Research Progress and Development Trends of Underwater Soft Biomimetic Robots

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Abstract. With the increasingly urgent demand for marine resource development, traditional rigid underwater robots have revealed limitations such as poor adaptability and weak interaction capabilities in complex and unstructured underwater environments. Underwater soft biomimetic robots, with their advantages of material flexibility, variable shape, and biomimetic motion, have become an important research direction for overcoming existing technological bottlenecks. This paper aims to explore the research progress and development trends of underwater soft biomimetic robots. Research shows that biomimetic structural design significantly improves the robot's environmental adaptability, while the integrated innovation of technologies such as aerodynamics, smart materials, and magnetic actuation holds promise for achieving long-term reliable operation and swarm collaboration capabilities. This paper provides theoretical reference and technological prospects for the development of underwater soft robots towards a more intelligent and efficient next generation.

Keywords: underwater robots; soft robots; flexible actuation; smart materials

1 Introduction

With the rapid development of modern science and technology, human beings have continued to develop energy, and resource shortage has gradually become one of the important challenges facing modern society. The ocean covers more than 70 percent of the Earth's surface and will be the major breakthrough area for resources in the future [1]. However, due to the influence of unstable factors such as extreme weather, unknown terrain, and diverse marine life, the performance requirements of underwater exploration equipment are extremely high. Therefore, underwater robots have gradually become a research hotspot in the scientific research field.

Significant progress has been made in robotic systems with breakthroughs in deep sea exploration, but rigid materials have shortages as well. For example, rigid robots are generally large and have fixed shells, making it difficult for them to navigate complex environments or interact with small and delicate objects. A type of flexible robot, soft robots with endlessly deformable bodies can get rid of the weaknesses of hard robots underwater.

Soft robots are made of flexible deformable materials, such as silicone and hydrogel, and can change shape and move through a drive device. Pinskier et al. explained how soft robots with

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more degrees of freedom and greater stability [2]. Underwater soft robots simulate the movement of marine organisms such as fish and amphibians underwater, have good environmental adaptability, and can move in narrow and complex seabed environments. Qu et al. analyzed the practicality and research results of underwater soft robots [3], which can carry out relatively precise exploration and reconnaissance work without damaging the marine environment.

Currently, underwater soft robots have been widely used in the monitoring of marine environment and climate, exploration of marine resources, and tracking of creatures on the seabed, which has shown great value in the economic, scientific, and military fields. But the main difficulties faced by underwater soft robots currently are to select soft materials that can maintain flexibility in a high-pressure underwater environment, to choose reliable sensors, and to achieve a certain degree of economy and efficiency.

This paper systematically analyzes the research progress of underwater soft biomimetic robots, mainly focusing on the biomimicry structural design, driving technology and application potential in different scenarios. It also summarizes the current key technological challenges, such as material durability, energy efficiency, and motion control, and provides an outlook on future development trends, pointing out that intelligent material innovation, drive system integration, and multi-robot collaboration will be key directions driving the development of this field.

2 Bionic objects and structural design

2.1 Structural design based on biomimetic objects

The essence of biomimetic soft robot structural design is to learn from the movement principles of organisms in nature and converting them into manufacturable mechanical structures. Various organisms employ distinct locomotion strategies, like wavy propulsion, jet thrust, flapping movement, and as well as manipulation and grasping capabilities. These principles can give us important references for the structure as well as drive system of the soft robot. Fig. 1 shows recent research on underwater soft robots which were developed by learning the movement mechanisms of different biomimetic objects.

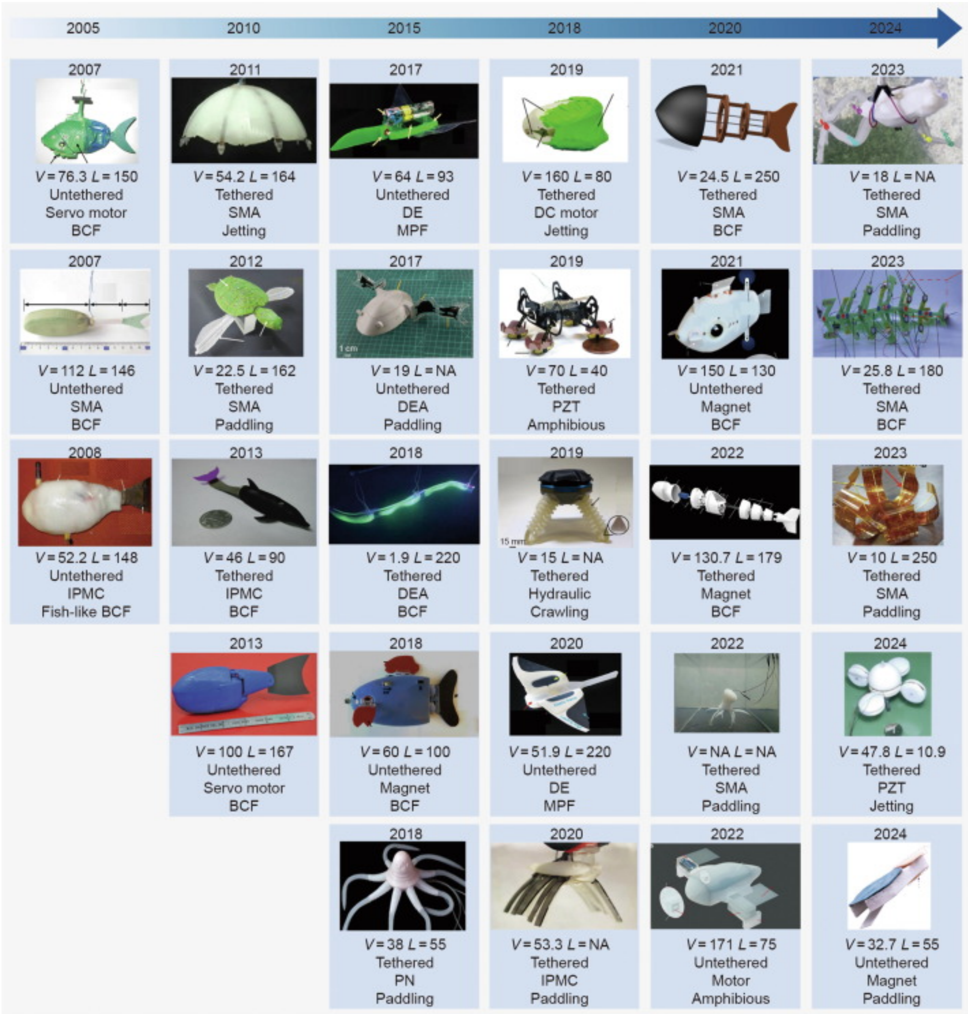

Fig. 1. Representative underwater soft robots [4]

Wave-driven organisms. Wave propulsion power is mainly found in aquatic animals including fishes, eels, and water snakes. Their movement relies on continuous lateral undulations generated by the body or tail fin to propel the body forward. Robots made with this kind of movement use bendy stuff and segmented drive structures to simulate the body movement of fish. In 2024, Zhao et al. proposed a completely soft biomimetic robotic fish [5], which uses a soft silicone body and a piezoelectric drive system to achieve long-term, non-disruptive autonomous swimming in a coral reef environment. The robot changes the frequency and amplitude of tail fin oscillation through piezoelectric actuators, and it could reach the maximum speed of 3.25 cm/s, which is a milestone of soft robots' application in real ocean environment.

Wave propulsion has some benefits including quiet operation, high efficiency, and strong adaptability, making it valuable for applications in underwater reconnaissance, environmental monitoring, and biomimetic research. Researchers are looking into smart stuff like dielectric elastomers ang liquid crystal elastomers that can keep on changing their forms without the need for complex pneumatic tubing. Meanwhile, the maturity of embedded sensor technology enables robots to perceive the fluid environment and make an adjustment flexibly at the same time it moves on a wave.

Jet-propelled organisms. Jet-driven organisms can move by ejecting liquid from liquid surroundings. Typical jet-propelled organisms include squid and jellyfish. These creatures use the contraction of their body cavities to produce a strong water flow and instantly speed up. In 2023, Wang et al. constructed a HASEL jellyfish robot [6], which is driven by soft actuators, enabling the robot to move quickly. Jet propulsion has the benefits of a simple structure, quick response, and ability to move efficiently in narrow areas. In the future, jet-propelled soft robots will take up an important position in situations like emergency rescue and great flexibility, such as emergency rescue and pipeline internal inspection. It will develop toward the improvement of jet efficiency and control of more accurate speed and direction.

Puffing Propulsion Biology. Representatives of flapping propulsion include manta rays, rays, and sea turtles. Lift and thrust are made by the periodic movement of the body or limbs. For the design of the flapping propulsion structure, it usually requires the realization of multi-degree-of-freedom control, such as the up-and-down flapping, twisting, and forward-and-backward sweeping. Li et al. designed a soft robot that mimics the sea turtle [7], which uses intelligent soft composite materials to deform the structure and imitate the movement process of the sea turtle. The formation of flapping propulsion systems has gone from simple degree of freedom structure to more complicated multi-material coupled structures, as well as multi-morphology coupling. In the future, in the field of soft robots, it is expected to realize more complex cooperative swimming, which can bring new possibilities to marine monitoring and distributed tasks.

Capture and attach organisms. There are organisms like octopuses and geckos that can stick onto and grasp tight. The muscular hydrostatic structure of octopuses enables them to perform flexible enveloping grasping [8], while the ciliary structure of geckos provides van der Waals force attachment ability [9]. In soft robots, octopus - like suction **-** cups and gecko - like **adhesives make use of** micro - and nano - structures to increase their adhesion ability. The octopus robot with opening and closing claws developed by Gong et al. uses its arms to perform grasping and movement functions [10], and can effectively control objects of different sizes. Therefore, grasping and attachment functions are a key direction for underwater soft biomimetic machines, which are related to environmental interaction and can grasp things and do things underwater.

2.2 Internal structural design

Aerodynamic network structure design. The pneumatic network structure is the main structure inside a soft robot. It controls shape changes with air chambers and a network of channels. This is similar to muscle fibers expanding and contraction of muscle fibers, providing distributed actuation and enabling complex morphological changes complex morphological changes.

The pneumatic networks are generally made up of PDM or silicone, with channel diameters ranging from 0.5 mm to 5 mm. The “PneuNet” pneumatic network uses a 3D-printed fiberreinforced pneumatic network to enable peristaltic crawling [11]. Network cavity alternation for the robot to walk on bad ground. Zhang et al. developed a soft gripper with an integrated pneumatic network [12]. Experiments proved that the modified pneumatic network can stand strains more than 200% under cyclic drive and exhibited good fatigue resistance.

Currently, it’s focusing on making brand new logic circuits that can replace these big, hard-to-move valves with something that responds really fast and gives strong results. However, improving the overall system response time, improving the long-term reliable airtightness, and developing a compact and efficient portable air source remain engineering challenges that need to be solved before they can be widely used by everyone.

Tendon-driven structure design. Tendon-driven structure narrows down on the mimicry of human's tendons forwarding force via a flexible frame with wires/cables to achieve the fine control. This design, combining rigid and flexible materials, provides high load-bearing capacity and is suitable for jointed robotic simulation.

Tendons are typically made from nylon fiber or Kevlar fiber. The MIT bionic cheetah uses a highly optimized tendons system on its leg structure [13], which enables high-speed dynamic running of more than 13 meters per second by using high-speed force control and elastic energy storage design.

Table 1: Quantitative Comparison of Tendon-Driven and Pneumatic-Driven Performance

Performance indicators	tendon drive	pneumatic drive	Comparative analysis
Response time	80-150ms	200-800ms	tendons are 3-5 times faster
Load/weight ratio	0.8	0.1-0.3	Tendons have strong load-bearing capacity
Energy efficiency	1.8-4.2	0.5-1.5	Different system dependencies
Control accuracy	±1.2 mm	±5-10 mm	High tendon precision

Table 1 presents a quantitative comparison of the performance of tendon-driven and pneumatic-driven mechanisms. As shown in Table 1, compared to pneumatic, this structure responds faster, but the wiring is more complex. However, tendons are prone to relaxation, requiring improved wear resistance. Therefore, reducing friction and hysteresis in the tendon path, addressing deformation under long-term loads, and developing intelligent control algorithms capable of coordinating complex movements of multiple tendons will be key to unlocking its full potential.

3 Drive technology analysis

The actuation technology of soft robots is important to make soft robots have soft deformations and continuous motions. In recent years, as material science, microfluidics, and flexible electronics, various actuation strategy as well, from traditional type like pneumatic and hydraulic systems to new type of smart material actuation and remotely controlling magnetic actuation technology, all of which provide important support for the functional expansion of soft robots.

3.1 pneumatic hydraulic drive

Fluid drive mainly includes pneumatic drive and hydraulic drive. Most advanced tech is to use the fluid pressure to make soft robots change shape to imitate muscles. Pneumatic drives use compressed air, while hydraulic drives use liquid. Wang et al. developed a pneumatic bistable actuator, which effectively accelerated the speed of the jellyfish robot [14]. Lai et al. developed the "Soft robotic glove" [15], whose microchannel network drives finger actuators, which can achieve rapid bending response through pneumatic drive, and is used for postoperative rehabilitation of patients.

Its pro side has accessible stuff, developed production methods, and being eco-friendly. They are suitable for grasping irregular objects and for complex underwater environments. However, their disadvantages include high design and sealing requirements, susceptibility to air leakage, significant dependence on control systems, and limited load-bearing capacity compared to rigid structures. Therefore, recent research has increasingly focused on integrated drive modules and high-efficiency sealing materials to better support autonomous and portable soft robot systems.

3.2 Smart materials driven

SMM shape memory material. The most commonly used shape memory materials are shape memory alloys (SMA) and shape memory polymers (SMP). They can be molded into a shape at a specific temperature and then restored to the original shape when heated to another specific temperature. By heating and cooling SMA, the stretching and shrinking of SMA can be achieved (see Fig. 2.b.). The self-folding robot created by Felton et al. is based on thermoplastic SMM and unfolds from a compact state into a crawling form under thermal stimulation [16], with an unfolding time of <10s. The recovery stress of SMA can reach hundreds of MPa, but its thermal drive response is slow, its energy efficiency is low, and it has thermal fatigue problems. At present, it is mostly used for specific tasks such as structural opening and closing, folding and unfolding.

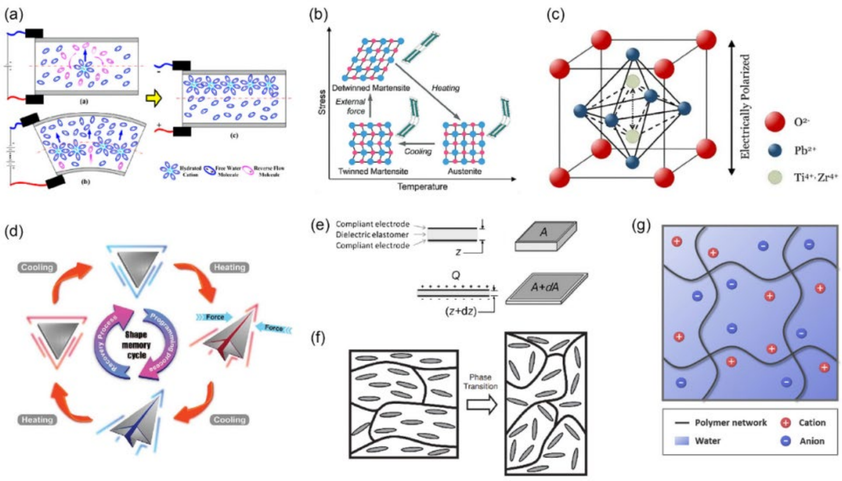

Fig. 2. Dynamic shape memory properties of smart materials [17]

Electroactive polymers (EAP). EAP is a type of polymer material that can undergo significant deformation or generate corresponding force under the action of an external electric field. They have advantages such as high energy density, fast response speed and light weight, and are known as "artificial muscles". EAP is mainly divided into two categories according to its working mechanism: ionic EAP and electronic EAP. Kim's team used DEA to create "artificial muscles" that can drive insect-scale robots and successfully drove a small robot weighing approximately the weight of a standard coin to achieve complex actions such as jumping and flying [18]. This shows the great potential of EAP in micro, high-dynamic soft robots. With the development of dielectric material modification and miniaturized driving power supply, EAP is expected to become the core driving mode of the next generation of high-dynamic soft robots.

Liquid crystal elastomer (LCE). LCEs are a class of smart materials with shape memory effect, which combine the orderliness of liquid crystals and the elasticity of polymers. LCEs can achieve large-scale deformation by controlling the orientation of LCE mediator units under specific temperature or light stimulation, as shown in Fig. 2.g. Urban et al. studied LCE-based light actuation [19], and they made LCEs sensitive to light of specific wavelengths through molecular design. When irradiated with light, LCE strips will bend. By controlling the position and shape of the light spot, the bending direction and degree of LCE actuators can be precisely controlled, thereby realizing remote manipulation of small objects, which has unique advantages in the fields of microfluidics and microassembly.

3.3 Magnetic drive

Magnetic drive uses electromagnetic materials and magnetic fields to convert magnetic energy into mechanical energy. Romano et al. developed a mechanical fish using an electromagnetic system [20], which can achieve realistic swimming posture and multimodal motion under magnetic field control. At present, by precisely controlling the magnetic field, it is possible to achieve precise control of the position, posture and motion mode of micro soft robots, and even achieve cluster collaborative operation. However, this technology still faces many challenges: it is necessary to improve the magnetization programming method to achieve more complex three-dimensional motion control; it is necessary to solve the challenges of navigation and imaging in complex physiological environments; it is necessary to solve the problems of real-time motion high-precision tracking. The focus of future research is moving towards more refined magnetization design and more penetrating magnetic field system.

4 Existing challenges and future development trends

4.1 Current Challenges of Underwater Soft Robots

Low durability of material and efficient energy consumption are two bottlenecks existing for underwater soft robots' large amount of potential in adapting the harsh environment. On the one hand, commonly used soft materials such as silicone rubber, polyurethane elastomers, and hydrogels are prone to aging, fatigue, and performance degradation under high pressure, high salinity, and long-term immersion environments. They are also subject to multiple effects such as biofouling, chemical corrosion, and mechanical wear and so on, they are also affected by other factors and restrict their service lifetime.

On the other hand, reduced material durability further increases system energy consumption. Traditional pneumatic or hydraulic drive methods have low energy efficiency, relying on external power supplies or large-volume energy storage devices, which limits the robot's autonomy and endurance. At the same time, complex deformation control and multi-degree-of-freedom motion place higher demands on energy management. Improve the durability of soft materials and achieve low-power driving but still maintain the performance of movement is currently the main research direction.

4.2 Future development trends

Breakthrough in smart materials. The development of future underwater soft robots will depend heavily on breakthroughs in smart materials. For example, dielectric elastomers are a class of polymer materials that undergo large-scale deformation under the action of an electric field. They have advantages such as high energy density, fast response speed and simple structure. Self-healing polymer materials can automatically restore their structural integrity and mechanical properties after the material is damaged through reversible chemical bonds or intermolecular interactions, providing an important means to improve the durability of the system. The self-healing soft pneumatic robot made by Legrand et al. can self-repair when it is worn or damaged during operation [21].

Unlike traditional soft materials that only provide passive compliance, the new generation of smart materials can achieve controllable deformation, performance self-regulation, and even structural reconstruction under external stimuli, providing a new technological path for robotic systems in complex underwater environments.

Driving technological innovation. In terms of actuation technology, electroactive polymers (EAPs), dielectric elastomers, and magnetic actuation are considered important future development directions. These actuation methods are good at responding quickly, taking up little space, and being easy to control, so they can make underwater movement more accurate and powerful. Simultaneously, machine learning and intelligent control algorithm combination can achieve adaptive control of complex soft structures, further improving the robot's motion performance and task completion capabilities in unknown environments. In recent years, researchers have started to use hybrid actuation strategies that couple multiple methods, combining fluid actuation, smart material actuation, or magnetic actuation to compensate for the shortcomings of a single actuation method. For example, fluid actuation can be used to achieve large deformation, while electroactive actuation can perform local fine adjustments. This hybrid approach results in significantly improved control and efficiency of the resulting motion.

5 Conclusion

This paper offers a thorough review on the design structure and actuation technology of underwater soft biomimetic robots via a systematic review of the relevant study achievements at home and abroad both domestically and internationally in recent years. It also analyzes the main difficulty it meets and the future development direction. Research reveals that biomimetic principles provide soft robots with an efficient mode of locomotion. Utilizing biological mechanisms, actuated flexible structures can be constructed, significantly improving the robot's adaptability and interaction capabilities in complex underwater environments. Regarding actuation technology, while traditional pneumatic and hydraulic actuation is relatively mature, it is gradually integrating with new technologies such as smart materials and magnetic actuation, driving robots towards greater convenience, speed, and precision. However, current research remains limited by bottlenecks such as the durability of soft materials, system energy efficiency, and reliable control in complex environments.

The further development of underwater soft robots in the future depends on innovative breakthroughs in smart materials, potentially leading to the creation of novel polymers with self-healing, environmental adaptability, and resistance to pressure and corrosion. Furthermore, artificial intelligence and adaptive algorithms for collaborative operations will be widely adopted, which will greatly expand the depth and scope of collaboration, and marine monitoring, marine resource exploration, marine environmental protection, and marine emergency rescue. Underwater soft robots are expected to continuously innovate in material and drive and intelligent system field, so as to become one of the most important intelligent equipment for the development and exploration of seas in the future.

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