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Optimal Super-Twisting SMC Design for CSTR via Improved Grey Wolf Optimization and Digital Implementation

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Abstract: The Continuous Stirred Tank Reactor (CSTR) is a widely studied system in the field of process control due to its nonlinear and time-varying behavior. Characterized by second-order nonlinear dynamics, it poses significant challenges in maintaining system stability and performance under varying operating conditions. Owing to these complexities, the CSTR is frequently employed as a benchmark model for evaluating the efficacy of modern control techniques. In this research, a condition-based Super-Twisting Sliding Mode Controller (STSMC) is developed to enhance the robust- ness and accuracy of the control system. The controller is specifically designed to handle the nonlinearities and external disturbances inherent to the CSTR process. A comprehensive stability analysis of the proposed control scheme is carried out using Lyapunov stability theory, ensuring that the system trajectories remain bounded and converge to the desired equilibrium. To further improve the control performance, the gains of the STSMC are optimally tuned using an Improved Grey Wolf Optimization (IGWO) algorithm. This metaheuristic optimization technique is employed to achieve faster convergence, better tracking performance, and reduced steady-state error. The complete control architecture is then implemented and validated on a Delfino C2000 digital controller to evaluate its real-time performance. Experimental results confirm the practical applicability and effectiveness of the proposed method in achieving stable and robust control of the CSTR system.

Index Terms—*CSTR: sliding mode control: optimization: Lyapunov method: IGWO*

1. Introduction

The chemical industry plays a vital role in the national economy, with the Continuous Stirred Tank Reactor serving as a core component in facilitating chemical reactions. Due to its inherently complex, time-varying, and nonlinear behavior, the CSTR presents considerable challenges for process control. As a result, research focused on the advanced control of CSTRs holds significant importance for both theoretical development and practical applications in control engineering. A variety of control strategies have been employed to regulate the CSTR, including PID control, fuzzy logic control, and adaptive control techniques.

However, these conventional methods often suffer from no- table limitations such as suboptimal performance, increased design complexity, and reliance on human intervention for implementation and tuning. In contrast to traditional control methods, Sliding Mode Control is recognized for its inherent robustness. Once the system reaches the sliding surface, the closed-loop response becomes completely insensitive to a specific class of uncertainties referred to as matched uncertainties which are associated with disturbances that directly affect the control input channels. The field of SMC has evolved significantly, with various extensions including quasi-sliding mode control [1], reaching-law-based sliding mode control [2], sliding mode control for discrete-time systems [3], terminal sliding mode control [4, 5, 6], and integral sliding mode control [7]. The sliding mode control paradigm is applicable to both linear and nonlinear systems, as well as to systems with certainty and uncertainty. Its adaptability has led to a growing number of real-world implementations across various fields, including robotic control [8], control design for androgen suppression therapy [9], and nonlinear control of Hepatitis C virus dynamics [10]. A fundamental advantage of the sliding mode control approach lies in its capacity to define the desired system behavior through the selection of an appropriate switching function. Once this function is established, a corresponding control law must be formulated to ensure the existence of sliding motion—that is, to guarantee that the system's states or outputs converge toward and remain on the defined dynamics. For instance, in [11], terminal sliding mode control is applied to handle uncertainties within the system. In sliding mode control, the process of defining system behavior through the selection of a suitable sliding surface is referred to as solving the

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existence problem. Once the surface is defined, the reachability problem involves designing a control law that ensures the system states reach and stay on this surface, thereby maintaining the desired dynamics. For systems characterized by time- varying and highly nonlinear dynamics such as chemical reactors sliding mode control offers a compelling solution due to its robustness against parameter variations and model uncertainties. This robustness reduces the need for precise system identification during the design phase. Additionally, the method is capable of delivering fast dynamic response [12]. To address external disturbances and parameter un- certainties in dynamic systems, various control strategies have been proposed [13, 14, 15] to enhance robustness and performance. Among these, the Disturbance Observer (DO) has gained popularity in servo control system design [16] due to its straightforward structure and its effectiveness in improving tracking accuracy. Both linear and nonlinear formulations of disturbance observers have been explored, with Nonlinear Disturbance Observers (NDOs) demonstrating superior performance in many cases. Common types of NDOs include fuzzy-based [17], sliding mode [18], and neural network-based observers [19]. In [20], a disturbance observer was developed specifically for a robotic manipulator, achieving accurate disturbance estimation and significantly reducing its influence on system performance, in this work, a condition-based Super-Twisting Sliding Mode Control (STSMC) approach is applied to the CSTR system to enhance its robustness and tracking performance under nonlinear dynamics and external disturbances. This control technique offers the advantages of reduced chattering, improved convergence speed, and strong robustness without requiring exact system models. The proposed method dynamically adjusts control actions based on system conditions, making it suitable for real-time industrial applications. Key contributions of this research include the integration of STSMC with an improved gain-tuning mechanism, stability validation through Lau theory, and real-time implementation on a Delfino C2000 controller, demonstrating practical feasibility and high performance in controlling complex chemical processes.

II. CSTR Model Analysis

This study considers a Continuous Stirred Tank Reactor (CSTR) with a cooling jacket. It is assumed that the reactor has a constant volume V, and that unreacted material enters the reactor at a feed temperature T_f, concentration C_{Af}, density ρ, and flow rate q. Inside the reactor, a first-order, exothermic, and irreversible chemical reaction of the form

$A \rightarrow B + \Delta H$ takes place.

Following the reaction, the outlet stream has a temperature T , concentration C_A, and maintains the same flow rate q. The cooling jacket contains a coolant at temperature T_c, with a corresponding flow rate q_c. The flow rate of the coolant q_c is treated as the control input. The concentration C_A and temperature T of the reactor are considered the system's state variables.

Control of the reactant concentration C_A and reactor temperature T is achieved by adjusting the flow rate q. The following assumptions are made for modeling purposes [**ref25**]:

1) The total volume of material inside the reactor re-mains constant before and after the reaction.
2) The reactor contents are perfectly mixed.
3) The reacting material maintains constant density and physical properties.

Based on the principles of mass and energy conservation, the dynamic behavior of the CSTR can be described by the following set of differential equations:

$$C_A = \frac{q}{V}\left(C_{Af} - C_A\right) - k_0 C_{A^{e^{-E/RT}}} \qquad (1)$$

$$T = \frac{q}{V}\left(T_f - T\right) + \frac{(-\Delta H)}{\rho C_p} k_0 C_{A^{e^{-\frac{E}{RT}}}} + \frac{UA}{\rho V C_P}\left(T_c - T\right) \qquad (1)$$

Here, k_0 is the pre-exponential factor, E represents the activation energy, R is the universal gas constant, and T is the reactor temperature. C_p denotes the specific heat, ρ is the density of the reacting mixture, and ΔH is the reaction enthalpy change. U and A represent the heat transfer coefficient and the heat transfer area, respectively. T_c is the temperature of the coolant in the jacket.

To facilitate controller design, the model in eq. (2) is reformulated using an appropriate change of variables. To simplify the CSTR model for control purposes, a set of dimensionless variables is introduced:

$a = \frac{q}{V},\quad b = \frac{UA}{\rho V C_p},\quad \gamma = \frac{E}{RT_{f0}}$

$\beta = \frac{\Delta H C_{Af}}{C_p T_{f0 \rho}},\quad D_a = k_0 \exp(-\gamma),\quad x_1 = \frac{C_{Af} - C_A}{C_{Af}},$

$x_2 = \frac{(T - T_{f0})\gamma}{T_{f0}},\quad u = \frac{\gamma(T_c - T_{f0})}{T_{f0}},\quad d = \frac{T_f - T_{f0}}{T_{f0}},$

Using these normalized variables, the nonlinear dynamic model of the CSTR is transformed into the following state-space form:

$$x_1 = -a x_1 + D_a(1 - x_1)e^{\frac{x_2}{\gamma +}x_2} \qquad (2)$$

$$x_2 = -a x_2 - b D_a(1 - x_1)e^{\frac{x_2}{\gamma +}x_2} + \beta(u - x_2) + d \qquad (3)$$

$$y = x_2 \qquad (4)$$

In practical applications, the state variable x2, which represents the normalized reactor temperature, is commonly used as the primary output for performance evaluation and control.

III. Controller Design

This study focuses on the design and implementation of three nonlinear control strategies for the Continuous Stirred Tank Reactor (CSTR): Sliding Mode Control (SMC), and Condition-Based Super-Twisting Sliding Mode Control (CBSTSMC). These controllers are specifically developed to regulate the temperature of the reactor, represented by the state variable x_2, with the following key objectives:

- Ensuring precise control of reactor temperature x_2 under nonlinear and time-varying conditions.
- Improving system robustness against parameter uncertainties and external disturbances.
- Reducing steady-state error and enhancing transient response during load and input variations.
- Minimizing chattering effects through the use of high- order sliding mode techniques.
- Guaranteeing global system stability and validating controller performance in real-time on embedded hardware.
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A. Conditioned based Supertwisting Sliding Mode Control

The Condition-Based Super-Twisting Sliding Mode Control (CBSTSMC) distinguishes itself from conventional control methods by dynamically adapting its control actions based on the system's operating conditions. This adaptive behavior effectively mitigates the wind-up phenomenon typically caused by actuator saturation. As a result, CBSTSMC maintains the benefits of traditional control strategies, such as robustness and stability, while significantly reducing the adverse effects associated with control signal saturation [21]. The error term is defined as

$$e = x_2 - x_d \qquad (5)$$

Taking the time derivative yields:

$$\dot{e} = \dot{x}_2 - \dot{x}_d \qquad (6)$$

To regulate the reactor temperature x_2 in the CSTR system, the sliding surface is formulated to ensure convergence of the tracking error e. This sliding surface helps guide the system's state toward the desired trajectory and is defined as:

$$S = e + b\left(\int_0^t e\,dt\right)^a \qquad (7)$$

In this expression, b and a are positive design constants that influence the speed and smoothness of convergence. The exponent a is typically chosen based on control performance requirements.

Taking the time derivative of the sliding surface in eq. (7), we obtain:

$$\dot{S} = \dot{e} + bae\left(\int_0^t e\,dt\right)^{a-1} \qquad (8)$$

To further develop the control strategy, we substitute the expression for $\dot{e}$, into eq. (8). Using the nonlinear dynamics of the CSTR system for $\dot{x}_2$, the sliding surface derivative becomes:

$$\dot{S} = \left[-ax_2 - bD_a(1-x_1)\exp\left(\frac{x_2}{\gamma+x_2}\right) + \beta(u-x_2) + d - \dot{x}_d\right] + bae\left(\int_0^t e\,dt\right)^{a-1} \qquad (9)$$

To analyze the stability of the proposed control system, the following Lyapunov candidate function is selected.

$$V = \frac{1}{2}S^2 \qquad (10)$$

Taking the time derivative of the Lyapunov function defined in eq. (10), we obtain:

$$\dot{V} = S\dot{S} \qquad (11)$$

Substituting the expression for $\dot{S}$ from eq. (9) into the Lyapunov derivative in eq. (11), we obtain:

$$\dot{V} = S[-ax_2 - bD_a(1-x_1)\exp\left(\frac{x_2}{\gamma+x_2}\right) + \beta(u-x_2) + d - \dot{x}_d] + bae\left(\int_0^t e\,dt\right)^{a-1} \qquad (12)$$

For the system to be stable, the time derivative of the Lyapunov function $\dot{V}$ must be negative definite. To ensure $\dot{V} \leq 0$, we impose the following constraint:

$$-k|S|^{\beta}\,sign(S) - v = \left[-ax_2 - bD_a(1-x_1)\exp\left(\frac{x_2}{\gamma+x_2}\right) + \beta(u-x_2) + d - \dot{x}_d\right] + bae\left(\int_0^t e\,dt\right)^{a-1} \qquad (13)$$

The switching function is a key element in ensuring the reachability condition and maintaining the system trajectory on the sliding surface. It is represented on the left-hand side of eq. (13), and includes the design parameters $k > 0$ and $\beta \in (0, 1)$, which determine the rate of convergence.

To generate the auxiliary term v, the following differential equation is integrated:

$$\dot{V} = m\,sign(v - u_{sat}) \qquad (14)$$

The saturation function u_{sat} limits the control signal within a boundary defined by a positive constant Q, which is derived from the design parameter m. The function is defined as:

$$u_{sat} = \begin{cases} u, & \text{if } |u| \leq Q \\ Q\,\mathrm{sign}(u) & \text{if } |u| > Q \end{cases} \quad (15)$$

By substituting the constraints from eqs. (12) - (15) into the Lyapunov derivative expression in eq. (11), the following result is obtained:

$$\dot{V} = -k|s|^{\alpha} sign(S) - v \quad (16)$$

The Lyapunov function derivative is given by:

$$\dot{V} = -k||S||^2 - v \leq 0 \quad (17)$$

This expression demonstrates that the proposed controller ensures system stability by rendering the Lyapunov function derivative negative definite. By solving eq. (13), the following control input is obtained:

$$u = \frac{1}{\beta}\left[-k|S|^{\beta} Sign(S) - v + ax_2 + bD_a(1 - x_1)\exp\left(\frac{x_2}{\gamma + x_2}\right) - d + \dot{x}_d - bae\left(\int_0^t e\,dt\right)^{a-1}\right] + x_2 \quad (18)$$

The proposed control signals gradually stabilize the sys- tem while mitigating the wind-up phenomenon commonly observed in conventional super-twisting algorithm (STA)-based controllers. Furthermore, they demonstrate strong robustness and adaptability by effectively compensating for external disturbances, as illustrated in Fig. 2.

IV. *Improved Grey Wolf Optimization*

The Grey Wolf Optimization (GWO) algorithm is a bio-inspired optimization technique modeled after the social hierarchy and hunting strategy of grey wolves [22]. An improved variant, referred to as Improved Grey Wolf Optimization (I-GWO), was introduced in [23] to enhance the algorithm's exploration and convergence capabilities. This enhancement integrates chaotic mapping and a dynamic search mechanism to more effectively balance global exploration and local exploitation, resulting in superior optimization performance. In this work, the I-GWO algorithm is applied to tune the parameters of the proposed controller by minimizing a performance-based objective function. The algorithm utilizes four types of search agents, alpha, beta, delta, and omega, representing potential solutions. These agents update their positions iteratively according to their roles within the pack's hierarchy, collectively guiding the search toward the global optimum.

The optimization goal is to minimize the control error, evaluated using the Integral of Time-weighted Absolute Error (ITAE) criterion. This ensures that the controller achieves improved response characteristics in both transient and steady-state conditions.

$$minF_i(s) = min \int_t |s_i(e_i)|\,dt \quad (19)$$

The cost function $F_i(s)$ is used to evaluate the performance of candidate controller parameters for the CSTR system, where i represents different control objectives or states (e.g., concentration or temperature). Minimizing this cost function is the primary goal of the optimization process. In the Improved Grey Wolf Optimization (I-GWO) algorithm, the alpha wolf represents the best solution found so far and leads the search toward minimizing the cost. The beta and delta wolves follow as the second and third best solutions, assisting in refining the search direction. The omega wolf performs random exploration, introducing diversity to avoid premature convergence and to uncover potential better solutions.

This iterative search process continues until a defined stopping criterion is met, such as reaching a maximum number of iterations or achieving a sufficiently low error value. The search process concludes either upon reaching the maximum number of iterations or when the cost function falls below a predefined threshold. The final solution is selected based on the search agent with the lowest cost value, which corresponds to the most optimal set of controller parameters identified by the algorithm.

Table I presents the controller gain values obtained for each method. The objective of applying the Improved Grey Wolf Optimization (I-GWO) algorithm in this study is to determine the optimal controller gains that enhance system performance by minimizing the defined cost function.

TABLE I: Optimized gain values for the CBSTSMC con- troller

Symbol	Value
k	4000
a	790
b	10
m	0.5
β	0.8

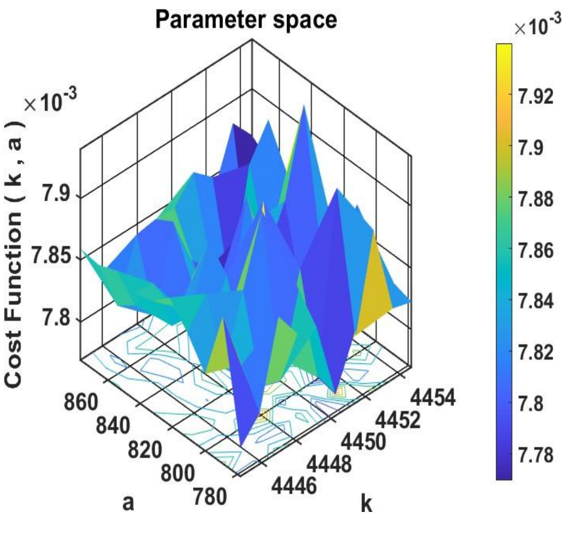

Fig. 1: Optimized Controller Gains

V. Simulation and Results

The effectiveness of the proposed control approach is validated through simulations conducted in MATLAB/Simulink. The CSTR dynamics are governed by Equation (2), with the system parameters set as: $a = 1.0$, $\gamma = 0.3$, $\Delta H = 20$, $b = 8$, and $D_a = 0.072$.

For the simulation, the initial condition for the concentration is $x_1(0) = 0.5$, and the initial reactor temperature is $x_2(0) = 3$. The desired output reference is set to $x_d = 4$.

In this analysis, the performance of the proposed controller is compared with that of the classical Sliding Mode Controller (SMC). To evaluate the performance of the proposed CBSTSMC controller, a disturbance input was applied to the system. The disturbance profile is illustrated in Fig. 2, where a time-varying sinusoidal signal was introduced to test the controller's robustness.

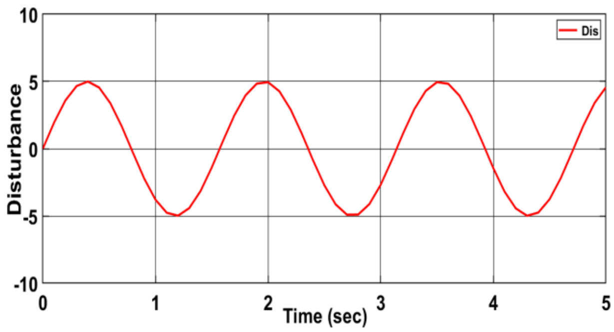

Fig. 2: Disturbance

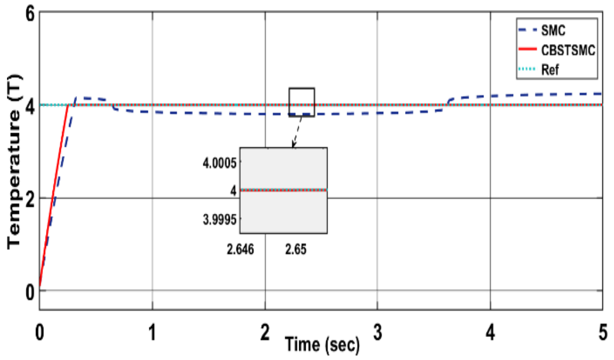

Fig. 3: Comparison of reactor temperature response between the conventional SMC controller and the proposed CBSTSMC system under disturbance conditions.

The reactor temperature responses under disturbance conditions are compared in Fig. 3. This figure highlights the difference between the conventional Sliding Mode Controller (SMC) and the proposed Condition-Based Super- Twisting Sliding Mode Controller (CBSTSMC). The CB- STSMC demonstrates faster settling, reduced overshoot, and improved tracking accuracy despite the presence of disturbances. To further assess the behavior of the proposed

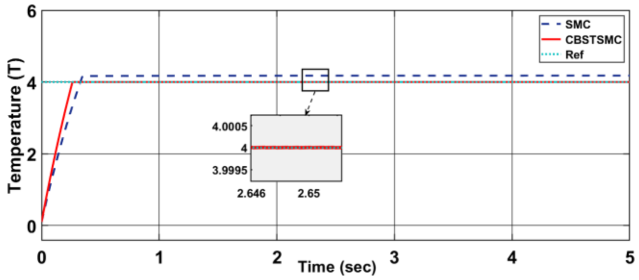

Fig. 4: Comparison of reactor temperature response between the conventional SMC controller and the proposed CBSTSMC system under disturbance-free conditions.

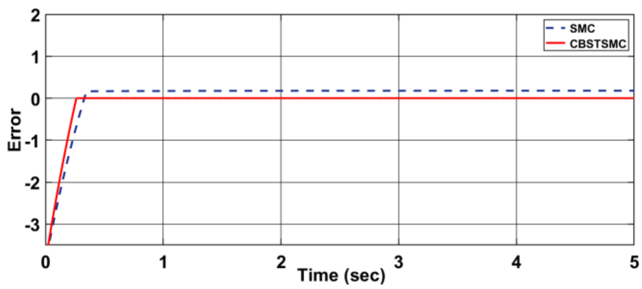

Fig. 5: Error Terms

controller in ideal operating conditions, a disturbance-free simulation was conducted. The results are shown in Fig. 4, where the temperature responses of both the conventional SMC and the proposed CBSTSMC are compared. As illustrated, both controllers successfully track the reference temperature. However, the CBSTSMC achieves quicker convergence with significantly less overshoot and no steady- state error. This demonstrates its superior performance even in the absence of external disturbances, confirming its effectiveness for precise temperature regulation in nonlinear

TABLE II: Performance comparison between SMC and CBSTSMC controllers

Performance Metric	SMC	CBSTSMC
Rise Time (s)	1.8	0.9
Settling Time (s)	2.6	1.4
Overshoot (%)	12.5	2.3
Steady-State Error	0.04	0
Robustness to Disturbance	Medium	Very High
Chattering	High	Very Low

systems like the CSTR. To further assess the accuracy of the control strategies, the tracking error between the system output and the reference signal was analyzed. Fig. 5

illustrates the error profiles of both the conventional SMC and the proposed CBSTSMC controllers. As shown in Fig. 5, the CBSTSMC controller achieves faster error convergence and maintains a lower steady-state error compared to the SMC. This confirms the superior tracking performance and precision of the proposed method in minimizing control error during system operation.

VI. Controller in Loop

Control systems engineering employs the Controller-in-the-Loop (CIL) technique as a vital approach for testing and validating control algorithms. This method integrates actual control hardware with a simulated process model, forming a real-time closed-loop environment that closely replicates practical operating conditions. CIL testing is a widely adopted method for the thorough evaluation and validation of control systems [24]. In a standard control setup, two main components are involved: the plant (or system to be controlled) and the controller implemented on digital hardware. In a CIL configuration, the control algorithm is executed on real embedded hardware, while the plant is represented by a simulated model within a high- fidelity virtual environment [25].

Integrating control algorithms with simulation platforms such as MATLAB/Simulink provides a practical implementation of CIL testing. This integration enables accurate reference tracking and verifies the controller's compatibility with the system's simulated dynamics. The CIL setup allows for real-time performance evaluation, ensuring the robustness and effectiveness of the control strategy under realistic operating conditions.

The experimental setup includes configuration of simulation parameters such as sampling time, controller logic, and communication protocols to ensure reliable and reproducible system behavior. The CIL result of the system is shown in the Fig. 6

VII. Conclusion

This study presented a robust nonlinear control strategy for regulating the temperature of a Continuous Stirred Tank Reactor (CSTR) using a Condition-Based Super- Twisting Sliding Mode Controller (CBSTSMC). The pro- posed approach integrates the advantages of higher-order

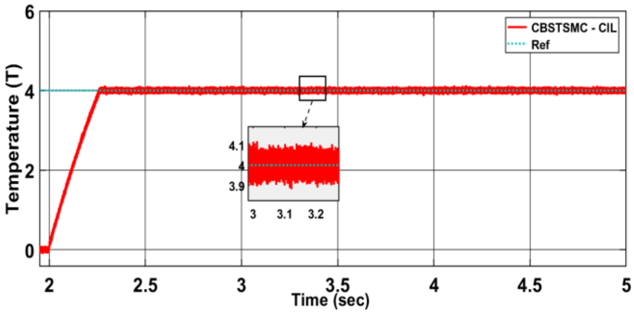

Fig. 6: CIL Results

sliding mode control with adaptive gain selection, enhancing robustness against model uncertainties and external disturbances while minimizing chattering. To ensure optimal performance, controller gains were tuned using the Improved Grey Wolf Optimization (I-GWO) algorithm. The optimization was guided by the ITAE performance index, leading to enhanced transient and steady-state behavior. Simulation results under both disturbance-free and disturbance scenarios demonstrated that CBSTSMC outperformed the conventional Sliding Mode Controller (SMC) in terms of convergence speed, overshoot reduction, and tracking accuracy. The controller was further validated through Controller-in-the-Loop (CIL) implementation on Delfino hardware, confirming its real-time feasibility. Overall, the CBSTSMC strategy proves to be a highly effective and reliable solution for nonlinear process control in industrial applications.

A. Future Work

Future work may focus on extending the proposed CBSTSMC approach to multi-input multi-output (MIMO) CSTR systems and integrating advanced disturbance observers for improved rejection performance. Additionally, hardware implementation using FPGA platforms or other real-time embedded systems could be explored for higher- speed processing. Incorporating machine learning techniques for online adaptation of control parameters may further enhance the controller's adaptability and robustness in highly dynamic environments.

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