

Research and Applications of Underwater Robots in the Nuclear Power Field

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Abstract: As a clean and efficient energy source, nuclear power is undergoing rapid global development. However, daily maintenance of nuclear reactor pools faces significant challenges and extreme conditions including high water temperatures, intense radiation, restricted underwater visibility, and complex underwater environments, where conventional manual operations exhibit low efficiency and elevate personnel exposure risks. Underwater robotic technology, particularly radiation-hardened ROVs and hybrid AUV-ROV platforms, has emerged as a critical research focus in the nuclear power sector due to its potential to replace human labor while enhancing operational safety and productivity. This paper systematically analyzes international advancements in underwater robotics for nuclear pool applications, with specific discussions on multi-purpose robotic systems, radiation-hardened technologies, hydrodynamic modeling, object detection algorithms, and autonomous path planning. Comparative evaluations of technical merits and limitations are provided, establishing a reference framework for future technological developments. These insights establish a technical benchmark for next-generation robotic solutions in nuclear asset management.

Keywords: Nuclear Power, Underwater Robots, Pool operation

1. Introduction

With the continuous advancement of socio-economic development and the deepening of industrialization, critical global challenges such as environmental degradation and energy crises have become increasingly prominent, posing significant constraints to sustainable human development. This urgent reality has driven the exploration of innovative energy solutions. Amid escalating global energy demands and growing environmental consciousness across nations and industries, nuclear energy has emerged as a widely recognized clean and efficient energy source, gaining substantial attention and adoption. In recent years, China has achieved groundbreaking progress in nuclear power plant construction and operational technology, particularly demonstrating notable advancements in safety assurance and maintenance efficiency. These developments not only reinforce the viability of nuclear energy but also set new benchmarks for secure and sustainable energy infrastructure worldwide.

However, since the inception of the nuclear industry, the world has witnessed three catastrophic nuclear meltdowns: the Three Mile Island accident (1979), the Chernobyl disaster (1986), and the Fukushima Daiichi nuclear accident (2011). These events not only incurred staggering economic losses but also triggered profound socio-political repercussions. The Chernobyl catastrophe catalyzed

a paradigm shift in global nuclear safety governance, elevating it to a strategic priority within international frameworks like IAEA regulations. Conversely, the Fukushima incident critically underscored the indispensable role of robotic systems in nuclear emergency response. Despite Japan's early investments in nuclear robotics since the 1980s—including pioneering prototypes like the Monirobo radiation monitoring robots—the absence of centralized strategic planning, standardized maintenance protocols, and operational training programs rendered these technologies ineffective during the 2011 crisis. For instance, only 5 of 17 deployed robots successfully completed missions due to communication failures and unanticipated radiation-induced sensor degradation, directly contributing to delayed containment efforts and exacerbating environmental contamination.

Nuclear reactor pools, as a core component of power plants, can be categorized into spent fuel pools (as shown in Figure 1-a) and refueling pools (as shown in Figure 1-b) based on their functions. The spent fuel pool serves to store and cool used nuclear fuel rods. If cracks, voids, or breaches occur in the spent fuel pool and cannot be promptly repaired, water leakage may occur. This would compromise the normal operation of the cooling system, potentially leading to nuclear fuel rod meltdowns or equipment damage, ultimately resulting in nuclear accidents. The refueling pool is designed to store reactor fuel. Any structural failure in this pool could cause nuclear fuel to rapidly leak out under water flow forces. Notably, refueling pool leakage represents one of the most common causes of nuclear accidents.

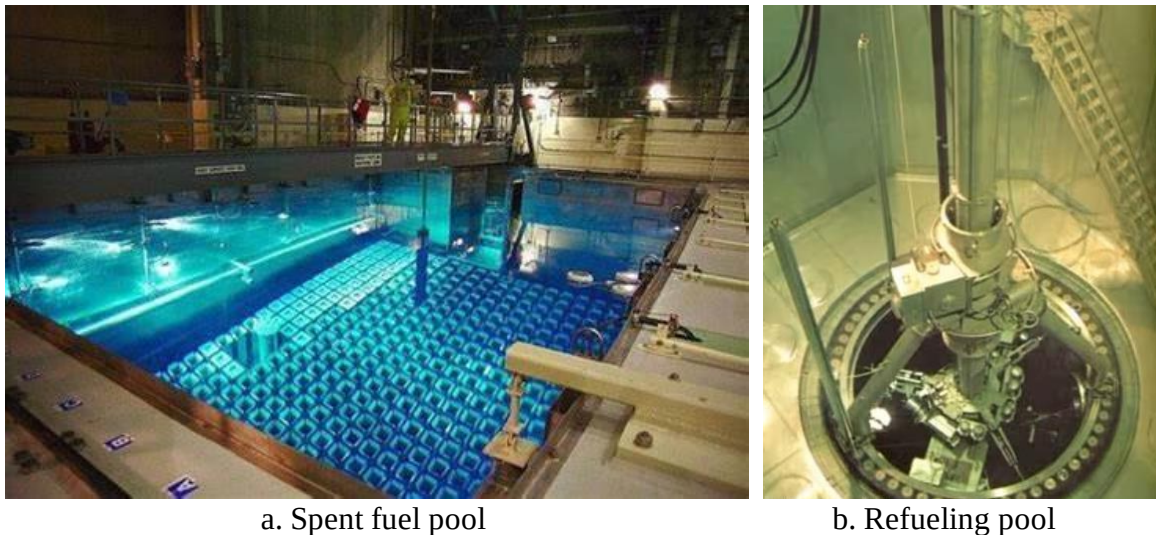


Figure 1: Nuclear reactor pool of a nuclear power plant in China

However, the internal environment of a nuclear power plant is complex, with narrow passageways and numerous obstacles within the structures. For instance, nuclear power plants are equipped with normally closed fire doors and various staircases with different lengths and slopes. Particularly in the pool operation areas, the pool water is deionized water containing boric acid, posing extreme conditions such as weak acid corrosion, high temperature, high pressure, and high radiation, which significantly limit manual operations. Nuclear reactor pools are made of stainless steel, and when cracks or damage occur on the pool walls or bottom, manual repair is required. Manual operations are not only labor-intensive and inefficient, but the radiation environment also poses serious health risks to workers. Additionally, draining the pool water for repairs can disrupt normal plant operations, leading to additional economic losses. Weld inspections and wall cleaning are also critical routine tasks for nuclear reactor pools, which currently rely on manual methods. These tasks similarly face challenges such as low efficiency and health risks to workers due to nuclear radiation exposure.

In the field of nuclear power plant pool operations, the development of underwater robotics technology has evolved from simple remote-controlled operations to intelligent autonomous operations. Early underwater robots were primarily used for basic observation and handling tasks. With advancements in sensor technology, control algorithms, and materials science, modern underwater robots have achieved greater autonomy, precision, and reliability. They are capable of performing a variety of tasks in complex underwater environments, such as equipment inspection, fault diagnosis, and maintenance, significantly enhancing the operational efficiency and safety of nuclear power plants.

Nevertheless, existing underwater robots still face several critical challenges when operating in the unique environment of nuclear power plant pools. For instance, maintaining long-term stable operation of robots in high-radiation environments, improving their positioning accuracy and motion control capabilities in complex water flows, and enabling multi-robot collaborative operations are pressing issues. This study aims to address these challenges by developing a high-performance underwater robot system specifically designed for nuclear power plant pool operations. By optimizing mechanical structure design, refining control algorithms, and integrating advanced sensor technologies, the research seeks to enhance the robot's operational capabilities and reliability in extreme environments. This research not only holds significant theoretical value but also provides robust technical support for the safe and efficient operation of nuclear power plants, demonstrating notable practical significance and application potential.

2. Current Research Status at Home and Abroad

2.1. Domestic Research Status

2.1.1. System Design and Application

Currently, in the field of general-purpose underwater robotics, with the rapid development of computer technology, information technology, sensing technology, and control technology, robots have initially acquired capabilities such as environmental perception, intelligent control, and obstacle avoidance. These advancements enable them to perform tasks such as environmental exploration, assembly, and rescue operations in conventional environments. However, the nuclear power sector presents unique environmental challenges, which impose higher demands on the system design and development of underwater robots specifically tailored for nuclear power applications.

A study by Zhao and colleagues analyzed the current applications and technological advancements of underwater nuclear power robots, covering various fields such as inspection, monitoring, debris removal, emergency response, and underwater welding. They proposed the current composition system of underwater nuclear power robots, and highlighted that related hardware equipment and remote communication in high-radiation environments are critical factors hindering technological progress. [1] Shen and his team designed an underwater drifting detector system specifically for visual inspection of the residual heat removal heat exchanger water tank in AP1000 third-generation nuclear power plants. This system enhances the efficiency and accuracy of non-destructive testing, featuring capabilities such as free-depth positioning, stable operation, and comprehensive process monitoring, tracking, and recording. It can also perform foreign object retrieval tasks. Field tests have demonstrated the system's excellent stability and practical applicability in real-world applications. [2]

Zhang and his team developed a robot system for nuclear emergency response. The dual-arm tracked robot (as shown in Figure 2a) demonstrates strong obstacle-crossing capability and stability when confronting challenges such as steep slopes, high-step obstacles, and deep stair gaps, while simultaneously fulfilling emergency tasks including video surveillance, radiation dose rate monitoring, and specific operational requirements. The compact wheeled robot (Figure 2b) features

a fully waterproof design, enabling it to access building interiors through narrow apertures and channels, or reach the bottom of water pools for sample collection and light-duty emergency operations. The Yaolong series of submersible robots (Figure 3) are specifically designed for underwater environments, capable of conducting environmental surveys and performing underwater emergency interventions. These robotic solutions effectively address the complex structural challenges and high environmental uncertainties characteristic of nuclear power plant emergency scenarios, with their operational performance and radiation resistance having been validated through simulation platform testing. [3]

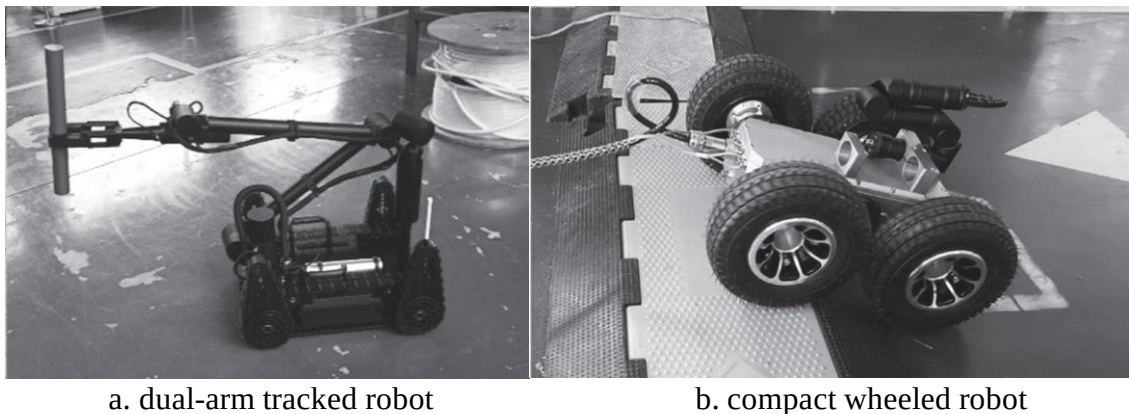


Figure 2: Robot for nuclear emergency response

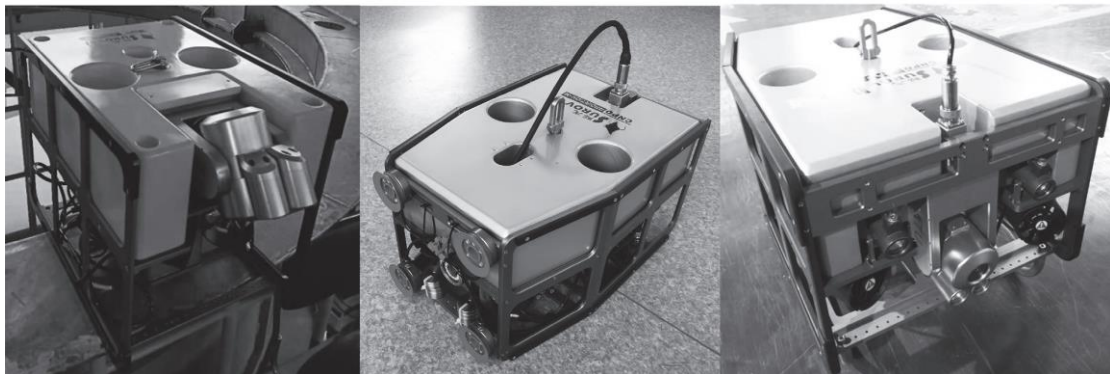


Figure 3: Yaolong series of submersible robots

2.1.2. Anti-Radiation Technology

As the nuclear reaction progresses, the water temperature inside the nuclear reactor pool will gradually rise, consistently maintained between 15-80°C throughout the year. Concurrently, the radiation levels within the pool will correspondingly intensify, with peak radiation levels potentially reaching up to 1 Sv/h. Therefore, when selecting robotic components and materials for manufacturing and processing, full consideration must be given to the impacts of intense radiation exposure, elevated water temperatures, and other environmental factors.

Ma and his team addressed the radiation resistance challenges for underwater mobile robots in nuclear power plants by designing a specialized system. This robot integrates a crawler-type mobile chassis with a positioning platform, utilizing underwater ultrasonic probes for high-precision navigation. To counter the high penetration capability of gamma rays, they established a shielding model and implemented comprehensive radiation hardening strategies. These include critical

component selection optimization, rational shielding design, dose monitoring in control compartments, and modular architecture deployment. This systematic approach significantly enhances robotic reliability under intense radiation environments, offering valuable references for radiation-resistant design in similar nuclear facility equipment. [4] Feng et al. analyzed the research status and key technologies of nuclear environment operating robots, proposing that their current roles involve daily patrol inspections and emergency response operations during accidents. The researchers classified these robots into four categories: detection, obstacle removal, maintenance, and decontamination robots. They identified radiation hardening techniques, communication methods, photoelectric detection, and intelligent control technologies as critical areas requiring immediate breakthroughs. Furthermore, the study highlighted that the development trends for nuclear environment operating robots focus on high stability, intelligence, and versatility. [5]

2.1.3. Hydrodynamic Forces

When robots operate underwater, they are subjected to various disturbance factors, primarily hydrodynamic forces generated by motion, which can be categorized as viscous hydrodynamic forces and inertial hydrodynamic forces. Additionally, the hydrodynamic characteristics in the unique environment of pool-based settings differ from those in open water environments. For currently common tethered underwater robots, it is also necessary to calculate cable forces, including both steady-state cable forces and dynamic cable forces. Research in the field of dynamics has always been a critical yet challenging aspect of underwater robotic applications.

Duan and his team, addressing the cleaning needs of nuclear power plant fuel pools, proposed a structural optimization design for an underwater cleaning robot. They employed topology optimization analysis to lightweight the robot's frame, fully utilizing the material properties under the premise of fixed overall dimensions. This significantly reduced the frame weight of the robot by 74% compared to before optimization, providing a reference for the optimal design of open-frame robots and other plate-like frame structures. The frame structures of the robot before and after optimization are shown in Figure 4. [6].

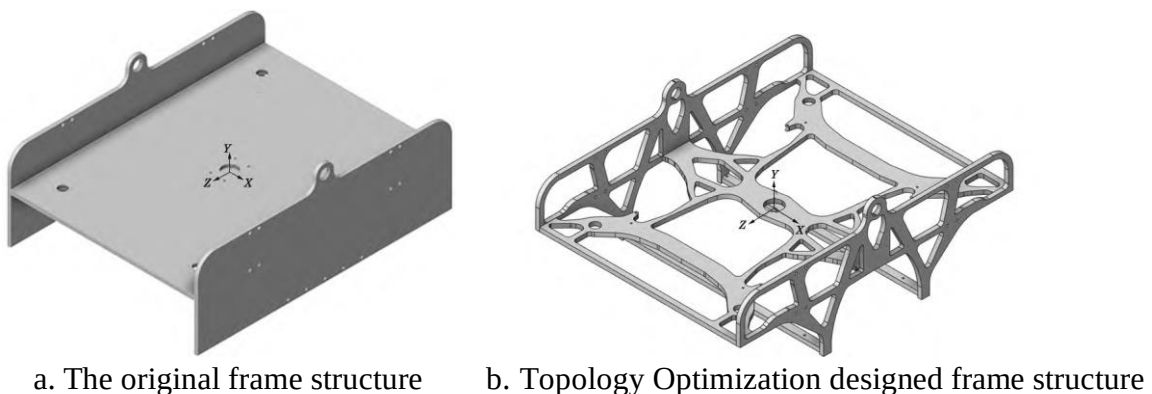


Figure 4: The frame structures of the underwater robot before and after optimization

Luo and his colleagues investigated the redundant thrust allocation strategy for the underwater welding robot HITUWV, focusing on the routine inspection and emergency repair of nuclear power plant pools. Confronted with the challenging environment where the temperature in the nuclear power pool can reach up to 80°C, they proposed a thrust allocation method called LS-QP-Switch, which ingeniously combines the Least Squares (LS) method with Quadratic Programming (QP). This method achieves optimal energy consumption in thrust allocation while adhering to the maximum thrust constraints. The effectiveness and feasibility of this approach were subsequently validated

through simulation.^[7] Li and his team, focusing on operations in nuclear power plant pools, designed an omnidirectional underwater robot system. They placed particular emphasis on investigating its dynamic characteristics, establishing both hydrodynamic and cable mechanical models. These models provide theoretical support for the stable control and precise operation of the robot.^[8] Dong and his team investigated an electrochemical water treatment underwater robot designed for chlorine-containing wastewater, integrating traditional water treatment processes with advanced robotic technology, specifically CDI (Capacitive Deionization) technology. They established the dynamic equations for the underwater robot through kinetic analysis and compared various methods, including empirical approaches, experimental methods, computational fluid dynamics, and control algorithms incorporating artificial intelligence. Their study analyzed the working principles, system modeling, motion control, and trajectory planning of the robot. They highlighted current issues such as the weak interaction capability between underwater robots and their surrounding environment, as well as the limitations of existing monitoring methods, which are often lack reliability. Furthermore, they predicted future technological directions, emphasizing the use of IoT-based multi-device joint monitoring to enhance result credibility, the development of highly reliable and stable motion control systems to improve response speed and operational efficiency, the exploration of new energy applications, and the utilization of artificial intelligence methods to optimize energy allocation for cost reduction and efficiency improvement. ^[9]

2.2. Overseas Research Status

Significant progress has been made internationally in the field of underwater robotics for nuclear power plant pool operations, with a focus on areas such as target detection, miniaturization design, path planning, ecological exploration, and multimodal locomotion.

2.2.1. Target Detection and Tracking

In the field of target detection, to address lightweight underwater targets requiring small model size and high detection accuracy, Song et al. proposed a YOLOv8-based target detection algorithm for underwater robots. By improving the convolutional layers—replacing the original convolution method with adaptive deformable convolution DCNv3—they effectively resolved image deformation issues in underwater target recognition. Additionally, they employed SPPCSPC technology to eliminate redundant computations, reduce complexity, and accelerate model runtime. Simultaneously, by substituting the CIoU (Complete Intersection over Union) loss function with WIoU loss v3, the model's recognition accuracy and image quality were significantly enhanced, achieving an mAP of 86.5%. This approach meets the demands for real-time detection requirements. ^[10] Furthermore, addressing challenges such as uneven underwater illumination, occlusions, viewpoint variations, and scale changes that constrain traditional target tracking methods—alongside the high computational cost and extensive training data requirements of deep learning approaches—Lee et al. developed a Siamese Region Proposal Network (SiamRPN)-based tracking algorithm leveraging deep learning. The architecture employs a twin-branch structure with shared weights, multi-scale anchor generation, and single-shot detection, augmented by underwater image enhancement and panoramic image stitching technologies. This integration enhances computational efficiency (reducing latency by ~40%), expands field-of-view coverage (up to 220°), and mitigates chromatic distortion, effectively overcoming traditional algorithms' limitations in complex environments with a tracking rate of 180 FPS. Future research prioritizes obstacle-aware multi-agent collaboration, multi-sensor fusion, enhanced panoramic imaging (e.g., fisheye lens integration), and robotic arm functional expansion for diversified operational capabilities. ^[11]

2.2.2. Miniaturization Design

In the field of miniaturization design, Wang et al., inspired by jellyfish, developed a centimeter-scale high-speed underwater robot JR, featuring a compact size of $\Phi 5 \times 3$ cm and achieving a maximum speed of 4.6 BL/s. This innovation offers critical insights for the design of small-scale underwater robots. [12] Zhou et al. proposed a miniature underwater robot named CSUR based on a piezoelectric pulsed jet actuator, capable of executing multiple motion modes in high-pressure environments and achieving a maximum linear velocity of 47.8 mm/s. [13] Li et al. further designed a piezoelectric pulsed jet-driven agile underwater robot with a body length under 5 cm, capable of achieving rapid locomotion in high-pressure environments up to 20 MPa. The robot demonstrated a vertical speed of 2.95 BH/s and a horizontal speed of 3.22 BL/s. [14]

2.2.3. Path Planning and Environment Exploration

In the field of path planning, Yang et al. addressed the limitations of existing path planning methods in complex underwater environments by proposing a reinforcement learning-based NPDDQN path planning algorithm integrated with an empirical screening mechanism. The algorithmic framework, as shown in Figure 5, enables rapid and effective obstacle avoidance in challenging conditions while prioritizing the evasion of high-risk obstacles through priority-aware capability, thereby significantly enhancing the autonomy and stability of underwater robots. Future research directions will focus on exploring collaborative path planning for multiple underwater robots and further algorithmic optimization. [15] Furthermore, Girdhar et al. developed the CUREE platform, which integrates robotic behavioral and perceptual algorithms. Equipped with capabilities such as low-altitude visual surveys, acoustic soundscape surveys, and habitat characterization, the platform has been successfully deployed in coral reef ecosystem exploration. The researchers noted that mitigating thruster noise interference with acoustic data, improving stereo vision-based depth estimation, and incorporating support for additional sensors are critical objectives for future development. [16]

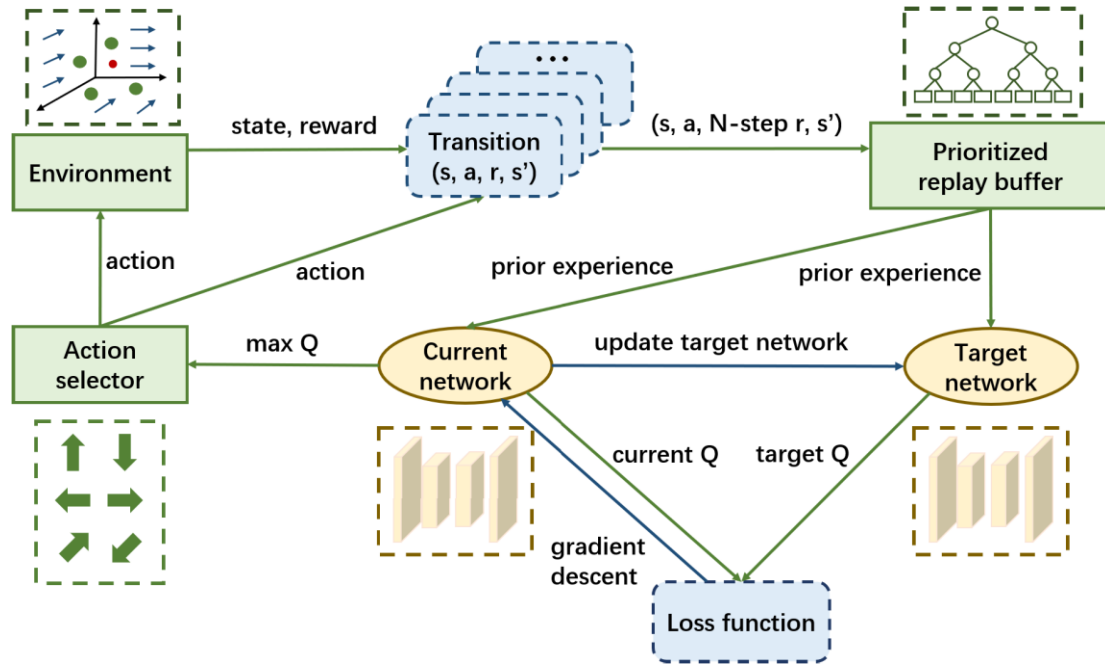


Figure 5: Algorithmic Framework

2.2.4. Multimodal locomotion

In the realm of multimodal locomotion, Kim et al. developed the HERO-BLUE robot, which integrates swimming and walking locomotion. Through the incorporation of multimodal fins and a bio-inspired spinal design, the robot achieves three distinct locomotion modes: swimming, walking, and crawling. [17] Su et al. investigated the symmetric oscillation and steering characteristics of a dual-fin-driven underwater robot with flexible fins, validating its capabilities in hovering, vertical floating, and diving in aquatic environments. [18]

2.2.5. Nuclear power plant applications

In the context of nuclear power plant applications, Mizuno et al., motivated by the post-Fukushima nuclear accident decommissioning efforts—particularly the debris retrieval phase heavily reliant on robotic technologies—conducted a systematic comparative study on three remote manipulator arm operation methods (manual teleoperation, teaching-based teleoperation, and planning-based teleoperation) for debris retrieval tasks within the Primary Containment Vessel (PCV) of Fukushima Daiichi Unit 3. By constructing four simulated environments replicating actual operational conditions, their analysis revealed:

1. Manual teleoperation exhibited low efficiency (prolonged task completion), compromised safety (high collision risk), and excessive operator workload;
2. Teaching-based teleoperation, while enabling collision-free operation, demanded the longest preparation time (up to $3.5\times$ baseline) due to manual path editing;
3. Planning-based teleoperation demonstrated superior performance, reducing operation time by 87–90% compared to manual control and achieving an 80–90% reduction in preparation time versus teaching-playback. However, safety protocols require further refinement to address residual risks in dynamic environments.[19]

In summary, international research has achieved significant advancements across multiple critical technological domains. Nevertheless, persistent challenges remain in areas such as high-pressure-resistant miniaturization design, real-time path planning in complex environments, and coordinated control of multimodal locomotion systems. These unresolved issues demand focused investigation and technological breakthroughs to drive the field forward.

3. Conclusion

Underwater robotics research for nuclear power plant pool operations constitutes a vital technological foundation ensuring the safe and efficient utilization of nuclear energy. These robotic systems effectively replace manual labor, drastically mitigating safety risks in high-radiation, high-temperature, and high-pressure environments while enhancing operational efficiency in reactor pool maintenance. Their applications span mission-critical tasks including equipment inspection, fault remediation, and emergency response, serving as a pivotal driver for advancing intelligent and automated nuclear facility management. Through a systematic analysis of domestic and international research landscapes and technological advancements, this review synthesizes the application potential and persistent challenges of underwater robotics in extreme nuclear environments, while delineating strategic priorities for future development.

Significant progress has been achieved in underwater robotics research for nuclear power plant pool operations both domestically and internationally, providing critical references and insights for technological advancement in this field. Domestic studies have demonstrated notable achievements in system design, radiation hardening, dynamic optimization, and multifunctional applications for robotic reliability in complex environments. International efforts exhibit leading advantages in target

detection, miniaturization design, path planning, and multimodal locomotion. Despite these advancements, critical limitations remain in radiation hardening, intelligent control, high-pressure miniaturization, multi-robot coordination, and energy management. Therefore, continued research in this domain remains imperative for safety enhancement, operational efficiency, and technological sovereignty.

As for the future prospects of underwater robotics in nuclear power plant pool operations, the ongoing development and refinement of robotic technologies will propel underwater robots for nuclear power plant pool operations into broader application domains, significantly enhancing operational safety and maintenance efficiency. Continuous advancements in underwater robotics are poised to deliver high-efficiency solutions and ultra-reliable performance, fundamentally transforming nuclear facility management paradigms. Despite persistent challenges—including radiation-hardened sensor degradation and multi-agent coordination bottlenecks—the convergence of multidisciplinary innovations and iterative technological evolution will drive the phased realization of fully autonomous, intelligent nuclear pool ecosystems. This transition is projected to reduce human radiation exposure by 97–99% while accelerating decommissioning timelines by 40–60%, thereby catalyzing the global transition toward sustainable nuclear energy systems aligned with affordable and clean energy.

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