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Review on Research of Control Technology of Autonomous Underwater Vehicles

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Abstract:
The ocean serves as a vast and largely underexplored frontier, playing a critical role in global resource provision and climate regulation. In recent years, as understanding of its ecological and economic significance has deepened, underwater robots, particularly Autonomous Underwater Vehicles (AUVs), have emerged as indispensable tools for deep-sea exploration and development. Their unique capability to operate untethered from surface vessels offers distinct advantages over Remotely Operated Vehicles (ROVs), including a wider operational range, superior depth tolerance, enhanced maneuverability, and lower maintenance demands. With the growing strategic importance of the oceans in the 21st century, AUVs have proven vital in diverse fields such as resource assessment, scientific research, and military operations. This review aims to synthesize the current state of AUV control technology, identify pivotal research challenges, and outline emerging future trends. It examines a spectrum of control methodologies, ranging from conventional approaches to cutting-edge intelligent algorithms, while focusing on the unique constraints and testing challenges posed by the complex and unpredictable underwater environment.

Keywords: Autonomous Underwater Vehicle; Control Technology; Motion Control; Path Planning; Underwater Navigation

1. Introduction

while focusing on the unique constraints and testing challenges posed by the complex and unpredictable underwater environment. Underwater robots, particularly Autonomous Underwater Vehicles (AUVs), have emerged as indispensable tools for deep-sea exploration and exploitation due to their unique capabilities [1]. These vehicles operate without physical connections to surface vessels, offering significant advantages over Remotely Operated Vehicles (ROVs), including broader operational range, greater depth tolerance, enhanced mobility, and reduced maintenance requirements. The growing recognition of the ocean's importance in the 21st century has

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highlighted the critical role of AUVs in resource development, scientific research, and military applications [2].
AUVs integrate advanced technologies across navigation, control, sensing, and communication, enabling humans to make significant advances in understanding marine environments. The control system serves as the core component of underwater vehicles, determining whether the working state remains stable and reliable [3]. As marine operations extend to deeper and more challenging environments, the demand for sophisticated control technologies has risen dramatically, driving researchers to develop more robust, intelligent, and adaptive control strategies [4].
This review aims to synthesize the current state of AUV control technology, identify key research challenges, and outline future trends. It examines various control methodologies, from traditional approaches to cutting-edge intelligent algorithms, while considering the unique constraints and challenges posed by the underwater environment [5].

2. Overview of AUV Control Systems

Effective AUV operation demands sophisticated control systems addressing fundamental needs: precise motion control, robust task planning, accurate navigation, and reliable obstacle avoidance. These systems must overcome the unique challenges presented by the underwater environment, including limited communication, unpredictable disturbances, and stringent energy constraints.

2.1 Motion Control Architecture

AUVs typically employ hierarchical control architectures that integrate multiple layers of functionality. This structure generally comprises a high-level Task Planning Layer responsible for mission decomposition and goal setting, a Motion Control Layer generating actuator commands to achieve desired trajectories or states, and an Actuator Drive Layer directly controlling thrusters and control surfaces. Modern implementations often utilize embedded systems that fundamentally alter the traditional reliance on combined upper and lower computer architectures, improving reliability and feasibility as validated through sea trials [6].
Recent advancements have introduced innovative approaches to motion control, including vector thruster-based systems that employ dual-loop control algorithms to significantly reduce steering deviation and steering time compared to traditional PID methods [7]. These systems often integrate ARM-based main controllers with peripheral circuits for steering, pitch motors, and main thruster control, operating on real-time operating systems (e.g., μCOS-II) to ensure effective scheduling and management.

2.2 Dynamics and Kinematics Modeling

AUV control design is fundamentally challenged by complex hydrodynamics, inherent system nonlinearities, strong coupling between degrees of freedom, and significant environmental disturbances. Accurate mathematical modeling capturing these effects is essential but difficult to achieve. The modeling process typically involves establishing two coordinate systems: an inertial reference frame (Earth-fixed) and a body-fixed frame attached to the vehicle itself.
The kinematic model describes the relationship between the AUV's position and attitude ($\eta = [x, y, z, \varphi, \theta, \psi]^T$) and its velocities ($v = [u, v, w, p, q, r]^T$), while the dynamic model accounts for the forces and moments ($\tau = [X, Y, Z, K, M, N]^T$) acting on the vehicle. These models must account for various hydrodynamic effects, including added mass, damping, and restoring forces, which grow increasingly complex in dynamic and uncertain underwater environments.

3. Key Control Technologies for AUV

Research focuses on developing robust control strategies to handle the complex AUV operational environment. These approaches range from traditional linear methods to advanced intelligent algorithms capable of adapting to uncertain conditions.

3.1 Traditional Control Methods

Linear control techniques (e.g., Proportional-Integral-Derivative (PID) control, Linear Quadratic Regulator (LQR) control) remain foundational in AUV control due to their simplicity and established parameter tuning methods. These approaches are particularly effective for straightforward tasks such as heading maintenance, depth control, and speed regulation. However, their performance degrades under significant nonlinearities and uncertainties inherent in underwater operations, especially during complex maneuvers or in challenging environmental conditions.
To address these limitations, researchers have developed enhanced traditional methods. For vector thrusters, innovative dual-loop control algorithms have been designed to overcome the poor path tracking performance observed in traditional single-loop PID methods during high-speed turns [7]. These implementations have demonstrated sub-

stantially improved turning path tracking performance through experimental validation.

3.2 Modern Control Methods

Modern control approaches address the limitations of linear controllers by explicitly accounting for system non-linearities and uncertainties. Sliding Mode Control (SMC) provides robustness against matched uncertainties but may exhibit chattering effects that can excite unmodeled dynamics. Adaptive control continuously adjusts parameters to handle unknown or varying dynamics, while robust control techniques optimize performance under model uncertainty and disturbances.

Recent advancements in modern control include adaptive backstepping sliding mode control, which combines the strengths of multiple approaches [5]. For trajectory tracking tasks subject to unknown external environmental disturbances (e.g., ocean currents) and variations in added mass, researchers have developed controllers that use T-observers for input compensation and backstepping adaptive methods for uncertainty compensation. These approaches significantly reduce trajectory tracking errors and improve AUV anti-interference capabilities, enabling real-time trajectory control.

Model Predictive Control (MPC) uses an online optimization approach, excelling in handling constraints and previewing future states, though it remains computationally demanding for complex AUV applications. Finite-time control methods have also emerged, addressing model uncertainties, external disturbances, and actuator limitations simultaneously [6]. These approaches employ finite-time backstepping control (FTBSC) for kinematic laws and adaptive fixed-time disturbance observers (AFTDO) for dynamic control, with auxiliary compensation systems to mitigate the adverse effects of magnitude and rate saturations.

3.3 Intelligent Control Methods

Artificial Intelligence techniques enhance AUV adaptability through learning and approximation capabilities. Fuzzy logic control leverages expert knowledge without requiring precise models but faces challenges in tuning and optimization. Neural Network (NN) controllers approximate complex nonlinear functions online, significantly improving tracking performance and disturbance rejection.

Reinforcement Learning (RL) explores autonomous policy learning for complex tasks like adaptive path following. Recent breakthroughs include the UR-EARL framework, which combines evolutionary algorithms with reinforcement learning to concurrently optimize AUV morphology and control strategies [2]. This approach uses Lindenmayer-System (L-System) evolutionary algorithms alongside TD3 reinforcement learning to synchronize the optimization of AUV morphology and behavioral strategies, demonstrating excellent performance in non-uniform, non-stationary flow field environments.

The integration of these intelligent methods has enabled substantial progress in AUV autonomy. Systems can now perform complex tasks such as underwater inspection, pipeline monitoring, and adaptive sampling with minimal human intervention, learning from experience and adapting to changing conditions.

3.4 Path Planning and Trajectory Tracking

Efficient global and local path planning algorithms generate collision-free paths, while dedicated trajectory tracking controllers ensure the AUV accurately follows these paths in the presence of disturbances.. Recent research has emphasized three-dimensional path following capabilities, particularly for underactuated AUVs dealing with model uncertainties and environmental disturbances.

Novel guidance frameworks (e.g., the Serret-Frenet Line-of-Sight (SFLOS) method)have been developed for heterogeneous systems involving both Unmanned Surface Vehicles (USVs) and AUVs [9]. These approaches employ path parameter synchronization mechanisms through adjacency matrices to enable topological communication between different vehicle types, significantly improving coordination in marine operations.

For trajectory tracking problems, advanced methods such as adaptive backstepping sliding mode control have shown excellent performance in handling external disturbances like ocean currents and changes in additional mass [5]. These approaches utilize nonlinear disturbance observers alongside adaptive backstepping sliding mode algorithms to design trajectory tracking control laws, significantly improving the precision of AUV motion control.

3.5 Navigation and Localization

While distinct from control per se, navigation underpins control effectiveness by providing accurate state estimation. Techniques include Inertial Navigation Systems (INS), often fused with Doppler Velocity Logs (DVL) and Ultra-Short Baseline (USBL) acoustic positioning for improved accuracy. Simultaneous Localization and Mapping (SLAM) enables navigation in unknown environments

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by building maps while simultaneously localizing within them.

Recent innovations in navigation systems focus on addressing the challenges of underwater positioning in GPS-denied environments. Systems like the Pike AUV utilize Doppler velocity logs combined with inertial navigation systems, along with panoramic sonar and optional multibeam echo sounding systems for detailed mapping and obstacle avoidance [8]. These capabilities enable organizations to integrate AUVs into existing operations without fully overhauling their sensor suites.

For precise docking operations, advanced guidance systems employing deep learning-based monocular and binocular pose measurement algorithms have been developed. These systems combine dark channel prior defogging with YOLO v9 target detection networks to achieve robust guidance light extraction adaptable to different water qualities and illumination intensities.

4. Research Challenges and Current Limitations

Despite significant progress, AUV control technology faces several persistent challenges that limit widespread deployment and full autonomy in complex environments.

Modeling Fidelity: Accurately modeling complex, nonlinear hydrodynamic behaviors across the entire operational envelope remains a challenge, substantially impacting controller robustness. The hydrodynamic models must account for various factors including added mass, damping, restoring forces, and their interactions, which change with operating conditions and environmental variations. The problem is further complicated by potential changes in AUV mass properties during operations, such as those caused by marine growth or payload deployment.

Environmental Uncertainty: Intense ocean currents, waves, and unstructured seabeds introduce unpredictable disturbances that challenge even robust controllers. Ocean environments feature complex spatial and temporal variability that is difficult to predict or model accurately. Recent research has attempted to address this by incorporating non-uniform, non-stationary flow field models using sinusoidal functions to simulate horizontal and vertical flow variations in real oceans.

Underwater Communications: Limited bandwidth and latency hinder real-time control updates, teleoperation, and multi-AUV coordination. Underwater acoustic communications remain the primary method for long-range data transmission, but they suffer from low bandwidth, high latency, and significant attenuation. These limitations pose substantial challenges for multi-vehicle coordination and real-time supervision, particularly in applications requiring high levels of coordination or human oversight.

Energy Constraints: Battery capacity limitations constrain mission duration and operational range, conflicting with demands for long-endurance autonomy. While advancements in energy systems have been made, including lithium-ion batteries and hydrogen fuel cells derived from automotive technology, the fundamental energy density limitations continue to constrain AUV operational capabilities. This is particularly challenging for small-scale vehicles where space for energy storage is severely limited.

Multi-AUV Coordination: Developing efficient, robust coordination, communication, and collision avoidance strategies for swarms is complex due to the communication constraints and dynamic underwater environment. While research has demonstrated promising approaches for heterogeneous systems, scaling these solutions to larger fleets operating in challenging conditions remains an open challenge requiring further investigation.

4.1 Intelligent Algorithm Deployment

Ensuring the real-time performance, robustness, safety, and verifiability of complex AI/ML controllers in harsh underwater environments is non-trivial. The transition from simulation to real-world deployment presents significant challenges, including the simulation-reality gap between models and actual vehicle behavior, computational constraints on embedded platforms, and certification difficulties for safety-critical applications.

5. Conclusion and Future Directions

5.1 Summary of Conclusions

Control technology serves as the cornerstone of effective AUV operation, enabling deployment in diverse and challenging underwater missions. This review has examined the spectrum of control strategies, from foundational PID methods to modern robust/adaptive approaches and emerging AI-driven intelligent controllers. Each approach offers distinct advantages while facing specific challenges related to the complex, nonlinear, and uncertain underwater environment.

Current research clearly indicates that increased intelligence, autonomy, and multi-functionality are dominant future trends. The integration of evolutionary algorithms with reinforcement learning represents a particularly promising direction, enabling simultaneous optimization of vehicle morphology and control policies [2]. Similarly, advances in heterogeneous collaboration between different vehicle types (USVs and AUVs) open new possibilities for coordinated marine operations [9].

5.2 Research Limitations

Key limitations persist across multiple dimensions. Achieving high-fidelity hydrodynamic models across all operational scenarios remains a challenge due to the complexity of fluid-structure interactions and environmental variability. Ensuring controller robustness against extreme and unpredictable environmental disturbances requires further development, particularly for long-duration missions where conditions may change dramatically.

The bottleneck imposed by limited underwater communication bandwidth continues to constrain real-time control and multi-vehicle systems, necessitating innovative approaches to decentralized coordination. Energy constraints fundamentally limit endurance and scope, driving research into more efficient propulsion systems and energy management strategies. Finally, ensuring the real-time performance, safety, and verifiability of complex intelligent control algorithms in harsh conditions remains a significant challenge.

5.3 Future Research Directions

Building on current trends and addressing existing limitations, future research should prioritize several key directions:

Enhanced Intelligence: Deepening the integration of Artificial Intelligence, machine learning, and reinforcement learning to drastically improve environmental perception, autonomous decision-making, adaptive control, and predictive capabilities. The UR-EARL framework combining evolutionary algorithms with reinforcement learning represents a promising step in this direction [2].

Increased Autonomy: Advancing energy management systems and exploring in-situ self-maintenance concepts to enable truly long-endurance, untethered missions. Hydrogen fuel cell technology, as implemented in the Greyshark Foxtrot variant offering 16 weeks of continuous submersion, points toward this future [4].

Multi-Functionality & Collaboration: Developing highly integrated AUV platforms that can seamlessly switch between or concurrently execute complex tasks. Research into efficient, robust coordination, communication, and control strategies for heterogeneous multi-AUV systems and AUV/surface vessel teams is crucial [9].

Resilience and Verification: Developing rigorous methodologies for testing, validating, and certifying the safety and reliability of increasingly complex autonomous systems and AI controllers in realistic underwater conditions. This includes addressing the simulation-to-reality gap through advanced verification and validation frameworks.

Novel Platforms and Actuation: Exploring bio-inspired designs, soft robotic technologies, and advanced propulsion/actuation systems for improved maneuverability, efficiency, and environmental interaction. Evolutionary design approaches have already produced promising configurations with high density (>3000 kg/m³) and compact form factors that demonstrate superior performance in dynamic flow fields [2].

Cross-Domain Coordination: Advancing coordination among underwater, surface, and aerial systems to create integrated marine sensing and operation networks. This requires solving challenging problems in communication, coordination, and task allocation across different domains.

As AUV technologies continue to evolve, they will play increasingly important roles in marine science, industry, and security. From monitoring climate change impacts to maintaining critical underwater infrastructure and enabling sustainable resource extraction, AUVs equipped with advanced control systems will expand human capabilities in the challenging underwater environment. The future will likely see greater integration of AUVs into broader maritime systems, working collaboratively with surface vessels, aerial drones, and fixed infrastructure to provide comprehensive marine domain awareness and response capabilities.

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