures. What matters most is that the structure of these underwater bionic micro-robots can be closer to the physiological structure of marine organisms, so that they can basically achieve the effects of bionics instead of a merely simple shape imitation.

6. Conclusion

Nowadays, the demand for bionic underwater robots is growing, and their function and research value are also gradually improving. At present, a lot of work about bionic underwater robots has been done at home and abroad in the still water or laminar flow. Results show that, in the fluid with a Reynolds number below 2000,underwater bionic robots can make good use of the current environment, and can accurately and completely complete the work of oil removal, exploration and so on.

However,, as mentioned in this paper, due to the complexity of the underwater environment, there is still a need for bionic underwater robots to optimize and improve the general trajectory prediction, the structural design and material selection, as well as the avoidance and improvement of the efficiency of providing kinetic energy for production. At the same time, engineers should be aware of the possibility that bionic underwater robots can play their role in different complex water flows. Besides, after accurate experiments, different types of underwater robots can meet the requirements of reducing output costs while still completing specific tasks with high accuracy.

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