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Feasibility study of underwater drilling robot based on razor clam

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Abstract. Razor acis lives in the low tidal area of the inner bay and thrives in the area with mild infiltration of fresh water. It uses its rhythmic contraction and foot burp and its unique anatomy to make holes. The extraordinary ability of razor clams to effectively penetrate the sediment has inspired innovation in the design of underwater drilling robots. Underwater drilling robots are currently widely used in the industrial world, such as underwater geological exploration, underwater shipwreck exploration, etc. However, the existing models of these robots mainly have a rigid structural design, which limits the flexibility of their drilling components, while their rough appearance also hinders their drilling efficiency. In response to these limitations, this paper proposes a robot with a soft, flexible body, and other enhanced functions designed to simulate a soft razor clam, replicate its peristaltic motion, minimize surface friction, and thus achieve superior drilling capability. This paper focuses on the development of software, segmented structure design, and studies designed to reduce surface friction and explore the mechanism of biomimetic motion.

Keywords: underwater bionic robot, razor clam robot, drilling holes, retractable.

1. Introduction

Advances in bionics have significantly driven robotics over the past few decades[1]. In the field of underwater robotics, the fauna of the natural world provides valuable inspiration to enable robots to operate more efficiently and flexibly in complex aquatic environments. The razor clam, known for its efficient burrowing ability, has attracted the attention of many scientists and engineers and become the focus of bionic research. Razor clams holes in the ocean floor and other sand through a synergy between muscles and shells. This capability is very appealing and provides key insights into the design of underwater robots that can navigate through difficult or constantly changing terrain. Currently, the design and operation of underwater robots face many challenges, including crossing complex terrain and performing efficiently at a low energy cost. To date, several studies have attempted to simulate the tunneling mechanism of living organisms to design robots[2,3].These studies have focused on understanding the behavioral and physical mechanisms of this organism and how these mechanisms translate into mechanical design. However, the current research on underwater drilling robots is still insufficient. Researchers have identified key factors in the process, such as rotation of the shell, rhythmic muscle contraction, and interaction with the material through friction and cutting movements. Although previous studies have done fundamental work in the development of bionic underwater burrowing robots, there are still some research gaps and areas to be perfected. First, the current study focuses on a single aspect of imitating mothering behavior, while the overall study of mothering bionics is limited. Moreover, existing studies on biological burrowing behavior often neglect comprehensive system efficiency optimization, material selection, and adaptation to different environmental conditions. Second, the precise control mechanisms of the burrowing behavior of organisms and their adaptability to different environmental conditions have not been fully understood or replicated. Furthermore, ensuring robotic performance while achieving cost-effectiveness and ease of maintenance remains a still unresolved issue in the current study[4]. The development of bionic razor clam underwater tunneling robots not only pushes the boundaries of robotics and bionics, but also provides new solutions for ocean exploration, underwater infrastructure construction, and maintenance. These robots are expected to perform tasks in extreme environments, such as deep-sea exploration, seabed archaeology, shipwreck exploration, and the laying or maintenance of submarine pipelines, greatly improving the safety and efficiency of operations. This paper is based on the feasibility of an underwater drilling robot. It explores how to design and build a new underwater drilling robot by borrowing the nature of razor clams. The study focuses on the natural burrowing behavior and its adaptability and efficiency, which are realized through a series of complex bionic processes, enabling the razor clam robot to quickly dig in the sandy or mud matrix. The author believes that the robot designed in this study has considerable applications in underwater pipeline inspection, seabed resources measurement, and rescue operations[5].

2. Bioanalysis

2.1. Biological behavior of razor drill

Razor clam (also known as sand silkworm, sea silkworm), is a pilaete annelid living in the seabed sand and mud, known for its unique biological behavior and role in the ecosystem. Burrowing behavior is an important life habit of razor clam. The following is the analysis of the biological behavior of razor clam drilling holes:

1. Objective: The main purpose of razor clams is to find food and shelter. Razor clams can reach deeper into the sand to find their food sources, such as bacteria, algae, and organic debris. Drilling also provides a safe shelter for razor clams from natural enemies and harsh environmental conditions.

2. Drilling method: Razor clam uses the front end of its body, especially the head and the first pair of barbed feet. Their bodies can secrete mucus that helps them travel through the mud, while the razor clam also uses the muscles of its body walls to advance.

3. Factors: The drilling behavior of razor clam is influenced by many factors, including the texture of sand, water temperature, salinity, and availability of food resources.

2.2. The physical mechanism of razor clam drilling holes

The burrowing behavior of razor clam is a highly specialized and efficient natural phenomenon, realized through a series of complex biomimetic processes, enabling rapid excavation in a sandy or mud matrix. This process not only demonstrates the unique ability of the razor clam to adapt to its environment, but also provides an important bionic inspiration for engineering and mechanical design. Here are the key aspects of the razor clam's digging behavior:

1. Shell rotation and compression: Razor clam begins the digging process by rotating and slightly squeezing one end of the shell. This rotation and compression help it create an initial anchor in the substrate.

2. Rhythmic muscle contraction: The razor clam uses the rhythmic contraction of its feet (a special muscle organ) to further penetrate the matrix. The feet extend and anchor to a deeper substrate and then contract, pulling the razor-clam body down.

3. Water shooting: During the excavation, razor clam also uses water to help release the substrate. It injects water into the matrix, reducing the density of the surrounding materials and making the burrowing process easier.

4. Friction and cutting interaction with material: The interaction between the shell and the foot includes friction and cutting, which help them dig effectively in a harder substrate.

5. Adaptability and efficiency: The cave behavior of razor clam has high adaptability and efficiency, and can adjust its cave strategy according to different substrate characteristics, so as to effectively dig and move in different environments.

2.3. Direction of bionic products inspired by razor clam

Bionics is an interdisciplinary field that aims to study the structure, function, and adaptive behavior of organisms in nature, taking inspiration to develop and design new technologies and products. The biological behavior study of razor burrowing provides an excellent subject of bionics, and its unique adaptability and efficiency have potential applications in engineering, medicine, and robotics. The following is the direction analysis of bionic products inspired by razor clam:

1. Structure and material bionic: the mucus secreted in the process of drilling can reduce the friction with sand and mud and improve the efficiency of movement. This property could inspire the development of novel lubricating materials used underwater to reduce the wear of mechanical equipment or to act as a lubricant to reduce tissue friction in medicine. In addition, the body structure, especially its front structure for drilling, can efficiently penetrate the soft or tight substrate. This structure can be used to design underground drilling equipment to improve their penetration and reduce energy consumption.

2. Behavior and Action Bionics: Razor clam adjusts its drilling strategy according to different substrate conditions, an ability that can be used to improve the robot's adaptability and flexibility in different environments. In addition, the muscle contraction pattern of razor clams produces wave-like motion, and this fluctuating propulsion method can provide a new type of propulsion for underwater robots or soft robots.

3. Ecological engineering application: Razor clam improves the ecological environment and promotes water exchange and nutrient circulation through its drilling behavior. Artificial facilities or methods that mimic this behavior can be used in environmental restoration projects in the ocean or wetlands.

4. Detection and sampling: Based on the razor clam drilling technology, it can develop more efficient geological detection tools to be used for sampling or studying underground structures. Referring to the principle of razor clam drilling, you can also design medical devices, such as minimally invasive biological sampling tools, which can improve operational accuracy and efficiency while reducing patient damage.

Through a thorough analysis of razor clam drilling behavior, bionics can not only help us understand how these organisms interact with the environment, but also inspire the development of a range of innovative technologies. These technologies have the potential to improve the quality of human life, improve work efficiency, and even solve some urgent environmental problems.

3. Research direction

In this paper, the fluctuation propulsion method (peristalsis) in the "behavior and action bionic", as well as the epidermal mucus and body structure of the "structure and material bionic", are selected to analyze the feasibility of the bionic razor clam. The combination of these aspects aims to develop an efficient and adaptable underwater drilling robot with the ability of a razor clam to adapt to a complex seabed environment.

3.1. Advantages of an underwater drilling robot with a bionic razor clam

First of all, the fluctuation propulsion method is adopted to imitate the natural movement of razor clam, which can effectively reduce the resistance of underwater activities and improve the movement efficiency of the robot. By simulating the movement strategy of razor clam, the robot can adjust its propulsion mode according to different environmental conditions and improve its adaptability in a diverse environment.

Secondly, the skin mucus of the bionic razor clam can develop new lubricating materials to reduce the friction between the robot and the seabed sediment and improve the drilling efficiency. Drawing on the design of the razor clam body structure, it can also optimize the shape of the robot to make it easier to penetrate the seabed sand or soft substrate.

3.2. The challenge of an underwater drilling robot

First, achieving fluctuating propulsion requires complex control systems to simulate the coordinated movement of razor clam muscles, which may be a technical challenge. Maintaining efficient fluctuating movements may also increase energy consumption, requiring optimized energy management strategies to ensure long-term task execution capabilities.

Second, in terms of material development, developing materials similar to the skin mucus in nature may face technical difficulties, requiring a balance between chemical stability, environmental friendliness, and cost-effectiveness. Moreover, biomimetic structures need to ensure sufficient strength and durability while maintaining high flexibility to cope with the complex physical environment of the sea floor.

4. Experimental design

4.1. Shell design

This paper proposed based on the razor clam underwater drilling robot simulation of natural form, using can reduce the resistance of underwater streamline double clamshell design, a layer is to help reduce friction or increase the adhesion of the substrate imitation razor shell surface texture shell, the other layer with a guide rail or inner shell of peristalsis drive mechanism. There are gaps between the two shells to store lubrication, which helps for better passage when drilling.

In terms of material selection, due to the presence of salts and other chemicals in the underwater environment, the material needs to be corrosion-resistant, while being strong and tough enough to withstand the physical pressure and effects of the underwater environment. In addition, it is necessary to ensure that the shell material is waterproof to prevent water from entering the robot and protect the electronic components and internal mechanical components. To reduce the overall weight of the robot and improve its underwater mobility and energy efficiency, light composites can also be considered.

In the design of the structure, based on the structure of the razor clam shell, the robot can use the double-layer structure design, the inner layer is shock absorption, the outer layer is rigid protection, and the middle of the lubricant will not be affected by the temperature, and can be released from the outer shell[6]. Design extended or adjustable parts that mimic the ability of razor clams to dig holes with their feet to improve the robot's adaptability to different environments and tasks.

In order to verify whether the shell shape of the drilling robot will affect the drilling process, this paper designed the following experiments: in 3d printing mode printing different shapes of the shell (conical, cylindrical, rectangle), manually making a slit, with the same initial speed release 3d printing shell, compare through the distance of the slit, to determine the best shape of the shell. The shell material and process of the underwater drilling robot need to consider the special requirements of water pressure resistance, corrosion resistance, softness, and light in the underwater environment. There are two possible suitable materials: soft and durable polymer materials, such as silicone, neoprene, and fluorine rubber, which can provide softness and wear resistance and have good water resistance; light composite materials, such as carbon fiber composite, glass fiber composite, which can reduce the weight of the robot and improve the processing capacity and walking efficiency in the underwater environment. This paper wants to verify the wear resistance, softness, and maximum bending curvature of various materials through experimental design to determine the use of the materials.

4.2. Sports mechanism

4.2.1. The first scenario. The robot consists of a flexible shell, an internal driving mechanism, and a sensing and control system. The shell is made of a special material, which can maintain a certain stiffness, has a certain variability and elasticity, and has good sealing performance. The drive mechanism uses a tissue structure similar to the razor clam muscle that allows the robot's shell to stretch and bend. The robot adopts the robot design of soft size and segmented structure of razor clam. In the beginning, the mechanical device is in a very smooth and deformable soft shell. When the robot is in the gap, it can be the mechanical structure in the mechanical shell. The mechanical structure is made of an uneven ridge (simulating the uneven decency of razor clam). Then use the mechanical mechanism to come out of the deformable soft shell, contraction, to simulate the razor clam peristalsis.

4.2.2. The second scenario. Considering that in the first scenario, if the fluctuating propulsion method (peristalsis) is used, the robot control system and energy efficiency ratio will be highly required, and there may be less battery life in the sea under the same battery capacity, we propose the second scenario.

The robot consists of the following parts: the flexible shell, the guide rail (as shown in Figure 1), the sensing and control system of the internal driving mechanism, and the mechanical foot for crawling. The design of the mechanical foot can be referred to the shell that is made of special materials, which can not only maintain a certain stiffness, but also have a certain variability and elasticity, and have good sealing performance[2]. The drive mechanism uses a similar tissue structure to the razor clam muscle, which is driven by a mechanical drive device, so that the mechanical foot can be extended and retracted along the guide rail. The robot uses the razor clam segment structure design. In the beginning, the interior of the machinery is very smooth and deformed. In the shell, when the robot is in the gap, it can extend the mechanical structure and mechanical feet within the shell. Later when drilling, the mechanical foot can be used to move.

Figure 1. This figure shows the guide rail used for stretching the sensing and control system of the internal driving mechanism and the crawling mechanical foot.

5. Results and discussion

In this study, the influence of shell shape on the drilling ability of underwater drilling robots was explored by designing shells with different shapes. Jiang Yichen et al. in the study of the comprehensive effect of underwater vehicle boat shape on resistance and flow noise showed that the conical shell was the best in penetrating slit, followed by the cylindrical shell, while the rectangular shell performed the worst[7]. This finding is consistent with the hypothesis of this paper that a streamlined design helps to reduce underwater friction and improve penetration. This paper also further explores the influence of different materials on robot performance. Wu Xinfeng's research on the wear resistance and thermal conductivity of ultra-high molecular weight polyethylene indicates that soft and durable polymer materials (such as high-density polyethylene) provide good wear resistance and flexibility while maintaining the robot's adaptability and persistence in the underwater environment[8]. In addition, light composites (such as carbon fiber and fiberglass composites) can reduce the weight of the robot, thus improving its mobility and energy efficiency.

6. Conclusion

This paper introduces a robotic underwater drilling rig based on razor clam and highlights the influence of shell shape on the penetration ability of the underwater drilling robot and the importance of material selection. The superior performance of the conical shell reveals the critical role of the streamlined design in improving penetration efficiency and reducing environmental resistance. In terms of material selection, this paper uses soft and durable materials and light composites to improve the performance of underwater robots. These materials not only improve robot durability and adaptability, but also optimize their energy consumption, which is crucial for robots performing underwater missions for long periods. This paper provides a new solution to the technical problem of underwater drilling joint operation, which has important application value and promotion prospects. In conclusion, this study proposed a more efficient and adaptable underwater drilling robot design scheme by using the razor clam digging behavior in nature and discusses the feasibility of the scheme. Future studies could further optimize the robot design, especially in the control mechanism, vision-based endurance and energy efficiency optimization, improve the passing performance of its drilling joints, and further improve the robot design and control mechanism to improve the operational efficiency and reliability of the robot in complex and challenging underwater environments, so as to meet the needs of underwater drilling joint operations in more fields[9,10].

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