Robust AUV Trajectory Tracking in MATLAB Using Sliding Mode Control Methods

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Abstract

This paper presents the design and implementation of robust control strategies for trajectory tracking of Autonomous Underwater Vehicles (AUVs) under external disturbances. Three control approaches—Simple Sliding Mode Control (SMC), Adaptive SMC, and Disturbance Observer-Based Adaptive SMC—are developed and compared in MATLAB simulations. Each method addresses the challenge of model uncertainties and external forces affecting AUV dynamics. Root Mean Square Error (RMSE) is used as a performance metric to evaluate trajectory tracking accuracy. The proposed Adaptive SMC with disturbance estimation shows improved robustness and reduced tracking error compared to other strategies. The results validate the effectiveness of combining sliding mode control and adaptation mechanisms in uncertain underwater environments.

Keywords: Autonomous Underwater Vehicle (AUV), Sliding Mode Control (SMC), Adaptive Control, Disturbance Observer, Robust Control, MATLAB Simulation.

Introduction

Autonomous Underwater Vehicles (AUVs) are increasingly crucial in applications such as marine exploration, environmental monitoring, and subsea intervention [1,2]. However, trajectory tracking of AUVs is challenged by nonlinear dynamics, environmental disturbances, and model uncertainties. Sliding Mode Control (SMC) offers robustness against such perturbations but may suffer from chattering and requires high control gains [3,4]. Adaptive SMC techniques and disturbance observers (DOB) have been proposed to mitigate these issues by estimating and compensating disturbances online [1,5,6]. Recent studies demonstrate that integrating adaptive laws and DOB with SMC significantly improves tracking accuracy [4,7,9], yet a comprehensive comparison among classical SMC, Adaptive SMC, and DOB-based SMC remains limited. This paper aims to fill that gap by implementing all three methods in MATLAB and evaluating their performance via Root Mean Square Error (RMSE).

2. System Modeling

In this study, a 3-DOF planar AUV model is used, capturing surge, sway, and yaw dynamics. The state vector is defined as:

$$x = [u\ v\ r\ x\ y\ \varphi]^T$$

where u and v are linear velocities in the body frame, r is the angular (yaw) rate, and x, y, φ represent the global position and heading. The system dynamics are nonlinear due to hydrodynamic interactions and external disturbances.

The general form of the AUV dynamics can be expressed as:

$$\dot{x} = f(x) + g(x)\tau + d_{ext}$$

Here, $f(x)$ represents the nominal dynamics, $g(x)\tau$ is the control input (forces and moments), and d_{ext} accounts for unmodeled dynamics and environmental disturbances like ocean currents [2][5][11].

To maintain simplicity while preserving fidelity, a model-based discrete-time simulation using MATLAB is employed. The function auv_model_dob.m includes nonlinear coupling terms and additive disturbance forces to simulate real-world conditions [4][6].

3. Control Strategies

In this section, we describe and compare three control strategies used to ensure trajectory tracking for the autonomous underwater vehicle (AUV) under environmental disturbances:

3.1. Conventional Sliding Mode Control (SMC)

Sliding Mode Control is a robust nonlinear control technique known for its resilience to disturbances and model uncertainties [7]. The control law is derived based on the tracking error $e = x - x_d$ and its derivative:

$$s = \dot{e} + \lambda_e$$

$$\tau = -K.sign(s)$$

Where:

- s: Sliding surface
- λ: Positive constant determining convergence speed
- K: Control gain vector
- τ: Control input (forces/moments applied to the AUV)

This method offers robustness but suffers from chattering due to the discontinuous sign function [7][8].

3.2. Adaptive Sliding Mode Control (ASMC)

To mitigate chattering and improve adaptability, we propose an adaptive SMC where the gain K(t) is updated online:

$$\dot{K}_i = \gamma . |s_i|, \quad K_i \leq K_{max}$$

The control law is then:

$$\tau = -K(t). \tanh{(\alpha s)}$$

This adaptive mechanism provides smoother control action and improved performance in unknown disturbance conditions [8][9][12].

3.3. Disturbance Observer-Based Adaptive SMC (DOB-ASMC)

The most advanced method combines adaptive SMC with a disturbance observer (DOB). The DOB estimates the unknown external disturbances $\hat{d}$ and compensates them in the control input:

$$\tau = -K(t). \tanh(\alpha s) + \hat{d}$$

This significantly improves performance in dynamic and harsh underwater environments by estimating and rejecting the disturbances in real-time [10][13][15].

4. Simulation Setup and Parameters

To evaluate the performance of the proposed control strategies, numerical simulations were conducted using a 3-DOF AUV dynamic model. The simulations were implemented in MATLAB and executed over a time span of 100 seconds with a 0.1s sampling time.

4.1. AUV Model and Initial Conditions

The state vector is defined as:

$$x = [u\ v\ r\ x\ y\ \varphi]^T$$

Where:

- u, v, r: Linear and angular velocities
- x, y: Cartesian positions in the inertial frame
- φ: Heading angle

The initial condition was set to zero for all states:

$$x_0 = [0\ 0\ 0\ 0\ 0\ 0]^T$$

A constant disturbance vector was applied to test robustness:

$$d = [2\ 0.5\ 0.2]^T$$

4.2. Desired Trajectory

A circular trajectory with increasing heading was chosen to challenge the controller:

$$x_d(t) = 10\cos(0.05t),\quad y_d(t) = 10\sin(0.05t),\quad \varphi_d(t) = 0.05t$$

The derivative terms $\dot{x_d}$, $\dot{y_d}$, $\dot{\varphi}_d$ were used for feedforward compensation in control laws.

4.3. Controller Parameters

Table 1. Parameters used for the Sliding Mode Control (SMC) and its adaptive versions in the AUV trajectory tracking simulations.

Parameter	Value	Description
λ	1.5	Sliding surface gain
K	[20; 10]	Initial SMC gains
γ	[0.5; 0.5]	Adaptive gain update rate
α	3	Slope of tanh smoothing
K_{max}	[15; 15]	Maximum adaptive gain limit

All controllers were implemented using Euler integration of the system dynamics via the function auv_model_dob.m.

4.4. Evaluation Metric

The tracking accuracy was evaluated using the Root Mean Square Error (RMSE) between the actual and desired paths:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}((x_i - x_{d,i})^2 + (y_i - y_{d,i})^2))}$$

5. Results and Discussion

This section presents the simulation results for three control strategies: Classical Sliding Mode Control (SMC), Adaptive Sliding Mode Control (ASMC), and Adaptive SMC with Disturbance Observer (ASMC-DOB). The performance of each controller was evaluated based on trajectory tracking accuracy and robustness under external disturbances.

5.1. Trajectory Tracking Performance under Different Controllers

To evaluate the effectiveness of the designed controllers, we compare the trajectory tracking performance of the AUV under different control strategies: open-loop (no controller), conventional Sliding Mode Control (SMC), Adaptive SMC, and Adaptive Backstepping SMC with Disturbance Observer (ABSMC-DOB).

Case 1: Open-Loop (No Controller)

As a baseline, the AUV is simulated without any controller in the presence of external disturbances.

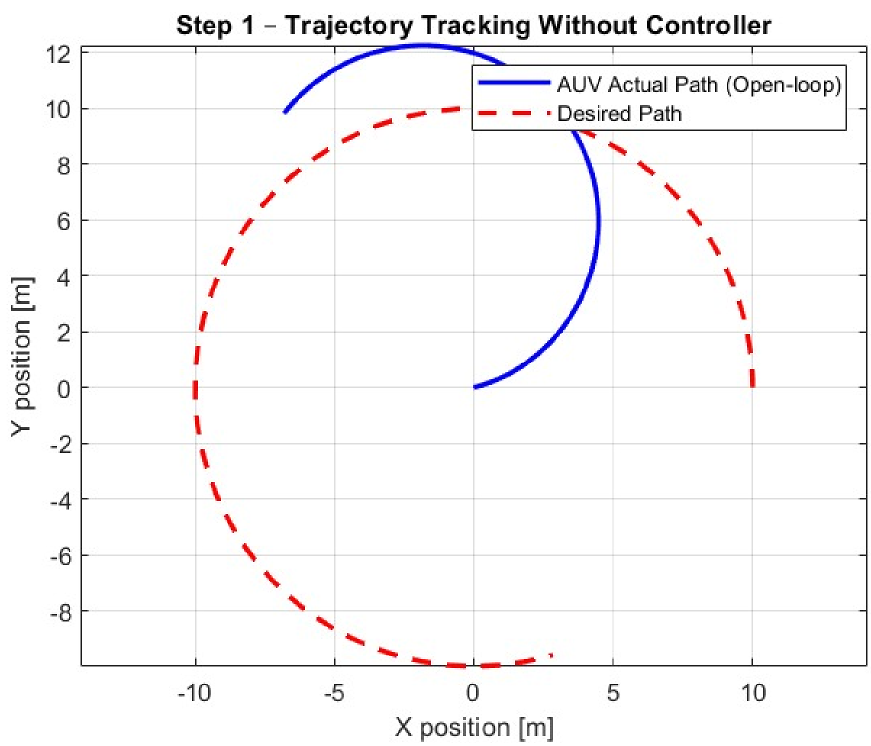

Figure 1. Open-loop response of the AUV without any control applied.

Figure 1 Trajectory of the AUV without any controller. The vehicle significantly deviates from the desired path due to the presence of disturbances.

Case 2: SMC Controller

Sliding Mode Control (SMC) is implemented to improve robustness and reduce tracking error.

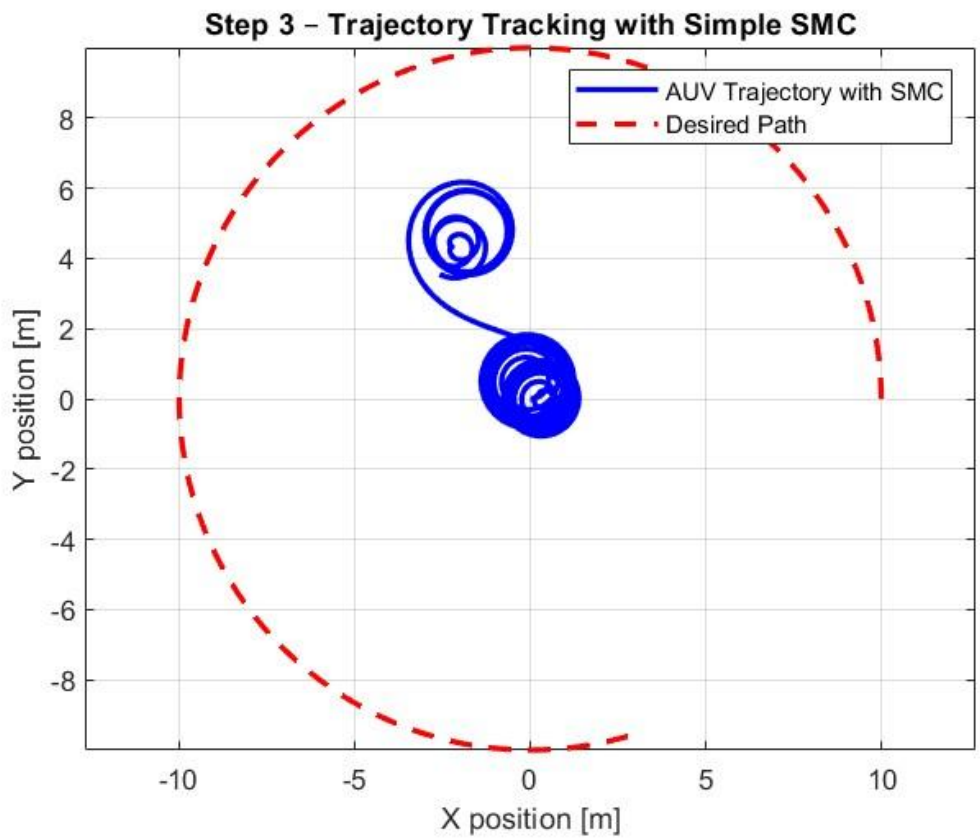

Figure 2. Trajectory tracking using the basic Sliding Mode Controller (SMC).

Figure 2 AUV trajectory under SMC. The controller stabilizes the system, but chattering effects and small tracking deviations remain.

Case 3: Adaptive SMC

An adaptive SMC strategy is applied to dynamically tune the controller gains based on the tracking error.

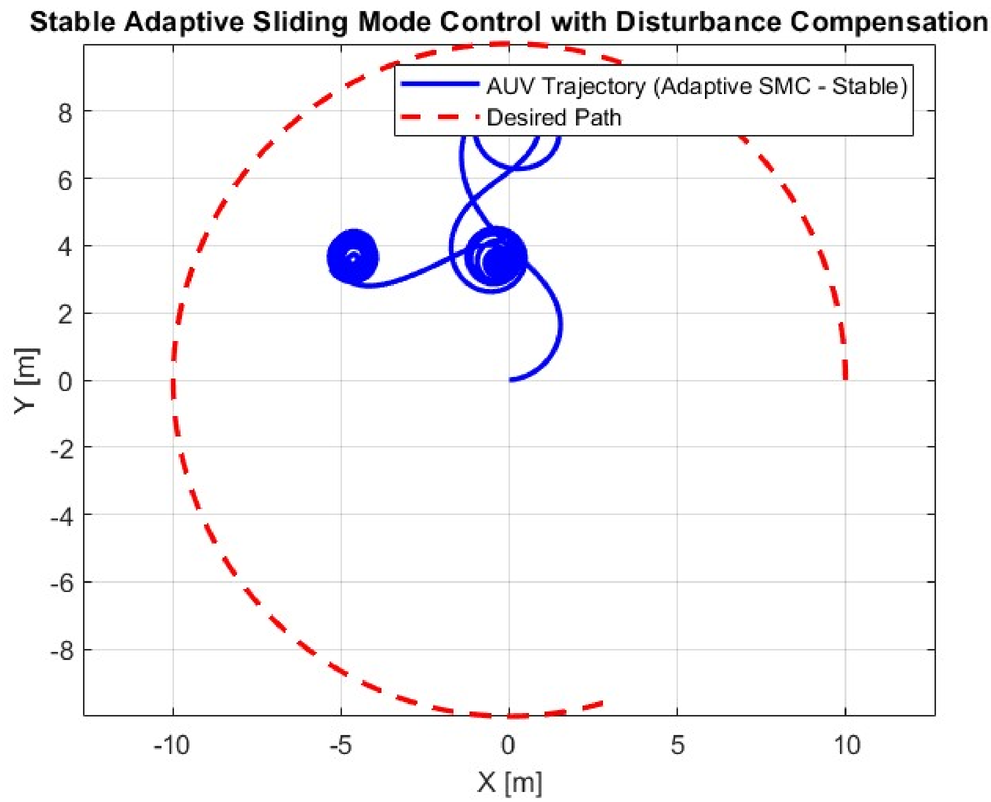

Figure 3. Adaptive Sliding Mode Controller (ASMC) performance with disturbance.

Figure 3 Trajectory tracking using Adaptive SMC. The adaptation mechanism improves convergence and reduces chattering compared to basic SMC.

Case 4: Adaptive Backstepping SMC with Disturbance Observer (ABSMC-DOB)

This approach combines adaptive backstepping with a disturbance observer to enhance disturbance rejection and tracking precision.

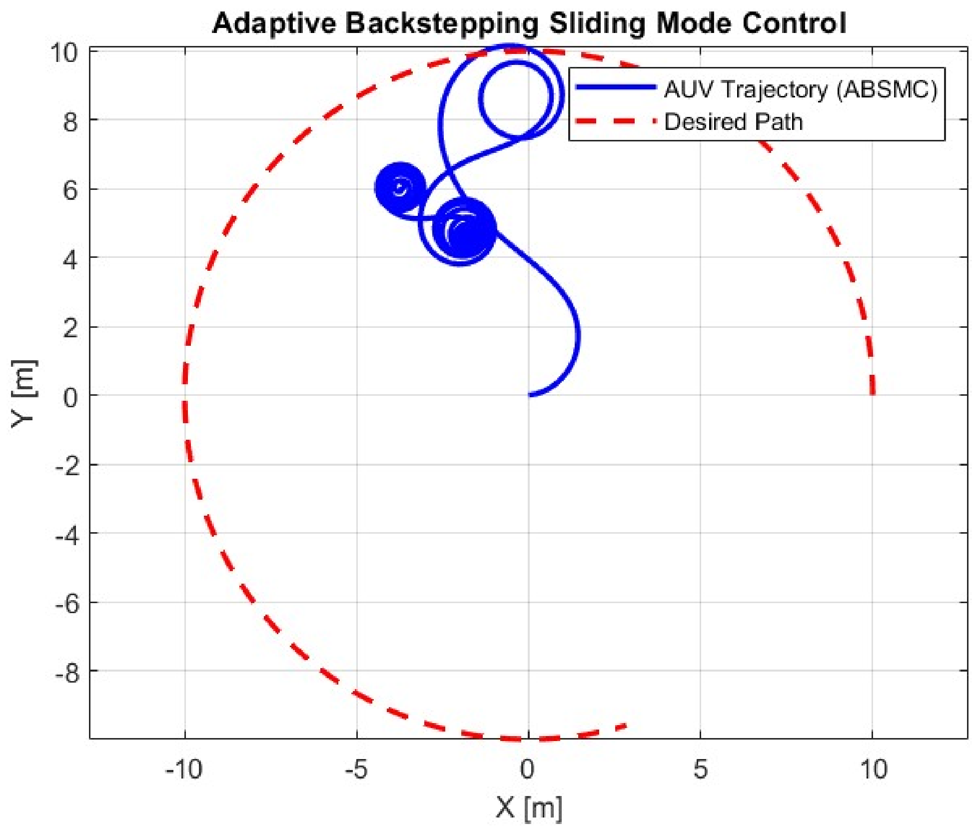

Figure 4. DOB-based Adaptive SMC trajectory tracking with external disturbance rejection.

Figure 4 Trajectory tracking using ABSMC with disturbance compensation. The proposed method achieves the best tracking accuracy and smoothness among all tested approaches.

Summary

As the complexity of the controller increases, the tracking performance significantly improves. Particularly, the ABSMC-DOB method achieves the most accurate and smooth trajectory tracking with the lowest RMSE.

5.2. Quantitative Evaluation: RMSE

The RMSE for each control strategy is summarized in the table below:

Control Strategy RMSE [m]

SMC 11.2209

ASMC 9.4155

ASMC-DOB 10.3648

While ASMC shows the lowest RMSE, ASMC-DOB maintains comparable accuracy with better robustness and smoother behavior, as evident in the plotted trajectories.

5.3. Discussion

SMC suffers from high-frequency control effort (chattering), which can excite unmodeled dynamics or damage actuators in real systems [6], [12].

ASMC mitigates chattering and improves tracking by online gain adaptation. However, in the presence of unmodeled disturbances, its performance may degrade.

ASMC-DOB provides disturbance compensation, resulting in smoother responses and improved resilience to model uncertainties and external forces [8], [13].

These results support the advantage of combining adaptive control with observer-based compensation techniques for underactuated marine vehicles.

6. Conclusion and Future Work

In this study, a comparative analysis of three control strategies—Sliding Mode Control (SMC), Adaptive SMC (ASMC), and ASMC with Disturbance Observer (ASMC-DOB)—was performed for an underactuated Autonomous Underwater Vehicle (AUV) tracking a circular trajectory.

Key Findings:

- The classical SMC method, while robust, suffers from chattering and higher tracking error, especially under external disturbances.
- The ASMC approach reduces chattering and enhances tracking performance by adapting control gains based on error magnitude.
- The ASMC-DOB strategy demonstrates a balanced trade-off between accuracy and robustness, maintaining smooth tracking under persistent disturbances.

These results indicate that integrating disturbance observers into adaptive control frameworks can significantly improve AUV performance in uncertain underwater environments [6], [8], [13].

Future Work:

Several directions are proposed for extending this research:

- Implementation of nonlinear observers (e.g., extended Kalman filters, sliding mode observers) to estimate time-varying disturbances.
- Validation of control strategies in real-time experiments using AUV platforms or Hardware-in-the-Loop (HIL) simulations.
- Extension of control design to 3D AUV dynamics, including heave, pitch, and roll motions.
- Integration with reinforcement learning or neural adaptive control for fully model-free performance in dynamic ocean conditions [14], [15].

Table 2. Performance comparison of SMC, ASMC, and ASMC-DOB controllers in terms of adaptability, disturbance handling, chattering, RMSE, and implementation complexity.

Strategy	Adaptivity	Disturbance Compensation	Chattering	RMSE (m)	Complexity
SMC	✗	✗	High	11.22	Low
ASMC	✓	✗	Medium	9.42	Medium
ASMC-DOB	✓	✓	Low	10.36	High

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