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TOPICAL REVIEW

Oceanic Challenges to Technological Solutions: A Review of Autonomous Underwater Vehicle Path Technologies in Biomimicry, Control, Navigation, and Sensing

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ABSTRACT Autonomous Underwater Vehicles (AUVs) epitomize a revolutionary stride in underwater exploration, seamlessly assuming tasks once exclusive to manned vehicles. Their collaborative prowess within joint missions has inaugurated a new epoch of intricate applications in underwater domains. This study's primary aim is to scrutinize recent technological advancements in AUVs and their role in navigating the complexities of underwater environments. Through a meticulous review of literature and empirical studies, this review synthesizes recent technological strides, spotlighting developments in biomimicry models, cutting-edge control systems, adaptive navigation algorithms, and pivotal sensor arrays crucial for exploring and mapping the ocean floor. The article meticulously delineates the profound impact of AUVs on underwater robotics, offering a comprehensive panorama of advancements and illustrating their far-reaching implications for underwater exploration and mapping. This review furnishes a holistic comprehension of the current landscape of AUV technology. This condensed overview furnishes a swift comparative analysis, aiding in discerning the focal points of each study while spotlighting gaps and intersections within the existing body of knowledge. It efficiently steers researchers toward complementary sources, enabling a focused examination and judicious allocation of time to the most pertinent studies. Furthermore, it functions as a blueprint for comprehensive studies within the AUV domain, pinpointing areas where amalgamating multiple sources would yield a more comprehensive understanding. By elucidating the purpose, employing a robust methodology, and anticipating comprehensive results, this study endeavors to serve as a cornerstone resource that not only encapsulates recent technological strides but also provides actionable insights and directions for advancing the field of underwater robotics.

INDEX TERMS Air-water trans-media vehicles, autonomous underwater vehicles, bionic models, Doppler velocity log, self-adaptive AUV-based localization, underwater acoustic sensor networks.

I. INTRODUCTION

Autonomous Underwater Vehicles (AUVs) or Underwater Unmanned Vehicles (UUVs) play a pivotal role across diverse industries and scientific domains, significantly contributing

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to underwater exploration and mapping. These state-of-the-art vehicles have become indispensable for tasks traditionally undertaken by manned vehicles, excelling in complex underwater environments characterized by unpredictable currents, varying water pressure, rugged topography, and harsh conditions. AUVs facilitate the automation of crucial functions, resulting in increased operational efficiency, cost reduction, and minimized risks to human operators. This transformative technology has revolutionized underwater research, empowering scientists and researchers to acquire precise and valuable data for fields such as marine biology, oceanography, and environmental studies [1].

Furthermore, AUVs have emerged as instrumental assets in diverse offshore industries, including oil and gas exploration, underwater infrastructure inspection, and pipeline maintenance. The capacity of AUVs to collaborate in joint missions, employing sophisticated algorithms and coordinated efforts, introduces novel and exciting possibilities. This collaborative approach enhances the overall effectiveness of underwater missions, facilitating comprehensive exploration and documentation of underwater ecosystems and resources. This underscores the versatility and adaptability of AUVs across a spectrum of applications in the marine and offshore sectors [2].

In the past two to three years, there has been a notable surge in the development and deployment of Remotely Operated Vehicles (ROVs) and AUVs, marking a significant stride in underwater technology. These advanced vehicles have showcased their capabilities across a spectrum of applications, including oceanographic surveys, bathymetric measurements, and underwater maintenance activities such as servicing oil platforms and fiber optic communication lines. Designing and implementing effective guidance and control systems for these vehicles necessitates expertise from multiple disciplines, encompassing vectorial kinematics and dynamics, hydrodynamics, navigation systems, and control theory. This interdisciplinary approach ensures the development of efficient, stable, and reliable control mechanisms, enabling ROVs and AUVs to navigate and operate effectively in challenging and dynamic underwater environments.

However, despite their remarkable advancements, AUV control still presents fundamental challenges that need to be addressed. Issues such as navigation in complex marine environments, dealing with external disturbances, and achieving precise depth control remain areas of active research and development. Solving these control challenges will further enhance the capabilities of AUVs and broaden their scope of applications. The design of these vehicles' guidance and control systems necessitates the expertise of a wide range of disciplines, including vectorial kinematics and dynamics, Hydrodynamics, navigation systems, and control theory. The fundamental issues with AUV control include parametric uncertainties (e.g., additional mass, hydrodynamic coefficients, and so on), and non-linear and coupled dynamics [4]. Several engineering difficulties linked with autonomy must be solved to obtain a high degree of autonomy with the high density, non-uniform, and unstructured seawater environment (disturbances, etc.), and the nonlinear response of the vehicle must be considered and overcome [5]. Underwater Robots have received a lot of attention as a promising research area. Many publications have been published to date in order to sift out, classify, and provide specific techniques for various elements of underwater robots. For example, some major sensing technologies, including underwater acoustic sensing, underwater optical sensing, underwater magnetic sensing, and underwater bionic sensing are presented in [6]. The literature of Neira et al. [7] provides a review of Unmanned Underwater Robotics, Structure Designs, Materials, Sensors, Actuators, and Navigation Control. The research of Barker et al. [8] briefly reviews the scientific inspiration and problems, development, and use of underwater robotic vehicles built for use in ice-covered seas, with special attention dedicated to the navigation systems utilized for under-ice deployments. The literature of Laranjeira et al. [9] discusses the advantages and disadvantages of using mixed reality (MR) to explore deep-sea areas with remotely operated vehicles. The strategy is twofold: virtual reality (VR) allows the scientist to study the world through visual 3D representation, transcending the constraints of local perception. Augmented reality (AR) concepts are intended to increase perception and interaction with the environment. The study of Connor et al. [10] summarizes the current state of underwater swarm robotics; it covers the design of the underwater robots, the methods used by individual robots to perceive their environment, the methods of communication available underwater, centralized and decentralized control, the foundation of swarm algorithms, the behaviors displayed when a swarm works collectively, and how swarms were applied underwater. Subsequently, in [11], underwater navigation, its advantages, challenges, and future ventures are presented. Wang et al. in [12] presents a comparative analysis on gliding Robots. Similarly, Huy et al. introduces sensing technologies and perception techniques for underwater robots [13]. Additionally, Li et al. [14] addresses challenges, recent developments, and design strategies on bioinspired soft underwater Robots. Finally, Ma et al. highlights terrain matching techniques for navigation of underwater Robots [15].

Table 1 provides an overview of above literature reviews that delve into AUVs technology. Each entry highlights specific focuses and corresponding limitations identified in the respective reviews. Offering a concise overview, this summary shows insights from multiple literature reviews, emphasizing both the identified strengths and the territories that beckon for further investigation in AUV technology that were not highlighted in the associated reviews. The literature presented in Table 1 focused on specific components like sensors, actuators, or materials, but they lack a holistic view by not addressing the integration of these components into a comprehensive underwater robot system. The absence of discussions on propulsion systems, communication models, and charging mechanisms indicates a gap in understanding the interconnectedness of these elements.

TABLE 1. Overview of several previous reviews.

Literature	Highlight	Limitation	References
Cong, Y *et al.*	Detailed review regarding the sensing technology process.	Does not include other prospects such as a propulsion system, navigation control, etc.	[6]
Neira, J., Sequeiros *et al.*	Discusses structure designs, materials, sensors, actuators, and navigation control.	Does not mention about control and communication system.	[7]
Barker, L. D., Jakuba *et al.*	Review vehicle design and navigation algorithms.	Leaves aspects like control systems, communication models, and applied sensors.	[8]
Laranjeira, M., Arnaubec *et al.*	Highlights the recent 3D perception and augmented reality developments.	Does not include the models where it can be implemented.	[9]
Connor, J., Champion, B., & Joordens, M. A.	Culminates algorithms, communication methods, and designs.	Does not include sensors for achieving such tasks.	[10]
Yinghao Wua, Xuxiang Taa, *et al.*	Highlights some typical underwater robot localization and navigation approaches,	Leaves other aspects like Charging, navigation, sensing etc.	[11]
Wang, J., Wu, Z, *et al.*	Comprehensive review of underwater gliding robots, and the methodologies used to guide future advancements.	Does not include sensors for achieving tasks, Charging systems, and navigation systems.	[12]
Huy, D. Q., Sadjoli, N., *et al.*	In-depth description of sensing technologies and perception techniques for underwater robots.	Omits other aspects which include charging and Navigation.	[13]
Li, G., Wong, *el al.*	Addresses challenges, recent developments, and design strategies on bioinspired soft underwater Robots.	Does not explore navigation methods, Charging methods, and Sensors for relative tasks.	[14]
Ma, T., Ding, S., *et al.*	Highlights Terrain matching techniques for Navigation.	Does not include the models that can be used for such Navigation.	[15]
Xu, Y., Zheng., *et al.*	Centers on feature-based underwater localization and navigation employing 2-D imaging sonar measurements	Does not explicitly mention potential limitations or areas for further improvement as well as does not explore other aspects like sensor, charging system and Control Schemes.	[16]
Zhong, Y., Hong, Z., *et al*	Addresses the challenge of modeling and controlling various swimming motions in fish locomotion, including cruising-straight, cruising-turn, and fast turns	Does not explore the fusibility of the kinematic model across different models does not highlight aspects such as Control methodologies and Navigation Algorithms	[17]

Table 1 presents an overview of various literature reviews on AUV technology, for instance in [9] a comprehensive study of sliding robots has been presented but does not incorporate other segments like charging system and control systems. furthermore, in [11] typical navigation process algorithms are presented but do not include sensors or related bionic models additionally, a comprehensive review of underwater gliding robots and methodologies for future advancements has been offered in [12] but overlooks critical components such as sensors for achieving tasks, charging systems, and navigation systems. Similarly, feature-based underwater localization and navigation using 2-D imaging sonar measurements is described in [16] but fails to address potential limitations, areas for improvement, and other crucial aspects like sensors, charging systems, and control schemes. Additionally, the challenge of modeling and controlling various swimming motions in fish locomotion has been addressed in [17] but neglects to explore the compatibility of kinematic models across different platforms and omits discussions on control methodologies and navigation algorithms. These deficiencies underscore the need for more comprehensive and integrated approaches in AUV technology research.

Fig. 1 represents the number of research papers published regarding AUVs in intervals of 5 years, starting from 1996 up to 2023. The graph showcases the distribution of research papers over time, providing insights into the volume of

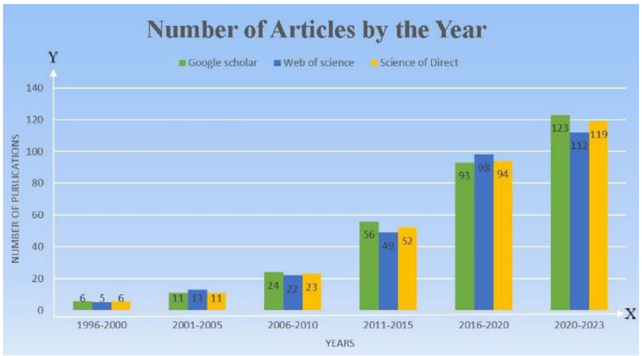


FIGURE 1. **Number of Articles published on AUV over last two decades.**

publications within each 5 years. It allows for visualizing any trends or patterns in the number of research papers published over the years, highlighting periods of increased or decreased activity in the field. After observing the graph, it can be concluded that the research in the field of AUV has substantially increased in the last decades after 2015.

The latest developments in UUV technology are covered in detail in this research paper, with a special emphasis on bionic models, control systems, navigational algorithms, and sensors. The most recent advancements in each of these fields are examined in the paper, along with trends, difficulties, potential uses, and applications. The use of biomimetic designs, such as bionic fins, flippers, and propulsion systems, which are inspired by marine animals and plants, is discussed in the paper's discussion of bionic models. The paper also looks at recent advancements in communication and networking, as well as trajectory planning, obstacle avoidance, and mission optimization algorithms that are used by AUVs. The development of navigation algorithms is also covered, including path planning optimization and the use of simultaneous localization and mapping algorithms. The paper concludes by examining recent developments in sensor technology, such as the miniaturization and integration of multiple sensors, which are essential for effective and efficient underwater exploration and monitoring.

This study serves as a vital compilation of cutting-edge biomimetic designs in underwater robotics, featuring diverse technologies inspired by marine creatures like fish, jellyfish, turtles, sea lions, and manta rays. Through a comprehensive table, it delineates innovative advancements, encompassing flexible fin ray structures, hydraulic actuators, dynamic algorithms, and a spectrum of technologies for charging systems, control systems, navigation algorithms, and sensors. These insights shed light on their potential applications for enhancing underwater propulsion, maneuverability, sensory capabilities, and overall autonomy. Crucially, the paper examines the limitations and challenges these designs may encounter, offering invaluable guidance for refining existing technologies and inspiring future developments in the realm of nature-inspired underwater robotics. This repository serves as a pivotal resource, guiding researchers and engineers toward the development of more efficient, adaptable, and nature-mimicking underwater vehicles, propelling advancements in this rapidly evolving field.

This study represents a significant contribution to the field of AUV technology, offering a coherently presented synthesis of crucial aspects in the realm AUVs. The following key contributions distinguish this study from existing studies.

- Holistic Integration: The study adeptly integrates various critical aspects of underwater robotics, including bionic-inspired models, control systems, navigation algorithms, charging systems, and sensors. This comprehensive approach allows for a nuanced understanding of the interconnected components of AUV technology.
- Cohesive Narrative: In contrast to many referenced papers that focus narrowly on specific facets, this study weaves together insights from diverse domains into a cohesive narrative. This approach provides a consolidated and accessible overview of advancements in underwater robotics, enhancing clarity and understanding.
- Guidance for Development: Going beyond singular insights, the study offers valuable guidance for researchers and engineers engaged in AUVs development. By integrating multiple critical domains, it provides a roadmap for a holistic and integrated approach, fostering a comprehensive understanding of AUV technology. This guidance is essential for navigating the complexities of designing and advancing AUVs in the rapidly evolving field of underwater robotics.

This paper on AUVs is structured into seven main sections, each delving into crucial aspects of AUV development and operation. The Introduction sets the stage by emphasizing the significance and challenges associated with AUVs, highlighting the necessity to delve into bionic-inspired models, control systems, and navigation models. The Bionic Models section traces the evolution of nature-inspired designs in AUV development, showcasing the progression from mimicking marine animal movements to the latest hybrid designs. It focuses on biomechanical aspects and unique features inspired by marine creatures, such as fish, dolphins, whales, and jellyfish, contributing to improved performance, maneuverability, and efficiency in underwater environments. The Charging System section delves into relevant charging and docking systems, highlighting recent improvements in the field of AUV charging. The Control System section explores effective control systems for AUVs, encompassing classical and modern approaches, including AI and machine learning. It addresses the challenges of underwater environments, enabling AUVs to adapt, optimize performance, and enhance decision-making capabilities. The Navigation Models section covers navigation capabilities, including sensor integration, SLAM, path planning, and obstacle avoidance, ensuring autonomous and intelligent AUV movement. The integration of various sensors and algorithms empowers AUVs to gather data, create maps, navigate autonomously, and avoid obstacles in the underwater environment. In essence, this research paper aims to offer readers a comprehensive understanding of the latest advancements in AUV technology, intending to inspire further research and development in this dynamic field.

II. BIONIC MODELS

The evolution of bionic models in AUVs has been driven by a desire to improve the performance and capabilities of these vehicles [18]. In this section, a brief overview of the major stages of the evolution of bionic models is discussed.

A. STAGES OF EVOLUTION

In the early days of AUV design, engineers looked to marine animals such as fish, dolphins, and whales for inspiration. The goal was to create AUVs that could move efficiently and maneuver effectively in the water. These early AUVs were often simple in design, using basic propellers and fins to move through the water [19]. For instance, in [20] a biomimicry model is developed using stingrays as its incitement. Similarly, in [21], authors took inspiration from Leptocephalus (Eel Larva) for its soft robot model. Furthermore, a jet propulsion model mimicking a scallop is developed in [22].

As AUV technology advanced, sensors and control systems were added to enhance the vehicle's ability to navigate and collect data [7]. These systems allowed AUVs to autonomously navigate through underwater environments, avoid obstacles, and collect data using a variety of sensors such as acoustic altimeter used in [23], Pressure sensor in [24], Long baseline (LBL) acoustic positioning sensor in [25], Inclinometer in [26], Magnetic compass in [27], True North-Seeking Three-Axis Gyrocompasses in [28] and Two-axis and three-axis magnetic sensors in [7].

The next step in the evolution of AUVs was the incorporation of artificial intelligence (AI) and machine learning (ML) algorithms. For example, an AUV could use machine learning to adjust its path based on the presence of underwater obstacles or changes in water currents [29]. The application of artificial intelligence techniques for fault diagnostics of AUVs is presented in [30], Furthermore, Object Detection and Tracking for a Small Underwater Robot is proposed in [31], Moreover, different advanced applications using neural networks for underwater water robots are illustrated in [32].

The latest evolution of AUVs involves the integration of multiple bionic models and advanced technologies. For example, an AUV may use a combination of fish and jellyfish-inspired designs and AI and ML algorithms to create a highly efficient and adaptable vehicle. These hybrid bionic models can perform complex tasks such as underwater exploration, ocean mapping, and environmental monitoring mentioned in [33].

B. BIONIC INSPIRED MODELS

Several bionic models have inspired the design of AUVs, including:

FIGURE 2. **Manta ray robot.**

1) BIOLOGICAL FISH MODELS

AUVs designed after biological fish models mimic the undulating movement of fish tails or fins for propulsion. These biomimetic underwater robots not only emulate the elegance of manta rays' swimming but also capitalize on their intricate wing-like structures and cutting-edge control mechanisms. By harnessing nature's design, these robots excel in maneuverability, making them invaluable for diverse aquatic missions, ranging from marine research to underwater surveillance, while minimizing disruption to delicate ecosystems Fig. 2 represents a manta ray robot and a biomimetic underwater robot designed to mimic the graceful swimming motion of manta rays, enabling efficient and agile underwater exploration and data collection. It utilizes its wing-like structures and advanced control systems to navigate through water and perform tasks in various aquatic environments. In the context of biomimetic underwater robots inspired by fish models, an equation relating to the geometry of the model can focus on the lift coefficient (C_L), which quantifies the lift generated by the wing-like structures. One such equation is

$$C_L = \frac{2.\pi.\alpha}{1+\sqrt{\left(\frac{\alpha}{\beta}\right)^2}} \tag{1}$$

where, α represents the angle of attack of the wing-like structure and β denotes the aspect ratio of the wing-like structure. This equation underscores the significance of optimizing the geometry of biomimetic designs, like those mimicking the elegant swimming motion of manta rays depicted in Fig. 2, in achieving efficient and agile underwater exploration while minimizing disruption to delicate ecosystems [34].

2) OCTOPUS MODELS

Octopuses are known for their remarkable underwater abilities, exceptional maneuverability, and ability to manipulate objects with their flexible arms. In the domain of biomimetic robotics inspired by the remarkable abilities of octopuses, an equation relevant to the provided description can focus on the bending behavior of soft-bodied robotic arms. A relevant

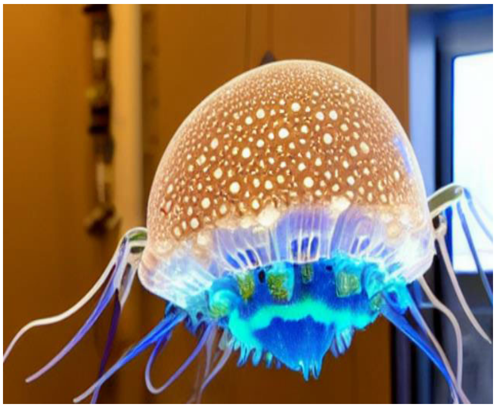


FIGURE 3. Jellyfish model robot.

FIGURE 4. Sea turtle model.

equation, stemming from the Euler-Bernoulli beam theory, delineates the deflection (δ) of a beam under a distributed load (q), expressed as,

$$\delta = \frac{q.L^4}{8EI} \tag{2}$$

where, L represents the length of the beam, E denotes the material's modulus of elasticity (such as the flexible silicone structure), and I signifies the cross-sectional area moment of inertia. Researchers have been inspired by these characteristics and have developed underwater robots that mimic the movements and functionality of octopuses. It is a soft-bodied robotic arm designed by the German Aerospace Center (DLR). The Octopus Gripper consists of a flexible silicone structure that can bend and adapt to different objects, just like an octopus arm. The gripper is equipped with suction cups that can adhere to various surfaces, enabling the robot to grasp and manipulate objects underwater [35]. Similarly, an octopus-bioinspired solution to movement and manipulation for soft robotics was proposed in [36]. Furthermore, another octopus model has been suggested for locomotion and grasping in water [37].

3) JELLYFISH MODELS

Underwater robots inspired by jellyfish, such as Robojelly developed by Virginia Tech and the University of Texas at Dallas, JEROS from the National University of Singapore, and Cyro created at Harvard University, mimic the efficient swimming mechanisms of these creatures. These robots utilize materials like silicone and electroactive polymers, incorporating features such as shape memory alloy actuators, artificial muscles, and embedded sensors. By replicating the propulsion and movement of jellyfish, these robots offer energy-efficient and maneuverable swimming capabilities. They find applications in marine exploration, environmental monitoring, and underwater tasks [38]. Fig. 3 represents a jellyfish model robot inspired by the elegant movements of jellyfish [39]. Another jellyfish-inspired robot has been developed driven by fluid electrode dielectric organic robot actuators [40].

4) LOBSTER MODELS

Lobsters are known for their excellent sensory perception and ability to navigate through complex underwater environments. AUVs modeled after lobsters have sensors and navigation systems that mimic the abilities of the crustacean [38].

5) SEA TURTLE MODELS

Sea turtles serve as an exemplary model for designing efficient underwater vehicles, as demonstrated in Figure 4, where AUVs emulate their streamlined shell-like structure and flippers for agile and precise movements in the water [41]. This bio-inspired approach not only enhances the AUVs' hydrodynamic performance but also facilitates their ability to navigate through complex underwater environments with ease. In contrast, [42] introduces a novel concept of a bio-inspired variable-stiffness morphing limb for amphibious robot locomotion. This innovation aims to emulate the adaptability and versatility of biological limbs, enabling amphibious robots to navigate both land and water environments efficiently. By mimicking nature's designs, these advancements in AUV and robot locomotion contribute to the development of highly capable and adaptable autonomous systems for various underwater and amphibious applications.

These bionic models are often combined with advanced technologies such as artificial intelligence, machine learning, and computer vision to create AUVs that can autonomously navigate, collect data, and perform specific tasks underwater [43].

Table 2 presents a comprehensive overview of various developments and technologies in underwater robotics inspired by different marine creatures. It outlines specific advancements, technologies used, the objectives behind each development, as well as potential disadvantages or limitations associated with these innovative designs. Each entry in the table focuses on a unique biomimetic robot or AUV, describing its technology, its intended purpose or objective, and the potential drawbacks or limitations that might affect its operational efficiency.

TABLE 2. Discussion on bionic models.

Development	Technology and Methodology	Objective	Disadvantages	References
Yellowfin Tuna	- Tunabot Flex using Actuation mechanism Theory.	- Leveraging the unique features of yellowfin tuna for biomimicry. - Aims to close the performance gap between robotic and biological systems.	- The design may not be well-suited for operations in shallow water. - Flexible fins could be damaged by obstacles or debris near the seabed.	[44]
Pangasius fish Hybrid Robot	- The robot employs a flexible fin ray tail structure. This structure serves as the soft body of the robot. - Driven by a servo motor. Motion Generation: Provides motion to the caudal fin of the fish-inspired robot.	- Develop a robot that mimics the motion of a fish using a flexible fin ray tail structure. - Achieve soft and flexible movement resembling the natural motion of fishtails.	- May be less efficient at generating forward thrust compared to other propulsion systems. - Undulating motion of the fins may create more turbulence and drag in the water.	[45]
HABH jellyfish	- Hydraulic actuators selected for higher forces and speeds. - Hydrogels chosen for flexibility and high water content.	- Aim to make the underwater robot transparent under broad acoustic detection, enhancing stealth during operations. - Specifically targets acoustic detection within the 10 kHz to 1 MHz range.	- Controlling the hydraulic system and tentacle movements requires sophisticated algorithms. - Hydrogel tentacles may experience wear and tear, reducing efficiency and lifespan. - Regular maintenance is essential to address wear-related issues and ensure optimal performance.	[46]
Macroscale Flagellated UUV	- Utilizes rotary actuation for soft body movement. - Incorporates soft materials, leveraging the fin ray effect for body and tail undulation.	- Aims to navigate and maneuver effectively in slender and narrow underwater spaces. -Seeks to mimic the natural body and tail undulation of fish for optimal maneuverability.	- Very sensitive to vibrations, which may affect the stability and precision of the robot posing challenges in maintaining stability during operation. - The soft materials and rotary actuation may be prone to mechanical wear over time, potentially affecting the longevity and reliability of the robotic system.	[47]
Similarity Evaluation and Biomimicry Manta Ray Robot	- Utilizes the Dynamic Time Warping (DTW) algorithm while introducing bias equations and time asymmetry coefficients. - Characterizes the time and space asymmetry of the pectoral fin motion of a manta ray.	- The central goal is to optimize the motion posture of the Manta Ray Robot and Seeking to replicate the nuanced and asymmetrical motion observed in the pectoral fins of a manta ray. - Aim to enhance the overall motion dynamics and efficiency of the Manta Ray Robot by incorporating bio-inspired asymmetry.	- Heavy computational burden requiring significant computational resources to find the optimal time alignment path. - The algorithm's complexity may lead to extended processing times, potentially affecting real-time applications.	[48]

TABLE 2. *(Continued.)* **Discussion on bionic models.**

Piezoelectric pulsed-jet actuator for developing a jellyfish-like structure	- Utilizes six Piezoelectric Pulsed-Jet Actuators (PJAs). - PJAs arranged crosswise to form a miniature cross-shaped underwater robot.	- Primarily designed for exploring, mapping, and sampling narrow areas of the deep sea.	- Frequency Response: Exhibits variability in the velocity-frequency response, especially concerning different frequencies and angles. - Achieving consistent and predictable performance may require sophisticated control algorithms due to the variability in response.	[49]
Turtle-inspired Robot with Variable Stiffness Hydrofoils	- Driven by two variable stiffness hydrofoils for thrust. - Employs two soft hind hydrofoils for controlling movement direction.	- Aims to achieve efficient fast swimming. - Designed for high spatial maneuverability, allowing precise control over movement.	- The design and structure of turtle-inspired robots with variable stiffness hydrofoils may limit their ability to carry heavy payloads or equipment. - In applications requiring the transport or deployment of instruments or sensors, the payload limitations may hinder the effectiveness of the robotic sea turtle. - The design's constraints may make it less versatile for tasks requiring substantial payload capacities.	[50]
Pectoral fins and gliding Manta-Ray robot	- Utilizes a system for adjusting buoyancy and mass. - Implements the NACA00 series airfoils as the basic airfoils. - Employs a two-dimensional airfoil optimization system.	- Flexibility and Long-Range Gliding Propulsion which aims to achieve flexibility and long-range gliding propulsion, is inspired by the Manta ray. - Designed for dynamic adjustments in buoyancy and mass for optimal gliding.	- The maneuverability and stability of the gliding propulsion are not up to the mark yet. - Challenges in achieving the desired levels of maneuverability and stability may impact overall performance - Further optimization and refinement may be necessary to meet desired standards of gliding efficiency.	[51]
Sea lion Robot	- Incorporates flippers inspired by the biomechanics of Otariidae. - Utilizes a serial mechanism consisting of a wobbling coin mechanism and an RSSR spatial crank-rocker mechanism.	- Aims to mimic the propulsion mechanisms observed in Otariidae for enhanced underwater movement. - Draws inspiration from the natural locomotion of Otariidae to improve the robotic system's propulsion efficiency.	- May be difficult to maintain due to the complexity of the serial mechanism and the bionic flippers. - The intricate nature of the serial mechanism could be prone to wear and tear over time, potentially affecting reliability. - Maintenance might require specialized knowledge due to the unique design, potentially limiting accessibility for repairs.	[52]

C. RECENT DEVELOPMENTS IN BIONIC MODELS

The mechanical mechanisms that have evolved in aquatic organisms are extremely effective in light of each species' habitat and way of life thanks to natural selection. The ability to move faster than artificial propeller-propelled vehicles has evolved in animals like dolphins and fish. Since the release of the first bionic fish in the world, ROBOTUNA, in 1994, researchers have studied bionic robotic fish in great detail. To further improve the stability, mobility, and bio-affinity of robots, the development of underwater vehicles using bionic means has become an international scientific research hotspot [53].

A basic issue that needs to be resolved is how to control the Movement of the pectoral and caudal fins to attain superior locomotor capabilities. A range of robots resembling manta rays' anatomy and movement has emerged. A novel vehicle that combines gliding and flapping propulsion inspired by a manta ray is presented in this article.

The geometric relationship of the design parameters of the undulating fin can be expressed by the equations

$$R = \frac{(d.L_1)}{(L_2 - L_1)} \tag{3}$$

$$\propto = \frac{(L_2 - L_1)}{(R_2 - R_1)} \tag{4}$$

$$d = R_2 - R_1 \tag{5}$$

The parameters D, L_1, L_2, R_1, and R_2 are integral to defining the geometry of the undulating fin. D represents the disparity between the radii of the inner and outer arcs of the fin, while L_1 and L_2 denote the lengths of the inner and outer arcs, respectively. R_1 and R_2 correspond to the radii of the inner and outer arcs. These parameters play a crucial role in describing the fin's shape both before and after it undergoes straightening, facilitating the understanding of its geometric transformations and ensuring the accurate representation of its design characteristics.

Furthermore, the current development of manta ray robots is usually based on functional bionics, and there is a lack of bionic research to enhance the similarity of motion posture. A similarity evaluation rule is constructed by a Dynamic Time Warping (DTW) algorithm to guide the optimization of the control parameters of a manta robot. The experimental results indicate that the similarity between the forward motion of the optimized robot and the original one has been analyzed and improved to 88.53% [54].

Alongside, for aquaculture biofuel cleaning a spherical underwater robot has been proposed which is equipped with one thruster for the forward propulsion system, and one rudder for steering the robot. Suckermouth Catfish inspired the conceptual designs of this underwater robot. The finite element analysis is implemented in the robot structure to test the structure mass properties and the fluid flow. Analysis shows satisfactory results, where the triangular shape produces a low coefficient of friction [55].

Finally, a robot inspired by the motion principle of jellyfish has been developed for deep-sea exploration. A novel piezoelectric pulsed-jet actuator (PJA) is used as the power source. Six PJAs were arranged to form an anti-hydro pressure miniature cross-shaped robot (CSUR) [56].

III. CHARGING SYSTEMS FOR UNDERWATER VEHICLES

AUVs' endurance is limited by onboard energy storage, primarily battery systems. To increase their range and autonomy, various underwater recharging methods are employed. Contact-based underwater recharging uses wet-mate connector technology, which requires high-precision docking and is susceptible to electrical safety issues. Wireless underwater charging techniques have been developed to overcome these constraints. AUVs require regular recharge, which can be done during operation or downtime, or by swapping batteries. Other methods include using environmental energy sources like solar, tidal, wave, geothermal, and wind energy. However, this advancement introduces new challenges, such as docking station construction, lowering to the seafloor, stabilization, establishing and maintaining connections during charging, and homing to a stationary charger [57], [58].

A. OVERVIEW OF AUV SWAPPING AND CHARGING SYSTEMS

1) BATTERY SWAPPING

Battery swapping is a common method for AUVs when surfaced, but it requires high downtime and requires a supporting vessel and crew. Such as in [57] Bluefin offers a battery swapping option with a mission turnaround time of less than 30 minutes, but the total surfacing, battery swapping, and descending time constitute 20% of the total operation time per AUV cycle [59].

2) SOLAR CHARGING

Solar charging provides an AUV with virtually unlimited endurance, but the AUV must surface during the day to harvest solar energy and store it in onboard batteries. For example, the SAUVI in [60], one of the first solar-powered AUVs, is a lightweight (90kg) system with two 30-W solar panels, 32 Ni-Cad cells (eight in series), and a charging controller. The second generation SAUV II as shown in Fig. 5 is intended for long-duration monitoring, surveillance, and station-keeping missions. It has 1m2 of solar panels on the roof and a 32 V, 2 kWh energy system. The solar power generated by underwater vehicles can be determined using the equation

$$P_{solar} = \eta_{solar}.A_{solar}.I_{solar} \tag{6}$$

where, P_{solar} represents solar power, η_{solar} denotes the efficiency of the solar panels, A_{solar} signifies the surface area of the solar panels, and I_{solar} represents the solar irradiance, which is the solar energy received per unit area. This equation encapsulates the relationship between these variables, providing insight into the solar charging capabilities

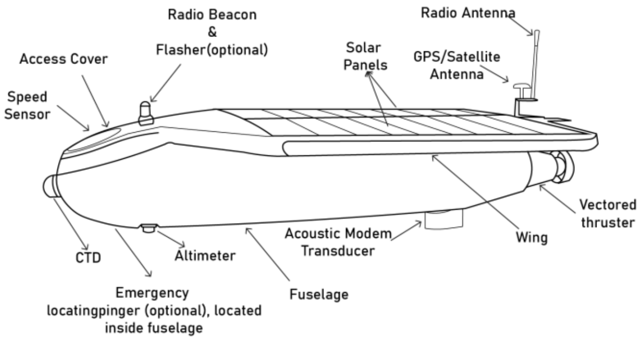


FIGURE 5. SAUV II [60].

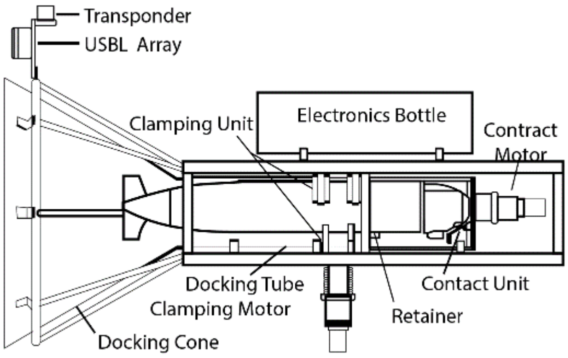


FIGURE 6. REMUS docking station [63].

of underwater vehicles. The requirement for the supporting vessel and human personnel to recharge or swap the battery and retrieve the AUV data reduces autonomy and raises mission costs. This constraint prompted the development of submerged recharging systems [61].

3) SUBMERGED (DOCK-BASED) RECHARGING SYSTEMS

A submerged recharging system is an underwater platform that allows for autonomous docking, battery recharging, and data transfer for an AUV. The platform consists primarily of a docking station that houses batteries, navigation, power, and data transfer systems. The docking station is required to keep the AUV stable across crosscurrents during power and data transfer. It can be supported by the seabed, a ship on the surface, or a buoy-supported mooring system. To approach the docking station for charging, the AUV requires a navigation system [62]. This section provides a brief overview of various docking mechanisms and homing systems.

The funnel-type docking station is the most popular docking structure as it provides a protective garage around an AUV and requires no additional hardware modifications on the AUV. This concept is implemented in REMUS docking stations in [63] and EURODOCKER [64]. Fig. 6 represents the REMUS docking station, which has an entry cone and the docking tube where the AUV is clamped down. The charging and data transfer is initiated via contact driven against the vehicle by a motor unit [64].

The Woods Hole Oceanographic Institution (WHOI), Woods Hole, Massachusetts, United States, developed a docking system for Odyssey class AUVs that uses deep-sea moorings that are supported as mentioned in [66]. The moorings support the AUV's massive battery, electronics, and docking system cables for data and power. The AUV is guided by the V-shaped latch to the docking pole, where the AUV is clamped by the carriage before the power transfer is initiated.

The MARINEBIRD mentioned in [67] is an experimental AUV with an underwater docking-based "landing-on-base" concept. The docking procedure is similar to landing an aircraft on the base. When the AUV approaches the base, hooks of the two catching arms drag it, holding the AUV firmly. The vehicle moves downward to latch the connectors and completes the docking process. The AUV's battery is then charged through an inductive coupler mechanism.

Researchers at Michigan Technological University in Houghton, Michigan, USA, created ROUGHIE, an underwater glider that can wirelessly charge from another AUV underwater, as mentioned in [68]. The glider is a functional robot, whereas the AUV serves as an energy carrier. The two vehicles are forced together using the wings as guides. The switchable magnet will be turned on by the glider after a successful capture so that the coupling can become rigid before the power transfer happens. The equation related to the wireless charging process between ROUGHIE, and the AUV acting as an energy carrier involves the power transfer efficiency (η_{transfer}), the distance between the vehicles (d), and the transmitted power ($\text{P}_{\text{transmitted}}$). It can be expressed as,

$$P_{recieved} = \eta_{transfer} . f(d) \tag{7}$$

where, $P_{received}$ is the power received by ROUGHIE and $f(d)$ represents the dependence of power transfer on the distance between the vehicles, encompassing factors such as electromagnetic field strength and attenuation.

4) HOMING SYSTEM

An AUV needs a homing navigation system to find a docking station. The homing system, which directs the AUV to the docking station, is essential for the autonomous charging of an AUV. Power transfer to the AUV begins once the homing and docking process is complete. The equation related to the homing navigation system for an AUV, crucial for directing it to a docking station for autonomous charging, involves the determination of the AUV's position relative to the known position of the docking station. This can be achieved through methods such as triangulation, as utilized in ultrashort baseline (USBL) or short baseline (SBL) systems, or dead reckoning (DR) systems. Letting P_{dock} represents the position of the docking station and P_{AUV} denote the estimated position of the AUV, the equation is,

$$P_{dock} = P_{AUV} + \Delta P \tag{8}$$

Expresses the displacement vector ΔP necessary for the AUV to navigate towards the docking station once the homing process is complete, facilitating autonomous charging. Ultrashort baseline (USBL), short baseline (SBL), and dead reckoning (DR) systems are examples of common homecoming systems [69]. The majority of AUVs use DR to find the closest docking station. Since USBL is extremely accurate to a range of one meter, it is used close to the docking station. Additionally, some AUVs employ optical and electromagnetic homing systems [70]. A review of navigation systems for AUVs is presented in [71]. Two methods of transferring power underwater are through direct electrical contact (DEC) and the WPT method.

5) DEC CHARGING METHOD

DEC charging is a popular underwater charging method. Establishing a secure electric connection underwater is a challenging task due to the high conductivity of salt water, biofouling, and the complexity involved in connection mechanisms. Underwater power connectors known as wet-mate connectors require high-precision mating [72]. The equation is as follows:

$$R_{connection} = f(\sigma_{water}, B_{fouling}, \varepsilon_{mating}) \tag{9}$$

Encapsulates the challenges of establishing reliable electric connections underwater with wet-mate connectors. It integrates factors such as saltwater conductivity (σ_{water}), biofouling ($B_{fouling}$), and mating precision (ϵ_{mating}), highlighting the intricate nature of underwater charging systems. Underwater wired (conductive) power delivery to an AUV is a technical challenge since the use of wet-mate connectors is discussed in [73] which requires high precision alignment, and it makes the system prone to failure due to biofouling and corrosion.

B. WPT METHODS FOR UNDERWATER APPLICATION

S

1) RADIATIVE WPT

Far-field WPT, also referred to as radiative WPT, includes power transfer techniques that make use of microwaves or laser beams. Microwave power transfer over long distances of up to a few meters is possible with a frequency range of 300 MHz to 300 GHz. When an experimental helicopter was powered wirelessly in the 1960s by Brown mentioned in [74] made the first demonstration of microwave power transfer. An energy-radiating antenna and a rectenna, which transform microwave power into direct current power, make up the microwave WPT system. The *RNF* region falls between the reactive near- and far-field regions of the transmitting antenna calculated from the formula as follows:

$$0.62\sqrt{\frac{D^3}{\lambda}} < RNF < \sqrt{\frac{2D^2}{\lambda}} \tag{10}$$

where, D is the longest dimension of the transmitting antenna and λ is the wavelength at 1900 MHz. Due to the attenuation provided by seawater at high frequencies, radio waves cannot be used in underwater applications, and the few attempts to implement radiative WPT in underwater applications to date have yielded inefficient systems [75], [76].

2) NONRADIATIVE WPT

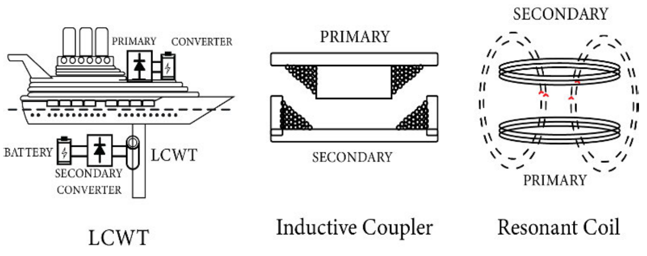
The primary drawback of radiative systems is that they are more susceptible to medium losses brought on by signal attenuation. Capacitive and inductive power transfer techniques are among the non-radiative WPT methods. These techniques have a maximum distance for power transfer through electric and magnetic fields of a few tens of centimeters. According to experiments highlighted in [76] and [77], a capacitive WPT (CWPT) system consists of submerged insulated electrodes spaced apart by a water medium and transfers power using high-frequency electric fields.

3) INDUCTIVE WPT

Nikola Tesla designed the IWPT system that used electromagnetic resonance in the 19th century [78]. He used resonance to produce higher voltages for wirelessly transmitting power over long distances. Even though some of his experiments weren't completed, they served as a starting point for subsequent work in the WPT field [79]. In the realm of inductive wireless power transfer (IWPT), the power transfer efficiency (η) can be encapsulated by the equation (11).

$$\eta = \frac{k^2.Q}{k + R_t + R_r} \tag{11}$$

where, k represents the coupling coefficient between transmitter and receiver coils, Q denotes the quality factor of the coils, and R_t and ${}_r$ signify the equivalent resistances of the transmitter and receiver coils, respectively. This equation offers a nuanced understanding of IWPT efficiency, considering factors such as coil geometry, coupling efficiency, and impedance matching. It underscores the complexity involved in optimizing power transfer efficiency and highlights the significance of coil design and system parameters in achieving efficient wireless charging, thereby emphasizing the advancements in IWPT technology discussed in the paragraph. In the last ten years, emerging wireless charging technology has spread, offering mature solutions for recharging a variety of devices with power ranging from microwatts to hundreds of kilowatts [80]. IWPT systems in the kW range that produce less than 10% of the loss are commonplace today. IWPT is currently employed commercially to charge EVs (electric vehicles), electronic devices, and biomedical systems. Safety, convenience, dependability, and a fully automated charging process are benefits of wireless charging [81]. High levels of misalignment between the two coils are permitted by IWPT and still result in effective power transfer. IWPT has been used to recharge AUVs mentioned in [82] and [83], ships mentioned in [84], underwater robotics mentioned in [85] and [86], and underwater sensors in [87] while they are submerged. IWPT eliminates DECs, biofouling-related issues, the possibility of leakage currents, and corrosion in saline



LCWT Inductive Coupler Resonant Coil

FIGURE 7. Illustration of LCWT, inductive coupler, and Resonant coils. [87].

environments. IWPT systems increase the AUV's energy autonomy, reducing the need for personnel and support vessels and lowering operational costs. Governments, businesses, and top research institutions have put a lot of effort into creating standards for IWPT in the air. These standards offer design specifications for IWPT systems that cover many different factors, such as power levels, operating frequencies, and shielding, primary and secondary designs. Application-specific SAE J2954 Technical Informational Report [88] is designed for EV charging. For aligned magnetic pads, SAE J2954 specifies power levels of 3.7, 7.7, 11.1, and 22 kVA operating at frequencies between 81.38 and 90 kHz and calls for a minimum efficiency of 85%. Commercially available standards for low-power IWPT applications in the air have been created by the Wireless Power Consortium (Qi standard) and the AirFuel Alliance (AirFuel Resonant and AirFuel RF) as shown in Figure 7 [89]. By standardizing the operating frequency from the industrial, scientific, andmedical bands to 6.78 MHz, the AirFuel Resonant. However, due to the significant attenuation that seawater provides to high-frequency signals, these standards are only applicable for in-air WPT and cannot be used directly in maritime applications.

Table 3 presents various technological developments in the realm of wireless power transfer (WPT) systems tailored for underwater vehicles (AUVs and UUVs). Each development aims to address specific objectives such as minimizing susceptibility to electromagnetic interference, enhancing energy efficiency, achieving stable output despite misalignments, and ensuring robustness in underwater conditions. However, each technology also comes with its set of disadvantages and challenges. For instance, implementations like the Fe-based Nanocrystalline Soft Magnetic Material and Direct-Quadrature Transmitter and Dipole Receiver offer improved efficiency and stability but may face issues such as susceptibility to external magnetic fields or higher power consumption. Meanwhile, developments like the Finite Element Analysis (FEA)-Based Coupler and Distributed Ferrite Cores focus on minimizing leakage magnetic fields and reducing electromagnetic interference but may encounter challenges in maintaining alignment and consistent performance under varying environmental conditions. Despite these limitations, each technological approach represents a step forward in advancing wireless power transfer capabilities for underwater vehicles, contributing to the overall evolution of underwater technology.

C. RECENT DEVELOPMENTS IN CHARGING SYSTEMS FOR UNDERWATER VEHICLES

Considering the limitations of the annular magnetic coupler A Circumferential Coupled Dipole-Coil Magnetic Coupler has been developed using a dipole-coil-based magnetic coupler with a novel circumferential coupling manner where the Experimental results show that the system transfers 630W underwater with a DC-DC efficiency of 89.7% [90]. Alongside, a docking design, based on a funnel-type docking station, an acoustic and optical combination guiding method and a position locking mechanism, is presented to smoothly dock the AUV and eliminate the dynamic disturbance during the charging process. Then, a novel magnetic structure with an overlapped direct-quadrature transmitter and a dipole receiver is proposed. The two-layer transmitting windings, decoupling each other, form a constant amplitude traveling wave under the space-time coordination mechanism for suppressing output fluctuation with misalignments. Moreover, a practical wireless charging circuit, based on a current doubler, is developed, modeled, and analyzed. To verify the proposal an experimental model is also constructed [91].

Furthermore, an IPT system structure has been developed, and corresponding design techniques to increase misalignment tolerance. The series-series compensation method is used in the proposed IPT system, which also has a variable inductor on the secondary side. Based on the existing mathematical model, a general design approach is suggested. The worst-case scenarios, or the highest possible level of misalignment, are used to optimize the system parameters. Without any communication link to the primary side, the control strategy for VI is established. Finally, a 1 kW IPT system is set up with a tolerance range of k of 0.15–0.5 and a variable output voltage of 74–150 V. The experimental results demonstrate that the maximum system efficiency exceeds 96% for full power output, and the horizontal and vertical direction misalignment ranges reach 47% and +140%, respectively [92].

Moreover, a hull-compatible coil structure serving as the foundation for the design of an ultra-rapid inductive power transfer system has been developed. The design was simulated for an 80kW system that can charge a commercial AUV battery at 10C. Additionally, a scaled-down prototype is created, with its peak power in saltwater reaching 5.18kW at 96.8% efficiency. The system also exhibits high efficiency throughout the entire power range and excellent 360-degree rotational misalignment tolerance [93]. Alongside this, a Radially Coupled Wireless Charging System for Torpedo-Shaped AUVs has been developed. The geometry parameters of the mathematical model of the curly coils were optimized using genetic algorithms. The ferrite core layout was examined and optimized using ANSYS Maxwell.

In saltwater, a prototype of the AUV wireless charging system showed a maximum efficiency of 94% at 2.2 kW. The system's rotation adaptivity was also tested, and the results showed stable output performance within the AUV's potential roll-angle variations [94].

TABLE 3. Overview of the latest charging systems.

Technology	Development	Objective	Disadvantages	Reference
Fe-based Nanocrystalline Soft Magnetic Material	Implementation a dipole-coil-based magnetic coupler with circumferential coupling.	- Reduce susceptibility of AUV electronics to electromagnetic interference. - Enhance overall energy efficiency through optimized magnetic coupling.	- Susceptible to interference from external magnetic fields, potentially impacting AUV performance. - Limited scalability in power transmission efficiency.	[89]
Direct-Quadrature Transmitter and Dipole Receiver	Creation of a novel magnetic structure with overlapped direct quadrature and dipole elements.	- Achieve stable output despite rotational misalignment. - Implement adaptive modulation techniques for efficient power consumption.	- Higher power consumption compared to simpler modulation techniques. - Limited adaptability to dynamic underwater environments.	[90]
Cross-Type Magnetic Coupler	Implementing a UUV landing gear-based cross-type magnetic coupler.	- Attain high signal quality despite UUV fuselage imbalance. - Ensure ease of deployment and robustness in various underwater conditions.	- Faces challenges related to signal quality and potential signal loss. - Increased mechanical complexity.	[91]
Finite Element Analysis (FEA)-Based Coupler	Designing a 360° folded spatial unipolar coil adapting to the cylinder AUV body shape.	- Minimize leakage magnetic field and sustain good rotational misalignment tolerance. - Integrate self-adjusting mechanisms for real-time adaptation to environmental changes.	- May not offer well-aligned power along 360° rotation despite challenges. - Potential increased manufacturing complexity and cost.	[92]
Distributed Ferrite Cores	Employing a pair of radially coupled coils.	- Reduce axial electromagnetic interference. - Extend effective coupling range through adaptive tuning mechanisms.	- Limited effective coupling range compared to other methods. - Susceptibility to environmental conditions, affecting consistent performance.	[93]
Compact Dipole-Coil-Based Receiver	Designing a magnetic coupler with cross-coupling for stable three-dimensional alignment.	- Achieve strong coupling but with limitations in power handling. - Optimize design for modular scalability in power handling capabilities.	- Compact dipole-coil-based receivers may have limited power handling capabilities. - Challenges in maintaining optimal alignment over extended operational periods.	[94]
Full-Bridge LLC Resonant Circuit with Loosely Coupled Coil and Step-Down Circuit	Developing a 200W Wireless Power Transfer (WPT) charging system.	- Develop wireless charging technology for underwater vehicles. - Implement adaptive noise canceling techniques for interference mitigation.	- Susceptible to interference and noise, potentially impacting reliability. - Limited adaptability to varying charging distances and orientations.	[95]

A brand-new magnetic coupler (MC) with a cross-coupling mode has been developed. It has the advantages of being lightweight in the receiver and fit to the surface, and it supports stable and effective charging for AUVs. The proposed magnetic structure, which consists of an arc bipolar transmitter and a small, dipole-coil-based receiver, makes use of horizontal flux to create a strong, stable coupling against three-dimensional misalignment. The MC structure is built and optimized in accordance with the characteristics of the magnetic field distribution. Based on the ANSYS Maxwell simulation, with which the MC's parameters are optimized, it is possible to determine the impact of geometric parameters on the performance of the MC. An AUV wireless charging system circuit is also developed in order to fully verify the performance of the designed MC. A 600 g receiver is used to test a wireless charging system prototype, which can deliver 1 kW at 95.1% dc-to-dc efficiency. The proposed MC is viable and can be used for charging the AUVs, according to the experimental results under various operating conditions [95].

Finally, a 200W WPT charging system is implemented based on the full-bridge LLC resonant circuit combined with the loosely coupled coil and the step-down circuit. The experimental results have validated that the system is able to operate in an underwater environment with an efficiency of up to 90.17% in freshwater and 87.05% in seawater [96].

IV. CONTROL SYSTEMS FOR UUVS AND THEIR RECENT DEVELOPMENTS

One of the most crucial components of UUV control is the UUV depth control technology. For instance, when two UUVs are docking underwater, both UUVs must maintain a constant attitude at a specific depth [97], [98]. The UUV motion control has the following characteristics. First, UUVs generally work in complex marine environments with complex and changeable external disturbances, so they should have strong robustness. Then, the UUV model is quite complex, which makes the controller design more difficult. Finally, UUVs are not always equipped with a high-performance processor, which requires the controllers to have better real-time performance [99].

A. THE UNDERWATER VEHICLE CONTROL SYSTEM

1) PROPULSION CONTROL SYSTEM

The propulsion control system is a critical component of an underwater vehicle's control system, as it enables the vehicle to move through the water and change its speed and direction as needed. For example, a Conceptual design of a hybrid propulsion underwater robotic vehicle with different propulsion systems for ocean observations is developed in [100]. Moreover in [101] Performance Evaluation of a Novel Propulsion System for the Spherical Underwater Robot (SURIII) is analyzed. Furthermore, the Design and Control of an Underwater Robot Based on Hybrid Propulsion of Quadrotor and Bionic Undulating Fin is proposed in [102].

Fig. 8 shows a block diagram for a propulsion control system which includes several crucial parts that combine to produce propulsion and regulate the motion of the vehicle. The equation for the propulsion system of underwater robots is given by

$$F = \rho.A.V_2.C_T \tag{12}$$

where, F represents the thrust generated by the propulsion system in Newton's, ρ denotes the density of the water in kilograms per cubic meter, A stands for the swept area of the propeller in square meters, V_2 signifies the velocity of the water exiting the propeller in meters per second, and C_T represents the thrust coefficient of the propeller, dependent on its design and operating conditions. This equation serves to approximate the thrust produced by the propulsion system, grounded in fluid dynamics principles governing the interaction between the propeller and the surrounding water. The shaft mode, which contains the shaft that transmits the rotational motion from the propeller to the engine model, is further connected to the propeller mode. The propulsion system's power source, which is commonly a combustion engine or an electric motor that transforms fuel or electrical energy into mechanical energy to push the propeller, is represented by the engine model. Finally, the governor, connected to the engine model, regulates and controls the engine's speed and power output to ensure efficient operation and stability of the propulsion system. Together, these components form a comprehensive block diagram that orchestrates the functioning of an underwater vehicle's propulsion system [103].

2) NAVIGATION CONTROL SYSTEM

The most common sensors used in underwater vehicle navigation are sonar, GPS, and inertial navigation systems. Sonar is used to detect and map the surrounding environment, providing information about the water depth, seafloor topography, and the presence of obstacles. GPS can be used to provide a rough estimate of the vehicle's position, while an inertial navigation system uses accelerometers and gyroscopes to measure the vehicle's acceleration and rotation, allowing for precise determination of its position and orientation e navigation control system combines the data from these sensors to calculate the vehicle's position and orientation in real-time, allowing it to maintain a predetermined course or navigate to specific waypoints. This multi-sensor approach ensures both global positioning and localized awareness, enhancing the vehicle's capability to traverse complex underwater terrains with efficiency and precision. Fig. 9 demonstrates the combination of data from these sensors to calculate the vehicle's position and orientation in real-time, allowing it to maintain a predetermined course or navigate to specific waypoints [104]. An essential equation utilized in navigation control systems for underwater robots is the Proportional-Integral-Derivative (PID) controller equation, given by

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) + K_d \frac{d}{dt} e(t). \tag{13}$$

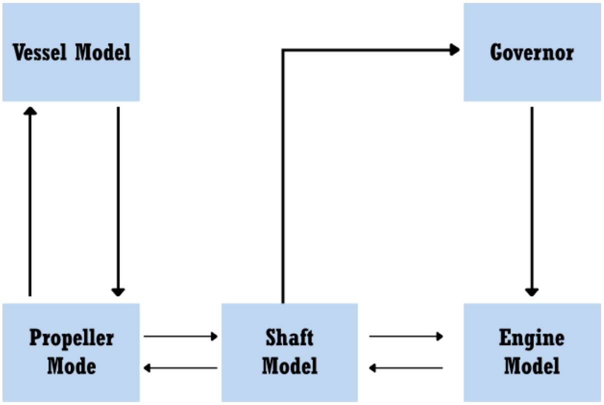


FIGURE 8. Propulsion control block diagram [103].

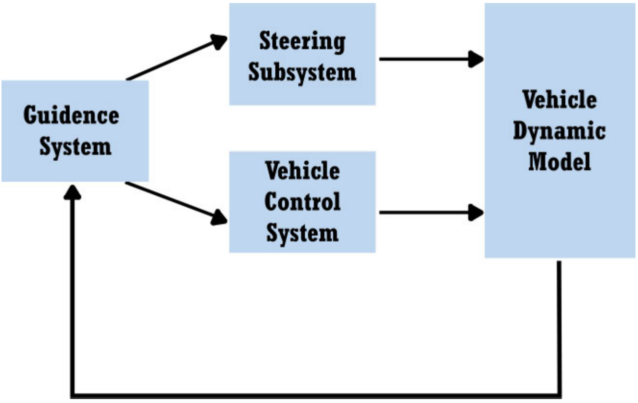


FIGURE 9. Navigation control system [105].

where, $u(t)$ denotes the control signal applied to the actuators at time t, while $e(t)$ represents the error signal, indicating the disparity between the desired and actual states. The terms K_P, K_i, and K_D are the proportional, integral, and derivative gains, respectively, determining the controller's response to the error. By adjusting the actuators based on this equation, the navigation control system enables precise maneuvering and orientation adjustments of the underwater robot to achieve its desired trajectory efficiently in various underwater environments. The navigation control system may also incorporate algorithms for path planning and obstacle avoidance, allowing the vehicle to navigate complex environments [105].

3) DEPTH CONTROL SYSTEM

This system maintains the depth of the underwater vehicle using depth sensors and ballast systems. Depth control is a very important research topic for aquatic robots. For example, when AUVs need to arrive at an area with a specified depth for more complex ocean tasks, it is crucial to achieve steady depth control. Besides, depth control is also an important part of navigation and path following. An equation fundamental to depth control systems for underwater robots is derived from buoyancy principles, relating the robot's depth to the net buoyant force (F_{buoy}) acting upon it. The equation incorporates parameters such as the density of water (ρ_{water}), gravitational acceleration (g), the volume of water displaced ($V_{displaced}$) by a robot, and a robot's mass (m).

$$F_{buoy} = \rho_{water} .g.V_{displaced} - mg \tag{14}$$

By adjusting the buoyant force, typically via adjustable ballast tanks or buoyancy control devices, the depth control system can effectively regulate the underwater robot's depth, enabling precise navigation and operation in various aquatic environments the traditional AUVs, the propellers equipped in vertical planes are usually used to generate the forces for diving or surfacing, which may cause environmental damage due to the noise [106]. In contrast, in [107] the underwater robot with a buoyancy control system based on the spermaceti oil hypothesis development of the depth control system is used for depth control. Similarly, in [108] Depth control of underwater robots is achieved using sliding modes and Gaussian process regression. Fig. 10 conveys the depth sensor control which includes the depth controller, Buoyancy system, and Depth controller [109].

4) ATTITUDE CONTROL SYSTEM

The altitude control system typically includes sensors that measure the depth or pressure of the water around the vehicle, as well as a ballast system that allows the vehicle to adjust its buoyancy. The ballast system can be adjusted by pumping water in or out of tanks, allowing the vehicle to change its weight and therefore its depth in the water. The altitude control system may also include feedback loops that monitor the vehicle's depth and adjust the ballast system accordingly to maintain a stable altitude. These feedback loops may incorporate sensors such as pressure gauges, accelerometers, or inclinometers to provide real-time data on the vehicle's position and orientation. The altitude control system must also take into account environmental factors such as water currents and temperature, which can affect the vehicle's buoyancy and stability. The system may need to adjust the ballast system in response to changing conditions to maintain a stable altitude [110]. Such an example is implemented in [111] where the altitude control is done through combined reinforcement learning with active disturbance rejection control.

5) COMMUNICATION AND TELEMETRY SYSTEM

The communication system typically includes acoustic modems, which use sound waves to transmit data through the water. These modems can transmit data at rates ranging from a few hundred bits per second to several megabits per second, depending on the modem's capabilities and the distance between the vehicle and the surface. The telemetry

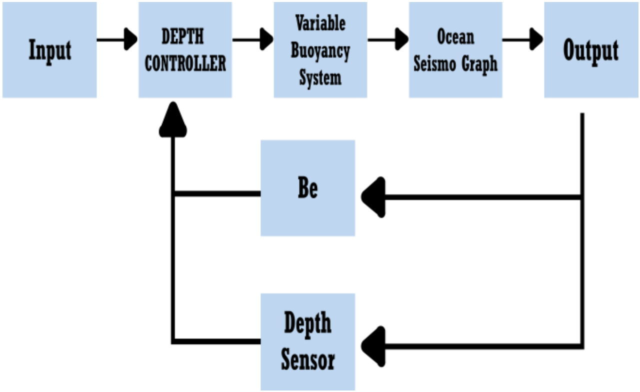


FIGURE 10. **Depth sensor control [109].**

system allows the vehicle to transmit data about its operation and environment to the surface, allowing operators to monitor the vehicle's performance and make adjustments as needed. This data can include information about the vehicle's depth, altitude, speed, and orientation, as well as data from sensors such as cameras, sonar, or other instruments [112]. Such an example can be found in [113] where the communication system for the underwater robot is developed, the Communication experiments with the robotic fish demonstrate the effectiveness of the developed electric current communication system.

B. THE LATEST CONTROL SYSTEMS

A controller design method for UUV depth control (VD-SIFLC) based on fractional calculus, fuzzy control, dynamic parameters, and a fast non-dominated sorting genetic algorithm (NSGA-II) has been proposed in [114]. Simulation results show that the controlled system with the VD-FIFLC could achieve better robustness and dynamic and steady-state performance

Table 4 shows different controllers used in AUVs with their technology development, the objective of each controller, and technology with the problems that the controllers may face. The table provides a summary of various control system developments for underwater robots, including the objectives, advantages, disadvantages, and references for each control method. Techniques range from fractional order control and machine vision systems to PID controllers and adaptive model predictive control, offering insights into diverse approaches for enhancing the performance and functionality of underwater robotic systems.

For locating animals of interest and extended visual observations a machine learning algorithm has been developed in [115] using a multi-object detector and a 3D stereo tracker which show constant input from the ML-Tracking algorithm to the vehicle controller throughout a 5+ Hour continuous observation of a siphonophore, a midwater gelatinous invertebrate.

Six-degree-of-freedom (6-DOF) hovering control is important for underwater robots to perform various tasks. A robot has been developed with tilting thrusters that improved its hovering performance. The stability of the hovering performance under tidal currents was demonstrated through disturbance experiments [116].

To achieve better mobility an underwater robot based on the hybrid propulsion of a quadrotor and undulating fin has been proposed and is controlled by hybrid Propulsion of a quadrotor [117]. In a further study, the hydrodynamic characteristics of the spherical robot are studied, and a model predictive of a control strategy based on these characteristics is proposed. When the current disturbance velocity was twice the robot's speed, the proposed strategy reduced the tracking error by 39% and 42% respectively [118].

A remotely operated underwater vehicle (ROV) is crucial in ocean exploration and underwater missions. Position control and movement of an ROV are not stable due to buoyancy, ocean currents, and surge waves. A novel switch proportional-integral controller combined with a buck-boost converter has been developed [119].

Finally, another paper proposes a synchronous navigation scheme for two BlueROV2 underwater vehicles for a coordinated multi-vehicle task. A model-free second-order sliding mode controller with finite-time convergence is used to accomplish this task. Simulation experiments were conducted to verify the controller's performance in the presence of high ocean currents [124].

V. MOST RECENT NAVIGATION ALGORITHMS

Due to the radio frequency signal's extreme attenuation and the energy-intensive nature of these systems, GPS-based solutions are not suitable for use in submerged situations. To lessen the radio frequency attenuation issue, the underwater nodes interact via acoustic signals to circumvent the attenuation issue that arises when utilizing radio frequency. The present underwater localization approaches take advantage of the spatiotemporal relationship between an unlocalized node and a small number of reference nodes in place of employing GPS to pinpoint the locations of the unlocalized nodes [125], [126].

Self-adaptive AUV-based Localization (SEAL) is designed to provide network-wide localization service to sensor nodes in sparsely deployed Underwater Sensor Networks (UWSN) using a high-speed AUV SEAL achieves significantly improved coverage while maintaining the energy efficiency of the AUV [127].

The designed adaptive noise canceller (ANC) represents a significant advancement in addressing the issue of noise interference from AUVs in towed array sensor systems [128]. By employing the partitioned fast block least-mean square adaptive algorithm, the ANC efficiently mitigates the radiated noise, resulting in improved sensor performance and enhanced navigation algorithm for the AUV.

TABLE 4. Overview of the latest control system.

Controller	Development	Objective	Disadvantage	Reference
Fractional Order Control	- UUV depth control (VD-SIFLC) and a fast non-dominated sorting genetic algorithm (NSGA-II). - Incorporates fractional-order control principles for enhanced system adaptability.	- Have good transient response and robustness under the premise of ensuring real-time performance. - Explore the benefits of fractional-order control in achieving improved UUV depth control.	- It has more parameters to tune than a classical PID. - It may lead to challenges in real-time parameter adjustment.	[113]
Machine Vision Systems (MVS)	- Multilevel system to control the movement of a multilink manipulator (MM). - Integration of advanced machine vision algorithms for real-time object detection.	- Dynamic positioning over various objects on the seafloor. - Enhance machine vision capabilities for more accurate and autonomous control.	- Need for regular monitoring. -Limited robustness in extreme lighting conditions may affect vision-based control.	[114]
Redundant Tilting Mechanism with PID Control	- Six-degree-of-freedom (DOF) hovering control. - Integration of redundant tilting mechanisms for improved stability.	- High accuracy determination of the shape and location of the work object relative to UUV. - Achieve robust hovering control through redundant mechanisms.	- Specific posture has to be maintained for underwater testing. - Redundant mechanisms may lead to increased system complexity and potential mechanical failures.	[115]
4-DOF Cascade PID Controller	- Stable, quiet, and efficient propulsion with high efficiency and high mobility at the same time. - Integration of cascaded PID control for precise coordination of propulsion systems.	- Underwater robot based on the hybrid propulsion of a quadrotor and undulating fin. - Optimize propulsion control for enhanced stability and maneuverability.	- It requires an additional measurement (usually flow rate) to work. - There is an additional controller that has to be tuned. - The control strategy is more complex. The added complexity may result in an increased likelihood of software bugs.	[116]
Adaptive Model Predictive Control (AMPC)	- Reducing tracking errors for a spherical underwater robot. - Incorporates adaptive model predictive control for improved trajectory tracking.	- Hydrodynamic control of the robot under static water and constant flow disturbance. - Enhance adaptive control strategies for improved trajectory following.	- Sensitive to parameter variation and all nonlinear parameters were not measurable. -Increased sensitivity may lead to tracking errors in the presence of uncertainties.	[117]
Proportional-Integral (PI) Controller with a Buck-Boost Converter (BBC)	- Six-axis ROV designed by an NI-roboRIO-based embedded system. - Integration of PI control with a buck-boost converter for improved energy efficiency.	- Hydrodynamic control of the robot under static water and constant flow disturbance. - Optimize energy efficiency through improved control and power management.	- The lower range of stability and no isolation from the input to the output side. -Limited stability may result in performance degradation during extreme conditions.	[118]

TABLE 4. ***(Continued.)*** **Overview of the latest control system.**

Relative-Position Output Feedback Consensus	- Swarm multiagent systems. - Development of advanced algorithms for consensus-based control among UUVs.	- Stability improvement of UUV. - Achieve consensus-based control for coordinated movements within a UUV swarm.	- Isn't reliable for the terrains it is not familiar with during programming. Limited adaptability may result in reduced performance in unfamiliar environments.	[119]
Gaussian Process (GP)	- Complex dynamics characterizing. - Integration of Gaussian Process for improved navigation strategies.	- Improvement in navigation by avoiding different obstacles by going over them. - Optimize navigation algorithms for obstacle avoidance using the Gaussian Process.	- They are not sparse and they lose efficiency in high-dimensional spaces namely when the number of features exceeds a few dozen. Limited efficiency may result in increased computational load.	[120]
Back Stepping Technique	- Improvement of path following for a quadcopter aircraft. - Application of back-stepping control technique for enhanced path following.	- Control of a Quadcopter with Uncertain Vehicle Mass, Moment of Inertia, and Disturbances. - Optimize path-following algorithms for improved quadcopter control.	- Applicability is limited to systems in strict feedback form, and an "explosion of terms" when operating with several levels of recursion. Increased complexity may result in challenges in real-time implementation.	[121]
Servo Compensator	- A robust output feedback Sliding Mode Control (SMC). - Integration of servo compensator for improved stability and control.	- Semi-global asymptotic stabilization of the internal state. - Achieve semi-global asymptotic stabilization through servo compensator.	- Needs additional controllers to improve stability and accuracy. - Increased complexity may result in challenges in real-time implementation.	[122]

This innovative solution ensures more accurate and reliable data acquisition, enabling AUVs to carry out complex underwater missions with reduced signal interference and enhanced operational efficiency [129].

Furthermore, the MAHKF algorithm introduces a novel approach by incorporating multiple fading factors, enabling it to adaptively adjust the Kalman filter parameters based on varying environmental conditions and uncertainties. The significant reduction in position errors by approximately 66.57%, 67.98%, and 64.51% showcases the algorithm's effectiveness in enhancing the localization accuracy of the UUV in all three spatial directions. These promising results demonstrate the potential of MAHKF as a robust and reliable solution for accurate navigation and localization tasks in challenging underwater environments [130].

Moreover, in scenarios where the AUV operates on the water's surface and benefits from the Global Positioning System (GPS) for position acquisition, a navigation strategy incorporating an adaptive fault-tolerance filter has been employed. This filtering approach effectively refines the GPS trajectory, enhancing accuracy. In contrast, when GPS data isn't available and the AUV operates underwater, the navigation system relies on the Variational Bayesian (VB) method. This technique serves to estimate the measurement error covariance of the Doppler Velocity Log (DVL), playing a pivotal role in optimizing navigation performance [131].

Finally, the kinematic stability of the motion of air–water trans–media vehicles (HAUVs) has been introduced and studied. The results show that the proposed criterion is effective in judging the vehicle's design, including the geometry and thruster power. The introduced criterion serves as a valuable tool to evaluate HAUV designs, ensuring their efficacy in navigating the intricate boundary between air and water ''Nezha'', a novel HAUV, was used as an example to demonstrate its stability [132].

VI. RECENT INTEGRATED SENSORS

The number of tactile sensors designed specifically for marine applications is still relatively small, although existing force/torque is potentially applicable to marine measurements. Marine mammals with tactile receptors can sense complex stimuli from organisms' motion. Tactile perception is the main way of perceiving the surrounding environment among most aquatic and semi-aquatic taxa, especially when hunting buried invertebrates or fishes. In light of that various sensors for underwater robots are being developed [135].

The self-powered triboelectric palm-like tactile sensor (TPTS) not only replicates the unique texture found in sea otter palms but also harnesses energy from surrounding movements to power itself, making it an energy-efficient and sustainable solution for underwater vehicles' tact Perceptual systems [136]. This innovative design not only enhances the UUVs' ability to interact with their environment but also reduces their reliance on external power sources.

As Kalman filter variants are widely used in underwater multi-sensor fusion applications for localization and navigation. An algorithm has been proposed where the RBF neural network is utilized to compensate for the lack of ESKF performance. Despite facing challenges such as high nonlinearity, modeling uncertainty, and external factors, our proposed method consistently delivers superior navigation and localization results [140].

Accurate sensor localization serves as a critical prerequisite for the successful deployment of underwater acoustic sensor networks (UASNs) [141]. In response to these challenges, researchers have developed an innovative solution: an AUV-aided localization approach for UASNs. This novel method leverages the AUV's capabilities to assist in accurate node positioning, enabling UASNs to overcome localization difficulties and optimize data acquisition for various underwater monitoring and research tasks.

Table 5 presents various algorithm developments for underwater systems, detailing their objectives, advantages, disadvantages, and references. These algorithms range from localization schemes utilizing self-adaptive AUV-based techniques to Doppler velocity log (DVL) implementations with deep learning frameworks. Each algorithm aims to enhance different aspects of underwater navigation, such as localization precision, noise cancellation, velocity estimation, and robust estimation in challenging environments. Alongside the possible limitation each system can face has been mentioned as well.

Moreover, the construction and testing of a part of the AUV body in the towing tank of the National Iranian Marine Laboratory represents a significant step forward in the development of underwater vehicles [141]. Through meticulous experimentation, the study demonstrates remarkable accuracy in measuring the axial velocity, with results showing an impressive precision of approximately 0.05m/s in the speed range of 0.5–4.5 m/s. This level of accuracy is crucial for optimizing AUV performance during various underwater missions, including navigation, data collection, and environmental monitoring, reinforcing the potential for enhanced efficiency and reliability in underwater vehicle operations. Such advancements in AUV design and testing contribute to the advancement of marine research, exploration, and applications across diverse underwater environments.

VII. DISCUSSION

In this section, a brief discussion of the aforementioned models and algorithms related to AUV is presented.

A. BIONIC MODELS

The evolution of bionic models in AUVs has significantly contributed to improving their performance and capabilities. By drawing inspiration from marine animals such as fish, dolphins, octopuses, jellyfish, lobsters, and sea turtles, engineers have developed AUVs that can move efficiently, maneuver effectively, and perform specific tasks underwater. These bionic models have been enhanced through the integration of advanced technologies like artificial intelligence, machine learning, and computer vision, enabling AUVs to autonomously navigate, collect data, and adapt to changing environments. The incorporation of bionic designs has led to the development of highly efficient and adaptable AUVs, expanding their potential applications in marine exploration, environmental monitoring, and underwater tasks.

1) BIOLOGICAL FISH MODELS

AUVs inspired by fish models mimic the undulating movement of fish tails or fins for propulsion. These models provide efficient and agile underwater exploration and data collection capabilities.

2) OCTOPUS MODELS

AUVs mimicking the movements and functionality of octopuses offer exceptional maneuverability and the ability to manipulate objects underwater. These models are characterized by flexible arms and adaptive gripping mechanisms.

3) JELLYFISH MODELS

AUVs inspired by jellyfish replicate the efficient swimming mechanisms of these creatures, utilizing materials like silicone, electroactive polymers, and shape memory alloy actuators. These models offer energy-efficient and maneuverable swimming capabilities.

4) LOBSTER MODELS

AUVs modeled after lobsters incorporate sensory perception and navigation systems inspired by the crustacean's abilities. These models enable effective navigation in complex underwater environments.

In conclusion, the evolution of bionic models in AUVs has been a promising area of research, with many innovative

TABLE 5. Analysis of the navigation models.

Algorithm	Development	Objective	Disadvantages	Reference
UWSN localization schemes	- Utilizes self-adaptive AUV-based localization techniques. - Incorporates advanced machine learning algorithms for real-time adaptation.	- Provide network-wide localization service to sensor nodes in sparsely deployed Underwater Sensor Networks. - Enhance localization precision through continuous learning from environmental dynamics.	- Prone to security issues like hacking due to the nature of wireless communication. - Challenges in dense and dynamic underwater environments affecting localization accuracy. - High energy consumption due to constant communication and computation. - Requires periodic recalibration to maintain accuracy under changing environmental conditions.	[126]
Partitioned fast block least-mean square adaptive algorithm	- Implements partitioned fast block least-mean-square adaptive algorithm. - Incorporates advanced signal processing techniques for noise cancellation.	- Mitigate AUV-radiated noise to improve the detection performance of a linear array towed by an AUV platform. - Achieve adaptability to varying noise patterns for enhanced noise cancellation.	- Challenges in highly variable noise environments, affecting adaptability. - Computational complexity increases with the size of the linear array. - Continuous adjustment of parameters may be required for optimal performance.	[127]
Doppler velocity log (DVL)	- Introduces BeamsNet, an end-to-end deep learning framework. - Implements novel training strategies for efficient deep learning.	- Estimate the DVL velocity vector for improved accuracy. - Enhance the framework's adaptability to diverse underwater conditions.	- Requires a large amount of labeled data. -Training and deploying deep learning models can be computationally intensive. -Regular model retraining may be necessary for accurate predictions.	[128]
H-infinite Kalman filtering algorithm	- Incorporates H-infinite Kalman filtering algorithm for UUV navigation. - Introduces advanced filtering strategies for robust estimation.	- Improve system robustness under extreme external environments and adapt to environmental change. - Optimize the filter for adaptability to varying environmental conditions.	- Possibility of unmolded deterministic disturbances. - Sensitive to sudden changes in environmental conditions. - Higher computational requirements compared to traditional Kalman filtering. - May exhibit reduced accuracy in complex underwater terrains.	[129]
Doppler velocity log (DVL)	- Proposes an adaptive navigation algorithm using deep learning.	- Improve measurement deviation of navigation sensors, especially MEMS sensors.	- Salinity and temperature affect calibration. - Reliance on deep learning introduces computational complexity.	[130]

TABLE 5. *(Continued.)* Analysis of the navigation models.

	- Implements novel training methodologies for improved learning.	- Enhance the adaptability of the algorithm to changing sensor characteristics.	- Limited interpretability of deep learning models. - May experience decreased accuracy in regions with extreme salinity variations.	
Huber loss function into the recursive least square method	- Incorporates Huber loss function into the recursive least square method. - Integrates advanced optimization techniques for robust control.	- Implement a robust identification algorithm to improve the control of the underwater robot's accuracy. - Optimize the algorithm for robust performance in challenging environments.	- Achieving robustness may increase computational complexity. - Challenges in tuning Huber loss function parameters. - May exhibit reduced performance in scenarios with rapid environmental changes.	[131]
INS/DVL integration system. With Variational Bayesian (VB) and Pressure sensors (PS)	- Develops an INS/DVL integration system with VB and Pressure sensors.	- Improve navigation accuracy for AUV.	- Lack of robust specific processors for optimal estimation. - Produces posterior distributions influenced by priors. - Increased computational complexity due to sensor integration and Bayesian methods. - May experience increased latency in processing sensor data.	[132]
Digital acoustic message	- Develops a tactical decision-aid framework for human decision-makers collaborating with AUVs. - Implements advanced decision-aid algorithms for dynamic decision-making.	- Improve navigation and reciprocal communication during under-ice missions. - Optimize the framework for real-time decision-making in complex environments.	- Requires higher bandwidth than usual. - Complexity in real-time decision-making due to decision-aid algorithm intricacies. - Potential challenges in adapting to rapidly changing environmental conditions. - May exhibit delays in decision-making under bandwidth constraints.	[133]

designs being developed that can perform complex tasks underwater. With the continued advancements in technology and the increasing demand for underwater exploration, the use of bionic models in AUVs will likely continue to play a significant role in the future of underwater robotics.

Each of these bionic models has been improved by using the latest innovations, allowing AUVs to complete difficult tasks independently of the latest innovations, allowing them to complete difficult tasks on their own. AUVs influenced by bionics are still being developed and researched, with an emphasis on enhancing stability, mobility, and bio-affinity. AUVs have a great deal of potential for a variety of underwater applications since they can use the biological mechanisms found in aquatic animals.

Dynamic temporal warping methods have been used in recent works to refine the control parameters of manta ray robots, enhancing their motion posture similarity, and obtaining superior locomotor capabilities. A spherical underwater robot for aquaculture and biofuel cleaning has also been developed as a result of conceptual designs inspired by suckermouth catfish, illustrating the viability of bionic methods in real-world contexts.

In conclusion, the evolution of bionic models in AUVs has been a promising area of research, with many innovative designs being developed that can perform complex tasks underwater. With the continued advancements in technology and the increasing demand for underwater exploration, the use of bionic models in AUVs will likely continue to play a significant role in the future of underwater robotics.

B. CONTROL SYSTEMS

The field of underwater robotics has seen tremendous growth in recent years, with UUVs being widely used for various applications, such as exploration, scientific research, and military operations. One of the most critical components of UUV control is depth control technology, which plays a vital role in maintaining a constant attitude at a specific depth while navigating complex marine environments.

Designing a depth control system for UUVs presents several challenges, such as strong external disturbances, complex UUV models, and real-time performance limitations. In this regard, the VD-SIFLC controller, based on fractional calculus, fuzzy control, dynamic parameters, and a fast non-dominated sorting genetic algorithm (NSGA-II), has been proposed, which achieved better robustness and dynamic and steady-state performance.

these characteristics was proposed, which reduced the tracking error significantly in the presence of high current disturbance velocity. Moreover, a synchronous navigation scheme for two BlueROV2 underwater vehicles was proposed using a model-free second-order sliding mode controller with finite-time convergence, which showed promising results in high ocean currents.

Lastly, remotely operated underwater vehicles (ROVs) are crucial in ocean exploration and underwater missions. However, maintaining stable position control and movement of ROVs is challenging due to various factors such as buoyancy, ocean currents, and surge waves. To overcome these challenges, a novel switch proportional-integral controller combined with a buck-boost converter

was developed.

In conclusion, the research conducted in the field of UUV control has led to significant advancements in underwater robotics technology. These research studies have addressed several challenges and proposed novel control strategies, improving the performance, robustness, and stability of UUVs in complex marine environments. These findings can contribute to the development of better UUV control systems, paving the way for more efficient and reliable underwater robotic operations in the future.

Furthermore, hovering control is crucial for UUVs to perform various tasks. The tilting thrusters-based underwater robot demonstrated stable hovering performance under tidal currents, improving its mobility. Additionally, a hybrid propulsion system based on a quadrotor and undulating fin has been proposed to achieve better mobility, and its control is based on hybrid propulsion.

C. CHARGING SYSTEM

The discussion of underwater charging systems for AUVs presented in the provided section highlights the critical challenges and recent developments in this field.

1) ENERGY AUTONOMY VS. CHARGING METHODS

The primary limitation of AUVs is their onboard energy storage, mainly relying on batteries. The discussion introduces various charging methods, including battery swapping, solar charging, submerged recharging systems, and wireless power transfer (WPT). Each method has its advantages and disadvantages, and the choice depends on factors like mission requirements, downtime tolerance, and operational costs. Battery swapping offers a quick turnaround but requires surface access and crew involvement, while solar charging provides near-unlimited endurance but relies on daylight hours. Submerged recharging systems and WPT methods offer autonomy without surfacing but come with the challenges of docking, homing, and power transfer.

2) DOCKING MECHANISMS

This section discusses several docking mechanisms, including funnel-type docking, deep-sea moorings, and innovative approaches like the ''landing-on-base'' concept. The choice of docking mechanism affects the efficiency and reliability of the charging process. For instance, the funnel-type docking station provides protection for AUVs during charging but may require modifications to the AUV itself. Understanding these mechanisms is crucial for the successful implementation of submerged recharging systems.

3) HOMING SYSTEMS

To enable autonomous charging, AUVs need homing systems to locate and approach the docking station accurately. This section mentions various methods like ultrashort baseline (USBL), short baseline (SBL), dead reckoning (DR), optical, and electromagnetic homing systems. The accuracy and reliability of these systems are vital for ensuring successful docking and charging. Advances in navigation technology play a crucial role in the effectiveness of underwater charging methods.

4) DIRECT ELECTRICAL CONTACT (DEC) CHARGING VS. WPT

This section compares DEC charging, which involves physical connectors, with WPT methods, which use wireless transmission of power. DEC charging is challenging due to

TABLE 6. Latest integrated sensors.

Sensor	Development	Objective	Disadvantages	Reference
Triboelectric Palm-like Tactile Sensor	- A tactile perceptual system for underwater vehicles. - Developed to have the ability to detect and distinguish normal and shear external load in real-time and approximate the external stimulation area.	- Achieve a tactile sensor system suitable for underwater vehicles. - Enable real-time detection and differentiation of external loads, enhancing environmental perception.	- Limited sensitivity and reliability in high-temperature environments, restricting its use in certain underwater conditions. - The tactile sensing mechanism may be prone to wear and tear, affecting long-term performance. Potential challenges in accurately distinguishing complex external loads due to the sensor's design.	[133]
LiDAR Camera and Inertial Measurement Unit	- Visual-based underwater positioning system. - Integration of a LiDAR camera and inertial measurement unit (IMU) to generate associated depth maps and offer information about altitudes.	- Develop an advanced positioning system for underwater applications. - Provide accurate depth maps and altitude information through sensor fusion.	- Susceptibility to inaccurate in-depth maps and altitude information if the system's components are not well-calibrated. - High power consumption, impacting the overall energy efficiency of the underwater vehicle. Dependence on clear visibility conditions for accurate LiDAR data acquisition.	[134]
3D-Laser Scanner with 2-Axis Mirror	- The first laser line scanner actively counteracts the refraction of the projected light in the context of underwater robotics. - Aim to prove that refraction-related distortions can practically be compensated for by using a 2-axis mirror, along with presenting a simple calibration algorithm.	- Mitigate refraction-related distortions in laser scanning for improved accuracy. - Demonstrate the effectiveness of compensating for refraction using a 2-axis mirror.	- Vulnerability to ambient light interference may limit its accuracy in certain lighting conditions. - Complex calibration process for compensating refraction-related distortions might require frequent adjustments. - Challenges in achieving consistent results across varying underwater environments.	[135]
Biaxial MEMS Mirror	- Designed to project optimally curved light shapes, transforming them into planes through the refraction process. - Aims to reduce the cost of a rotating mirror actuated by a galvanometer, producing accurate results with minimized distortions.	- Achieve cost reduction in mirror actuation for improved affordability. - Minimize distortions in projected light shapes for accurate results.	- High initial fabrication and assembly costs, potentially limiting scalability and widespread adoption. - Mechanical wear and tear of the MEMS mirror components may affect long-term reliability. - Limited versatility in projecting light shapes for certain applications.	[136]
Radial Basis Function (RBF) Neural Network with ESKF	- A multi-sensor fusion algorithm for underwater vehicles. - Developed to compensate for the lack of Extended Kalman Filter (ESKF) performance by improving the innovation error term.	- Enhance sensor fusion capabilities for improved estimation. - Minimize estimation mean square error (MSE) using the steepest descent optimization approach.	- Complexity in tuning the neural network due to the nonlinear nature of unit activation output characteristics. - Increased computational load during real-time operation, potentially impacting system responsiveness. - Potential instability in the network when adapting to dynamic underwater environments.	[137]
Water Velocity Sensor	- Development of a water velocity sensor for the estimation of sideslip angle. - Designed to measure surge and sway velocity for underwater vehicles.	- Create a specialized sensor for estimating sideslip angle in underwater vehicles.	- Limited suitability for environments with water intoxications or high pollution levels due to potential sensor contamination. - Susceptibility to fouling, which may affect accuracy over extended deployment periods. - Challenges in accurately estimating sideslip angle in turbulent water conditions.	[138]

issues like precision alignment, biofouling, and corrosion. On the other hand, WPT methods offer advantages like greater flexibility, reduced maintenance, and compatibility with underwater environments. The choice between these methods depends on the specific needs of the AUV and the operational conditions.

5) WPT METHODS FOR UNDERWATER APPLICATIONS

This section explores two categories of WPT: radiative and non-radiative. Radiative WPT using microwaves or laser beams faces challenges due to signal attenuation in seawater. Nonradiative methods, such as capacitive and inductive power transfer, offer solutions for shorter distances but are more efficient in underwater environments. Inductive WPT, in particular, has gained prominence in various applications, including AUVs, due to its reliability and adaptability.

6) RECENT DEVELOPMENTS

The discussion highlights recent developments such as the Circumferential Coupled Dipole-Coil Magnetic Coupler. This innovation addresses some of the limitations of existing magnetic couplers, achieving high efficiency in underwater power transfer. Such advancements are critical for enhancing the energy autonomy of AUVs, reducing the need for frequent recharging or battery swapping, and ultimately extending mission capabilities.

Table 6 provides an overview of diverse navigation algorithms developed for underwater localization, addressing the challenges posed by GPS limitations in underwater environments. SEAL, a self-adaptive AUV-based localization system, enhances coverage and energy efficiency. It employs a partitioned fast block least-mean square adaptive algorithm-based active noise control (ANC) to mitigate AUV-radiated noise. Another approach, Doppler velocity log Beams Net, employs an end-to-end deep learning framework to enhance the accuracy of velocity vector estimates. MAHKF, an adaptive H-infinite Kalman filtering algorithm, focuses on reducing position errors, while Variational Bayesian is utilized to estimate measurement error covariance from Doppler velocity log (DVL) data when GPS is unavailable. Additionally, a study on the kinematic stability of HAUVs introduces a novel criterion for vehicle design, exemplified by Nezha. These algorithms collectively offer promising solutions to enhance underwater navigation and localization across diverse applications.

D. NAVIGATION ALGORITHMS

Underwater localization approaches rely on acoustic signals due to the extreme attenuation and energy-intensive nature of GPS-based systems. SEAL is a self-adaptive AUV-based localization system that achieves improved coverage and energy efficiency. A partitioned fast block least-mean square adaptive algorithm-based ANC has been developed to mitigate AUV-radiated noise. Doppler velocity log Beams Net is an end-to-end deep learning framework that improves the accuracy of velocity vector estimates. MAHKF is an adaptive H-infinite Kalman filtering algorithm that reduces position errors. Variational Bayesian is used to estimate the measurement error covariance of DVL when GPS is unavailable. The kinematic stability of HAUVs has been studied, and a novel criterion for vehicle design was introduced, with Nezha as an example. These approaches offer promising solutions for underwater navigation and localization in various applications.

E. SENSORS USED

The development of sensors for marine applications is still relatively small, but various types of sensors are being developed for underwater robots. Tactile sensors are being designed to mimic the leathery, granular texture in the palms of sea otters. Novel visual-based underwater positioning systems based on LiDAR cameras and inertial measurement units have been developed, while underwater 3-D laser scanners are being used for inspection and navigation. Kalman filter variants and RBF neural networks are utilized in underwater multi-sensor fusion applications for localization and navigation, and accurate sensor localization is crucial for the deployment of underwater acoustic sensor networks. These advancements in sensor technology will contribute to the progress of underwater robotics and enhance their capabilities in exploring and monitoring the marine environment.

The outcome of this review has provided the recent advancements for unmanned AUVs for navigation and exploration. It also familiarizes the development of biomimicry models, which discusses the latest control system that is being used for different tasks, reviews the algorithms that have been developed within the last 5 years, and finally talks about the sensors that are being implanted to achieve those goals. For each case what is it developing, what is the objective for the development, and the problems it may face during implementation has been presented. Finally, the review concludes with valuable recommendations for future research and development in this field, aiming to drive further progress and innovation.

VIII. CONCLUSION

Control issues with AUVs provide several challenges due to their nonlinear dynamics, the existence of disturbance, and observation sounds. Shallow water phenomena caused by the combination of wave dynamics, tidal currents, coastal currents, and artificial objects, particularly in shallow, limited water areas, offer a challenging environment for operating AUVs. As a result, directing AUVs to monitor trajectories in shallow waters remains a challenge.

Advancements in collaborative AUV technologies have shown promise in addressing these challenges. Communication, collaborative localization and navigation, surveillance, and intervention missions have seen progress. Hybrid technology, combining acoustic and light-based communication, emerges as a viable solution. Long-range communications are handled acoustically, while light-based communication ensures inter-vehicle communication, crucial for collision avoidance. Collaborative navigation benefits from a hybrid approach, using acoustic methods for medium/long-range navigation and visual-based techniques for formation maintenance and collision avoidance.

In reflection, the journey of underwater robotic evolution unveils a remarkable trajectory marked by ingenuity, technological leaps, and collaborative exploration. From the inception of bio-inspired designs mimicking fish motion through innovations like flexible fin ray tail structures to the utilization of advanced materials such as hydraulic actuators and hydrogels for acoustic transparency, the field has witnessed substantial progress. However, challenges persist, particularly in the delicate balance between efficiency and the weighty demands of payload capacity and maintenance. An insight into these findings from this study with their past and present developments with the concerns they possess are as follows:

- Hydraulic actuators, preferred for their higher forces and speeds over pneumatic systems, coupled with hydrogel materials, contribute to omnidirectional transparency for acoustic detection. Sophisticated control algorithms are required for precise tentacle movements, but wear and tear on hydrogel components pose longevity concerns.
- In the realm of bio-inspired robotics, the adoption of rotary actuation and soft materials mimicking the fin ray effect provides agility for navigating narrow spaces. However, these systems are sensitive to vibrations, limiting their robustness. Additionally, dynamic time-warping algorithms for mimicking manta ray motions present heavy computational burdens.
- Underwater robots inspired by sea turtles and manta rays offer promising solutions for efficient swimming and maneuverability. However, limitations in payload capacity and difficulties in maintenance pose challenges. Buoyancy and mass adjustment systems employing airfoils enhance gliding propulsion for manta ray-inspired vehicles but face stability issues. Advancements in magnetic couplers, utilizing various configurations and materials, present opportunities for wireless charging and data transfer in underwater vehicles. However, challenges such as susceptibility to external magnetic interference and limitations in power handling persist.
- In terms of control systems, fractional-order control mechanisms, machine vision systems, and adaptive model predictive control have been explored for precise maneuvering and stability. Yet, these approaches may require complex tuning and face limitations in certain conditions.
- In sensor technologies, triboelectric tactile sensors, LiDAR cameras, and water velocity sensors have been developed for enhanced environmental perception. However, challenges include reliability in extreme conditions, susceptibility to fouling, and limitations in accuracy.

Looking beyond the current milestones in UUV technology, the future presents a landscape rich with potential advancements. Future research endeavors are poised to concentrate on refining collaborative AUV technologies. Some of such future directions are mentioned below,

- AI and ML: The integration of artificial intelligence (AI) and ML techniques into underwater robots holds promise, allowing them to adapt to changing environments. Swarm robotics, where multiple underwater robots work together, has the potential to significantly enhance efficiency and effectiveness in exploration and monitoring missions.
- Enhanced Environmental Sensing: Future research could focus on improving the environmental sensing capabilities of AUVs through advancements in sensor technologies. This includes developing more reliable and robust sensors for improved data collection in challenging underwater conditions.
- Autonomous Decision-Making Algorithms: Exploring and refining autonomous decision-making algorithms would be crucial. This involves developing AI and machine learning algorithms that enable AUVs to adapt to dynamic environments, make real-time decisions, and optimize mission objectives.
- Swarm Robotics Optimization: Further exploration into optimizing swarm robotics for underwater missions could be a promising avenue. Understanding how to enhance coordination, communication, and collaboration among multiple AUVs in a swarm can significantly improve their efficiency and effectiveness.
- Energy Efficiency and Charging Systems: Developing more energy-efficient propulsion systems and exploring innovative charging solutions can extend AUV mission durations. This includes advancements in battery technologies, wireless charging methods, and energy harvesting techniques.
- Integration with Emerging Technologies: Investigating the integration of AUVs with emerging technologies, such as blockchain and IoT, presents exciting possibilities. Research in this area could focus on enhancing data security, real-time monitoring, and remote control capabilities.
- Biomimicry Advancements: Advancing biomimicry in AUV design can lead to more efficient and adaptable underwater vehicles. Researchers could explore new bio-inspired models, materials, and propulsion systems inspired by marine life to improve AUV performance.
- Integration of 5G Technology: As 5G technology continues to advance, exploring its integration into underwater communication systems could revolutionize AUV capabilities. High-speed and low-latency communication can

open up new possibilities for underwater data transfer and remote control.

Overall, the prospects of AUV technology are vast and exciting. Ongoing research and development efforts are fueling the continuous expansion of capabilities in these robots, leading to a revolutionary transformation of how we explore and operate in the underwater environment.

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REFERENCES

[1] N. Vedachalam, R. Ramesh, V. B. N. Jyothi, V. D. Prakash, and G. A. Ramadass, "Autonomous underwater vehicles-challenging developments and technological maturity towards strategic swarm robotics systems," *Mar. Georesources Geotechnol.*, vol. 37, no. 5, pp. 525–538, May 2019.

[2] F. Bu, H. Luo, S. Ma, X. Li, R. Ruby, and G. Han, "AUV-aided optical—Acoustic hybrid data collection based on deep reinforcement learning," *Sensors*, vol. 23, no. 2, p. 578, Jan. 2023.

[3] F. Santoso, M. A. Garratt, and S. G. Anavatti, "State-of-the-art integrated guidance and control systems in unmanned vehicles: A review," *IEEE Syst. J.*, vol. 15, no. 3, pp. 3312–3323, Sep. 2021.

[4] Y. Mousavi, A. Zarei, A. Mousavi, and M. Biari, "Robust optimal higher-order-observer-based dynamic sliding mode control for VTOL unmanned aerial vehicles," *Int. J. Autom. Comput.*, vol. 18, no. 5, pp. 802–813, Oct. 2021.

[5] S. Heshmati-Alamdari, G. C. Karras, and K. J. Kyriakopoulos, "A predictive control approach for cooperative transportation by multiple underwater vehicle manipulator systems," *IEEE Trans. Control Syst. Technol.*, vol. 30, no. 3, pp. 917–930, May 2022.

[6] Y. Cong, C. Gu, T. Zhang, and Y. Gao, "Underwater robot sensing technology: A survey," *Fundam. Res.*, vol. 1, no. 3, pp. 337–345, May 2021.

[7] J. Neira, C. Sequeiros, R. Huamani, E. Machaca, P. Fonseca, and W. Nina, "Review on unmanned underwater robotics, structure designs, materials, sensors, actuators, and navigation control," *J. Robot.*, vol. 2021, pp. 1–26, Jul. 2021.

[8] L. D. L. Barker, M. V. Jakuba, A. D. Bowen, C. R. German, T. Maksym, L. Mayer, A. Boetius, P. Dutrieux, and L. L. Whitcomb, "Scientific challenges and present capabilities in underwater robotic vehicle design and navigation for oceanographic exploration under-ice," *Remote Sens.*, vol. 12, no. 16, p. 2588, Aug. 2020.

[9] M. Laranjeira, A. Arnaubec, L. Brignone, C. Dune, and J. Opderbecke, "3D perception and augmented reality developments in underwater robotics for ocean sciences," *Current Robot. Rep.*, vol. 1, no. 3, pp. 123–130, Sep. 2020.

[10] J. Connor, B. Champion, and M. A. Joordens, "Current algorithms, communication methods and designs for underwater swarm robotics: A review," *IEEE Sensors J.*, vol. 21, no. 1, pp. 153–169, Jan. 2021.

[11] Y. Wu, X. Ta, R. Xiao, Y. Wei, D. An, and D. Li, "Survey of underwater robot positioning navigation," *Appl. Ocean Res.*, vol. 90, Sep. 2019, Art. no. 101845.

[12] J. Wang, Z. Wu, H. Dong, M. Tan, and J. Yu, "Development and control of underwater gliding robots: A review," *IEEE/CAA J. Autom. Sinica*, vol. 9, no. 9, pp. 1543–1560, Sep. 2022.

[13] D. Q. Huy, N. Sadjoli, A. B. Azam, B. Elhadidi, Y. Cai, and G. Seet, "Object perception in underwater environments: A survey on sensors and sensing methodologies," *Ocean Eng.*, vol. 267, Jan. 2023, Art. no. 113202.

[14] G. Li et al., "Bioinspired soft robots for deep-sea exploration," *Nature Commun.*, vol. 14, no. 1, p. 7097, Nov. 2023.

[15] T. Ma, S. Ding, Y. Li, and J. Fan, "A review of terrain aided navigation for underwater vehicles," *Ocean Eng.*, vol. 281, Aug. 2023, Art. no. 114779.

[16] Y. Xu, R. Zheng, S. Zhang, and M. Liu, "Robust inertial-aided underwater localization based on imaging sonar keyframes," *IEEE Trans. Instrum. Meas.*, vol. 71, pp. 1–12, 2022.

[17] Y. Zhong, Z. Hong, Y. Li, and J. Yu, "A general kinematic model of fish locomotion enables robot fish to master multiple swimming motions," *IEEE Trans. Robot.*, vol. 40, pp. 750–763, 2024.

[18] K. Ren and J. Yu, "Research status of bionic amphibious robots: A review," *Ocean Eng.*, vol. 227, May 2021, Art. no. 108862.

[19] M. Hermes, M. Ishida, M. Luhar, and M. T. Tolley, "Bioinspired shape-changing soft robots for underwater locomotion: Actuation and optimization for crawling and swimming," in *Bioinspired Sensing, Actuation, and Control in Underwater Soft Robotic Systems*. Cham, Switzerland: Springer, 2021, pp. 7–39.

[20] A. Cloitre, V. Subramaniam, N. Patrikalakis, and P. V. Y. Alvarado, "Design and control of a field deployable batoid robot," in *Proc. 4th IEEE RAS EMBS Int. Conf. Biomed. Robot. Biomechatronics (BioRob)*, Rome, Italy, Jun. 2012, pp. 707–712.

[21] C. Christianson, N. N. Goldberg, D. D. Deheyn, S. Cai, and M. T. Tolley, "Translucent soft robots driven by frameless fluid electrode dielectric elastomer actuators," *Sci. Robot.*, vol. 3, no. 17, pp. 1–9, Apr. 2018.

[22] M. A. Robertson, F. Efremov, and J. Paik, "RoboScallop: A bivalve inspired swimming robot," *IEEE Robot. Autom. Lett.*, vol. 4, no. 2, pp. 2078–2085, Apr. 2019.

[23] F. Kirchner, S. Straube, D. Kühn, and N. Hoyer, *AI Technology for Underwater Robots*. Berlin, Germany: Springer, 2020.

[24] J. González-García, A. Gómez-Espinosa, E. Cuan-Urquizo, L. G. García-Valdovinos, T. Salgado-Jiménez, and J. A. E. Cabello, "Autonomous underwater vehicles: Localization, navigation, and communication for collaborative missions," *Appl. Sci.*, vol. 10, no. 4, p. 1256, Feb. 2020.

[25] T. Salgado Jimenez, J. L. G. Lopez, L. F. Martinez-Soto, E. Olguin-Lopez, P. A. Resendiz-Gonzalez, and M. Bandala-Sanchez, "Deep water ROV design for the Mexican oil industry," in *Proc. OCEANS'10th IEEE SYDNEY*, May 2010, pp. 1–6.

[26] D. A. Koshaev, "AUV relative position and attitude determination using acoustic beacons," *Gyroscopy Navigat.*, vol. 13, no. 4, pp. 262–275, Dec. 2022.

[27] F. Maurelli, S. Krupiński, X. Xiang, and Y. Petillot, "AUV localisation: A review of passive and active techniques," *Int. J. Intell. Robot. Appl.*, vol. 6, no. 2, pp. 246–269, Jun. 2022.

[28] Z. Li and F. H. Durgin, "Design, data, and theory regarding a digital hand inclinometer: A portable device for studying slant perception," *Behav. Res. Methods*, vol. 43, no. 2, pp. 363–371, Jun. 2011.

[29] X. Xia, N. Hu, J. Liu, G. Chen, Q. Yang, and Y. Chen, "Development and innovative design research of underwater bionic fish products under hybrid propulsion technology," *Wireless Commun. Mobile Comput.*, vol. 2021, pp. 1–11, Nov. 2021.

[30] A. Inzartsev, A. Pavin, A. Kleschev, V. Gribova, and G. Eliseenko, "Application of artificial intelligence techniques for fault diagnostics of autonomous underwater vehicles," in *Proc. OCEANS MTS/IEEE Monterey*, Sep. 2016, pp. 1–6.

[31] M.-F.-R. Lee and Y.-C. Chen, "Artificial intelligence based object detection and tracking for a small underwater robot," *Processes*, vol. 11, no. 2, p. 312, Jan. 2023.

[32] K. Kumar and G. S. M. Thakur, "Advanced applications of neural networks and artificial intelligence: A review," *Int. J. Inf. Technol. Comput. Sci.*, vol. 4, no. 6, p. 57, Jun. 2012.

[33] S. M. Youssef, M. Soliman, M. A. Saleh, M. A. Mousa, M. Elsamanty, and A. G. Radwan, "Underwater soft robotics: A review of bioinspiration in design, actuation, modeling, and control," *Micromachines*, vol. 13, no. 1, p. 110, Jan. 2022.

[34] M. Wu, X. Zheng, R. Liu, N. Hou, W. H. Afridi, R. H. Afridi, X. Guo, J. Wu, C. Wang, and G. Xie, "Glowing sucker octopus *(Stauroteuthis syrtensis)*-inspired soft robotic gripper for underwater self-adaptive grasping and sensing," *Adv. Sci.*, vol. 9, no. 17, pp. 1–11, Jun. 2022.

[35] P. S. Matharu, Z. Wang, J. H. Costello, S. P. Colin, R. H. Baughman, and Y. T. Tadesse, "SoJel—A 3D printed jellyfish-like robot using soft materials for underwater applications," *Ocean Eng.*, vol. 279, Jul. 2023, Art. no. 114427.

[36] M. Calisti, M. Giorelli, G. Levy, B. Mazzolai, B. Hochner, C. Laschi, and P. Dario, "An octopus-bioinspired solution to movement and manipulation for soft robots," *Bioinspiration Biomimetics*, vol. 6, no. 3, Sep. 2011, Art. no. 036002.

[37] M. Cianchetti, M. Calisti, L. Margheri, M. Kuba, and C. Laschi, "Bioinspired locomotion and grasping in water: The soft eight-arm OCTOPUS robot," *Bioinspiration Biomimetics*, vol. 10, no. 3, May 2015, Art. no. 035003.

[38] H. Jiang, X. Han, Y. Jing, N. Guo, F. Wan, and C. Song, "Rigid-soft interactive design of a lobster-inspired finger surface for enhanced grasping underwater," *Frontiers Robot. AI*, vol. 8, Dec. 2021, Art. no. 787187.

[39] Q. Wang, X. Lu, N. Yuan, P. Jiang, J. Yao, Y. Liu, and J. Ding, "Centimeter-scale underwater robot with high-speed inspired by jellyfish," *IEEE Robot. Autom. Lett.*, vol. 8, no. 5, pp. 2976–2982, May 2023.

[40] C. Christianson, C. Bayag, G. Li, S. Jadhav, A. Giri, C. Agba, T. Li, and M. T. Tolley, "Jellyfish-inspired soft robot driven by fluid electrode dielectric organic robotic actuators," *Frontiers Robot. AI*, vol. 6, pp. 1–11, Nov. 2019.

[41] X. Hou, Z. Li, S. Guo, L. Shi, H. Xing, and H. Yin, "An improved backstepping controller with an LESO and TDs for robust underwater 3D trajectory tracking of a turtle-inspired amphibious spherical robot," *Machines*, vol. 10, no. 6, p. 450, Jun. 2022.

[42] R. L. Baines, J. W. Booth, F. E. Fish, and R. Kramer-Bottiglio, "Toward a bio-inspired variable-stiffness morphing limb for amphibious robot locomotion," in *Proc. 2nd IEEE Int. Conf. Soft Robot. (RoboSoft)*, Apr. 2019, pp. 704–710.

[43] B. Sun, W. Li, Z. Wang, Y. Zhu, Q. He, X. Guan, G. Dai, D. Yuan, A. Li, W. Cui, and D. Fan, "Recent progress in modeling and control of bio-inspired fish robots," *J. Mar. Sci. Eng.*, vol. 10, no. 6, p. 773, Jun. 2022.

[44] C. H. White, G. V. Lauder, and H. Bart-Smith, "Tunabot flex: A tuna-inspired robot with body flexibility improves high-performance swimming," *Bioinspiration Biomimetics*, vol. 16, no. 2, Mar. 2021, Art. no. 026019.

[45] S. M. Youssef, M. Soliman, M. A. Saleh, A. H. Elsayed, and A. G. Radwan, "Design and control of soft biomimetic pangasius fish robot using fin ray effect and reinforcement learning," *Sci. Rep.*, vol. 12, no. 1, pp. 1–14, Dec. 2022, Art. no. 21861.

[46] J. Zhang, T. Zhang, E. Dong, C. Zhang, Z. Lin, Z. Song, H. Li, N. X. Fang, and Y. Zhang, "Bioinspired hydrogel jellyfish with mechanical flexibility and acoustic transparency," *Cell Rep. Phys. Sci.*, vol. 3, no. 10, Oct. 2022, Art. no. 101081.

[47] C. Armanini, M. Farman, M. Calisti, F. Giorgio-Serchi, C. Stefanini, and F. Renda, "Design and control of soft biomimetic pangasius fish robot using fin ray effect and reinforcement learning," *IEEE Trans. Robot.*, vol. 38, no. 2, pp. 731–747, Dec. 2022.

[48] Y. Cao, S. Ma, Y. Cao, G. Pan, Q. Huang, and Y. Cao, "Similarity evaluation rule and motion posture optimization for a manta ray robot," *J. Mar. Sci. Eng.*, vol. 10, no. 7, p. 908, Jun. 2022.

[49] X. Zhou, K. Li, Y. Liu, J. Sun, H. Li, W. Chen, and J. Deng, "Development of an antihydropressure miniature underwater robot with multilocomotion mode using piezoelectric pulsed-jet actuator," *IEEE Trans. Ind. Electron.*, vol. 70, no. 5, pp. 5044–5054, May 2023.

[50] Y. Yan, X. Wang, X. Qi, J. Hou, C. Chen, J. Ma, H. Xing, Y. Chen, and Y. Zhao, "Development of a turtle-inspired robot with variable stiffness hydrofoils," in *Proc. IEEE Int. Conf. Mechatronics Autom. (ICMA)*, Aug. 2022, pp. 493–498.

[51] D. Zhang, G. Pan, Y. Cao, Q. Huang, and Y. Cao, "A novel integrated gliding and flapping propulsion biomimetic manta-ray robot," *J. Mar. Sci. Eng.*, vol. 10, no. 7, p. 924, Jul. 2022.

[52] Y. Liu, H. Li, S. Deng, S. Wang, S. Liu, and Z. Wang, "Biomimetic robotic sea lion foreflippers: Design, modeling, and experimentation," *IEEE/ASME Trans. Mechatronics*, vol. 27, no. 6, pp. 5679–5689, Dec. 2022.

[53] F. E. Fish, "Advantages of aquatic animals as models for bio-inspired drones over present AUV technology," *Bioinspiration Biomimetics*, vol. 15, no. 2, Feb. 2020, Art. no. 025001.

[54] H. Huang, C. Sheng, J. Wu, G. Wu, C. Zhou, and H. Wang, "Hydrodynamic analysis and motion simulation of fin and propeller driven manta ray robot," *Appl. Ocean Res.*, vol. 108, Mar. 2021, Art. no. 102528.

[55] I. Y. Amran and K. Isa, "Modelling analysis of spherical underwater robot for aquaculture biofouling cleaning," in *Proc. 12th Nat. Tech. Seminar Unmanned Syst. Technol.* Singapore: Springer, 2020, pp. 29–45.

[56] J. Xing, W. Jin, K. Yang, and I. Howard, "A bionic piezoelectric robotic jellyfish with a large deformation flexure Hinge," *IEEE Trans. Ind. Electron.*, vol. 70, no. 12, pp. 12596–12605, Jan. 2023.

[57] T. Wang, Q. Zhao, and C. Yang, "Visual navigation and docking for a planar type AUV docking and charging system," *Ocean Eng.*, vol. 224, Mar. 2021, Art. no. 108744.

[58] J. Manikandan, S. Akash, A. Vishwanath, R. Nandakumar, V. K. Agrawal, and K. Manu, "Design and development of contactless battery charger for underwater vehicles," in *Proc. Michael Faraday IET Int. Summit*, Kolkata, India, Sep. 2015, pp. 362–367.

[59] E. A. Asrami and M. Moonesun, "Numerical and experimental investigation of the hydrodynamic lift and drag coefficients of a solar-powered AUV in near-surface mode," *Int. J. Maritime Technol.*, vol. 18, pp. 1–14, May 2023.

[60] D. M. Crimmins, C. T. Patty, M. A. Beliard, J. Baker, J. C. Jalbert, R. J. Komerska, S. G. Chappell, and D. R. Blidberg, "Long-endurance test results of the solar-powered AUV system," in *Proc. OCEANS Conf.*, Sep. 2006, pp. 1–5.

[61] J. Esteba, P. Cieslak, N. Palomeras, and P. Ridao, "Docking of non-holonomic AUVs in presence of ocean currents: A comparative survey," *IEEE Access*, vol. 9, pp. 86607–86631, 2021.

[62] R. Stokey, B. Allen, T. Austin, R. Goldsborough, N. Forrester, M. Purcell, and C. von Alt, "Enabling technologies for REMUS docking: An integral component of an autonomous ocean-sampling network," *IEEE J. Ocean. Eng.*, vol. 26, no. 4, pp. 487–497, Oct. 2001.

[63] A. Brighenti, L. Zugno, F. Mattiuzzo, and A. Sperandio, "EURODOCKER—A universal docking-downloading recharging system for AUVs: Conceptual design results," in *Proc. IEEE Ocean. Eng. Soc.*, Sep. 1998, pp. 1463–1467.

[64] R. Stokey, M. Purcell, N. Forrester, T. Austin, R. Goldsborough, B. Allen, and C. von Alt, "A docking system for REMUS, an autonomous underwater vehicle," in *Proc. Oceans MTS/IEEE Conf.*, vol. 2, Oct. 1997, pp. 1132–1136.

[65] A. Babić, F. Mandić, and N. Mišković, "Development of visual servoing-based autonomous docking capabilities in a heterogeneous swarm of marine robots," *Appl. Sci.*, vol. 10, no. 20, p. 7124, Oct. 2020.

[66] M. N. Haji, J. Tran, J. Norheim, and O. L. de Weck, "Design and testing of AUV docking modules for a renewably powered offshore AUV servicing platform," in *Proc. Int. Conf. Offshore Mech. Arctic Eng.*, vol. 84386, Aug. 2020, p. V06BT06A024.

[67] BR Page. (2016). *Design of a Mobile Underwater Charging System*. [Online]. Available: https://digitalcommons.mtu.edu/cgi/viewcontent.cgi?article=1370&context=etdr

[68] A. M. Yazdani, K. Sammut, O. Yakimenko, and A. Lammas, "A survey of underwater docking guidance systems," *Robot. Auto. Syst.*, vol. 124, Feb. 2020, Art. no. 103382.

[69] B. N. J. Vandavasi, H. Venkataraman, and A. R. Gidugu, "Machine learning-based electro-magnetic field guided localization technique for autonomous underwater vehicle homing," *Ocean Eng.*, vol. 280, Jul. 2023, Art. no. 114692.

[70] L. Paull, S. Saeedi, M. Seto, and H. Li, "AUV navigation and localization: A review," *IEEE J. Ocean. Eng.*, vol. 39, no. 1, pp. 131–149, Jan. 2014.

[71] B. Allen, T. Austin, N. Forrester, R. Goldsborough, A. Kukulya, G. Packard, M. Purcell, and R. Stokey, "Autonomous docking demonstrations with enhanced REMUS technology," in *Proc. OCEANS*, Boston, MA, USA, Sep. 2006, pp. 1–6.

[72] H. Painter and J. Flynn, "Current and future wet-mate connector technology developments for scientific seabed observatory applications," in *Proc. OCEANS*, Sep. 2006, pp. 1–6.

[73] W. Brown, J. Mims, and N. Heenan, "An experimental microwave-powered helicopter," in *Proc. IRE Int. Conv. Rec.*, New York, NY, USA, Mar. 1966, pp. 225–235.

[74] K. Shizuno, S. Yoshida, M. Tanomura, and Y. Hama, "Long distance high efficient underwater wireless charging system using dielectric-assist antenna," in *Proc. Oceans St. John's*, Sep. 2014, pp. 1–3.

[75] S. Yoshida, M. Tanomura, Y. Hama, T. Hirose, A. Suzuki, Y. Matsui, N. Sogo, and R. Sato, "Underwater wireless power transfer for non-fixed unmanned underwater vehicle in the ocean," in *Proc. IEEE/OES Auto. Underwater Vehicles (AUV)*, Tokyo, Japan, Nov. 2016, pp. 177–180.

[76] M. Urano, K. Ata, and A. Takahashi, "Study on underwater wireless power transfer via electric coupling with a submerged electrode," in *Proc. IEEE Int. Meeting Future Electron Devices, Kansai (IMFEDK)*, Jun. 2017, pp. 36–37.

[77] N. Tesla, "Apparatus for transmitting electrical energy," U.S. Patent 1 119 732, Dec. 1, 1914. [Online]. Available: https://teslauniverse.com/nikola-tesla/patents/us-patent-1119732-apparatus-transmitting-electrical-energy

[78] Y. D. Ko and Y. J. Jang, "The optimal system design of the online electric vehicle utilizing wireless power transmission technology," *IEEE Trans. Intell. Transp. Syst.*, vol. 14, no. 3, pp. 1255–1265, Sep. 2013.

[79] S. Y. R. Hui and W. W. C. Ho, "A new generation of universal contactless battery charging platform for portable consumer electronic equipment," *IEEE Trans. Power Electron.*, vol. 20, no. 3, pp. 620–627, May 2005.

[80] R.-F. Xue, K.-W. Cheng, and M. Je, "High-efficiency wireless power transfer for biomedical implants by optimal resonant load transformation," *IEEE Trans. Circuits Syst. I, Reg. Papers*, vol. 60, no. 4, pp. 867–874, Apr. 2013.

[81] M. D. Feezor, F. Yates Sorrell, and P. R. Blankinship, "An interface system for autonomous undersea vehicles," *IEEE J. Ocean. Eng.*, vol. 26, no. 4, pp. 522–525, Oct. 2001.

[82] T. Orekan and P. Zhang, *Underwater Wireless Power Transfer Smart Ocean Energy Converters*. New York, NY, USA: Springer, 2019.

[83] G. Guidi, J. A. Suul, F. Jenset, and I. Sorfonn, "Wireless charging for ships: High-power inductive charging for battery electric and plug-in hybrid vessels," *IEEE Electrific. Mag.*, vol. 5, no. 3, pp. 22–32, Sep. 2017.

[84] B. Allotta, L. Pugi, A. Reatti, and F. Corti, "Wireless power recharge for underwater robotics," in *Proc. IEEE Int. Conf. Environ. Electr. Eng. IEEE Ind. Commercial Power Syst. Eur.*, Milan, Italy, Jun. 2017, pp. 1–6.

[85] T. Assaf, C. Stefanini, and P. Dario, "Autonomous underwater biorobots: A wireless system for power transfer," *IEEE Robot. Autom. Mag.*, vol. 20, no. 3, pp. 26–32, Sep. 2013.

[86] H. Jun, A. Asada, T. Ura, Y. Yagita, and Y. Yamauchi, "High speed acoustic network and noncontact power supplier for seafloor geodetic observing robot system," in *Proc. OCEANS*, May 2006, pp. 1–3.

[87] D. Yoshioka, H. Sakamoto, Y. Ishihara, T. Matsumoto, and F. Timischl, "Power feeding and data-transmission system using magnetic coupling for an ocean observation mooring buoy," *IEEE Trans. Magn.*, vol. 43, no. 6, pp. 2663–2665, Jun. 2007.

[88] *Wireless Power Transfer for Light-Duty Plug-In/Electric Vehicles and Alignment Methodology*, Standard J2954A, SAE Int., Warrendale, PA, USA, 2012. [Online]. Available: https://www.sae.org/standards/content/j2954_201711/

[89] C. Cai, Y. Zhang, S. Wu, J. Liu, Z. Zhang, and L. Jiang, "A circumferential coupled dipole-coil magnetic coupler for autonomous underwater vehicles wireless charging applications," *IEEE Access*, vol. 8, pp. 65432–65442, 2020.

[90] S. Wu, C. Cai, A. Wang, Z. Qin, and S. Yang, "Design and implementation of a uniform power and stable efficiency wireless charging system for autonomous underwater vehicles," *IEEE Trans. Ind. Electron.*, vol. 70, no. 6, pp. 5674–5684, Jun. 2023.

[91] C. Cai, J. Liu, S. Wu, Y. Zhang, L. Jiang, Z. Zhang, and J. Yu, "Development of a cross-type magnetic coupler for unmanned aerial vehicle IPT charging systems," *IEEE Access*, vol. 8, pp. 67974–67989, 2020.

[92] A. Mostafa, Y. Wang, H. Zhang, S. Tangirala, and F. Lu, "An ultra-fast wireless charging system with a hull-compatible coil structure for autonomous underwater vehicles (AUVs)," in *Proc. IEEE Transp. Electrific. Conf. Expo. (ITEC)*, Jun. 2022, pp. 279–284.

[93] M. Lin, R. Lin, D. Li, and R. Duan, "Development of a radially coupled wireless charging system for torpedo-shaped autonomous underwater vehicles," *J. Mar. Sci. Eng.*, vol. 11, no. 6, p. 1180, Jun. 2023.

[94] C. Cai, S. Wu, Z. Zhang, L. Jiang, and S. Yang, "Development of a fit-to-surface and lightweight magnetic coupler for autonomous underwater vehicle wireless charging systems," *IEEE Trans. Power Electron.*, vol. 36, no. 9, pp. 9927–9940, Sep. 2021.

[95] J.-W. Liu, Y.-S. Cheng, and K.-C. Ho, "Development of a wireless charging system based on LLC resonant converter for underwater drone," in *Proc. 11th Int. Conf. Power Electron. ECCE Asia*, May 2023, pp. 2579–2584.

[96] C. Bal, G. O. Koca, D. Korkmaz, Z. H. Akpolat, and M. Ay, "CPG-based autonomous swimming control for multi-tasks of a biomimetic robotic fish," *Ocean Eng.*, vol. 189, Oct. 2019, Art. no. 106334.

[97] I. Glushko, E. Olenew, M. Komar, L. Kniese, R. Sokolovskyi, O. Kebkal, R. Bannasch, and K. Kebkal, "Software control architecture for the BOSS manta ray AUV actuation system," in *Proc. IEEE/OES Auto. Underwater Vehicle Workshop (AUV)*, Porto, Portugal, Nov. 2018, pp. 1–5.

[98] Z. Peng, J. Wang, D. Wang, and Q.-L. Han, "An overview of recent advances in coordinated control of multiple autonomous surface vehicles," *IEEE Trans. Ind. Informat.*, vol. 17, no. 2, pp. 732–745, Feb. 2021.

[99] J. Kadiyam and S. Mohan, "Conceptual design of a hybrid propulsion underwater robotic vehicle with different propulsion systems for ocean observations," *Ocean Eng.*, vol. 182, pp. 112–125, Jun. 2019.

[100] S. Gu and S. Guo, "Performance evaluation of a novel propulsion system for the spherical underwater robot (SURIII)," *Appl. Sci.*, vol. 7, no. 11, p. 1196, Nov. 2017.

[101] Y. Bi, D. Lu, Z. Zeng, and L. Lian, "Dynamics and control of hybrid aerial underwater vehicle subject to disturbances," *Ocean Eng.*, vol. 250, Apr. 2022, Art. no. 110933.

[102] K. K. Yum, B. Taskar, E. Pedersen, and S. Steen, "Simulation of a two-stroke diesel engine for propulsion in waves," *Int. J. Nav. Archit. Ocean Eng.*, vol. 9, no. 4, pp. 351–372, Jul. 2017.

[103] J. Choi, S. Kim, Y. Lee, T.-J. Kim, and H.-T. Choi, "Relative pose estimation of underwater robot by fusing inertial sensors and optical image," in *Proc. 11th Int. Conf. Ubiquitous Robots Ambient Intell. (URAI)*, Nov. 2014, pp. 204–208.

[104] M. Martelli and M. Figari, "A design framework for combined marine propulsion control systems: From conceptualisation to sea trials validation," *Ocean Eng.*, vol. 254, Jun. 2022, Art. no. 111282.

[105] S. Kundu and D. R. Parhi, "Navigation of underwater robot based on dynamically adaptive harmony search algorithm," *Memetic Comput.*, vol. 8, no. 2, pp. 125–146, Jun. 2016.

[106] T. Inoue, K. Shibuya, and A. Nagano, "Underwater robot with a buoyancy control system based on the spermaceti oil hypothesis development of the depth control system," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Oct. 2010, pp. 1102–1107.

[107] G. S. Lima, S. Trimpe, and W. M. Bessa, "Sliding mode control with Gaussian process regression for underwater robots," *J. Intell. Robotic Syst.*, vol. 99, nos. 3–4, pp. 487–498, Sep. 2020.

[108] L. Christensen, J. de Gea Fernández, M. Hildebrandt, C. E. S. Koch, and B. Wehbe, "Recent advances in AI for navigation and control of underwater robots," *Current Robot. Rep.*, vol. 3, no. 4, pp. 165–175, Aug. 2022.

[109] R. Fareh, M. Baziyad, T. Rabie, and M. Bettayeb, "Enhancing path quality of real-time path planning algorithms for mobile robots: A sequential linear paths approach," *IEEE Access*, vol. 8, pp. 167090–167104, 2020.

[110] E. Simetti, G. Indiveri, and A. M. Pascoal, "WiMUST: A cooperative marine robotic system for autonomous geotechnical surveys," *J. Field Robot.*, vol. 38, no. 2, pp. 268–288, Mar. 2021.

[111] Z.-Q. Su, M. Zhou, F.-F. Han, Y.-W. Zhu, D.-L. Song, and T.-T. Guo, "Attitude control of underwater glider combined reinforcement learning with active disturbance rejection control," *J. Mar. Sci. Technol.*, vol. 24, no. 3, pp. 686–704, Sep. 2019.

[112] I. Carlucho, M. De Paula, and G. G. Acosta, "An adaptive deep reinforcement learning approach for MIMO PID control of mobile robots," *ISA Trans.*, vol. 102, pp. 280–294, Jul. 2020.

[113] B. Zhu, L. Liu, L. Zhang, M. Liu, Y. Duanmu, Y. Chen, P. Dang, and J. Li, "A variable-order fuzzy logic controller design method for an unmanned underwater vehicle based on NSGA-II," *Fractal Fractional*, vol. 6, no. 10, p. 577, Oct. 2022.

[114] K. Katija, P. L. D. Roberts, J. Daniels, A. Lapides, K. Barnard, M. Risi, B. Y. Ranaan, B. G. Woodward, and J. Takahashi, "Visual tracking of deepwater animals using machine learning-controlled robotic underwater vehicles," in *Proc. IEEE Winter Conf. Appl. Comput. Vis. (WACV)*, Jan. 2021, pp. 859–868.

[115] J. Bak, Y. Moon, J. Kim, S. Mohan, T. Seo, and S. Jin, "Hovering control of an underwater robot with tilting thrusters using the decomposition and compensation method based on a redundant actuation model," *Robot. Auto. Syst.*, vol. 150, Apr. 2022, Art. no. 103995.

[116] X. Zeng, M. Xia, Z. Luo, J. Shang, Y. Xu, and Q. Yin, "Design and control of an underwater robot based on hybrid propulsion of quadrotor and bionic undulating fin," *J. Mar. Sci. Eng.*, vol. 10, no. 9, p. 1327, Sep. 2022.

[117] A. Li, S. Guo, M. Liu, and H. Yin, "Hydrodynamic characteristic-based adaptive model predictive control for the spherical underwater robot under ocean current disturbance," *Machines*, vol. 10, no. 9, p. 798, Sep. 2022.

[118] C.-L. Kuo, Y.-C. Pu, and Q.-A. Chen, "Position tracking of an underwater robot based on floating-downing PI control," *Processes*, vol. 10, no. 11, p. 2346, Nov. 2022.

[119] X. Luan and Y. Sun, "Research on cooperative encirclement strategy of multiple underwater robots based on wolf swarm algorithm," *J. Phys., Conf. Ser.*, vol. 1570, no. 1, Jun. 2020, Art. no. 012017.

[120] A. H. Chang, C. M. Hubicki, J. J. Aguilar, D. I. Goldman, A. D. Ames, and P. A. Vela, "Learning terrain dynamics: A Gaussian process modeling and optimal control adaptation framework applied to robotic jumping," *IEEE Trans. Control Syst. Technol.*, vol. 29, no. 4, pp. 1581–1596, Jul. 2021.
[121] W. Xie, D. Cabecinhas, R. Cunha, and C. Silvestre, "Adaptive backstepping control of a quadcopter with uncertain vehicle mass, moment of inertia, and disturbances," *IEEE Trans. Ind. Electron.*, vol. 69, no. 1, pp. 549–559, Jan. 2022.
[122] M. Ahsan, "Lyapunov redesign approach for robust output regulation of a class of autonomous underwater vehicles using conditional servocompensator," in *Proc. Austral. New Zealand Control Conf. (ANZCC)*, Nov. 2020, pp. 238–243.
[123] X. Yang and Y. Xing, "Tuning for robust and optimal dynamic positioning control in BlueROV2," *IOP Conf. Ser., Mater. Sci. Eng.*, vol. 1201, no. 1, Nov. 2021, Art. no. 012015.
[124] A. Konoplin, V. Filaretov, and A. Yurmanov, "A method for supervisory control of manipulator of underwater vehicle," *J. Mar. Sci. Eng.*, vol. 9, no. 7, p. 740, Jul. 2021.
[125] F. Vladimir, K. Alexander, Z. Alexander, and K. Nikita, "System of high-precision movements control of underwater manipulator," in *Proc. 31st DAAAM Int. Symp.*, Vienna, Austria, Oct. 2020, pp. 752–757.
[126] T. Ojha, S. Misra, and M. S. Obaidat, "SEAL: Self-adaptive AUV-based localization for sparsely deployed underwater sensor networks," *Comput. Commun.*, vol. 154, pp. 204–215, Mar. 2020.
[127] C. Chi, V. Pallayil, and M. Chitre, "Design of an adaptive noise canceller for improving performance of an autonomous underwater vehicle-towed linear array," *Ocean Eng.*, vol. 202, Apr. 2020, Art. no. 106886.
[128] N. Cohen and I. Klein, "BeamsNet: A data-driven approach enhancing Doppler velocity log measurements for autonomous underwater vehicle navigation," *Eng. Appl. Artif. Intell.*, vol. 114, Sep. 2022, Art. no. 105216.
[129] J. Wang, X. Chen, and P. Yang, "Adaptive H-infinite Kalman filter based on multiple fading factors and its application in unmanned underwater vehicle," *ISA Trans.*, vol. 108, pp. 295–304, Feb. 2021.
[130] D. Lu, S. Song, J. Wang, Y. Cai, and H. Shen, "Review on the development of SINS/DVL underwater integrated navigation technology," *Control Theory Appl.*, vol. 38, pp. 1–10, Sep. 2021.
[131] T. Wei, D. Lu, Z. Zeng, and L. Lian, "Trans-media kinematic stability analysis for hybrid unmanned aerial underwater vehicle," *J. Mar. Sci. Eng.*, vol. 10, no. 2, p. 275, Feb. 2022.
[132] D. Zeng, L. Yan, X. Cao, and K. Zeng, "Robust identification algorithm for unmanned underwater vehicles dynamics model parameters," *J. Phys., Conf. Ser.*, vol. 2338, no. 1, Sep. 2022, Art. no. 012091.
[133] X. Mu, B. He, S. Wu, X. Zhang, Y. Song, and T. Yan, "A practical INS/GPS/DVL/PS integrated navigation algorithm and its application on autonomous underwater vehicle," *Appl. Ocean Res.*, vol. 106, Jan. 2021, Art. no. 102441.
[134] F. Ju, Y. Wang, Z. Zhang, Y. Wang, Y. Yun, H. Guo, and B. Chen, "A miniature piezoelectric spiral tactile sensor for tissue hardness palpation with catheter robot in minimally invasive surgery," *Smart Mater. Struct.*, vol. 28, no. 2, Feb. 2019, Art. no. 025033.
[135] P. Xu, J. Liu, X. Liu, X. Wang, J. Zheng, S. Wang, T. Chen, H. Wang, C. Wang, X. Fu, G. Xie, J. Tao, and M. Xu, "A bio-inspired and self-powered triboelectric tactile sensor for underwater vehicle perception," *npj Flexible Electron.*, vol. 6, no. 1, pp. 1–10, Apr. 2022.
[136] H. Yang, Z. Xu, and B. Jia, "An underwater positioning system for UUVs based on LiDAR camera and inertial measurement unit," *Sensors*, vol. 22, no. 14, p. 5418, Jul. 2022.
[137] Y. Ou, J. Fan, C. Zhou, S. Tian, L. Cheng, and M. Tan, "Binocular structured light 3-D reconstruction system for low-light underwater environments: Design, modeling, and laser-based calibration," *IEEE Trans. Instrum. Meas.*, vol. 72, pp. 1–14, 2023.
[138] M. Castillón, A. Palomer, J. Forest, and P. Ridao, "Underwater 3D scanner model using a biaxial MEMS mirror," *IEEE Access*, vol. 9, pp. 50231–50243, 2021.
[139] N. Shaukat, A. Ali, M. J. Iqbal, M. Moinuddin, and P. Otero, "Multi-sensor fusion for underwater vehicle localization by augmentation of RBF neural network and error-state Kalman filter," *Sensors*, vol. 21, no. 4, p. 1149, Feb. 2021.
[140] M. Sabet and H. Nourmohammadi, "Water velocity sensor with the ability to estimate the sideslip angle based on Bernoulli's law for use in autonomous underwater vehicles," *Ocean Eng.*, vol. 263, Nov. 2022, Art. no. 112252.
[141] J. Yan, D. Guo, X. Luo, and X. Guan, "AUV-aided localization for underwater acoustic sensor networks with current field estimation," *IEEE Trans. Veh. Technol.*, vol. 69, no. 8, pp. 8855–8870, Aug. 2020.

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