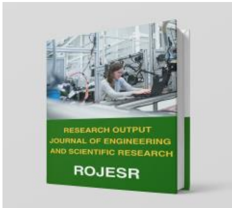

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Bio-Inspired Robotics for Underwater Exploration

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ABSTRACT

The field of bio-inspired robotics leverages the principles of natural selection and the unique adaptations of marine life to develop advanced underwater exploration technologies. By mimicking the locomotion, sensing, and structural mechanisms of aquatic organisms, engineers and scientists have created innovative robotic systems that can navigate and operate efficiently in the challenging underwater environment. This paper explores the design and engineering principles behind bio-inspired underwater robots, highlights specific examples of these technologies, and discusses their applications in environmental monitoring, pipeline servicing, and marine debris collection. It also addresses the current challenges and future directions in this rapidly evolving field, emphasizing the potential for bio-inspired robotics to contribute significantly to both technological advancement and environmental conservation.

Keywords: Bio-inspired robotics, Underwater exploration, Marine life adaptations, Autonomous underwater vehicles (AUVs), Environmental monitoring.

INTRODUCTION

Through the ages, humans have sought to understand the way animals and plants function. By observing life, we have made countless advances in our understanding of the world, identifying simple principles serving as an inspiration for great advances in many areas. By learning how nature solves problems, such as water-repelling characteristics seen in superhydrophobic surfaces for anti-biofouling applications, or using animal models of defensive systems to create new types of armor, we also have been able to solve challenging modern problems. In robotics, mechanical engineers have moved beyond the belief that resilience and robustness require power to harvest these natural principles; therefore increasing the endurance and ingenuity of mechanisms created for different types of applications [1, 2]. The interdisciplinary field of bio-inspired robotics seeks to gather information, derive concepts, and construct mechanisms and materials that resemble crucial features of living systems. This approach is not rooted in ethological or cognitive research, although it is guaranteed to provoke reflections and questions on the subject: there is an interest in translating key peculiarities that have been developed through long-term natural selection into useful technical applications. Among the various living systems that can be used as a source of inspiration, adhesion, sensing, and actuation that are employed by different animal species represent some of the most explored fields of bio-inspired robotics. Bio-inspired robotics has been proposed for plenty of application ideas, such as targeted drug-delivery systems or exploratory missions in environments that are inappropriate for manned operations. In particular, underwater research represents a challenging field, where even the most common problems may lead to the need for innovations in the field of robotic design. Although the underwater world shares many commonalities with the one we live in, such as gravity, it is a hostile environment for man-made machinery. Wildlife species that have evolved to live permanently or temporarily in this different environment through complex adaptations underwent a long-term process of natural selection, exploiting specific sensors and actuators that are capable of surpassing many limitations in the aquatic milieu; this inspired scientific progress in the development of innovative solutions [3].

DEFINITION AND SIGNIFICANCE

Marine vehicles are increasingly used in diverse missions. The term marine vehicles refers to underactuated autonomous vehicles that carry out their actions with direct contact with water, considering both the surface and the submerged regions. Examples are drones and robot submarines or an Autonomous Underwater Vehicle (AUV). AUVs have shown high quality throughout specific missions, such as the SEARCH class, which is proven for the deployment and re-entwining of submunitions in combination with the T-SAS class. However, typical features of the underwater scenario turn out some serious challenges concerning the mission complexity. High added value applications include mine reconnaissance, heavy marine operation assistance, environmental monitoring, and emergency operative prognostications following offshore incidents [4, 5].

EXAMPLES OF BIO-INSPIRED DESIGNS IN UNDERWATER ROBOTICS

A selection of recent examples of bio-inspired concept designs is provided here to give insight into the range of possibilities for biological inspiration for swimming behavior in bio-inspired underwater robotics. Several examples are also given of what can be accomplished by pairing biological traits with task-specific design features in both nature's and robotic swimmers. Design features from both aquatic and aerial robots are used to highlight this concept marine propulsor. It is acknowledged that this list is by no means comprehensive in its coverage of possible inspiration sources. However, these examples serve to illustrate the concept of bio-inspirations in underwater robotics [6]. Where possible, the design features are given for the successful biological model followed by those of the bio-inspired swimmer as the best basis for comparison. The naval architecture type, when known, is given for the bio-inspired swimmer. Animal data and appendage resonant frequencies are typically relevant to the system in the free stream. Often animals operate at kinematic limits, and therefore biological data is expected to be more extreme than the bio-inspired swimmer [3].

BIOLOGICAL INSPIRATION FROM MARINE LIFE

In order to perform effectively in a hostile and dynamic environment such as the ocean, several marine organisms have developed elegant and powerful mechanisms for locomotion and sensing that are inspiration for robotics research. In particular, the fish provides inspiration for propulsion and maneuvering, and the crustacean provides inspiration for the design of the exoskeletons and sensory structures. The quest for bioinspired underwater robots has led to progress in the art of fish-like structures and designs that are capable of taking advantage of the body-caudal fin swimming mechanism characteristic of fish. This style of propulsion can be traced back to the Ichthyostega, an early tetrapod that developed lobed pectoral fins that allowed it to climb out of the water onto constantly changing river shore surfaces [7, 8]. The undulating body and tail that generate asymmetrical wake patterns in undulatory swimmers are the key to fast motion due to the fact that water is denser than air and the body and tail of the swimmer are surrounded. This is why high-speed aerial reconnaissance aircraft such as the SR-71 Blackbird must use a turbojet for propulsion as compared to the undulating musculature in fish such as the yellowfin tuna. The undulating body and tail generate unsteady hydrodynamic forces that turn the fluid-induced tail and head wakes into a rowing effect that propels the swimmer through the fluid. The relative size of the tail and body to the generating unsteady wave that makes the rowing effect generates a thrust force makes large amplitude bodily undulations necessary for fast motion. The small time scale associated with shedding of viscous vortices from the leading and trailing edges of the body and the tail makes high-frequency body-caudal fin undulations ideal for minimizing the energy removed from the swimmer's motion by drag and thus maximizing the biological swimmer's speed [9].

BIOLOGICAL MECHANISMS AND ADAPTATIONS IN MARINE ORGANISMS

Powered by its high energy density and endurance, long-term undersea exploration has been an important and challenging issue and has drawn much attention. Taking inspiration from marine animals that possess remarkable and exquisite characteristics in their own environment as a response to natural selection over years, bio-inspired underwater robots have been designed. They are given promising prospects for work in different underwater operations, such as uncrewed or remotely operated probes, ocean survey, data gathering and monitoring, environmental protection, subsea cable deployment and recovery, pipeline maintenance, as well as search and rescue [10, 11]. In this paper, the anatomy, power unit, control system, and locomotion mechanisms of biological marine species are reviewed. Prototypes of the conceptions derived from marine players are also discussed, which provides an insightful understanding of the development tendency, benefits, and challenges when created in the use of biological inspirations in underwater robotics [12, 13].

With the advances of mechanical material upgrade and design and control of the creature-inspired robots, a series of accomplished or advanced apparatuses that are implicitly or explicitly inspired by biology have been created and used in accomplishing a chain of mission-critical tasks. For instance, animal machines or their related technologies can adopt tasks such as wildlife tracking and monitoring, search and rescue, formation flying, distributed surveillance, communication networks for devices, astronaut assistance tasks, autonomous takeoff and obstacle avoidance missions, inspection missions on cone-shape Petrobras platform, and bullet-response tasks on fighter jets, and so on [14, 15]. The advantage of bio-inspiration includes the excellent characteristics of animals and plants in their environment, such as the ability to operate well in specific environments, tips for using different materials and structures, locomotion abilities of various gaits, great energy metabolism, information collection and processing, responses towards uncertain difficulties, extremely complex behaviors, abundant operability, and others, which have been proven to be very practical in robot design [16].

DESIGN AND ENGINEERING PRINCIPLES IN BIO-INSPIRED UNDERWATER ROBOTS

Engineers, together with biologists and paleontologists, have been working for decades to draw inspiration from nature, mimicking animal musculoskeletal structure, bio-materials properties, sensorial system (visual and non-visual), and control principles (centralized and distributed nervous system) to create robots with or without onboard intelligence. Bio-inspired robots can be particularly successful in tasks that require the extraction of the high degree of versatility and sustainability that animals have obtained from billions of years of evolution. In extreme and unstructured environments, like underwater, bio-inspired robots can also benefit from the opportunistic traveling strategy that animals have developed, exploiting many different types of locomotion depending on the environmental conditions and the speed/energy requirements of the operation [17, 18]. Inspiration from nature represents the first of the three great categories of robots, whose common characteristic is autonomous behavior. By giving the command to the robot to go or to perform a task (high level of intelligence), they can plan and generate the movements necessary to reach the objective, to avoid obstacles, to interact with the environment, and to compensate perturbation in open loop using bio-controllers and non-redundant machines. Using feedback mechanisms and compensation strategies, the bio-robots can also interact with the complex and often unpredictable underwater environment. The characteristics of the materials and the structure of the autonomous machines lead to the second category of robots—that interact and are in synergy with the underwater environment in a way that makes it extremely complex for a human operator to reproduce the machines' behavior and emulate an intelligent action [19, 20].

HYDRODYNAMICS AND PROPULSION SYSTEMS

The underwater environment exerts an important influence upon the movement of objects through it. The main factors to consider in the design of a vehicle are interconnected, and it is necessary to study the interactions among them. The most relevant hydrodynamics principles are viscosity, external fluids, and buoyancy. These two principles lead aquatic vehicles to have a specific shape, which maximizes the efficiency of their movement, known as hydrodynamic shape [21]. Three propulsors have been shown to be the most efficient methods of steady horizontal/subhorizontal propulsion used in nature: tails/deformable bodies, undulation, and oscillation. Most biorobotic propulsion systems are modeled on these. The nature of aquatic drag leads some vehicles to prefer specific methods of locomotion/propulsion and design, focusing on maximizing the efficiency of low speeds, with some oscillation modes being observed. We propose that biorobotic features such as these can be used to apply other methods of streamlining of animals in these low efficiency areas and thus improve animal swimming performance. The term "steady" refers to the fact that propulsion is not achieved by the absorption and emission of force (frequently cyclic, transitory) as with robot oscillatory swimming (e.g., tuna and sunfish), which leads some biorobotic specialists to classify this locomotion as oscillatory-fin swimming [22].

APPLICATIONS OF BIO-INSPIRED UNDERWATER ROBOTICS

There are multiple applications of bio-inspired underwater robotics that we discuss in this survey, including pipeline servicing, marine debris collection, and help for coral reef restoration. The robotics focus on a variety of bio-inspired propulsion means like fish-like robots, jellyfish robots, jet-based ones for fast speed, and octopus-like ones for delicate manipulation at low speeds. After providing a review of bio-inspired underwater robotics in this survey, we found that there were few consolidated works on using a system biology approach specifically towards aquatic locomotion. Training policies and coordination of the robots also are in the early stages of automation and there is little biologically-inspired control learning going on so far [23]. Pipeline servicing is a challenging task carried out at sea bed depths where divers can only work for a short and finite duration. Using conventional underwater remotely operated vehicles (ROVs) like the ones used by oil companies is costly. We discuss the various fish-inspired robots and detailed interim prototypes suitable for CWS. Another application is the collection of marine debris, which is growing at an alarming rate. Removal of the debris is critical as it causes injuries to the marine life. A study identified from boat-based surveys that 79% of the plastic debris in ocean originated from watersheds along coast-lines. A fish-like robot from the ARROWS project was proposed in 2012 and a small prototype for the collection of debris was demonstrated in 2013. Robotic loads can navigate in waters of up to tens of knot speeds, making debris removal a possible application. Furthermore, future development of robotic debris collecting missions should include an encapsulation system to trap in biological waste during capture [24, 25].

ENVIRONMENTAL MONITORING AND CONSERVATION

Oceans are important to mitigate climate change, produce oxygen, and contain biodiversity. The United Nations has included the "Life below water" show on its list of Sustainable Development Goals, defining targets to sustainably manage and protect marine and coastal ecosystems from pollution, including by creating awareness of the importance of their biodiversity. Monitoring biodiversity and hazards, understanding how marine fauna respond to changes, and developing and testing platforms and robotic systems are crucial perspectives [26, 27]. Passive methods, specifically MoOREDARs and sound recorders, are drastically broadening our knowledge about coastal species from echolocating beaked whales to snapping shrimp sounds in the context of ocean acidification. Mass spawning events in corals can be monitored thanks to the chorus of their sex cells, recorded from surface buoys in the Great Barrier Reef. Fast light action in microzooplankton was detected by a biologically-inspired model based on the photosynthetic electron transport chain. Soundscapes are fundamental to benthic ecology and ecosystems dynamics (e.g., study of deep-sea corals). Spawning events can be monitored thanks to the chorus of their sex cells, recorded from surface buoys in the Great Barrier Reef. Fast light action in microzooplankton was detected by a biologically inspired model based on the photosynthetic electron transport chain. Soundscapes are fundamental to benthic ecology and ecosystems dynamics (e.g., study of deep-sea corals).

CHALLENGES AND FUTURE DIRECTIONS IN BIO-INSPIRED UNDERWATER ROBOTICS

In the previous sections, we have discussed the various aspects of bio-inspired robotics research. We have sampled the recent trend of creating bio-inspired systems. We have chosen to focus on underwater vehicles, resulting in the enumeration of a few significant, novel vehicle concepts, each influenced by a unique aspect of aquatic life, all mentioned here. In Table 1, a listing of recent bio-inspired mobile underwater vehicles, along with the biological models that have been used in the design, characteristics, and observations for these designs are given, showing the range and diversity of this rapidly evolving area. In this chapter, we highlighted several theoretical and practical ideas of artificial creatures. Many new challenges arise for the near future, and they certainly influence the development of a variety of topics within bio-inspired robotics, such as cooperative behavior, artificial-creature-environment interaction, and long-duration autonomy. Finally, as a long-awaited future perspective, we hope that the theoretical models expressing the relation between the functioning principle of natural creatures and the basic processes of the environments in which they live and hunting around a complete design methodology will become clearer in the nearby future. It is our hope that bio-inspired robotics will eventually contribute to other similar useful activities related to environmental and economical problems [28]. Bio-inspired robotics is a relatively new but active research area. In general, it should provide several advantages. Since it benefits from what exists in nature, unnecessary problems will be eliminated by rigorous natural selection processes. From the implementation perspective, for instance, hardware reliability and cost reduction will be significantly guaranteed by the principle of natural evolution. Since sensors or actuators in robotic systems need to satisfy real, practical, hardware, sensory, nervous system, and environmental constraints, we focus on the main three challenges in the development and modeling of autonomous, real creatures. First, multiple timescales of nervous system functioning that ensure the robustness of the design. Second, sensory nervous system integration on real hardware with limited computational capability and weak sensory information. Third, the actual performance of creatures in ecologically-valid tasks. Underwater robots built around models that do not capture an accurate match with actual creature and environment interaction are not sustainable. In addition, studies of actual creature behavior and the related bio-designs have shown that the most parsimonious explanation of a structure or behavior may not always be the correct [29].

CONCLUSION

Bio-inspired robotics represents a promising approach for addressing the complexities of underwater exploration. By harnessing the evolutionary adaptations of marine organisms, researchers have developed robotic systems with enhanced propulsion, sensing, and structural capabilities. These advancements facilitate a range of applications, from environmental monitoring and conservation to pipeline servicing and debris collection. Despite the significant progress, challenges remain, including the integration of sensory and control systems and achieving long-duration autonomy. Continued interdisciplinary collaboration and research are essential for overcoming these challenges and unlocking the full potential of bio-inspired underwater robotics, ultimately contributing to sustainable marine ecosystem management and technological innovation.

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