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The Design and Optimization Technology of Propulsion Systems for Operative Underwater Robots

Guo Chen

College of Engineering, Ocean University of China, Qingdao, China
chenguo@stu.ouc.edu.cn

Abstract: The importance of underwater robots is evident in ocean exploration, resource development, and environmental monitoring. However, the harsh underwater environment requires higher efficiency, stability, and intelligence from their propulsion systems. The challenges faced by operational underwater robots today include low propulsion efficiency, poor adaptability to extreme environments, and a lack of sufficient autonomous control capabilities. To address these issues, this paper reviews the definition, requirements, core technologies, and key performance indicators of underwater robot propulsion systems by analyzing relevant literature from 2016 to 2024. It emphasizes optimization strategies aimed at enhancing propulsion efficiency, fault diagnosis and identification, reliability, durability, and adaptive control. Besides, it summarizes the current technical challenges and provides a reference for subsequent research. The results show that optimizing the propulsion system of operational underwater robots relies primarily on bionic design, new materials, adaptive control, deep learning, and fault diagnosis technologies to enhance propulsion efficiency, stability, durability, and environmental adaptability. However, optimizing the propulsion system involves challenges such as energy control, cost, and multi-objective optimization. Future research should prioritize efficient, low-energy propulsion, multi-modal perception, and intelligent adaptive control to advance underwater robot technology.

Keywords: Operational underwater robot, Propulsion system, Fault diagnosis identification, Adaptive control

1. Introduction

Underwater robots are key enablers of ocean exploration and development, widely used in research, resource exploitation, marine engineering, and defense operations. Their propulsion system, as the core power source, determines up to 80% of their operational efficiency. However, in the complex and ever-changing marine environment, propulsion systems are prone to problems like thrust loss, torque instability, and motor overload, often resulting from motor failures, thruster short circuits, or debris entangling the propeller blades. According to statistics, propulsion system failure accounts for 43% of the reasons for mission interruption, becoming a key factor affecting the stable operation of underwater robots. Thus, optimizing the propulsion system of operational underwater robots is crucial for enhancing their stability. In recent years, accelerated research and development efforts worldwide have led to notable progress in propulsion system optimization, giving rise to innovative propulsion technologies and algorithmic models. However, key challenges persist, including the limited practical application of new bionic structures, poor adaptability to extreme environments, insufficient autonomy in complex conditions, and propulsion efficiency and endurance that still fall short of expectations. Examining the propulsion systems of operational underwater robots, this paper surveys recent progress in boosting efficiency, diagnosing faults, strengthening reliability and durability, and refining adaptive control strategies. Through case comparisons, it explores future trends and offers guidance for propulsion system design.

2. Overview of underwater robot propulsion systems

Based on their functions and application areas, underwater robots can be classified into Remotely Operated Vehicles (ROV), Autonomous Underwater Vehicles (AUV), Human-Occupied Vehicles (HOV), and hybrid ROV/AUV types. Among them, ROV are suitable for performing complex underwater operations, while AUV are better suited for large-scale environmental monitoring. For locomotion modes, underwater robots can be divided into free-swimming, tracked, and walking types. At present, the main propulsion methods of underwater robots include propeller propulsion, hydraulic propulsion, bionic propulsion, and tracked propulsion [1].

2.1. The definition and requirements of operational underwater robots

With the ability to operate stably at depths from tens to thousands of meters, operational underwater robots are specifically developed as intelligent tools for handling complex underwater tasks. These robots are widely employed in fields like marine engineering, oil and gas exploration and extraction, oceanographic research, military operations, and underwater rescue. In comparison to other types of underwater robots, operational underwater robots offer clear benefits in environmental adaptability, precise control, operational capability, stability, and endurance, thereby enabling them to perform demanding and sustained operations in harsh deep-sea environments. The demand for operational underwater robots varies widely across different applications. For example, in marine engineering, robots must offer strong pressure resistance, corrosion resistance, and long endurance to meet the demands of long-term operations in deep-sea, high-pressure, high-salinity environments. In military missions, the focus shifts to high mobility, low noise, and stealth to enhance survivability in combat scenarios. In marine research, these robots rely on precise sensors for monitoring, surveying, and biodiversity studies. Besides, with the development of intelligent control technology, the demand for autonomous decision-making, adaptive environmental adjustment and intelligent operation of operational underwater robots is also growing in order to cope with the challenges brought by the complex and dynamic environment of the deep sea.

2.2. Core technologies and design principles of propulsion systems

To meet diverse operational needs, operational underwater robots adopt various propulsion systems such as propeller, hydraulic, biomimetic, and tracked types, each designed with a balance of thrust, efficiency, power transmission, adaptability, and energy consumption in mind. Propeller thrusters are the most widely used propulsion method, generating thrust through motor-driven blade rotation and the reactive force of water. As a mature technology, their design focuses on optimizing thrust, efficiency, stability, and power transmission. In recent years, innovative optimization schemes have been proposed based on traditional propeller propulsion. For example, the UPR-UPU-UR vector propulsion mechanism, combined with a PID control strategy, significantly improves system flexibility and adaptive control capabilities [2]. Hydraulic thrusters, which use hydraulic motors to drive blade rotation, are typically employed in deep-sea operations due to their ability to generate high thrust. Key design factors for hydraulic systems include sealing, pump efficiency, and motor leakage to reduce energy loss. However, their overall efficiency remains low with considerable heat loss, making improvements in pump efficiency and power transmission structure the main focus of

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ongoing development [3]. Biomimetic thrusters mimic biological propulsion mechanisms, offering low noise and high efficiency, making them suitable for military reconnaissance and long-duration missions. Their design emphasizes mobility, low noise, and extended endurance. Advanced smart materials enhance structural design, improving efficiency and stability. Tracked thrusters, driven by motors, are ideal for seabed operations due to their strong obstacle-crossing capability. Their design prioritizes seabed adaptability, durable track materials, and high-torque, low-speed motors. Due to high energy use, lightweight and efficient designs are crucial.

2.3. Key performance indicators of propulsion systems for operational underwater robots

Key performance indicators of operational underwater robot propulsion systems include efficiency, stability, pressure resistance, and corrosion resistance, hence ensuring reliable operation in complex underwater environments. Propulsion efficiency is a critical metric for evaluating a system's energy utilization, defined as $\eta_p = \frac{\mathrm{P_{out}}}{\mathrm{P_{in}}}$. The propulsion efficiency is affected by the propulsion structure design, the mechanical characteristics of the water flow environment and the hardware performance, and is usually between 30% and 60%. Stability, a key performance metric, includes attitude control, motion consistency, interference resistance, and dynamic response. The attitude stability roll angle is required to be controlled within $\pm 5°$, the pitch angle is within $\pm 5°$, and the yaw angle is required to be controlled within $\pm 2°$. Under constant thrust, the speed fluctuation should be less than $\pm 0.1\mathrm{m/s}$, the acceleration fluctuation should be less than $\pm 0.1\mathrm{m/s^2}$, and the trajectory deviation in linear motion should be less than 2 m. Anti-interference ability includes water flow resistance and collision recovery ability. Dynamic response performance requires that the response time is less than 1 s, the overshoot in the dynamic response process should be less than 5%, and the steady-state error should be less than 2%. For deep-sea operational underwater robots, pressure and corrosion resistance are especially important. Pressure resistance is reflected in maximum operating depth, categorized as shallow water (100 to 300 m), medium-depth (300 to 3,000 m), deep water (3,000 to 6,000 m), and ultra-deep water over 6,000 m. Corrosion resistance, shaped by material choice and surface treatment, reflects the system's ability to withstand biofouling, stress cracking, and corrosion fatigue. Other key performance indicators of the propulsion system include real-time data transmission and noise control. Wired transmission typically requires a bandwidth of 100 Mbps to 1 Gbps, while wireless ranges from 1 to 10 kbps. The propulsion system's noise should be under 120 dB at a one-meter distance, with overall system noise ranging from 100 to 140 dB. Battery endurance lacks a unified industry standard, but for medium-sized operational underwater robots, it generally ranges from 8 to 24 hours.

3. Optimization strategies for propulsion systems of operational underwater robots

3.1. Technological approaches to enhancing propulsion efficiency

Propulsion efficiency is a core metric that directly influences an underwater robot's mobility and endurance. Therefore, improving propulsion efficiency is essential for enhancing their operational capabilities. High-efficiency systems not only reduce energy consumption but also extend operation time and improve task performance. Common approaches to boosting propulsion efficiency include biomimetic propulsion technology, material optimization, and intelligent control algorithms.

Based on fluid dynamics, streamlined hull designsreduce drag and boost propulsion efficiency. By optimizing the contact between the water flow and the robot surface and reducing turbulence, the bionic ostracod underwater robot adopts a two-stage tail fin design that imitates the oscillation mode of fish, which can produce a larger amplitude and a stable oscillation frequency, thereby significantly reducing resistance and improving propulsion efficiency [4]. In addition, underwater attachments

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have a significant impact on the propulsion efficiency of small ROV and AUV, and may even cause propulsion system failures. In order to solve this problem, the application of new materials has become another important way to improve propulsion efficiency. For example, the use of superhydrophobic coatings can significantly reduce the accumulation of biological attachments, reduce the attachment of seaweed plants and microorganisms, and further improve propulsion efficiency. The anti-adhesion properties of these materials can effectively avoid obstacles attached to the surface of underwater robots, thereby maintaining the efficient operation of the propulsion system. In terms of control systems, optimizing image recognition technology is also a key factor in improving propulsion efficiency. Jin et al. proposed a CNN-based underwater image recognition method that overcomes the limitations of traditional techniques. By increasing the underwater target recognition rate by about 11.44%, it significantly improves the recognition accuracy and efficiency of the system. The prediction time for a single image is only 34.3ms, which provides underwater robots with faster real-time response capabilities [5]. In addition, Sun and Lv et al. introduced an enhanced YOLOv4-based method for detecting underwater attached organisms. Retinex-based image enhancement helped overcome light and turbidity interference in recognition [6]. This further improves the recognition efficiency of attached objects and optimizes the operation capability of the propulsion system in complex environments.

3.2. Fault diagnosis and identification technologies for propulsion systems

In complex environments, timely fault detection and diagnosis in propulsion systems are vital to ensure reliable operation and reduce maintenance costs and downtime. However, traditional fault diagnosis methods, such as vibration monitoring and acoustic monitoring, usually have problems of low diagnostic accuracy and easy misjudgment. These methods rely on artificially set features and rules, and it is difficult to cope with complex and changeable fault modes. As a result, accuracy and reliability are often limited, especially under noise and complex environmental interference, where traditional methods struggle to deliver efficient fault diagnosis. In recent years, deep learning has been applied to propulsion system fault diagnosis, offering significant advantages. By automatically extracting features from raw data, it eliminates the need for manual feature selection and enhances diagnostic accuracy and efficiency via powerful pattern recognition and classification capabilities. In addition, trained on extensive datasets, deep learning models accurately identify faults, providing reliable diagnostics. Sequential CNN methods extract both global and local features from state data to classify various propulsion system faults. Compared with traditional deep learning algorithms, this method has significantly improved diagnostic efficiency and accuracy. Previous studies have shown that sequential convolutional neural networks can accurately identify different types of faults, and their fault diagnosis accuracy is as high as over 98%, which greatly improves the accuracy and response speed of diagnosis compared with traditional methods [7]. Unlike traditional vibration and acoustic monitoring, deep learning methods improve fault diagnosis accuracy by autonomously learning data features, minimizing human errors and noise interference. Also, it can handle various complex fault modes and maintain high recognition accuracy, even with unknown fault types.

3.3. Optimization of propulsion system reliability and durability

The reliability and durability of the propulsion system are crucial for deep-sea underwater robots, as they operate in extreme conditions like high pressure, low temperatures, and corrosion. Specifically, high pressure stresses the system's structure, low temperatures impact electronic and mechanical components, and corrosion can damage external and internal parts. As such, the propulsion system design and materials must withstand harsh conditions for reliable long-term operation. In material optimization, the use of deep-sea composite materials has become critical to enhancing propulsion

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system performance. Epoxy-based synthetic foam buoyancy materials, known for their low density and high strength, are widely used in underwater robots such as ROV and AUV. These materials offer excellent buoyancy and withstand high-pressure stress, ensuring the stability of underwater robots in deep-sea operations. Besides, new composite materials like conductive polymer hydrogels with enhanced mechanical properties, have shown excellent performance [8]. In prototype tests with mechanical fish, these hydrogels demonstrated over 600% tensile strength, very low hysteresis (less than 4%), and excellent fatigue resistance (more than 30 Jm^{-2}). With a low Young's modulus, the material offers good elasticity and adaptability in deep-sea environments, effectively enhancing the pressure resistance and reliability of the propulsion system. To boost the reliability and durability of the propulsion system, sealing designs and anti-corrosion coatings play a crucial role. For instance, double O-rings and magnetic fluid seals effectively balance pressure differences, thereby improving pressure resistance. Moreover, the use of pressure compensators further improves the stability of the propulsion system in high-pressure environments. And surface treatment technologies, including superhydrophobic materials, prevent biofouling, reduce corrosion risk, and offer self-cleaning and drag reduction functions, improving propulsion efficiency and minimizing system wear. However, superhydrophobic materials are still in the research stage, and their durability and long-term effects need to be further verified [9]. And these optimizations strengthen the propulsion system, allowing underwater robots to better endure deep-sea conditions, improving reliability and durability.

3.4. Enhancement of adaptive control in propulsion systems

Adaptive control allows underwater robots to adjust parameters and motion states in real-time based on environmental changes and their own conditions, ensuring stable system operation. In propulsion systems, it effectively adapts to dynamic environmental changes, enhancing the robot's flexibility. Traditional fixed-parameter control methods have error rates of 20-30% in dynamic environments, while adaptive control reduces errors to under 5%, improving stability and accuracy. As machine learning and deep learning technologies advance, this algorithm have matured, thus revealing great promise. One promising technology is the adaptive control scheme based on higher-order control barrier functions (HoCBF-QP), which meets the constraints of time-varying systems. Simulation results exhibit its excellent performance in solving tracking control problems with input saturation and output constraints [10]. This method effectively controls high-relative and time-varying systems, enhancing system stability and control accuracy in practical applications. Besides, Ji et al. proposed a meta-learning and adaptive hybrid control method that integrates the feature representation power of deep neural networks (DNN) with the rapid adjustment ability of adaptive control. The method optimizes thrust distribution by learning a high-order fluid dynamics model offline and adjusts the thrust compensation coefficient in real time via an online adaptive rule. Compared to the traditional PID controller, the trajectory tracking accuracy is improved by about 31.3%. Under the conditions of 1.2 m/s water flow and S-shaped trajectory, the control error can be stably controlled within 0.5 meters and the tracking can be continued for 600 seconds [11]. Through these advanced adaptive control methods, underwater robots can show higher accuracy and stronger stability in complex environments. With advances of deep learning and machine learning, adaptive control in propulsion systems will boost robots' ability to operate in diverse environments, driving broader applications in deep-sea exploration and resource extraction.

4. Technical challenges and future prospects

4.1. Existing technical challenges

The propulsion system of operational underwater robots requires balancing multiple factors, such as efficiency, stability, pressure and corrosion resistance, and endurance, which are interdependent. In particular, despite the high-precision control achieved by adaptive control algorithms, they often increase energy consumption; similarly, achieving low communication latency, high endurance, and long transmission distance at the same time remains challenging. ROV with high loads and large depths face high energy consumption, which makes it difficult to achieve a balance between control accuracy and propulsion efficiency. The main technical bottlenecks currently involve endurance, positioning accuracy, and sensor data processing. For example, the surveying accuracy of I-AUV has a deviation of 15% to 20%, and the mapping process cannot reflect environmental changes in real time, and the operation takes a long time [12]. The water-glass-air interface problem faced by the sensor also causes the performance of the visual algorithm to drop by 30% to 40%. The gap between theory and practice cannot be ignored. Economic cost and material manufacturability are key factors that hinder the practical application of many research results. High costs and complex verification lead to discrepancies between theoretical and real-world values, thus making propulsion system optimization more challenging. Also, the contradictions in propulsion system optimization are particularly prominent. To achieve comprehensive optimization, algorithms or system designs must balance the conflicting needs, as improving control accuracy can increase energy consumption, and enhancing endurance and stability may impact positioning accuracy or working depth.

4.2. Future development direction and outlook

In the future, the propulsion system of operational underwater robots will evolve across multiple areas, with a focus on algorithm optimization, mechanical structure enhancements, new materials, and energy applications. New propulsion methods such as flexible propulsion, electromagnetic jet propulsion, and multi-power coordinated propulsion will be widely utilized in underwater robots. Flexible propulsion improves propulsion efficiency and maneuverability by mimicking biological propulsion mechanisms, hence making it ideal for tasks in complex water flow environments and low-noise conditions. Electromagnetic jet propulsion generates electromagnetic fields to drive water flow, reduce wear on mechanical components, and provide a more stable and efficient propulsion method [13]. Hydrogen fuel cells, with their high energy conversion efficiency and zero-emission characteristics, offer significant potential for underwater robots. Compared to traditional batteries, they provide longer battery life, lower noise, and reduced environmental impact, making them ideal for long-term deep-sea operations. Additionally, the use of ultra-light materials will decrease the robot's weight, enhancing its flexibility and efficiency in complex environments. On the autonomy front, artificial intelligence algorithms will boost underwater robots' adaptability and task execution efficiency [14]. AI can optimize path planning, task allocation, and obstacle avoidance, while enabling multi-robot collaboration through autonomous control, improving operational efficiency and task completion. This improves both accuracy and flexibility in complex environments.

5. Conclusion

This paper analyzes the optimization of the propulsion system of the operational underwater robot, covering multiple aspects such as bionic design, new materials, image recognition technology, adaptive control, deep learning technology, and fault diagnosis and identification. The application of these technologies helps to improve propulsion efficiency, stability, environmental adaptability, and pressure and corrosion resistance, but still faces challenges in energy consumption, cost control, and multi-objective optimization. In addition, the lack of available underwater data, the difficulty in achieving high-precision posture control, the lack of industry standards, and the insufficient level of intelligent autonomy still need to be solved. Future research should focus on algorithm optimization, advanced materials and energy, propulsion innovation, and AI integration in underwater robots.

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Although operational underwater robots show strong potential, their wider application still depends on ongoing research and technological innovation.

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