Sliding Mode Control Techniques for Autonomous Underwater Vehicles: A Comprehensive Review and Future Outlook

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Abstract

Autonomous Underwater Vehicles (AUVs) operate in highly uncertain and dynamic underwater environments, making robust and adaptive control strategies essential for reliable navigation and mission execution. Sliding Mode Control (SMC) and its advanced variants—including Adaptive Sliding Mode Control (ASMC), High-Order SMC (HOSMC), Terminal SMC (TSMC), and hybrid intelligent approaches—have gained significant attention due to their inherent robustness and disturbance rejection capabilities. This paper presents a comprehensive review of over 48 recent research articles on SMC-based techniques applied to AUVs, analyzing their strengths and limitations in terms of robustness, chattering reduction, tracking accuracy, computational complexity, and real-time feasibility. Comparative analysis highlights the trade-offs among classical and modern control schemes, emphasizing the importance of hybrid and learning-based methods for enhanced adaptability. Furthermore, this review identifies key research gaps, such as unmatched disturbance handling, energy-efficient control, fault tolerance, and scalability to multi-AUV systems. Finally, promising future research directions are proposed to guide the development of next-generation control algorithms that balance robustness, intelligence, and efficiency in underwater autonomous navigation.

Keywords

Autonomous Underwater Vehicles (AUVs); Sliding Mode Control (SMC); Adaptive Control; High-Order Sliding Mode; Robust Nonlinear Control; Chattering Reduction; Hybrid Intelligent Systems; Marine Robotics

1. Introduction

Autonomous Underwater Vehicles (AUVs) have gained significant attention over the last two decades due to their critical roles in underwater exploration, oceanographic data collection, pipeline inspection, military surveillance, and search-and-rescue missions [31], [44]. Operating in highly unstructured, nonlinear, and uncertain marine environments poses significant control challenges for AUVs. These vehicles face unpredictable ocean currents, hydrodynamic uncertainties, and sensor noise, which often degrade the performance of traditional linear control techniques [1], [41].

Sliding Mode Control (SMC) has emerged as one of the most robust control methods suitable for such conditions due to its insensitivity to matched disturbances and modeling errors [3], [18], [45]. Classical SMC ensures asymptotic convergence and strong robustness; however, its main drawback is the chattering phenomenon, which may excite unmodeled dynamics or damage mechanical actuators [5], [6].

To address these limitations, a range of enhanced SMC techniques has been proposed. Adaptive Sliding Mode Control (ASMC), for instance, introduces online tuning of control gains to handle time-varying parameters and bounded uncertainties without requiring precise knowledge of system bounds [11], [14], [15]. Terminal and Fast Terminal SMC methods provide finite-time convergence by utilizing nonlinear sliding manifolds [16], [17], [45]. High-Order Sliding Mode Control (HOSMC) techniques further reduce chattering while maintaining robustness by including derivatives of the sliding variable [13], [19].

Recent advances have also focused on hybridizing SMC with intelligent and soft computing methods such as Fuzzy Logic, Artificial Neural Networks, Reinforcement Learning, and Model Predictive Control (MPC) [22], [23], [26], [28], [47]. These approaches improve adaptability, tracking performance, and generalization in highly dynamic conditions. Particularly in underwater robotics, such hybrid controllers have demonstrated remarkable performance in real-time navigation and trajectory tracking [32], [34], [38].

Several review studies have addressed AUV control systems [41], [42], [44], but a dedicated, in-depth analysis of the evolution and application of Sliding Mode Control and its hybrid forms in underwater systems remains lacking. Therefore, this paper aims to provide a comprehensive and comparative review of SMC, ASMC, HOSMC, and hybrid control strategies applied to AUVs. We analyze the advantages and limitations of each technique based on criteria such as robustness, accuracy, computational complexity, and real-time applicability. Finally, we summarize existing gaps in the literature and propose potential directions for future research [42], [48].

2. Theoretical Background

Effective control of Autonomous Underwater Vehicles (AUVs) requires robust methods that can deal with the nonlinear dynamics, strong coupling, and unpredictable underwater disturbances. Among various nonlinear control techniques, Sliding Mode Control (SMC) and its extensions have shown great promise due to their robustness, simplicity, and adaptability [3], [18], [45].

2.1 Classical Sliding Mode Control (SMC)

SMC is a variable structure control technique designed to drive the system state to a predetermined sliding surface and maintain it there for all subsequent time. Once on the surface, the system exhibits desirable dynamics that are robust to matched uncertainties [3], [19].

Let $e(t) = x_d(t) - x(t)$ denote the tracking error. A typical sliding surface is defined as:

$$s(t) = \dot{e}(t) + \lambda e(t)$$

Where $\lambda > 0$ is a positive design constant.

The standard SMC law is given by:

$$u(t) = u_{eq}(t) - K.sign(s(t))$$

Where $u_{eq}(t)$ is the equivalent control (assuming perfect model knowledge), and K is a gain selected to dominate the uncertainties.

While SMC provides strong robustness and finite-time convergence, it suffers from a phenomenon known as chattering, caused by high-frequency switching near the sliding surface [5], [6], [18]. Chattering can induce unwanted vibration and actuator wear—especially critical in underwater thrusters.

2.2 Adaptive Sliding Mode Control (ASMC)

To overcome the need for precise upper bounds on uncertainties (required to choose K), ASMC adapts the switching gain dynamically, leading to better performance and reduced conservativeness [11], [14], [15].

An example adaptive law is:

$$\dot{k}(t) = \gamma|s(t)|$$

Where $\gamma > 0$ is an adaptation gain. In many cases, the gain $k(t)$ increases when the system is far from the sliding surface and stabilizes when it nears convergence [13].

In AUV applications, ASMC has shown improved energy efficiency and adaptability in changing ocean conditions [32], [34].

2.3 High-Order and Terminal Sliding Mode Control

High-Order SMC (HOSMC) addresses the chattering problem by applying the sliding condition to derivatives of the sliding surface. In the second-order SMC, the control law ensures that both $s(t)$ and $\dot{s}(t)$ converge to zero, leading to smoother control inputs [17], [19], [45].

For instance, the Super-Twisting Algorithm (STA), one of the most used HOSMC schemes, defines:

$$u(t) = -k_1 |s|^{1/2} . sign(s) - k_2 \int sign(s)dt$$

with appropriate gains $k_1, k_2 > 0$.

Terminal Sliding Mode Control (TSMC), on the other hand, introduces nonlinear sliding surfaces to ensure finite-time convergence. A typical surface is:

$$s(t) = \dot{e}(t) + \lambda e(t)^{\alpha} \qquad with\; 0 < \alpha < 1$$

TSMC is particularly useful for fast convergence in time-sensitive missions, such as docking or evasive maneuvers in AUVs [14], [16], [38].

2.4 Hybrid and Intelligent Sliding Mode Approaches

To enhance robustness and adaptability, researchers have developed hybrid schemes that integrate SMC with intelligent control paradigms. For example:

- Fuzzy-SMC dynamically adjusts control gains based on rule-based logic [22], [26].
- Neural Network-SMC leverages learning capabilities to estimate model uncertainties or switching gains [23], [29].
- Reinforcement Learning-SMC enables online adaptation in highly dynamic, unstructured underwater scenarios [28], [47].

These hybrid methods show superior performance in trajectory tracking, energy efficiency, and fault tolerance [32], [34], [38].

3. Comparative Analysis of Sliding Mode and Hybrid Control Techniques

Controlling AUVs under unpredictable underwater conditions requires strategies that balance robustness, precision, and computational feasibility. In this section, we systematically compare classical Sliding Mode Control (SMC), its advanced variants (ASMC, HOSMC, TSMC), and hybrid methods based on intelligent systems in terms of their performance, complexity, and applicability.

3.1 Robustness and Disturbance Rejection

Classical SMC is inherently robust against matched disturbances and modeling uncertainties, making it a favorable choice for underwater systems where model inaccuracies are common [3], [18], [45]. However, its performance degrades when dealing with unmatched disturbances, such as external forces acting outside the control direction, or when system dynamics change over time [5], [41].

ASMC addresses this issue by updating the switching gain based on online estimation of uncertainties, resulting in improved performance under time-varying conditions [11], [14], [15]. For example, in [34], an ASMC scheme successfully rejected depth perturbations caused by internal waves.

HOSMC and TSMC both improve robustness while reducing chattering, with TSMC offering finite-time convergence and better tracking under time constraints [16], [17], [38]. Hybrid methods—especially fuzzy and neural-network-enhanced SMC—adaptively handle both matched and unmatched uncertainties, though at the cost of more complex tuning and training procedures [22], [26], [29].

3.2 Chattering Reduction

Chattering is one of the most critical drawbacks in SMC-based control [6], [18]. While classical SMC suffers from high-frequency switching, HOSMC and TSMC effectively reduce or eliminate this issue [13], [17], [45]. In particular, the Super-Twisting Algorithm (STA) in second-order SMC has demonstrated significant reduction in chattering without losing robustness [19].

Fuzzy and neural-SMC controllers dynamically adjust control inputs based on smooth approximations, further minimizing abrupt transitions in control action [22], [23], [28].

3.3 Tracking Accuracy

In trajectory tracking tasks—such as waypoint following or pipeline inspection—accuracy is a critical performance measure. ASMC, TSMC, and intelligent SMC variants have demonstrated superior tracking performance compared to classical SMC in several experimental and simulation studies [26], [32], [34].

In [38], a combination of reinforcement learning and terminal SMC enabled accurate path following in a simulated dynamic environment with variable currents.

3.4 Complexity and Computational Load

Classical SMC is mathematically straightforward and easy to implement in real-time, making it ideal for low-cost embedded AUV systems [3], [5]. However, its simplicity comes at the cost of limited adaptability.

ASMC and TSMC introduce additional parameters and online adaptation mechanisms, which moderately increase computational burden [13], [14].

Hybrid techniques, particularly those involving neural networks or deep learning, demand high computational power and are generally more suitable for high-end AUV platforms with onboard GPUs or edge computing support [23], [29], [47].

3.5 Practical Applications and Real-Time Feasibility

Several experimental studies have validated SMC and ASMC on real AUV platforms in field conditions. For example, in [32], ASMC was tested on a Remotely Operated Vehicle (ROV) for depth control under current disturbances. In [26], a fuzzy-SMC controller improved energy efficiency during long-duration navigation tasks.

However, the deployment of hybrid learning-based SMCs in real-time systems remains limited due to computational overhead, parameter tuning complexity, and safety concerns during training [28], [47].

3.6 Summary Table

Table 1Comparative analysis of classical SMC, advanced SMC variants, and hybrid control methods for AUV applications in terms of robustness, chattering, accuracy, computational complexity, and real-time feasibility.

Control Method	Robustness	Chattering	Accuracy	Complexity	Real-Time Applicability
Classical SMC	High	High	Moderate	Low	Excellent
ASMC	Very High	Moderate	High	Moderate	Good
HOSMC	Very High	Low	High	Moderate	Good
TSMC	High	Low	High	Moderate	Good
Fuzzy-SMC	High	Very Low	High	Moderate	Good
Neural-SMC	Very High	Very Low	Very High	High	Moderate
RL-based SMC	High	Low	Very High	Very High	Limited

4. Discussion and Future Directions

The comprehensive review and comparison of Sliding Mode Control (SMC) techniques reveal their growing relevance in the control of Autonomous Underwater Vehicles (AUVs). While SMC remains attractive due to its simplicity and robustness, the evolution toward adaptive, high-order, and hybrid versions addresses many of its traditional limitations.

4.1 Key Findings

Robustness remains the cornerstone of SMC approaches. Despite their different formulations, most techniques provide excellent resilience to matched disturbances and system uncertainties [3], [14], [45].

Chattering mitigation is a central theme across recent studies. High-order SMC (e.g., Super-Twisting) and fuzzy-logic controllers are widely adopted for smooth control signal generation without compromising robustness [13], [17], [26].

Tracking precision is significantly improved using adaptive and terminal sliding surfaces. These approaches allow fine-grained control, particularly in time-constrained and dynamic environments [16], [34], [38].

Hybrid intelligence (e.g., Fuzzy, Neural Networks, RL) provides significant advantages in adaptability and learning capabilities, but introduces additional design complexity and computational overhead [22], [28], [47].

Real-world deployment is still limited for AI-integrated control schemes. Most field-tested implementations rely on classical or adaptive SMC due to ease of implementation and reliability [5], [26], [32].

4.2 Research Gaps and Open Challenges

Despite substantial progress, several research gaps remain:

1. Unmatched Disturbance Handling: Many existing SMC variants focus on matched disturbances. Addressing unmatched uncertainties—like lateral currents or thruster degradation—requires more advanced observer-based or robust hybrid designs [41], [44].
2. Model-Free and Learning-Based Methods: While reinforcement learning and neural networks show promise, their stability guarantees and interpretability in mission-critical systems like AUVs remain challenging [28], [47].
3. Energy-Aware Control: Very few studies consider energy constraints explicitly. Designing SMC variants that optimize energy use while maintaining tracking performance is crucial for long-duration AUV missions [34], [46].
4. Fault-Tolerant Control: Integration of SMC with fault diagnosis modules is underexplored. In mission-critical applications, controllers should ensure stability under partial actuator or sensor failures [36], [48].

5. Scalability to Multi-AUV Systems: Most literature focuses on single-AUV control. Future research must investigate cooperative SMC designs for multi-agent underwater missions with communication delays and decentralized architectures [43].

4.3 Future Directions

Based on the identified gaps and the evolution of the field, we propose several research directions:

- Development of unified adaptive-hybrid SMC frameworks combining high-order SMC, fuzzy logic, and learning-based estimation to tackle both matched and unmatched uncertainties efficiently.
- Deployment of lightweight learning-based control suitable for embedded processors on AUVs, using model compression, online adaptation, and safe reinforcement learning.
- Integration of energy models and mission planning within the control loop to jointly optimize path tracking, energy usage, and task success under environmental constraints.
- Design of modular SMC-based fault-tolerant architectures with built-in redundancy and auto-reconfiguration under faults.
- Experimental validation on diverse AUV platforms under realistic ocean environments to bridge the gap between theoretical advancements and operational readiness.

5. Conclusion and Contributions

In this review, we provided a comprehensive analysis of Sliding Mode Control (SMC) and its advanced and hybrid variants for Autonomous Underwater Vehicle (AUV) navigation and control. From classical SMC to adaptive, higher-order, terminal, and intelligent-hybrid methods, the evolution of control strategies reflects a balance between robustness, adaptability, and implementation feasibility.

Key Contributions of This Work:

1. Systematic categorization and comparison of over 48 research papers spanning classical to intelligent SMC techniques for AUVs.
2. Identification of core advantages and drawbacks of each control strategy based on precision, disturbance rejection, chattering behavior, and complexity.
3. Highlighting gaps in current literature, especially concerning unmatched disturbances, fault tolerance, and scalability.
4. Proposing a roadmap for future developments, including energy-efficient control, lightweight AI models, and multi-agent coordination in underwater scenarios.

Closing Remarks:

Sliding Mode Control continues to be a powerful technique in underwater robotics. However, to meet the growing demands of autonomy, energy awareness, and reliability in real-world oceanic environments, next-generation control strategies must be intelligent, adaptive, and computationally scalable. This review lays the groundwork for future research in this domain, enabling the development of more resilient and efficient underwater vehicles.

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