

Data-Driven Model-Free Adaptive Sliding Mode Control for Multi DC Motor Speed Regulation

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Abstract

This paper proposes the distributed data-driven model-free adaptive sliding mode control approach to address the consensus problem of nonlinear multi-agent systems. Firstly, the equivalent data model for each agent is constructed using the compact-form dynamic linearization (CFDL) technique. Secondly, by utilizing process information from neighboring agents, the novel sliding surface is employed to ensure the boundedness of distributed measurement error. Subsequently, a distributed model-free adaptive sliding mode controller is developed for accurate consensus tracking. Finally, the effectiveness of the proposed control approach is verified through experiments on multi DC motor system.

KEYWORDS

Data-driven control, model-free adaptive sliding mode control, nonlinear multi-agent systems, multi DC motor speed control.

I. INTRODUCTION

Multi-agent systems (MASs) are composed of multiple interconnected agents that cooperate to achieve a common objective. Among the key benefits offered by MASs are decision making efficiency, enhanced fault tolerance, and strong adaptability to the dynamics environments. Due to the above characteristics, MASs have gained widespread attention in both theoretical and practical applications such as sensor networks, transportation, agriculture, and industrial automation systems [1]–[3]. One of the fundamental challenges in multi-agent coordination is the distributed consensus problem, which aims to enable all agents to synchronize to a common trajectory despite diverse initial states [4]–[6]. However, traditional model-based control strategies often prove inadequate for handling complex system dynamics, necessitating advanced distributed coordination approaches to ensure reliable convergence and accurate performance.

Despite their effectiveness in specific scenarios, traditional control strategies [10]–[13] heavily depend on precise models, where accurate system modeling is critical for controller design. However, with the continuous evolution of industrial processes and increasing system dynamics complexity, obtaining precise mathematical models becomes a challenging task. This modeling difficulty restricts the applicability of conventional methods in practical systems. In modern industrial environments, large volumes of process information reflecting complex and uncertain system behaviors are continuously collected during operation. Motivated by the limitations of model-based approaches, growing attention has emerged toward data-driven control strategies [14]–[16], which directly leverage system data to design control algorithms without requiring explicit mathematical models. In particular, the data-driven model-free adaptive control (MFAC) method proposed in [17], [18] and further enhanced in [19] has shown strong potential in handling unknown and time-varying systems, providing a practical solution for real-world industrial applications.

Therefore, how to use this data to achieve system consensus control has become a powerful new topic. The data-driven control [17]–[20] refers to control systems utilizing system I/O data solely. Various data-based approaches have been developed, including model-free adaptive control, iterative learning control, virtual reference feedback tuning [21], PID control [22] and others. Among these, the model-free adaptive control approach [23]–[25] has been proposed, and has a great significance in

addressing the aforementioned challenges. The design process relies solely on I/O data of the system, significantly avoiding the reliance on mathematical models. The algorithm has proven effective in practical domains such as motor systems, chemical industries, and machinery, demonstrating the adaptability and usefulness of the algorithm.

Alternatively, sliding mode control [26] has emerged as a highly attractive approach for control researchers due to the robustness to parameter uncertainties and the capability to ensure fast responses. Currently, a novel sliding mode control method based on I/O data is presented in [27], which eliminates the need for explicit system models. Although considerable progress has been made in controlling nonlinear MASs, the dynamic couplings and complex nonlinear behaviors among agents [14] can be challenging in practical implementation.

However, the effectiveness of existing approaches [31]–[34] is limited in highly uncertain environments because they typically rely on input-affine structures with known or partially known dynamics. How to achieve consensus tracking problem utilizing the model-free adaptive sliding mode controller approach for nonlinear MASs remains an open question.

Inspired by the above discussions, this paper proposes a data-driven model-free adaptive sliding mode control scheme. The contributions of this paper are structured as follows:

- 1) A novel distributed sliding surface is proposed, incorporating neighboring agents process information. This design guarantees the boundedness of distributed measurement errors and enhances system convergence through a newly designed stability mechanism. Compared to existing methods that rely on known or partially known dynamics, the offered approach achieves distributed adaptive sliding mode coordination without requiring system models, resulting in faster convergence speed and improved performance.
- 2) A data-driven model-free adaptive sliding mode control algorithm is developed, integrating the CFDL technique with sliding mode robustness. This proposed design enables effective consensus tracking of nonlinear MASs and improves dynamic response. Unlike existing model-free adaptive methods limited to single-agent or input-affine systems, the proposed approach extends to distributed nonlinear systems, achieving faster convergence without prior model knowledge.
- 3) A refined PPD estimation algorithm is applied, allowing each agent to construct a real-time data model using only input-output data. In contrast to existing model-free adaptive control based methods, this work integrates PPD estimation within distributed sliding mode control, ensuring parameter boundedness and maintaining adaptive performance under nonlinear and time-varying environments, contributing to faster adaptation and system stability.

The following sections will outline the remaining content of this paper: Section II provides the preliminaries and problem formulation. The main results are discussed in Section III. Section IV shows the simulation and performance analysis, demonstrating the effectiveness of the proposed method under distinct operating conditions. At the end, conclusions are summarized in Section V.

II. PRELIMINARIES AND PROBLEM FORMULATION

A. Directed Graph Theory

The directed graph $\mathcal{G} = (\mathcal{V}, \mathcal{E}, \mathcal{A})$ is employed to describe the information exchange between agents. Here, $\mathcal{A} = [a_{ij}] \in \mathbb{R}^{N \times N}$ represents the adjacency matrix, $\mathcal{V} = \{v_1, v_2, \dots, v_N\}$ is the set of vertices, and $\mathcal{E} = [(v_j, v_i) | v_i \in \mathcal{V}] \subseteq \mathcal{V} \times \mathcal{V}$ is the set of edges. Moreover, $\mathcal{N}(i) = \{j \in \mathcal{V} | (i, j) \in \mathcal{E}\}$ denotes the neighbor set of agent i , where $a_{ij} \neq 0$. No self-loop is allowed in this article, which means $(i, i) \notin \mathcal{E}$ for any $i \in \mathcal{V}$, $a_{ii} = 0$. Furthermore, the degree matrix $K = \text{diag}(k_1, \dots, k_N)$. If $k_i > 0$, agent i can directly obtain the information from the leader. The Laplacian matrix L is defined as $L = (\mathcal{D} - \mathcal{A})$, here $\mathcal{D} = \text{diag}(d_1, \dots, d_N)$ and $d_i = \sum_{j=1}^N a_{ij}$ denotes the in-degree matrix. Moreover, the graph is strongly connected if the path exists between every pair of vertices.

B. Problem Formulation

Consider the nonlinear multi-agent systems composed of N agents:

$$y_i(k+1) = f_i(y_i(k), u_i(k)), \quad i = 1, 2, \dots, N \quad (1)$$

where $u_i(k) \in \mathbb{R}$ and $y_i(k) \in \mathbb{R}$ represent the system input and output signals of agent i , respectively. $f_i(\cdot)$ signifies an unknown nonlinear function.

Assumption 1: The partial derivative of $f_i(\cdot)$ with respect to $u_i(k)$ is continuous.

Assumption 2: The system (1) satisfies the generalized Lipschitz condition, meaning that if $\Delta u_i(k) = u_i(k) - u_i(k-1) \neq 0$ then $|\Delta y_i(k+1)| \leq b|\Delta u_i(k)|$ holds for any k , where $\Delta y_i(k+1) = y_i(k+1) - y_i(k)$.

Remark 1: The above assumptions are general and commonly adopted in data-driven control. Specifically, assumption 1 is a general condition for common nonlinear systems. Assumption 2 implies that the system input variation rate constrains the rate of change of the system output. In fact, in many industrial processes, the finite energy of the input applied to a physical plant ensures that the corresponding output variation remains bounded. This boundedness is essential for the stability of the system and feasibility of adaptive control algorithms when facing time-varying or rapidly changing system inputs.

Assumption 3: The communication graph \mathcal{G} is strongly connected, ensuring that each follower can directly receive information from at least one leader.

Lemma 1: Consider the nonlinear multi-agent system (1) satisfying above three assumptions. If $|\Delta u_i(k)| \neq 0$ holds, then the system can be transformed into the CFDL data model as follows:

$$\Delta y_i(k+1) = \phi_i(k) \Delta u_i(k) \quad (2)$$

wherein $\phi_i(k)$ is called pseudo partial derivative (PPD), satisfying $|\phi_i(k)| \leq b$.

The distributed measurement error of $\xi_i(k)$ for N agents is established as:

$$\xi_i(k) = \sum_{j \in N_i} a_{ij}(y_j(k) - y_i(k)) + d_i(y_d(k) - y_i(k)) \quad (3)$$

if the agent i can receive data from the leader, then $d_i = 1$; otherwise, $d_i = 0$. Additionally, $y_d(k)$ represents the reference trajectory.

Remark 2: The data model in (2) represents the CFDL of the nonlinear system (1), where the PPD $\phi_i(k)$ characterizes the local linear approximation at each time step. The CFDL technique requires no prior knowledge about the system dynamic model, making it highly applicable for distributed multi-agent systems, which often exhibit complex, nonlinear, and time-varying dynamics. Furthermore, since the dynamic behavior of the time-varying PPD may be highly complex and challenging to verify, adopting a data-driven method to extract the numerical characteristics of $\phi_i(k)$ becomes a preferred approach for adaptive controller design.

III. MAIN RESULTS

This section is divided in two parts. The first part introduces the model-free adaptive controller design, which is based on the CFDL technique. The second part introduces the sliding mode controller design, which is formulated based on the distributed measurement error. The overall block diagram of the proposed control scheme is shown in Fig. 1.

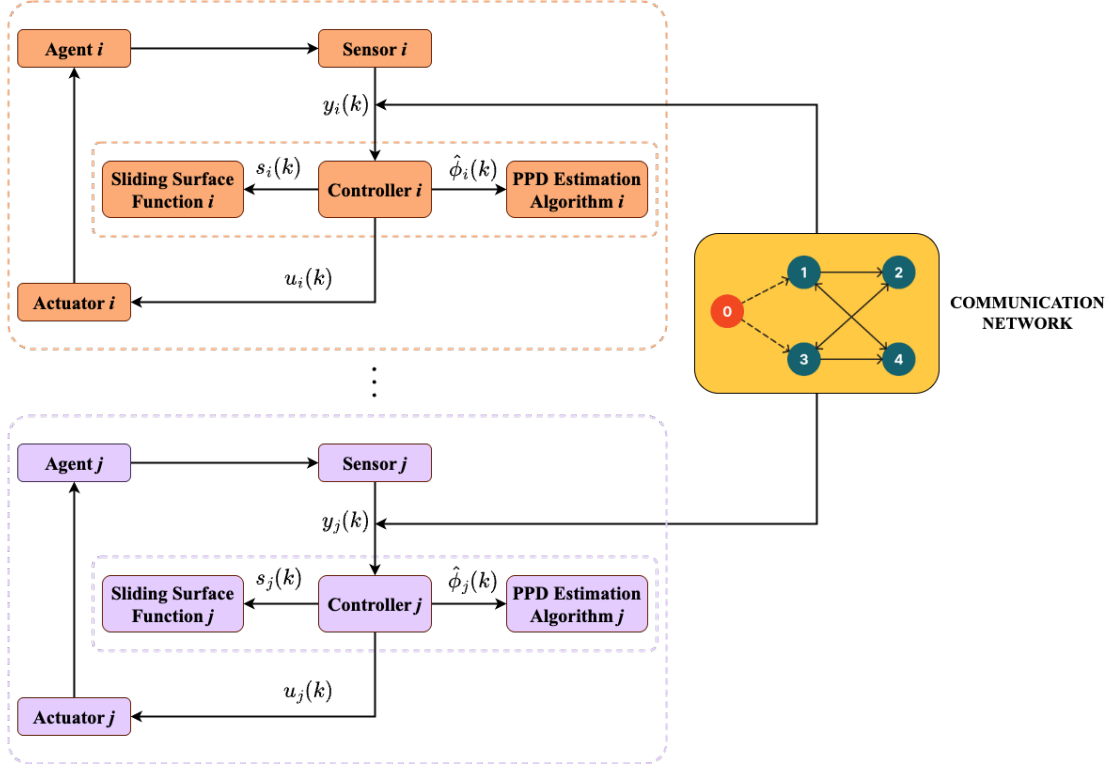


Fig. 1: Block diagram.

A. Model-Free Adaptive Sliding Mode Controller Design

Consider the following PPD criterion function for the parameter with unknown dynamics in (2):

$$J(\phi_i(k)) = |\Delta y_i(k) - \phi_i(k) \Delta u_i(k-1)|^2 + \mu |\phi_i(k) - \hat{\phi}_i(k-1)|^2 \quad (4)$$

By utilizing the optimal condition $\frac{\partial J(\phi_i(k))}{\partial \phi_i(k)} = 0$, the updating law with reset algorithm is derived:

$$\hat{\phi}_i(k) = \hat{\phi}_i(k-1) + \frac{\eta \Delta u_i(k-1)}{\mu + \Delta u_i(k-1)^2} (\Delta y_i(k) - \hat{\phi}_i(k-1) \Delta u_i(k-1)) \quad (5)$$

$$\hat{\phi}_i(k) = \hat{\phi}_i(1), \text{ if } |\hat{\phi}_i(k)| \leq \epsilon \text{ or } \text{sign}(\hat{\phi}_i(k)) \neq \text{sign}(\hat{\phi}_i(1)) \quad (6)$$

herein, $\eta \in (0, 1)$, $\mu > 0$ represents a positive weight factor. Additionally, ϵ is a small positive number and $\hat{\phi}_i(k)$ signifies the estimated value of $\phi_i(k)$.

To design the MFAC control algorithm, the pseudo partial derivative $\hat{\phi}_i(k)$ is estimated using the update law (5) and utilized to compute the control input. Subsequently, the following MFAC algorithm is implemented:

$$u_{i,\text{MFA}}(k) = u_{i,\text{MFA}}(k-1) + \frac{\rho \hat{\phi}_i(k)}{\lambda + \hat{\phi}_i(k)^2} \xi_i(k) \quad (7)$$

where $\rho \in (0, 1)$ is a step-size constant to ensure stability and convergence.

This algorithm iteratively adjusts the control input based on the estimated PPD and measurement error to achieve effective tracking.

To design the sliding mode controller, the sliding surface function is given by:

$$s_i(k) = \alpha \xi_i(k) - \xi_i(k-1) \quad (8)$$

herein $\alpha > 1$ represents a positive constant.

Furthermore, from (2) and (3), the formula (3) is updated as

$$\xi_i(k+1) = \xi_i(k) - \left(\sum_{j \in N_i} a_{ij} + d_i \right) \phi_i(k) \Delta u_i(k) + \sum_{j \in N_i} a_{ij} \Delta y_j(k) + d_i \Delta y_d(k+1) \quad (9)$$

wherein $\Delta y_j(k+1)$ is replaced with $\Delta y_j(k)$ because the data at the next moment cannot be obtained.

Therefore, with the assistance of reaching law $s_i(k+1) = 0$, the following equivalent control law can be derived.

$$\Delta u_{i,SM}^{eq} = \frac{\omega \hat{\phi}_i(k)}{\sigma + \hat{\phi}_i(k)^2} \left(\frac{\xi_i(k) + \sum_{j \in N_i} a_{ij} \Delta y_j(k) + d_i \Delta y_d(k+1)}{\sum_{j \in N_i} a_{ij} + d_i} - \frac{\xi_i(k)}{\alpha \left(\sum_{j \in N_i} a_{ij} + d_i \right)} \right) \quad (10)$$

The controller consists of an equivalent control law and switching control law, which means:

$$u_{i,SM}(k) = u_{i,SM}(k-1) + \Delta u_{i,SM}^M(k) + \Delta u_{i,SM}^s(k) \quad (11)$$

Additionally, the switching control law $\Delta u_{i,SM}^s(k)$ is presented:

$$\Delta u_{i,SM}^s(k) = \frac{\omega \hat{\phi}_i(k)}{\sigma + \hat{\phi}_i(k)^2} \tau_s \text{sign}(s_i(k)) \quad (12)$$

As a consequence, taking into consideration (10), (11) and (12), the controller is summarized as follows:

$$u_{i,SM}(k) = u_{i,SM}(k-1) + \frac{\omega \hat{\phi}_i(k)}{\sigma + \hat{\phi}_i(k)^2} \left(\frac{\xi_i(k) + \sum_{j \in N_i} a_{ij} \Delta y_j(k) + d_i \Delta y_d(k+1)}{\sum_{j \in N_i} a_{ij} + d_i} - \frac{\xi_i(k)}{\alpha \left(\sum_{j \in N_i} a_{ij} + d_i \right)} + \tau_s \text{sign}(s_i(k)) \right) \quad (13)$$

Subsequently, the final input is:

$$u_i(k) = u_{i,MFA}(k) + \Gamma_i u_{i,SM}(k) \quad (14)$$

where the parameter Γ_i is a gain factor.

B. Stability Analysis

Theorem 1: For the system (1) satisfying assumptions 1-3, using the designed algorithms (5) along with the reset law (6), the sliding surface (8) and controller (13) can ensure the boundedness of $\hat{\phi}_i(k)$. Simultaneously, the distributed measurement error remains bounded.

Proof: The proof is divided into two parts, which prove the boundedness of $\tilde{\phi}_i(k)$, and ensure that $\xi_i(k)$ remains bounded, respectively.

Part i: Define $\tilde{\phi}_i(k) = \hat{\phi}_i(k) - \phi_i(k)$. Using the PPD estimation algorithm (5), the following result is derived:

$$\begin{aligned} \tilde{\phi}_i(k) &= (\hat{\phi}_i(k-1) - \phi_i(k-1)) + \frac{\eta \Delta u_i(k-1)}{\mu + \Delta u_i(k-1)^2} (\phi_i(k-1) \Delta u_i(k-1) \\ &\quad - \hat{\phi}_i(k-1) \Delta u_i(k-1)) - \phi_i(k) + \phi_i(k-1) \\ &= \tilde{\phi}_i(k-1) + \frac{\eta \Delta u_i(k-1)}{\mu + \Delta u_i(k-1)^2} (\phi_i(k-1) \Delta u_i(k-1) \\ &\quad - \hat{\phi}_i(k-1) \Delta u_i(k-1)) - \phi_i(k) + \phi_i(k-1) \\ &= \tilde{\phi}_i(k-1) + \frac{\eta \Delta u_i(k-1)}{\mu + \Delta u_i(k-1)^2} \Delta u_i(k-1) (\phi_i(k-1) - \hat{\phi}_i(k-1)) - \phi_i(k) + \phi_i(k-1) \\ &= \left(1 - \frac{\eta \Delta u_i(k-1)^2}{\mu + \Delta u_i(k-1)^2} \right) \tilde{\phi}_i(k-1) - \Delta \phi_i(k) \end{aligned} \quad (15)$$

Denote that the term $\frac{\eta\Delta u_i(k-1)^2}{\mu+\Delta u_i(k-1)^2}$ is monotonically increasing with respect to $\Delta u_i(k)^2$, and its minimum value is $\frac{\eta\epsilon^2}{\mu+\epsilon^2}$. Therefore, there must be a constant q_1 satisfying the inequalities $0 < \eta \leq 1$ and $u_i > 0$

$$0 < \left| 1 - \frac{\eta\Delta u_i(k-1)^2}{\mu + \Delta u_i(k-1)^2} \right| \leq 1 - \frac{\eta\epsilon^2}{\mu + \epsilon^2} = q_1 < 1 \quad (16)$$

Because of $|\phi_i(k)| < \bar{d}$, and $|\Delta\phi_i(k)| < 2\bar{d}$, the following equation (15) is written as:

$$\begin{aligned} |\tilde{\phi}_i(k)| &\leq q_1|\tilde{\phi}_i(k-1)| + 2\bar{d} \\ &\leq q_1^2|\tilde{\phi}_i(k-2)| + 2q_1\bar{d} + 2\bar{d} \\ &\vdots \\ &\leq q_1^{k-1}|\tilde{\phi}_i(1)| + \frac{2\bar{d}}{1-q_1}(1-q_1^{k-1}) \end{aligned} \quad (17)$$

which implies $\tilde{\phi}_i(k)$ is bounded. Since the boundedness of $\phi_i(k)$ is guaranteed by Lemma 1.

Part ii: The boundedness of $\xi_i(k)$.

By combining (5) with (9), the expression for $\xi_i(k+1)$ is updated:

$$\begin{aligned} \xi_i(k+1) &= \xi_i(k) + \sum_{j \in N_i} a_{ij} \Delta y_j(k) + d_i \Delta y_d(k+1) - \frac{\omega\phi_i(k)\hat{\phi}_i(k)}{\sigma + \hat{\phi}_i(k)^2} \left(1 - \frac{1}{\alpha}\right) \xi_i(k) \\ &\quad - \frac{\omega\phi_i(k)\hat{\phi}_i(k)}{\sigma + \hat{\phi}_i(k)^2} \sum_{j \in N_i} a_{ij} \Delta y_j(k) - \frac{\omega\phi_i(k)\hat{\phi}_i(k)}{\sigma + \hat{\phi}_i(k)^2} d_i \Delta y_d(k+1) + \left(\sum_{j \in N_i} a_{ij} + d_i \right) \tau_s \text{sign}(s_i(k)) \\ &= \left(1 - \frac{\omega\phi_i(k)\hat{\phi}_i(k)}{\sigma + \hat{\phi}_i(k)^2} \left(1 - \frac{1}{\alpha}\right)\right) \xi_i(k) + \left(\sum_{j \in N_i} a_{ij} \Delta y_j(k) - \frac{\omega\phi_i(k)\hat{\phi}_i(k)}{\sigma + \hat{\phi}_i(k)^2} \sum_{j \in N_i} a_{ij} \Delta y_j(k) \right) \\ &\quad + \left(d_i \Delta y_d(k+1) - \frac{\omega\phi_i(k)\hat{\phi}_i(k)}{\sigma + \hat{\phi}_i(k)^2} d_i \Delta y_d(k+1) \right) + \left(\sum_{j \in N_i} a_{ij} + d_i \right) \tau_s \text{sign}(s_i(k)) \\ &= \left(1 - \frac{\omega\phi_i(k)\hat{\phi}_i(k)}{\sigma + \hat{\phi}_i(k)^2} \left(1 - \frac{1}{\alpha}\right)\right) \xi_i(k) + \left(1 - \frac{\omega\phi_i(k)\hat{\phi}_i(k)}{\sigma + \hat{\phi}_i(k)^2}\right) \left(\sum_{j \in N_i} a_{ij} \Delta y_j(k) \right. \\ &\quad \left. + d_i \Delta y_d(k+1) \right) - \frac{\omega\phi_i(k)\hat{\phi}_i(k)}{\sigma + \hat{\phi}_i(k)^2} \left(\sum_{j \in N_i} a_{ij} + d_i \right) \tau_s \text{sign}(s_i(k)) \end{aligned} \quad (18)$$

Subsequently, take $0 < h_0 < h_i(k) < \frac{\omega C_0}{2\sqrt{\sigma}} < 1$ into consideration, wherein

$$\begin{cases} \phi_i(k) < C_0 \\ h_i(k) = \frac{\omega\phi_i(k)\hat{\phi}_i(k)}{\sigma + \hat{\phi}_i(k)^2} \\ g_i(k) = \left(1 - h_i(k)\right) \left(\sum_{j \in N_i} a_{ij} + d_i \right) \Delta y_d(k+1) - h_i(k) \left(\sum_{j \in N_i} a_{ij} + d_i \right) \tau_s \text{sign}(s_i(k)) \\ |g_i(k)| < g_0 \end{cases}$$

The following inequality is obtained by taking the absolute value of each term of (18).

$$\begin{aligned} |\xi_i(k+1)| &\leq \left|1 - h_i(k)\left(1 - \frac{1}{\alpha}\right)\right| |\xi_i(k)| + |g_i(k)| \\ &\leq \left|1 - h_i(k)\left(1 - \frac{1}{\alpha}\right)\right| |\xi_i(k)| + g_0(k) \\ &\vdots \\ &\leq 1 - h_0\left(1 - \frac{1}{\alpha}\right)^k |\xi_i(0)| + \frac{g_0(1 - (1 - h_0(1 - \frac{1}{\alpha}))^2)}{h_0(1 - \frac{1}{\alpha})} \end{aligned} \quad (19)$$

Therefore, the following result will be given as

$$\lim_{k \rightarrow \infty} \xi_i(k) = \frac{\alpha g_0}{(\alpha - 1)h_0} \quad (20)$$

In summary, both the parameter estimation $\hat{\phi}_i(k)$ and the measurement error $\xi_i(k)$ remain bounded under the proposed adaptive sliding mode control scheme. The condition $0 < h_0 < h_i(k) < \frac{\omega C_0}{2\sqrt{\sigma}} < 1$ ensures that the adaptive parameters are stable, thereby enabling effective performance of the distributed controller. This completes the proof.

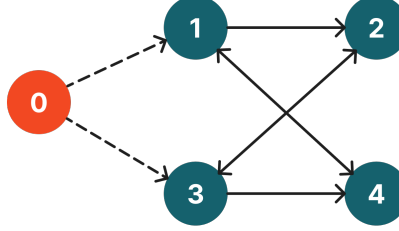


Fig. 2: Communication topology among agents.

IV. SIMULATION EXAMPLE

This section describes the usefulness of the provided control approach, which is validated by both numerical simulations and physical experiments results. The DC brushed motors operate at 12V with a no-load speed of 293 ± 21 RPM and a gear ratio of 20, providing increased torque. Hall encoders with 13 pulses per revolution are used to capture rotor motion. The motor speed is measured in revolutions per second (r/s) based on encoder measurements and the sampling interval t . The total number of encoder counts per revolution is calculated as $rT = 4N_e R_r$, where N_e is the encoder line count equal to 13, R_r is the reduction ratio equal to 20. The number of rotations is determined using $N_r = \frac{m}{rT}$, with m representing the total encoder count. The output data model of each agent is governed by:

$$y_i(k+1) = 0.5y_i(k) + b_i u_i(k) - 0.02y_i(k)^{p_i} + 0.45,$$

Noting that the multi-agent systems are heterogeneous, with four agents having different dynamic models. In addition, these models are not used in the control design but only serve to generate the I/O data required for the MAS simulations. As illustrated in Fig. 2, the virtual leader is designated as vertex 0. It can be observed that only agents 1 and 3 can receive information from the leader, forming a strongly connected communication graph. The Laplacian matrix of the graph is given as follows:

$$L = \begin{bmatrix} 1 & 0 & 0 & -1 \\ -1 & 2 & -1 & 0 \\ 0 & -1 & 1 & 0 \\ -1 & 0 & -1 & 2 \end{bmatrix}$$

with $D = \text{diag}(1, 0, 1, 0)$.

Example 1: In this example, the reference trajectory is a time-invariant signal $y_d(k) = 0.6$. The initial parameters are chosen as $u_i(1) = 0$, $y_i(1) = 0$, and $\hat{\phi}_i(1) = 1$ for all agents in this simulation. The control gains are set as $\Gamma_1 = \Gamma_3 = 0.45$ and $\Gamma_2 = \Gamma_4 = 0.15$. The system model parameters include $[b_1, b_2, b_3, b_4] = [\frac{6m}{rT}, \frac{5.75m}{rT}, \frac{6m}{rT}, \frac{5.75m}{rT}]$ and $[p_1, p_2, p_3, p_4] = [3, 2, 3, 2]$, $m = 600$, $rT = 1024$. Other parameters are $\tau_s = 10^{-5}$, $\eta = 1$, $\mu = 0.005$, $\rho = 7.5$, $\lambda = 350$, $\omega = 10$, $\sigma = 95$, $\alpha = 15$, and $\epsilon = 10^{-5}$.

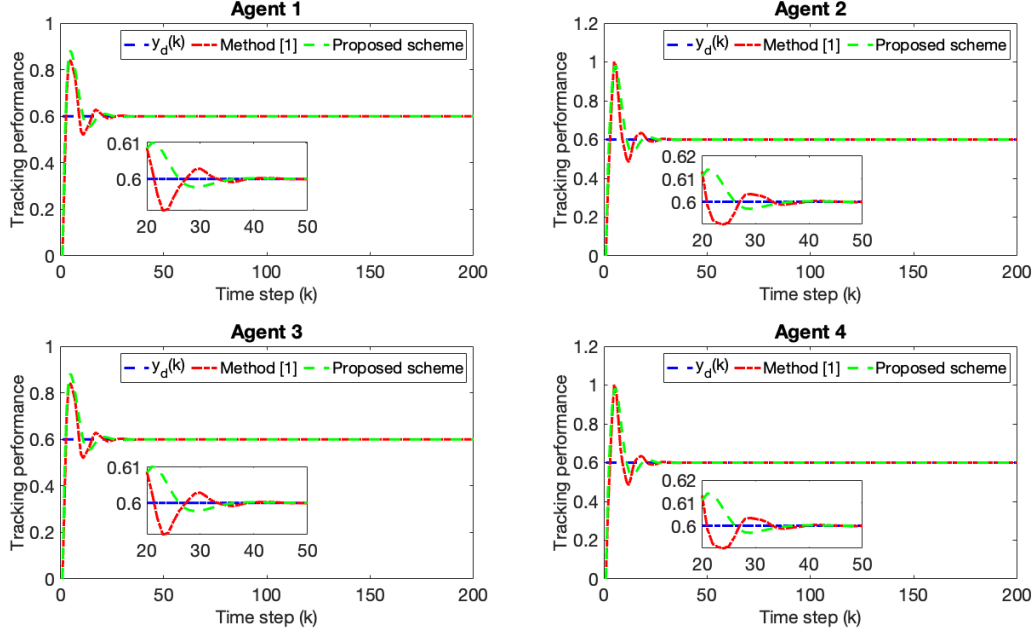


Fig. 3: Tracking performance.

Fig. 3 demonstrates that the proposed scheme achieves superior control performance compared to method [1]. As shown in the above figure, the proposed method ensures faster convergence, smaller overshoot, and improved steady-state tracking accuracy. While method [1] exhibits the oscillations and slower response in transient phase, this highlights the stronger adaptability and robustness of the proposed method. Moreover, Fig. 4 illustrates the distributed measurement errors, which remain bounded within the range of $[-0.02, 0.02]$, indicating accuracy of the proposed control strategy.

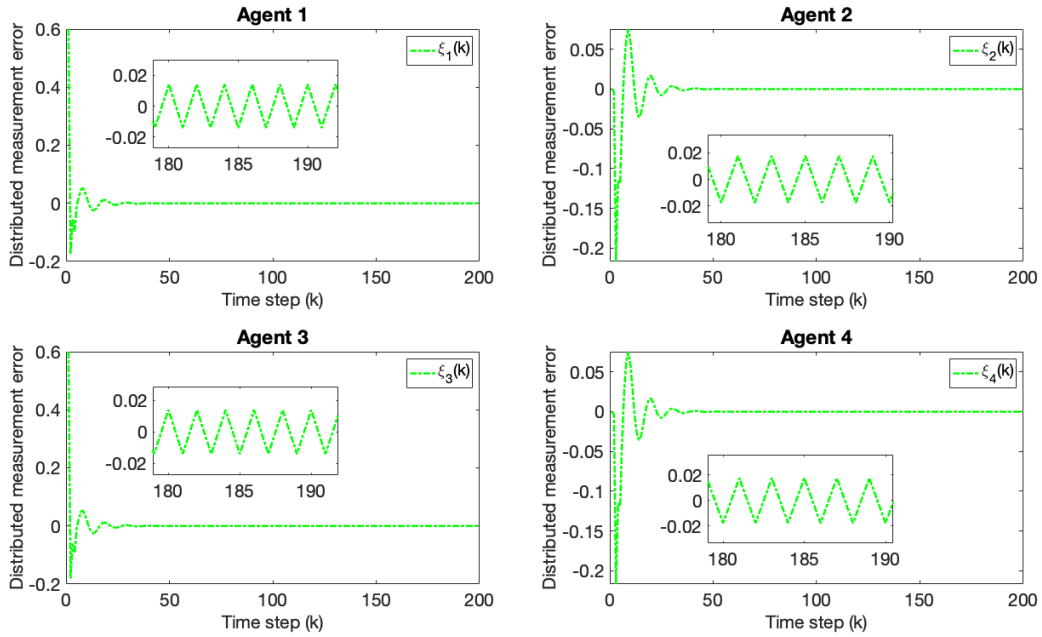


Fig. 4: Distributed measurement errors.

TABLE I: Mean square error comparison (Example 1)

$\text{MSE}_i(k)$	Method [1]	Proposed scheme
Agent 1	4.9135×10^{-3}	4.0732×10^{-3}
Agent 2	3.2197×10^{-3}	2.2558×10^{-3}
Agent 3	4.9135×10^{-3}	4.0732×10^{-3}
Agent 4	3.2197×10^{-3}	2.2558×10^{-3}
Average	4.0666×10^{-3}	3.1649×10^{-3}

To quantitatively evaluate the advantages of the developed method, the mean square error (MSE) is calculated for each agent. The MSE values are presented in TABLE I. For each agent, the MSE is calculated according to the formula:

$$\text{MSE}_i(k) = \frac{1}{m} \sum_{k=1}^m \xi_i^2(k)$$

where m denotes the total number of time steps. In comparison to the existing approach [1], the developed strategy demonstrates significant improvement in accuracy, reducing the average MSE across agents by a factor of approximately 1.29. This notable reduction confirms the effectiveness of the proposed technique.

Example 2: The expression for the reference trajectory is:

$$y_d(k) = 0.6 \sin(0.07\pi(k)) + 0.6 \cos(0.04\pi(k)), k \in [0, 200]$$

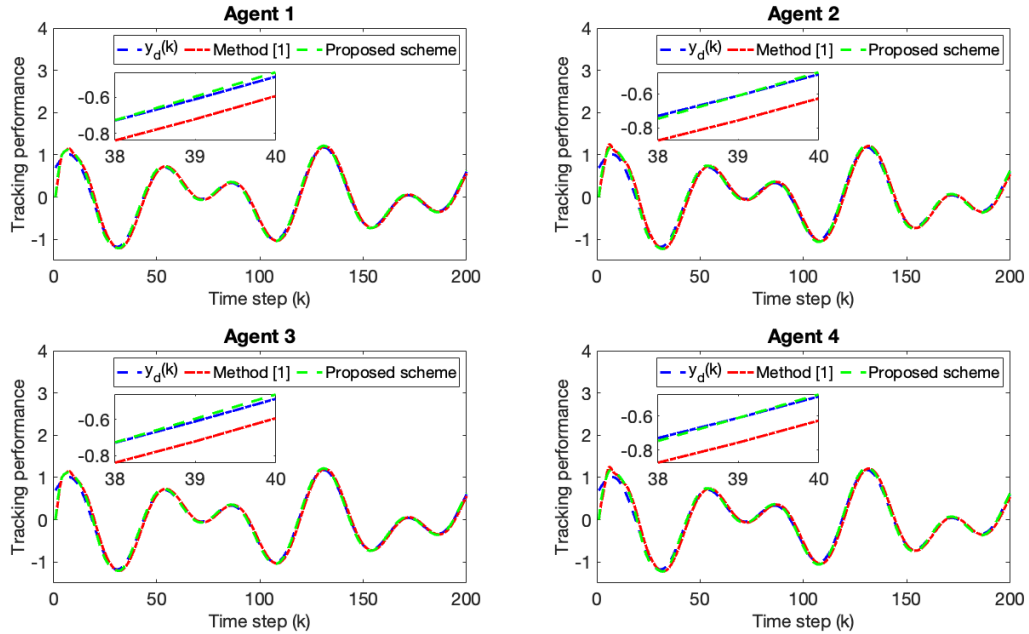


Fig. 5: Tracking performance.

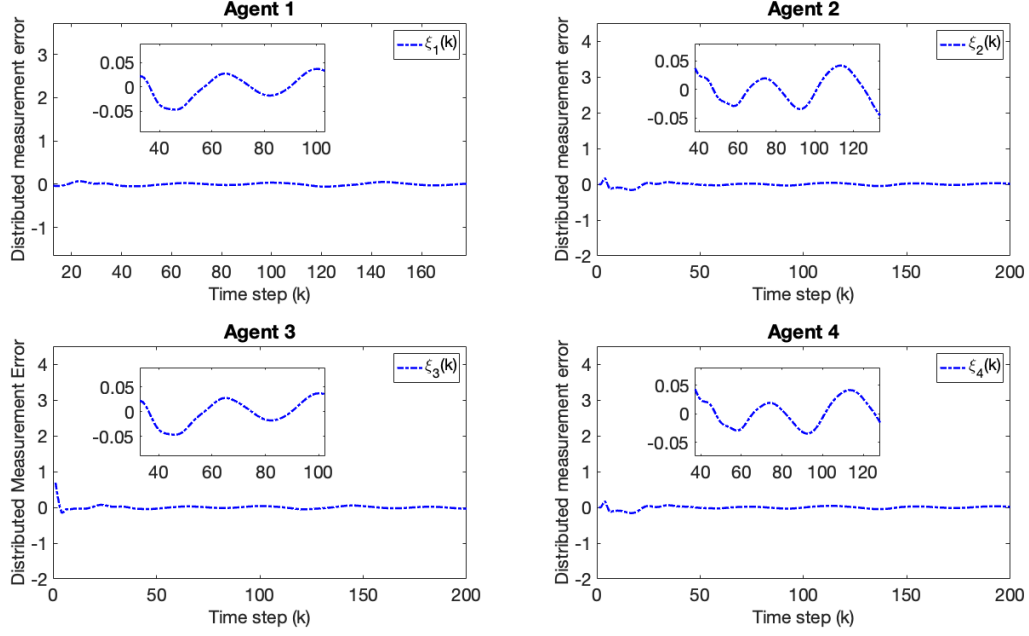


Fig. 6: Distributed measurement errors.

Fig. 5 presents the tracking performance for the time-varying trajectory. All agents successfully track accurately the reference trajectory. Compared to the existing method [1], the proposed scheme achieves the faster response, reduced steady-state error, and improved tracking accuracy. As highlighted, the proposed approach closely follows the reference trajectory, whereas method [1] exhibit the deviations and slower error convergence. Additionally, as shown in Fig. 6 the distributed measurement errors among agents are bounded. Therefore, the proposed method demonstrates superior adaptability under time-varying conditions, ensuring high-performance tracking. For time-varying reference trajectories, the mean squared errors of distributed measurements for two control strategies are detailed in TABLE II. Relative to the conventional approach [1], the proposed scheme reduces in average MSE by approximately 1.16.

TABLE II: Mean square error comparison (Example 2)

$MSE_i(k)$	Method [1]	Proposed scheme
Agent 1	2.8319×10^{-3}	2.6984×10^{-3}
Agent 2	1.4561×10^{-3}	9.8907×10^{-4}
Agent 3	2.8319×10^{-3}	2.6984×10^{-3}
Agent 4	1.4561×10^{-3}	9.8907×10^{-4}
Average	2.1445×10^{-3}	1.8432×10^{-3}

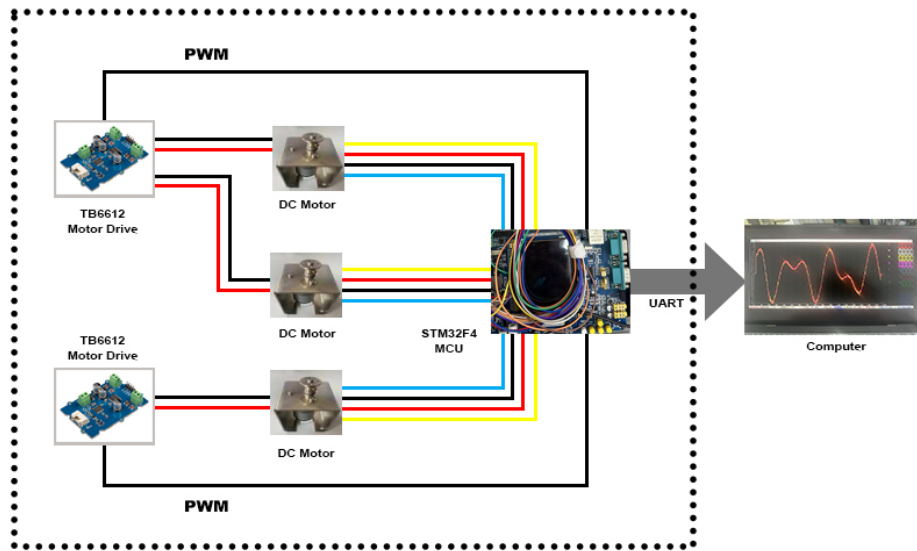


Fig. 7: System connection diagram of multi DC motor consensus tracking control.

To verify the proposed consensus tracking control methodology, the experimental validation is conducted using a multi DC motor system, as illustrated in Fig. 8. The system consists of three DC motors equipped with Hall encoders and reduction gears, an STM32F407 main control chip, two motor drive modules, and an LCD display module. The microcontroller unit STM32F407ZGT6 is used for high-resolution pulse width modulation output generation to achieve precise motor speed control. The timer module is utilized for this purpose.

In addition, the controller code is written in C language using STM32CubeIDE, while STM32CubeMX is used for pin configuration. The main purpose of the experiment is to ensure that the three motors accurately track the reference trajectory:

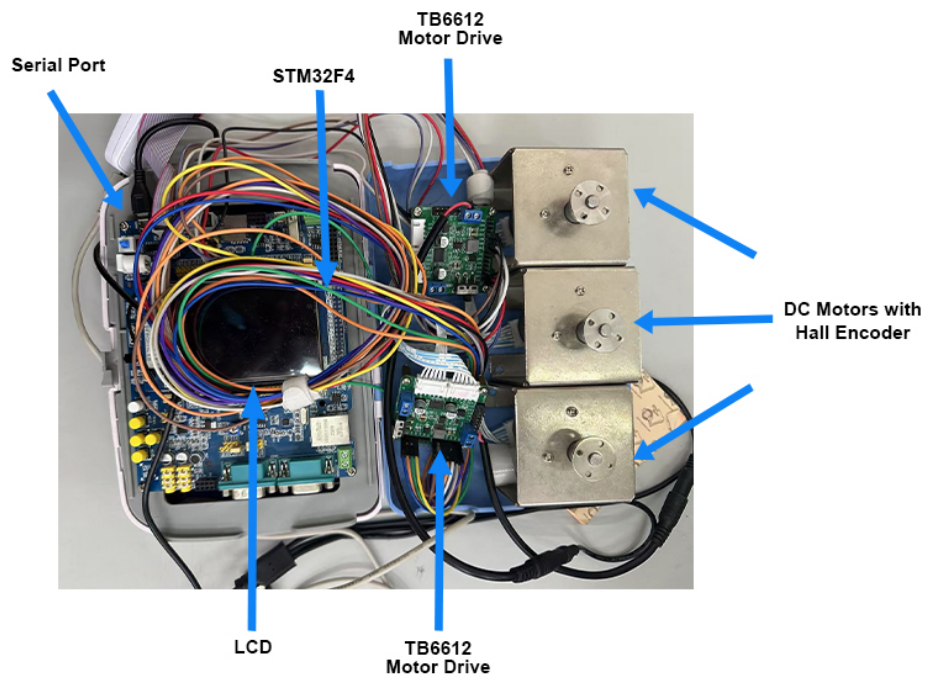


Fig. 8: Multi DC motor system.

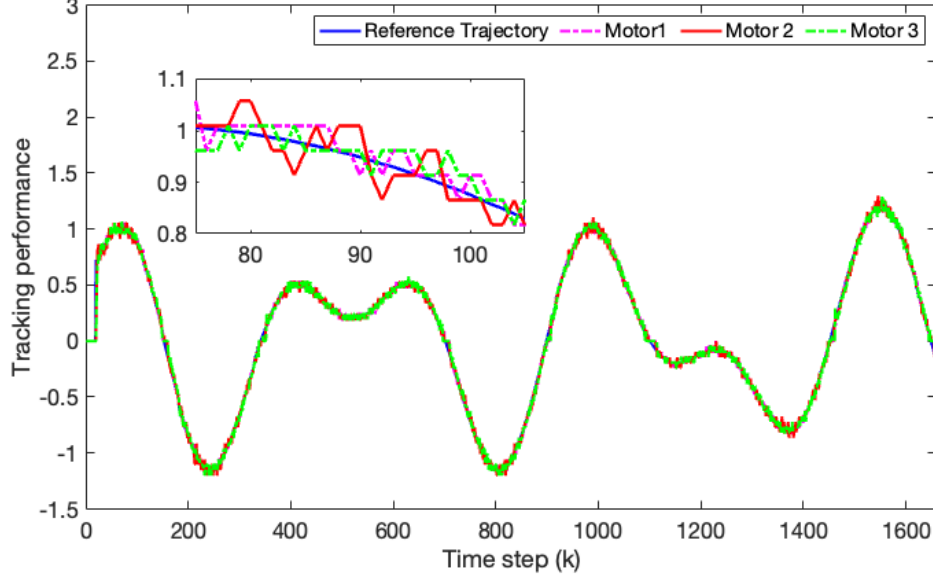


Fig. 9: Tracking performance.

Fig. 9 shows the tracking performance of multi DC motor demonstrating the effectiveness of the proposed control method. Overall, the simulation results suggest that the proposed control system is capable of tracking a constant desired trajectory for multiple agents. While initial transient errors may occur, the system ultimately achieves a steady-state condition with minimal tracking error. The variations in tracking performance among the agents highlight the potential influence of individual characteristics and external factors.

The distributed errors for three DC motors result in mean squared errors of 1.0840×10^{-3} , 1.5036×10^{-3} , and 1.4887×10^{-3} , respectively. The average of 1.3588×10^{-3} demonstrates the effectiveness of the proposed control method in practical applications. Meanwhile, the method consistently maintains mean squared error around 10^{-3} .

Remark 3: The tracking performance is related to the key design parameters, including ρ , ω , σ , α , and the sampling period. However, the algorithm ability to address system uncertainties can be enhanced by appropriately increasing ρ and ω . Furthermore, it is necessary to make precise adjustments to other parameters, such as Γ_i and τ_s , to achieve accurate performance.

V. CONCLUSION

In this study, the model-free adaptive sliding mode control approach is presented to address the consensus problem of MASs. Firstly, the equivalent data model for each agent is obtained using the CFDL method. Secondly, a novel sliding surface is presented to ensure that the distributed measurement error remains bounded. Moreover, the developed strategy effectively mitigates the impact of distributed measurement errors across agents. The simulation results, quantitatively demonstrate the superiority of the proposed technique. Specifically, the mean squared error for each agent is calculated, revealing an average mean squared error reduction of approximately 1.29 compared to the existing approach [1], and approximately 1.16 for time-varying signals. Finally, the effectiveness of the proposed control approach is verified through physical experiments on multi DC motor system.

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