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Advances in Bio-inspired Swimming Robots for Underwater Exploration: A Review

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Abstract. Bio-inspired swimming robots have become a focal point in underwater robotics due to their superior energy efficiency, enhanced maneuverability, and adaptability compared to traditional robots. This paper reviews the latest progress in bio-inspired fish robots, highlighting their advantages, the challenges faced by researchers, material selection, design methodologies, and real-world applications. The comparison between bio-inspired and traditional robots demonstrates how biomimetic designs can improve the performance and efficiency of underwater systems. Furthermore, advancements in materials and control mechanisms have enabled new applications, from environmental monitoring to military operations, offering promising prospects for future underwater exploration technologies.

Keywords: Biomimetic robotics, Robotic fish, Underwater exploration, Energy efficiency, Environmental monitoring.

1. Introduction

Bio-inspired robots, particularly those mimicking the swimming mechanisms of fish, have attracted considerable attention due to their enhanced flexibility, energy efficiency, and maneuverability compared to traditional propeller-based systems. Propeller-driven robots often face limitations, such as high energy consumption and difficulty in executing quick, precise turns. Inspired by the evolutionary success of fish, biomimicry leverages natural fluid mechanics to create robots that excel in complex underwater environments.

Fish have evolved superior swimming capabilities over millions of years, making their locomotion patterns an ideal model for improving underwater robots. Robotic models that mimic fish fin dynamics, particularly flexible propulsion surfaces, have demonstrated increased thrust and reduced energy consumption compared to conventional systems [1]. As a result, bio-inspired swimming robots are now central to research on underwater exploration and environmental monitoring, offering new possibilities for tasks that require silent, agile, and energy-efficient robots. Robotic models, such as those mimicking fish fin functions, have already demonstrated enhanced thrust and efficiency compared to traditional propulsion mechanisms, underscoring the potential of flexible propulsive surfaces [2]. This shows that bio-inspired robots can greatly improve underwater capabilities. Bio-inspired designs offer a way to improve how robots move in water and use less energy. Traditional propeller-based robots don’t move as smoothly or efficiently as fish-like robots. Robotic fish, such as the models developed to replicate the undulating body motions of real fish, have proven more efficient and agile in complex underwater environments [3]. Fish move by waving their bodies and fins, which makes them better at saving energy and moving smoothly in water. As identified in the review of fish swimming modes, bio-inspired designs can greatly improve the agility and efficiency of underwater systems by incorporating the natural undulating and oscillatory movements seen in fish [4]. By copying these natural movements, robotic systems can improve their performance underwater.

Bio-inspired robotics combines biology with technology, which helps us make important improvements in underwater robots. Research on fish bio-robotics has shown how hydrodynamic interactions between dorsal and caudal fins contribute to enhanced propulsion and maneuverability.[2] This research shows how fish tails create small whirlpools in the water to help them move forward, and how robots can copy this to become more efficient. The development of robotic fish has been driven by the observation of fish swim patterns, focusing on how specific swim modes can be replicated for use in real-world applications [3]. Robotic models help us understand forces that are hard to measure in live fish. Miniature robotic fish designed for education and research have proven effective in replicating natural swimming dynamics and are crucial in advancing bio-inspired underwater vehicles.[3] These small robots help improve our understanding of fish movements. Recent advancements in the modeling and control of robotic fish, especially in incorporating flexible actuators and sensors, have further improved the precision and functionality of these systems, making them more adaptable for real-world applications [5,6].

In this paper, we explore the latest advancements in bio-inspired swimming robots, focusing on the design, materials, and real-world applications. A comparative analysis highlights how these systems outperform traditional robots, making them suitable for diverse underwater environments. This review also outlines the key challenges in the field, including material durability, control complexity, and limitations in autonomous decision-making. The structure of this paper is as follows: Section 2 presents recent research on bio-inspired robotic fish, emphasizing key challenges. Section 3 discusses practical applications, while Section 4 explores advancements in materials and design. Finally, Section 5 summarizes the findings and offers future research directions.

2. Research Progress in Bio-Inspired Robotic Fish

Bio-inspired robotic fish designs draw from a variety of swimming modes observed in nature. Two major types of locomotion are common: body/caudal fin (BCF) propulsion and median/paired fin (MPF) propulsion. BCF propulsion, characterized by undulating body movements, enables fast swimming and is used by approximately 85% of fish species, while MPF propulsion offers greater maneuverability at lower speeds [2]. These modes provide key insights into how to improve the design and functionality of robotic fish.

2.1. Hydrodynamics and Vortex Dynamics

Research has shown that replicating fish-generated vortices can enhance robotic swimming efficiency. For example, the interaction between the anal and caudal fins improves vortex formation, boosting lift and thrust efficiency [7]. By emulating this mechanism, bio-inspired robots can swim with reduced drag and improved energy conservation. Vortex dynamics provide an additional advantage by creating controlled flow patterns, enabling more precise maneuverability in turbulent or confined underwater environments.

2.2. Flexible and Adaptive Propulsion Systems

One of the significant innovations in robotic fish design is the integration of flexible materials that allow for adaptive propulsion. Soft-bodied robotic fish, utilizing both BCF and MPF propulsion mechanisms, have demonstrated superior performance in diverse aquatic conditions [8]. These flexible designs enable robots to adapt autonomously to varying underwater environments, representing a breakthrough in prolonged underwater operation. By imitating the natural undulation and oscillation of fish bodies, these robots achieve enhanced propulsion and agility.

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2.3. Autonomous Control and Decision-Making

Robotic fish are increasingly equipped with autonomous control systems that allow for real-time adjustments in speed, direction, and behavior. These systems help robots respond to dynamic underwater environments, such as shifting currents and obstacles. Recent advances in modeling and control have focused on optimizing robotic fish for stability and agility in nonlinear hydrodynamic conditions, leading to improved precision in real-world applications [5]. This adaptability is crucial for complex underwater tasks, such as navigating coral reefs or monitoring deep-sea ecosystems.

3. Practical Applications of Bio-Inspired Robotic Fish

Bio-inspired robotic fish are now employed in a range of real-world scenarios, from environmental monitoring to military operations. Their ability to swim silently and efficiently makes them ideal for tasks that require minimal disruption to marine life or a stealthy presence in sensitive areas.

3.1. Environmental Monitoring

One of the primary uses of bio-inspired robots is in environmental monitoring. These robots can collect water samples, measure pollution levels, and track changes in ecosystems, such as coral reefs. Their silent operation allows them to move through fragile ecosystems without disturbing local wildlife. By mimicking natural fish movements, bio-inspired robots can integrate seamlessly into marine environments, gathering data with minimal environmental impact [9].

3.2. Underwater Exploration

Bio-inspired robotic fish are also highly suited to underwater exploration, particularly in areas that are difficult or dangerous for humans to access. Their agility allows them to navigate confined spaces such as underwater caves or wrecks. Moreover, their energy-efficient design enables longer missions with fewer interruptions for recharging or maintenance.

3.3. Military Operations

In military applications, bio-inspired robotic fish offer unique advantages in stealth operations. Their fish-like appearance allows them to blend into the natural environment, reducing the risk of detection. These robots are used for surveillance, mine detection, and reconnaissance, particularly in coastal areas or regions where conventional unmanned underwater vehicles (UUVs) might be spotted [2]. Their low noise profile and natural swimming behavior also make them suitable for anti-submarine warfare.

4. Innovative Materials and Design Choices for Bio-Inspired Swimming Robots

The performance of bio-inspired robots is significantly influenced by the materials used in their construction. Recent developments in soft robotics, flexible actuators, and smart materials have contributed to more efficient and durable robots.

4.1. Soft and Smart Materials

Materials such as electroactive polymers (EAPs) and soft silicone-based compounds are increasingly used to replicate the flexible, muscle-like movements of fish. EAPs respond to electrical stimuli, enabling smooth, energy-efficient propulsion that closely mimics the undulating motion of real fish [10]. Soft robotics also benefit from the use of hydraulic actuators, which offer greater flexibility and adaptability in underwater environments [11].

4.2. Self-Healing and High-Strength Nanocomposites

Recent advances in material science have introduced self-healing polymers and nanocomposites that can withstand the harsh conditions of deep-sea exploration. Self-healing materials allow robots to repair minor damage autonomously, extending their operational lifespan in environments where manual maintenance is not feasible [10]. Nanocomposites, with their lightweight yet durable properties, provide enhanced resistance to high-pressure conditions, making them ideal for deep-sea missions [12].

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4.3. Advanced Actuators and Control Systems

In addition to material advancements, bio-inspired robotic fish have benefited from improvements in actuators and control systems. Piezoelectric actuators, which convert mechanical stress into electrical energy, have proven effective in reducing power consumption for long-duration missions [10]. Moreover, adaptive control systems allow robots to fine-tune their movements based on environmental feedback, ensuring optimal performance in dynamic underwater environments.

5. Conclusion

Bio-inspired swimming robots have made remarkable progress in recent years, driven by innovations in design, materials, and control systems. These robots offer improved energy efficiency, maneuverability, and adaptability compared to traditional propeller-based systems, making them ideal for a wide range of underwater applications. By mimicking the natural movements of fish, bio-inspired robots have become essential tools for environmental monitoring, underwater exploration, and military operations. Ongoing research into flexible materials and advanced control systems will further enhance the capabilities of these robots, paving the way for future innovations in autonomous underwater systems.

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