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Biomimicry and Aquatic Robotics: Sustainable Innovation for Marine Ecosystem Monitoring in South Africa

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Encheng Wang is a senior at The Hill High School in Pennsylvania. His background is quite different from that of other students. He was born in Botswana, grew up in South Africa, and moved to the United States during high school. Due to his experiences in South Africa, he possesses a unique perspective and a strong interest in the country's environment, ecology, and economy.

ABSTRACT

Advancements in biomimicry have led to the design and development of aquatic robots capable of conducting deep-sea surveys to identify patterns and the magnitude of damage caused by various threats, including natural and human factors. The innovative underwater vehicles have proven effective for global submarine monitoring due to their high maneuverability levels, operational efficiency, and minimal disturbance to the ocean environment and aquatic life. Therefore, this project examines the potential of biomimetic aquatic robots for fostering sustainable marine ecosystem monitoring in South Africa. The analysis reveals that the technologies provide a promising solution for increasing marine awareness and enhancing the country's blue growth. However, the solutions' associated shortcomings, such as substantial investment capital, high operating and maintenance costs, and ethical concerns, might limit South Africa's ability to optimize the inherent benefits of the innovations. Thus, continued research is crucial for designing, developing, deploying, and maintaining more cost-effective and highly ethical biomimetic aquatic robots for sustainable marine ecosystem monitoring.

Keywords: *biomimicry, environmental sustainability, innovative solutions, marine ecosystem monitoring, South Africa, aquatic robotics, nature-inspired robotics, ecological impact, eco-friendly deep-sea exploration, energy-efficient underwater vehicles.*

INTRODUCTION

The global marine ecosystems have faced growing threats in the recent past, ranging from climate change to pollution and exploitation. Environmental pressures are increasingly becoming critical in the Global South, where healthy marine systems play a vital role in coastal economies, serving as sources of fisheries, biodiversity, and tourism. Given the traditional monitoring tools' lack of precision and associated cost-inefficiencies, marine researchers are increasingly resorting to biomimicry, the design of innovative coastal monitoring technologies that imitate aquatic animals, to sustainably explore potential threats to marine environments and implement evidence-based conservation mechanisms, especially in resource-limited settings, such as South Africa (Aguzzi et al., 2024). Thus, biomimetics enables the creation of technologies that can successfully navigate complex deep-sea terrains and gather valuable real-time data without causing significant ecological disruption. Thus, biomimicry offers a more innovative approach to monitoring marine ecosystems and sustainable coastal conservation in developing nations such as South Africa.

BACKGROUND

Biomimicry, or biomimetics, which emulates nature's models, systems, and elements to resolve complex anthropogenic problems, offers transformative potential for innovative marine conservation globally. In particular, nature-inspired aquatic robotic systems that mimic the movement and behavior of marine organisms have been employed worldwide to monitor biodiversity, detect pollutants, and facilitate habitat restoration with minimal ecological disruption. For instance, Boston's Green Harbors Project (GHP) utilizes biomimetics for salt marsh monitoring and restoration, guarding the ecosystem against invasive species and ensuring harbor water quality (Biomimicry, n.d.). The Wuliangsuhai Watershed in China provides another case study of nature-based and bio-inspired solutions for coastal protection. The project's application of biomimicry has facilitated sustainable habitat monitoring and led to significant ecological restoration (Jia et al., 2023). Thus, these geographically diverse examples demonstrate the popularity and effectiveness of biomimetics in fostering sustainable marine ecosystems. Biomimicry is an innovative approach to collecting the necessary data for achieving Sustainable Development Goal (SDG) 14 worldwide, including the Global South.

South Africa boasts a diverse array of marine ecosystems characterized by subtropical coral reefs, mangroves, seamounts, and temperate kelp forests. The country's adjacent ocean environment is one of the world's most diverse marine habitats, characterized by significant variations in oceanographic diversity across three expansive biogeographic regions. However, various South Africa's marine ecosystems, including coastal, offshore, inshore, and estuary areas, are currently threatened by indiscriminate habitat destruction, resource overexploitation, anthropogenic pollution, and climate change. A report by South Africa's Department of Forestry, Fisheries, and the Environment notes that 58% of the country's coastal and inshore ecosystems are threatened, 41% of the offshore habitats are affected, and 43% of estuary marine environments face destruction. Struwig et al. (2024) identify environmental disasters, such as oil spills and marine dumping, as the leading threats to South Africa's marine environment. Other issues include climate change, disease events, and illegal fishing. The complexity and scale of these challenges underscore the need for integrated systems that include high-tech and ecologically harmonious components, such as biomimetic robots, to aid in the sustainable management of South Africa's marine ecosystem.

LITERATURE REVIEW

Biomimicry in aquatic robotics involves designing marine life-inspired robots, such as those resembling fish or other deep-sea animals, to enhance efficiency, maneuverability, and eco-friendly underwater inspection and exploration. Traditional submarine vehicles often used for marine ecosystem monitoring tend to cause environmental disturbances while exhibiting low efficiency and undesirable maneuverability levels. Consequently, biomimicry addresses such limitations by leveraging the natural designs and capabilities of sea creatures, thereby improving efficiency, motility, and ecological interactions. Bu et al. (2022) note that biomimetic aquatic robots offer promising solutions for resolving 21st-century marine inspection and beach safety challenges due to their robust maneuverability and low environmental destruction risks. However, optimizing the potential of such innovations depends on their design features, including the actuation techniques used. Empirical evidence suggests that aquatic mobile robotics have the potential to revolutionize marine monitoring and exploration with the Ocean Internet of Things (IoT) by utilizing propulsion mechanisms, such as microbial fuel cell (MFC) technology (Elhadad et al., 2024). Designers can extend the MFC's lifespan by using spore-forming Bacillus as an anodic catalyst, enhancing the microbial fuel cell's ability to endure harsh marine conditions and reactivate in favorable settings. Thus, current literature demonstrates the ability of underwater biometric aquatic robotics to foster the sustainable management of marine ecosystems globally.

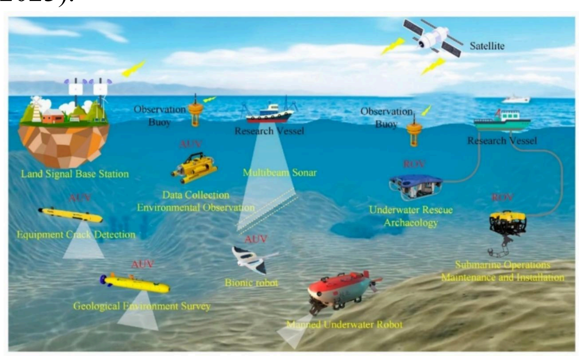
The invention of a biomimetic aquatic robot has generated considerable global interest among marine scientists and conservationists. Consequently, several studies have been conducted to assess their innovativeness and applications for sustainable monitoring of marine ecosystems. Prakash et al. (2024) argue that the growing interest in biomimetic systems, particularly in the marine sector, is driven by the challenges posed by harsh deep-sea environments. The authors' literature review establishes that biomimetic marine robots are leading the development by imitating various diverse structures and behaviors of marine life and leveraging acquired adaptation characteristics of oceanic organisms to thrive in harsh underwater conditions. Based on their research findings, Prakash et al. (2024) conclude that the biomimetic marine robotics niche not only presents a paradigm shift in marine ecosystem monitoring but also offers an opportunity for sustainable exploration of the deep-sea environments and resolving technological solutions management challenges. In particular, mimicking marine life has enabled engineers and conservationists to solve complex environmental challenges and sustainably operate marine ecosystems. Despite their inherent design and engineering challenges, biomimetic aquatic robots are a promising solution to 21st-century challenges for the sustainable management of oceanic ecosystems.

Engineers have optimized the application of biomimetic aquatic robotics in sustainable marine ecosystem monitoring by designing underwater bionic creatures that can swim, grasp, and bipedal walk, revolutionizing deep-sea exploration. The innovative designs demonstrate the potential of biomimetic robots to replace humans in challenging exploratory tasks in harsh underwater environments. For instance, Wu et al. (2024) designed and developed a novel octopus-inspired robot bearing eight soft limbs to enhance underwater flexible motion and achieve comprehensive subsea operations. The new bionic creation exhibited underwater bipedal walking capabilities, multi-arm swimming, and object-grasping ability. The robot utilized a cable-driven flexible arm to move on the deep-sea floor in bipedal walking mode. Thus, the case study demonstrates the potential of biomimetic aquatic robots to navigate and explore expansive environments swiftly, enhancing their applicability for responsible marine ecosystem monitoring. Similarly, Vasquez-Charcape et al. (2024) propose Fisher-X, a biomimetic robot inspired by the hadal snailfish Pseudoliparis swirei. The innovative marine ecosystem management tool can monitor water bodies adjacent to industrial facilities for pollutants, such as acid mine drainage and wastewater containing xenobiotics. The study findings indicate that Fisher-X's deep-sea exploration potential exceeds that of conventional ecological monitoring undertakings, such as habitability surveys, mapping of aquatic environments, and physicochemical characterization. Robotic innovations inspired by the natural underwater world are a promising solution to various 21st-century challenges facing sustainable marine ecosystem monitoring and management.

TECHNOLOGICAL INNOVATIONS

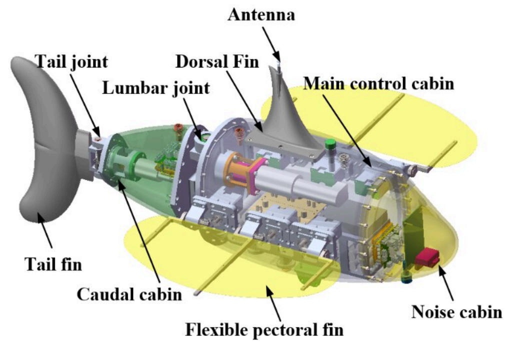
Biomimicry-based technological innovations are characterized by design solutions inspired by nature, such as the bionic fish, to enhance and create highly maneuverable, efficient, and eco-friendly vehicles for sustainable dee-sea explorations. In particular, the biomimicry design philosophy entails learning from and imitating nature's attributes and behavioral characteristics to create sustainable solutions to human challenges. The perspective is corroborated by Aguilar-Planet and Peralta (2024), who note that the biomimetic design philosophy focuses on copying biology to generate innovative solutions based on natural features analogy. For instance, designing a biomimetic aquatic robot inspired by the streamlined shape of a fish exemplifies biomimetic. Consequently, underwater nature-inspired robots, such as remotely operated vehicles (ROV) and autonomous underwater vehicles (AUVs) (Figure 1), are characterized by nature-inspired design features, including propulsion mechanisms (Li et al., 2023). The capabilities enable marine innovations to maneuver the harsh deep-sea environment efficiently and at high speeds while adjusting effectively to ensure low energy costs. Various actuators have been adopted for biomimetic aquatic robots since the inaugural model was designed in 2008 (Zhang et al., 2025). Notable examples include shape memory alloy (SMA) springs, motors, actuators, direct current (DC) motors, time ratio control (TRC) systems, and SMA applications in combustion. Advancements in actuation systems are often necessitated by the need to enhance the performance of oceanic robots in challenging underwater conditions.

Figure 1
AUV and ROV Application Scenarios (Li et al., 2023).



The bionic fish exemplifies a design principle inspired by nature, known as biomimicry or biomimetics. RobDact (Figure 2), a bionic deep-sea vehicle, features large, flexible pectoral fins that resemble the enlarged homopterygium of the Dactylopteridae fish. The device's mechanical structure also comprises a tail fin and antenna, which are critical for mobility within the aquatic environment. Each pectoral fin acts as an undulating extension, consisting of three rays that are actuated independently using the steering gear, enabling the underwater vehicle to achieve enhanced low-speed stability. A study conducted by Cao et al. (2022) demonstrated that combining computational fluid dynamics with a force measurement experiment enhances RobDact's efficiency, maneuverability, and controllability. Thus, the device's four motion modes, including low-speed forward, yaw, high-speed forward, and snorkeling, enable it to navigate harsh marine conditions, overcoming the limitations of propeller-based biomimetic aquatic robots. Lie et al. (2023) note that bionic-based propulsion mechanisms, such as those adopted in RobDact, enhance the maneuverability, flexibility, and adaptability of deep-sea bionic fish in marine environments. Consequently, bionic-based underwater robots exhibit higher performance in marine ecosystem monitoring than their propeller-driven counterparts. The nature-inspired design principles of biomimetic aquatic robots enable these devices to effectively and efficiently navigate challenging underwater terrains, making them suitable for the sustainable exploration of marine ecosystems.

Figure 2
RobDact's Mechanical Structure (Cao et al., 2022).



APPLICATIONS OF BIOMIMETIC AQUATRIC ROBOTICS IN SOUTH AFRICA

South Africa utilizes ocean monitoring for various applications, including marine spatial planning and monitoring hazardous algal blooms, with the Operational Ocean and Coastal Information Management System (OCIMS) providing a critical platform. The OCIMS aims to enhance maritime awareness and foster South Africa's blue growth. In particular, the solution helped establish knowledge tools for marine spatial planning, domain awareness, search and rescue operations, water quality monitoring, and harmful algal bloom detection (Krug et al. 2024). The aids are utilized by stakeholder across government departments, industry, and civil society to execute their day-to-day roles and responsibilities. In particular, biomimetic aquatic robotics offer a promising and sustainable approach for monitoring South Africa's marine ecosystems and other stakeholders, such as OCIMS, by allowing them to mimic nature's solutions for efficient, eco-friendly deep-sea exploration and data collection. South Africa can utilize innovative underwater vehicles for various marine ecosystem monitoring activities while minimizing disturbance to aquatic life and deep-sea habitats.

Marine ecosystem management stakeholders in South Africa can utilize biomimetic aquatic robots inspired by nature to efficiently and sustainably map complex deep-sea environments, such as coral reefs and kelp forests, overcoming the limitations of propeller-driven traditional underwater vehicles. Traditional submarine mapping techniques, such as manned diving and solar survey, rely on proper propulsion mechanisms, making them less efficient, low in maneuvering capabilities, time-consuming, costly, and hazardous, especially in complex deep-sea explorations. Therefore, the agility and maneuverability, energy efficiency, sensor integration, and autonomous operation of biomimetic aquatic robots make them ideal for monitoring underwater habitats and conserving aquatic life in challenging marine ecosystems, such as those in South Africa. Wang et al. (2024) propose an intelligent underwater exploration biomimetic robot that has the potential to address the limitations of traditional deep-sea vehicles in navigating complex submarine environments. A series of simulations on the prototype confirm its effectiveness, including the ability to achieve intelligent motion planning, accomplished yaw control, and obstacle avoidance. Biomimetic aquatic robots, such as robotic fish, soft robots, and AUVs, offer a valuable solution for the sustainable monitoring of South Africa's marine ecosystems by facilitating the collection of critical data for evidence-based planning and management of the country's blue resources.

South Africa can utilize biomimetic aquatic robots for deep-sea exploration, including conducting geological surveys to identify critical underwater features and assessing the impact of anthropogenic activities on the seabed. Given their maneuverability, efficiency, and eco-friendliness, the innovations offer promising solutions for the sustainable management of the country's marine ecosystems. Research suggests that biomimetic aquatic robots are potential tools for the sustainable exploration of seafloor characteristics, such as morphology and composition (Cui et al., 2023). Thus, since the second half of the 20th century, innovative deep-sea biomimetic robots have been utilized to aid human explorations of submarine environments. Still, the use of underwater vehicles to perform various marine ecosystem management tasks has significantly improved with continued technological advancements. For instance, in 2017, a Zhejiang University professor designed and developed a deep-sea robot capable of cleaning marine life 100 meters below the water surface (Cui et al., 2023). The robot transmitted a selfie video submarine, indicating the cleaning process. Biomimetic aquatic robots offer South Africa valuable and sustainable opportunities for exploring its marine ecosystems, including identifying harmful human activities and their impact on submarine features and aquatic life.

Marine ecosystem managers and stakeholders in South Africa can also employ biomimetic aquatic robots to assess the health and well-being of deep-sea habitats by identifying regions affected by anthropogenic pollution, climate change, and other threats. Innovative technologies can autonomously map the seabed, providing valuable data-driven insights into the marine environment's conditions and enabling informed decision-making for the conservation of fragile ecosystems. Cardenas et al. (2024) observe that coral reefs worldwide, including those in South Africa, face significant threats from both natural and anthropogenic factors. Consequently, the authors conducted a study to analyze the techniques currently utilized in coral reef monitoring, focusing on aquatic robotics and their potential for revolutionizing the sector. Evidence from the researchers' systematic review of the existing literature across engineering and earth sciences reveals that artificial intelligence-powered and machine learning-based robotics offer innovative, sustainable solutions for coral reef monitoring, thereby contributing to the conservation of vulnerable aquatic ecosystems. Biomimetic aquatic robots have significant potential for enhancing the exploration and monitoring of marine ecosystems in South Africa by generating valuable insights for sustainable marine ecosystem management.

ECONOMIC AND ENVIRONMENTAL IMPACTS OF BIOMIMETIC AQUATIC ROBOTS

Employing biomimetic aquatic robots for marine ecosystem exploration and monitoring provides an eco-friendly and cost-effective approach to the sustainable management of blue resources in South Africa. The approach enhances the country's conservation efforts, minimizes social risks associated with human interventions in underwater research, and generates substantial economic benefits. Research suggests that futuristic technologies can accurately collect substantial data volumes from coral reefs without disturbing the morphology of the deep-sea environment (Cardenas et al., 2024). Therefore, the ability of biomimetic aquatic robots to collect and transmit valuable data for marine ecosystem management responsibly and efficiently, with minimal ecological damage and economic costs, makes them ideal for submarine monitoring compared to traditional approaches that often rely on human divers or propeller-based vessels. Additionally, robots inspired by aquatic life can be utilized for continuous exploration of submarine conditions, continuously collecting the necessary data to understand the long-term destruction patterns of marine ecosystems (Wang et al., 2024). Their design prioritizes resource optimization and operational efficiency, significantly minimizing their ecological footprint compared to conventional robotic systems. The economic and environmental benefits of biomimetic aquatic robotics, characterized by minimal resource consumption, reduced environmental footprint, and cost-effective exploration of challenging deep-sea habitats, make them ideal for fostering sustainable marine ecosystem monitoring in South Africa.

CHALLENGES AND FUTURE DIRECTIONS

Despite their substantial economic and environmental benefits, designing, developing, operating, and maintaining biomimetic robots can be a challenging task. Biomimicry-based technologies often require significant initial investment for their complex engineering features, specialized materials, and rigorous testing, making them costly for individuals and less-established organizations. Cardenas et al. (2024) note that using biomimetic aquatic robots for coral reef monitoring is costly due to the high initial costs of developing, deploying, and maintaining underwater vehicles. Nature-inspired robots require quiet, efficient, and costly high-performance actuators to showcase mimetic behavior, making them expensive to acquire and maintain. Additionally, studies by Bu et al. (2022) and Cardenas et al. (2024) reveal that nature-inspired robots, such as bionic fish, require specialized skills for effective operation and maintenance, adding to their overall cost. Skilled labor is critical for analyzing and interpreting the information gathered using bionic marine creatures. Therefore, the widespread adoption of innovative underwater vehicles for marine undertakings in South Africa is limited by the high costs of acquisition and operational requirements.

Using biomimetic aquatic robots for marine ecosystem monitoring is also characterized by ethical concerns, which might limit their applications. Consequently, successfully adopting innovative technologies entails considering the necessary regulatory requirements to minimize their adverse impacts on aquatic life and marine environments. Since biomimicry-based robotics is constantly evolving, aquatic life-inspired robots require continued costly upgrades, and adopting organizations need to invest in capacity development to equip workers with the necessary knowledge and skills to operate the improved models. Thus, there is a need for continued research on biomimicry-based aquatic robotics to explore more cost-effective and ethical approaches for their design, development, and operation.

CONCLUSION

Biomimetic aquatic robots offer a promising solution for the sustainable monitoring of South Africa's marine ecosystems, significantly contributing to OCIMS's goal of enhancing maritime awareness and promoting the country's blue economy growth. The country's existing policy, regulatory, and institutional frameworks facilitate the adoption of innovative technologies for deep-sea exploration and impactful management of national submarine resources. However, the successful development, deployment, and maintenance of aquatic life-inspired robots in South Africa requires stakeholders to address associated challenges, such as high initial investment, costly skilled labor, and ethical considerations. Resolving the limitations of adopting biomimetic aquatic robots for underwater exploration enables South Africa to capitalize on both economic and environmental benefits. Therefore, there is a need for continued research in biomimicry to develop highly innovative approaches for designing and developing cost-effective, ethical aquatic life-inspired robots for underwater monitoring.

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