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Modular Design of Underwater Detection Robotic Arm for Small Water Applications

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ABSTRACT
As the problem of global water pollution becomes increasingly serious, issues such as waste pollution and ecological maintenance in small water bodies—including coastal areas, rivers, and lakes—are gaining attention. Traditional underwater robotic arms are primarily designed for deep-sea high-precision operations, which often involve high costs, complex structures, and poor adaptability, making them unsuitable for the low-cost and highly flexible requirements of small water applications. This study proposes a modular underwater robotic arm system tailored for small water environments. Through modular architecture and standardized interface design, the system enables rapid reconfiguration and functional expansion of the robotic arm, enhancing its operational capability and reliability in turbid water conditions. The research employs theoretical analysis, simulation verification, and feasibility demonstration. It begins with clarifying design objectives through requirement analysis, followed by modular system architecture design, detailed design and theoretical calculation of key components (e. g., standardized quick-connect interfaces), kinematic simulation and performance evaluation using multibody dynamics software, and finally, validation of system feasibility through a detailed experimental plan. This study delivers a low-cost, highly reliable modular underwater robotic arm system, offering a practical technical solution for the widespread adoption of underwater operation equipment in small water bodies. It holds significant importance for advancing underwater robotics technology toward affordability and adaptability.

KEYWORDS
Underwater robotic arm; Modular design; System design; Theoretical analysis; Kinematic simulation

1 Introduction

With the acceleration of global industrialization and the expansion of human activities, water pollution has become a major worldwide challenge. According to a 2021 United Nations Environment Programme (UNEP) report, 4.8 to 12.7 million metric tons of plastic waste enter marine environments annually, much of which accumulates in small water bodies such as coastal zones, rivers, and lakes, causing severe ecological damage. The ecological quality of these areas, which serve as critical interfaces between human activity and natural ecosystems, directly affects the quality of life and ecological safety of nearby residents.

Traditional methods for underwater waste removal and ecological maintenance mainly rely on manual diving operations, which are not only inefficient and limited in scope but also pose significant safety risks to operators. These challenges are exacerbated in small water environments characterized by low visibility, complex hydrology, and varied types of debris (e. g., plastic bottles, bags, and discarded fishing nets). Thus, there is an urgent need for intelligent, automated underwater equipment designed for small water applications.

As the core actuation component of underwater robots, the technical capability of the robotic arm directly determines operational performance. In recent years, with advances in artificial intelligence and robotics, underwater equipment has been evolving toward intelligence, light weight, and lower cost. In particular, within the context of China's "Ocean Power" strategy and the "Green Mountains Are Golden Mountains" ecological concept, the development of low-cost, high-performance underwater equipment for small waters such as coasts, rivers, and lakes is of great practical importance and has broad application prospects.

After decades of development, underwater robotic arm technology has made significant progress in drive mechanisms, structural design, and control strategies. Domestic and international research institutions and companies have developed various robotic arms suitable for different depths and scenarios. For example, the hydraulically driven arm developed by the Woods Hole Oceanographic Institution (WHOI) in the U.S. has been successfully deployed in deep-sea scientific missions, and the underwater hydraulic manipulator system developed by Harbin Engineering University in China has also demonstrated excellent performance in deep-sea precision tasks. However, such high-end systems—designed for deep-sea applications—prioritize extreme performance (e.g., depth, precision, load capacity) and often use integrated designs, special materials, and high-performance components, resulting in complex structures, high cost (typically ranging from hundreds of thousands to millions of RMB), and a need for professional maintenance. These factors make them unsuitable for fragmented, high-frequency, low-cost operations in small water environments.

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In contrast, there is a noticeable lack of low-cost, modular robotic arm products designed for small waters such as coasts, rivers, and ponds. These environments are unique due to their shallow depth (typically <10 meters), complex hydrology (currents, silt), low visibility (often <1 meter), and diverse debris types. These conditions impose strict requirements on robotic arms in terms of light weight, adaptability, reliability, cost, and ease of operation.

In recent years, modular robotics has attracted widespread attention for its ability to adapt to different tasks and environments through reconfiguration. Smith et al. (2023) proposed a modular joint design in Ocean Engineering, demonstrating the use of standardized interfaces to reconfigure underwater robotic arms and validating the flexibility offered by modularity. The ROBO-ONE team from Zhejiang University also developed a modular robotic arm system that showed good reconfigurability in laboratory settings. However, these studies have limitations: existing modular solutions focus largely on theoretical validation and large-scale systems without fully considering the environmental constraints of small waters; magnetic interfaces are prone to failure in silt-laden environments; communication protocols among heterogeneous modules (e.g., arm and sensors) are not unified; field reconfiguration success rates remain low (<60%); and there is a lack of task-specific optimization, such as for garbage collection.

Based on this background, the core research question of this study is: How can a modular underwater robotic arm system that combines low cost, high reliability, and task adaptability be designed for small water applications? Specifically, the study addresses the following sub-questions: How can modular architecture design significantly reduce system cost and improve adaptability without compromising performance? How can the reliability of inter-module connections be ensured in real underwater environments, especially those with silt and turbidity? How can effective environmental perception and operational capability—particularly target recognition and grasping in low visibility—be achieved under low-cost constraints?

To address these questions, this study employs the following methodology: operational requirements and technical bottlenecks are clarified through literature review and case analysis; a modular design based on functional decomposition and reusability principles is used for system architecture; module connection reliability is enhanced via standardized snap-fit interface design; environmental perception in low-visibility conditions is improved through multi-sensor fusion technology; and a distributed control architecture based on CAN bus and ROS is implemented to ensure system flexibility and scalability.

This paper is structured into five sections: Section 2 details the research methodology; Section 3 presents the research results; Section 4 provides discussion and analysis; and Section 5 summarizes the findings and outlines future work.

2 Research methodology

2.1 Relevant theories

The theoretical foundation of this study includes:

(1) Modular design theory: Based on principles of functional independence and interface standardization, this reduces inter-module coupling to enable rapid reconfiguration, maintenance, and functional expansion.

(2) D-H parameter method: The Denavit-Hartenberg method is used to establish kinematic models and derive forward/inverse kinematic equations, providing a basis for motion simulation and control.

(3) Multi-sensor fusion theory: A hierarchical fusion strategy employing the Extended Kalman Filter (EKF) algorithm integrates data from sonar, vision, and tactile sensors to achieve accurate and reliable environmental state estimation.

(4) Distributed control theory: The control system is built on the CAN bus protocol, leveraging its multi-master and high-reliability features to achieve decentralized control and system robustness.

2.2 Theoretical improvements

This study introduces the following improvements to existing theory.The mechanical model of the standardized quick-connect interface is optimized by incorporating a dynamic force analysis during mating and unmating, accounting for O-ring deformation resistance, ball-head guiding force, and hydraulic forces. This results in significantly reduced theoretical mating force while maintaining sealing performance and connection stiffness through optimization of the cam curve and ball-head radius.

A lightweight layered sensor fusion strategy is enhanced to dynamically adjust state vector dimensions and update frequencies according to different sensing layer requirements, greatly reducing computational complexity without sacrificing accuracy, thereby improving system real-time performance.

2.3 Data analysis methods

The following data analysis methods are used:

(1) Theoretical calculation and calibration: The safety factor method is applied to evaluate the strength, stiffness, and sealing of all key mechanical structures.

(2) Finite element analysis (FEA): Software such as ANSYS/ABAQUS is used for static simulation of key components to optimize structural design.

(3) Kinematic simulation analysis: The MATLAB Robotics Toolbox is used for kinematic simulation, and the reachable workspace and theoretical positioning accuracy of the robotic arm are evaluated using Monte Carlo methods.

(4) Experimental data processing: Descriptive statistics will be used to analyze repeatability; hypothesis testing will compare performance under different sensor configurations; and Failure Mode and Effects Analysis (FMEA) will assess system reliability.

3 Research results

3.1 Overview of results

Through systematic design and simulation, this study validates the theoretical value of the proposed modular underwater robotic arm in terms of interface reliability, motion performance, sensing capability, and system feasibility. This section presents core findings from theoretical calculations, modeling, and simulation.

3.2 Data presentation and results

3.2.1 Standardized snap-fit interface performance simulation

Finite element analysis was conducted on the quick-connect interface. Under a applied torque of 50 N·m, the maximum equivalent stress at the critical section was 195 MPa, well below the yield strength of the material (6061-T6 aluminum alloy), with a safety factor of 1.38. Simulation of sealing ring contact pressure showed a minimum value of 2.8 MPa, exceeding the required 1.5 MPa.

Table 1 Theoretical performance indicators of the interface

Performance Indicators	Theoretical Calculation/Simulation Value	Design Objective	Conclusion
Maximum withstand torque	50 N·m	40 N·m	Achieved
Maximum equivalent stress	195 MPa	< 275 MPa	Compliant
Safety factor	~1.38	> 1.2	Compliant
Insertion force	35 N	< 40 N	Meets standard

3.2.2 System kinematic simulation results

Based on the D-H parameter model, workspace simulation was performed in MATLAB. Using Monte Carlo methods, one million points were randomly generated to map the reachable workspace of the robotic arm end-effector. The simulation showed that the theoretical workspace of the three-degree-of-freedom configuration is a relatively complete spherical region with a maximum radial reach of 0.85 m. Under ideal conditions (ignoring transmission backlash, structural deformation, and control error), the theoretical repeatability positioning accuracy is ±1.5 mm. Actual accuracy will depend on servo motor performance, reducer clearance, and structural stiffness.

3.2.3 Feasibility of perception and control system architecture

Theoretical calculation of communication delay in the CAN bus-based distributed control network showed that, at a 1 Mbps baud rate, the worst-case delay for transmitting one standard message frame is less than 0.3 ms, fully meeting real-time control requirements for the underwater robotic arm.

3.3 Subgroup comparison (design alternatives)

A theoretical comparison was conducted between two sealing solutions for the interface:

Table 2 Theoretical comparison of sealing solutions

Solution	Advantages	Disadvantages	Reason for Selection
Magnetic fluid seal	Good dynamic sealing, zero friction, long service life	High cost, requires protection against magnetic leakage	Suitable for rotating joints
O-ring seal	Mature technology, low cost, high reliability	High friction resistance, static seal only	Suitable for module end faces

4 Discussion

4.1 Summary of results

This study has developed a modular underwater robotic arm system design supported by detailed theoretical calculations and simulations. Simulation results indicate that the core standardized quick-connect interface exceeds design specifications in both mechanical and sealing performance. Kinematic analysis confirms that the workspace and theoretical accuracy meet application requirements, and the control system architecture provides theoretical guarantees for real-time performance.

4.2 Interpretation of results

The strong agreement between simulation and theoretical results validates the initial design assumptions and model accuracy. The high reliability of the interface stems from an innovative double-ball-head locking mechanism with mechanical-electrical separation, avoiding the failure risks of pure magnetic adsorption in silt environments. Kinematic performance benefits from rational joint configuration and modular structure. The distributed control architecture reflects careful consideration of system reliability and future scalability.

4.3 Limitations

This study has the following limitations:

(1) Simulation vs. reality gap: Unmodeled factors such as material fatigue, machining and assembly errors, and underwater turbulence may lead to discrepancies between physical and simulated performance.

(2) Practical performance of sensing algorithms: Effectiveness in real turbid water environments, especially in recognizing and grasping irregular and soft objects, requires validation through physical experiments.

(3) Energy management and autonomy: Accurate energy consumption assessment and higher-level autonomous decision-making are not fully addressed.

4.4 Practical applications

This design can be directly applied in environmental protection (e. g., rubbish removal from rivers and lakes), aquaculture (e.g., net inspection and dead fish removal), and as a platform for scientific research and education. Most importantly, the low-cost and high-reliability features of this design are expected to promote broader adoption of underwater robotic technology.

5 Summary

This study systematically accomplished the modular design of an underwater detection robotic arm for small water applications. An innovative modular system architecture was proposed, a highly reliable standardized snap-in interface was designed and validated through theoretical calculations and finite element simulations, a kinematic model was established and simulated, a sensing scheme and distributed control system based on multi-sensor fusion were planned, and a comprehensive feasibility analysis along with a detailed experimental plan were conducted. This research provides a practical engineering solution supported by sufficient theoretical verification, laying a solid foundation for addressing the challenges of underwater operation equipment in constrained waters.

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