

Review on Consensus Control of Multi-Agent Systems

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Abstract: This review provides a comprehensive analysis of consensus control strategies for multi-agent systems (MASs) mainly by researching and analysing the control formula designs of different representative MAS. Key approaches are highlighted, such as finite-time consensus, pinning control, consensus control under DoS attacks, and other advanced control strategies. Each control strategy is discussed in detail regarding its applicability, advantages, and limitations. Furthermore, the strategies' ability to address rapid convergence, robustness, and security in complex network environments is emphasized. Besides, several current research trends and key challenges, such as robustness under dynamic uncertainties and resource-constrained communication, are also explored. Future opportunities for enhancing the stability and security of MASs are explained in the final section of this review.

Keywords: Multi Agent Systems(MASs), Consensus Control, Distributed Control

1. Introduction

Multi-agent systems (MASs) have become a critical framework for coordinating distributed systems in various fields, including robotics, power grids, and autonomous vehicles. Achieving consensus among agents remains a challenging task due to the need to synchronize their states under diverse conditions. This synchronization must be maintained despite disturbances, uncertain dynamics, and communication constraints. To address these challenges, researchers have proposed numerous control strategies, ranging from traditional finite-time consensus methods [1] to advanced event-triggered mechanisms [2]. Recent advancements in the consensus control of MASs have focused on improving convergence speed, robustness, and adaptability, particularly in dynamic and complex environments. While traditional approaches laid the groundwork, contemporary research emphasizes addressing specific challenges such as communication limitations, security threats, and scalability [3, 4]. A variety of innovative strategies have been developed to mitigate these issues while ensuring reliable system performance and consistent operation.

This review provides a comprehensive analysis of the current state of MASs consensus control research. It examines the strengths, applicability, and limitations of different approaches [5]. Furthermore, it highlights significant recent developments and identifies areas requiring further innovation. The discussion explores how existing methods have evolved to address theoretical and practical challenges. This focus sheds light on emerging trends and unresolved issues, inspiring continuous advancements in the field.

The primary aim of this review is to assess existing MAS consensus control strategies systematically. It evaluates their performance across various scenarios while identifying critical gaps

in the research. A particular emphasis is placed on bridging the gap between theoretical progress and practical implementation. This approach ensures the feasibility of proposed strategies in real-world applications, such as robotic coordination, smart grid management, and autonomous systems.

By emphasizing system resilience [6], efficiency, and adaptability, the review offers valuable insights into future research directions. It underlines the importance of robust and scalable control strategies capable of reliable performance in increasingly complex and uncertain environments. This analysis not only deepens the understanding of existing approaches but also guides the development of innovative solutions tailored to real-world challenges.

2. Consensus Control Analysis

This section provides several consensus control strategies equations with detailed explanations. A comprehensive analysis of the applicability and strengths of each consensus is given as well.

2.1. Finite-Time Consensus and H^∞ Control

Finite-time consensus control methods have become popular in the study of Multi-Agent Systems due to the urgent response requirements of MASs in real-life situations. Nonlinear controllers designed using Lyapunov stability theory can achieve global consensus in finite time and enhance robustness against external disturbances [1]. A recent study has revealed that by adding nonlinear control terms in directed topologies, the system can swiftly achieve a consensus state through this control strategies. The control strategy of Finite-time consensus and H^∞ control is presented as follows:

$$u_q(t) = \sum_{p=1}^k G_{qp} H e_p(t) - B e_q(t) - b_1 h_q^{\frac{b-1}{2}} \text{sign}(e_q(t)) |e_q(t)|^b, q = 1, 2, \dots, n \quad (1)$$

Here, $u_q(t)$ denotes the control input of agent q ; G_{qp} represents an element of the coupling gain matrix indicating the connection strength between agents; H is a positive definite matrix used for system stability; $e_q(t)$ denotes the error state; B is the feedback control matrix; b_1 is a positive value adjusting the control strength; h_q is the error weighting coefficient; and b is the control exponent satisfying $0 < b < 1$ [1].

Applicability and Advantages: This controller is suitable for applications requiring rapid finite-time convergence and robustness against external disturbances. Its nonlinear control term, based on Lyapunov stability theory, accelerates convergence and ensures robust performance in environments with strong disturbances.

2.2. Synchronization via Pinning Control

In large-scale complex networks, effective resource utilization is essential for achieving synchronization within the system. Pinning control strategies can synchronize the entire network by managing a select few key nodes [3], which considerably reduces the time and errors associated with processing large volumes of data. This method demonstrates notable scalability and efficiency, aiding in resource conservation and enhancing control effectiveness in practical applications. Effective for synchronizing complex networks, the control strategy of pinning control is presented as follows:

$$u_i(t) = -c \sum_{j \in \mathcal{N}_i} (x_i(t) - x_j(t)), i = 1, 2, \dots, n \quad (2)$$

Here, $u_i(t)$ denotes the control input; c is the coupling strength; $\mathcal{N}_i$ represents the neighbor set of node i ; and $x_i(t)$ and $x_j(t)$ denote the states of nodes i and j , respectively [3].

Applicability and Advantages: Pinning control is highly efficient in large-scale networks where synchronization can be achieved by controlling a small subset of nodes. It demonstrates excellent scalability and control efficiency, making it resource-efficient.

2.3. Consensus Control Under DoS Attack

With the growing diversity of network attack methods, such as hidden Denial-of-Service (DoS) attacks, the security of MASs faces new challenges. To tackle this, fault detection that can actively recognize attacks and adjust control gains is integrated with consensus control in controller designs [4], improving the system's stability and resilience under security threats. These control strategies can work with real-time feedback, using fault detection mechanisms to identify unusual behaviors in the system and differentiate between typical disturbances and malicious interference. When an attack is detected, the controller modifies control parameters and then reconfigures consensus weights to mitigate the attack's effects. Besides, distributed fault detection algorithms assist real-time monitoring of abnormal behaviors in local areas, thus enhancing the system's adaptability. This guarantees that even amid attacks, the system can sustain consistency and stability.

The control strategy of consensus under DoS attack including combined control and fault detection design is presented as follows:

$$u_i(k) = K_{\eta_{\delta_k}}(x_i(k) - x_{re}(k)) + u_{re}(k), i = 1, 2, \dots, n \quad (3)$$

$$x_i(k+1) = A_{\tau_k}x_i(k) + B_{\tau_k}u_i(k) + F_{\eta_{\delta_k}}r_i(k), i = 1, 2, \dots, n \quad (4)$$

Here, $u_i(k)$ denotes the control input; $K_{\eta_{\delta_k}}$ is the control gain adjusted by attack patterns; $x_{re}(k)$ represents the reference state; $u_{re}(k)$ is the reference input; A_{τ_k} and B_{τ_k} are the system matrices; $F_{\eta_{\delta_k}}$ is the residual gain; and $r_i(k)$ denotes the residual signal [4].

Applicability and Advantages: Suitable for networked systems in secure environments, this method shows strong robustness against random attacks and fast recovery.

2.4. Lyapunov Redesign-Based Consensus Control

To counter unknown dynamic disturbances, Lyapunov-based controllers incorporate robust control terms, ensuring consensus convergence in uncertain environments [5]. This method improves the system's response speed and robustness, enabling Multi-Agent Systems to remain stable and reach consensus despite energetic uncertainties. By integrating robust terms, the system can adjust for unforeseen disturbances, guaranteeing stability under changing conditions. Lyapunov methods offer a solid theoretical basis for designing controllers that effectively manage these uncertainties, bolstering the resilience of MASs in real-world scenarios.

The control strategy of a Lyapunov redesign-based controller enhancing robustness and disturbance resistance in MASs is presented as follows:

$$u_i = -\theta \sum_{j=1}^N a_{ij}(x_i - x_j) - y_i - \eta \nabla f_i(x_i) + \psi_i - \bar{\phi}_i(x_i, t), i = 1, 2, \dots, n \quad (5)$$

Here, u_i denotes the control input of agent i ; a_{ij} represents the elements of the connection matrix; x_i and x_j are the states of the agents; y_i is the auxiliary state; η and θ are tuning parameters; ψ_i is the robustness control term; and $\bar{\phi}_i(x_i, t)$ is the known uncertainty component [5].

Applicability and Advantages: This controller is applicable to MASs with dynamic uncertainties and ensures convergence stability under unknown dynamic disturbances.

2.5. Distributed Adaptive Security Consensus Control

The distributed adaptive security consensus control method [6] addresses the challenges posed by nonlinear multi-agent systems operating under network decay and intermittent cyber-attacks. This control strategy is designed to ensure bounded consensus among agents even in the presence of communication degradation. The control approach includes two key points. First, an adaptive neural network-based observer is employed to reconstruct decayed or disrupted communication signals, enabling accurate state estimation. Second, distributed adaptive controllers are developed to address nonlinear dynamics and maintain consensus. These controllers estimate unknown dynamics using adaptive techniques, ensuring that agents achieve coordinated behavior despite uncertainties and network irregularities.

The proposed strategy demonstrates robustness by maintaining performance under challenging conditions. Adaptability through the use of neural networks, which approximate nonlinear functions with high precision is also highlighted. Simulations on a coupled forced pendulum system validate the method's effectiveness in achieving bounded consensus and resilience to attacks. This makes it a promising solution for multi-agent systems in real-world applications with resource constraints and cyber-security concerns.

The control strategy of distributed adaptive security consensus control compensating for signal loss through observers is presented as follows:

$$u_i(t) = U_i(t)H_i e_i \quad (6)$$

$$\dot{\hat{v}}_i(t) = f(t, \hat{v}_i(t)) + Bu_i(t) + F(\hat{v}_i - v_i), i = 1, 2, \dots, n \quad (7)$$

Here, $u_i(t)$ denotes the control input; $U_i(t)$ represents the adaptive gain matrix varying over time; H_i is the feedback control matrix; e_i denotes the error signal; $\hat{v}_i(t)$ is the state estimate; and $F(\hat{v}_i - v_i)$ is the compensation term [6].

Applicability and Advantages: This controller is suitable for environments experiencing attacks and signal loss, with dynamic gain adjustment enhancing security and consensus.

2.6. Data-Driven Event-Triggered Consensus Control

To ease communication demands and enhance resource utilization, event-triggered mechanisms have been incorporated into consensus control strategies [2]. This technique allows for distributed consensus control in systems with unknown dynamics, reducing communication frequency and making it suitable for resource-constrained environments. By triggering communication only when predefined events occur, it conserves bandwidth and computational resources while maintaining system performance and consensus convergence. Event-triggered control is thus seen as a promising solution for large-scale multi-agent systems with limited resources. Moreover, this strategy preserves system performance and ensures convergence to consensus, thereby boosting overall system efficiency and scalability. Consequently, event-triggered consensus control is increasingly acknowledged as a promising solution for large-scale multi-agent systems and other applications facing strict resource constraints.

The control strategy of data-driven event-triggered control which can reduce communication frequency is presented as follows:

$$u_i(t) = K \sum_{j \in N_i} (x_j(t) - x_i(t)), i = 1, 2, \dots, n \quad (8)$$

$$\Sigma_i = \{[A, B] \mid [AB]^T \Theta_i [AB] \leq 0\} \quad (9)$$

Here, $u_i(t)$ means the control input; K is the feedback gain; $x_i(t)$ and $x_j(t)$ represent the agent states; N_i is the neighbor set; and Θ_i is the stability matrix derived from data [2].

Applicability and Advantages: Widely used in resource-limited distributed systems, this event-triggered mechanism achieves fully distributed consensus control by reducing communication frequency.

3. Main Challenges

Despite the substantial progress made in multi-agent systems consensus control, several significant challenges persist, hindering the smooth deployment and scalability of these systems in real-world applications.

Ensuring the consistency and stability of systems remains a challenge when facing complex dynamic topologies, strong disturbances, and nonlinear uncertainties [2, 5]. These factors make it difficult to achieve reliable performance under varied and unpredictable conditions. To address these issues, further research is required to develop more robust control strategies that can adapt to increasingly complex scenarios, ensuring stability and reliability across diverse operating environments, such as those encountered in autonomous vehicles or smart grids.

Effectiveness of Security Defense remains a paramount concern as current security-focused methods are often inadequate in addressing advanced and sophisticated attack vectors, particularly Advanced Persistent Threats (APTs). These attacks, characterized by their stealth and longevity, target critical system vulnerabilities and can severely compromise system integrity. To mitigate these risks, designing forward-looking detection and defense mechanisms is crucial. Integrating the latest advancements in security technologies, such as intrusion detection systems and blockchain-based verification protocols, should be a focal point in future research, ensuring that MASs are resilient to evolving threats.

Communication and Control in Resource-Constrained Environments is also needed to be further researched. In scenarios with limited communication bandwidth and computational resources, it is essential to reduce communication frequency and computational complexity without sacrificing the performance of the system. Optimizing algorithms to strike an appropriate balance between communication efficiency and system stability remains a major hurdle[2]. This optimization should consider the trade-offs involved in minimizing communication overhead while maintaining the synchronization of agents, particularly in environments like smart cities or industrial IoT networks, where resource limitations are common.

Real-World implementation and validation of MASs control strategies remain a critical gap. For these strategies to be effective, they must be experimentally validated in real-world scenarios, including autonomous vehicle fleets, smart grids, and robotics. This validation process must address practical constraints such as hardware limitations, sensor inaccuracies, and real-time computational requirements. Without such validation, there remains a significant risk that the proposed algorithms will not perform as expected under the diverse and dynamic conditions of practical applications.

Heterogeneity within multi-agent systems introduces complexity in achieving consensus, as agents may possess diverse capabilities, dynamic models, and operational constraints. Coordinating heterogeneous agents requires sophisticated algorithms that can accommodate varying states and behaviors while ensuring cohesive system-wide agreement [7]. The integration of heterogeneous agents without sacrificing consensus accuracy or convergence speed remains a significant hurdle. Besides, there is a lack of comprehensive frameworks that can universally accommodate the wide range of heterogeneities present in MASs.

4. Future Directions

Looking forward, the field of multi-agent systems consensus control is poised to explore several promising research avenues, aimed at overcoming existing challenges and unlocking new capabilities.

These future research directions are expected to significantly enhance the robustness, efficiency, and applicability of consensus algorithms across a wide array of domains.

Deep reinforcement learning (DRL) has emerged as a powerful tool for optimizing cooperative strategies in MASs. DRL algorithms enable agents to autonomously learn optimal policies through interaction with their environment. This capability is particularly beneficial in decentralized systems, where agents must make decisions with limited global information. Techniques such as multi-agent reinforcement learning (MARL) allow agents to develop communication protocols and improve coordination, addressing challenges like communication constraints and resource limitations. For instance, learn-to-communicate frameworks within MARL[8] have been shown to enhance the efficiency of MAS operations in scenarios with limited communication bandwidth.

Green Consensus Protocols address the growing need for sustainable and energy-efficient operations in MAS. For instance, Chen propose a minimum-energy distributed consensus control approach that leverages network approximation techniques to minimize the energy consumption of multi-agent systems during coordination[9]. This method enables more efficient energy usage by optimizing the control algorithms to reduce the overall power requirements of the agents while maintaining the desired consensus behavior. Future research is needed to explore the design of low-energy consensus algorithms and environmentally friendly communication protocols that minimize the energy footprint of multi-agent coordination processes. Developing green consensus mechanisms aligns with global sustainability goals and enhances the long-term viability of MASs deployments.

Usage of Neural Network can efficiently improve the capability of MASs control strategies. Neural networks have proven effective in addressing nonlinear dynamics and system uncertainties in MASs by approximating unknown functions with high precision, thereby enhancing control robustness and adaptability. By approximating unknown functions with high precision, adaptive NN-based controllers can handle nonlinearity and provide robust consensus control. For example, a recent study [10] proposed an NN-based observer to recover degraded signals caused by network decay and intermittent attacks, maintaining system performance and achieving bounded consensus under adverse conditions. Additionally, fault-tolerant NN controllers have been utilized to detect and compensate for actuator faults, ensuring stable operation despite hardware failures.

Quantum Consensus Algorithms represent an emerging frontier, exploring the potential of quantum computing to enhance consensus control of MASs. Quantum algorithms could exploit quantum parallelism to achieve faster convergence rates and solve complex coordination problems more efficiently than classical counterparts. Recent studies[11] have demonstrated how quantum-inspired consensus methods can improve the security and reliability of multi-agent systems, particularly in nonlinear scenarios, by implementing secure protocols that ensure robust performance under uncertain conditions. As quantum technology progresses, the development of quantum-based consensus protocols could offer significant computational advantages, paving the way for large-scale MAS applications.

Autonomous Systems and the Internet of Things (IoT) are anticipated to drive the need for robust consensus mechanisms in highly interconnected and heterogeneous environments. In applications such as autonomous driving, smart manufacturing, and smart cities, achieving consensus among a vast array of diverse and distributed agents is critical for coordinated operation and optimal performance. However, as highlighted by Lin et al., the presence of heterogeneous time-varying inputs and communication delays in directed graphs[12] complicates the task of achieving consensus. These factors introduce uncertainty in agent interactions, requiring the development of advanced algorithms to ensure reliable and timely coordination across a diverse set of agents. Furthermore, Mo et al. extend this challenge by focusing on distributed hybrid control for heterogeneous multi-agent systems, particularly in environments with variable communication delays. Their work on DC microgrids[13] demonstrates that hybrid control strategies can effectively manage the instability

caused by delays and heterogeneity, ensuring that coordination and stability are maintained even under dynamic and uncertain conditions. Studies suggest that future research will likely focus on scalable and flexible consensus frameworks that seamlessly integrate with IoT infrastructures, addressing both communication delays and the diverse capabilities of agents. This will be essential for supporting autonomous decision-making and ensuring optimal performance across multiple hierarchical levels in complex systems.

Integration of Heterogeneous Systems is in great demand researching MASs consensus control. Modern MASs often consist of diverse agents with varying dynamics and capabilities. Consensus control mechanisms that support interoperability among heterogeneous agents should be emphasized, considering differences in dynamics, communication protocols, and functional roles within the systems.

Standardization and Interoperability are essential for ensuring that diverse MASs can operate cohesively and efficiently. Future efforts will likely focus on developing standardized protocols and interoperability frameworks that facilitate seamless communication and coordination among heterogeneous agents from different manufacturers and platforms. Establishing common standards will promote wider adoption and integration of MASs consensus control technologies across various industries.

5. Conclusion

In this review, key advancements and challenges have been examined in the field of consensus control for multi-agent systems (MASs). The ability to synchronize and coordinate agents in a decentralized environment remains a complex task, particularly when accounting for the dynamic nature of real-world systems and the presence of uncertainties and disturbances. The various consensus strategies discussed, including finite-time consensus, pinning control, and methods resilient to denial-of-service (DoS) attacks, illustrate the diversity of approaches aimed at addressing these challenges. Each method offers distinct advantages, such as enhanced robustness, fast convergence, and the ability to withstand security threats, yet each also has inherent limitations that need further exploration.

Despite the progress made, significant hurdles remain in ensuring the reliability and scalability of MASs in practical applications. These challenges include maintaining system stability under dynamic topologies, optimizing communication in resource-constrained environments, and fortifying systems against increasingly sophisticated cyber-attacks. In light of these issues, the field must evolve towards the development of consensus protocols that are not only secure and robust but also computationally efficient and adaptable to a wide range of operational conditions.

Besides, the integration of emerging technologies such as deep reinforcement learning (DRL), neural networks (NNs), and quantum algorithms holds great promise for overcoming some of the current limitations. These techniques could lead to more adaptive, scalable, and secure consensus strategies, significantly improving system performance in complex and heterogeneous environments. Furthermore, the push towards green consensus protocols is particularly timely, given the growing emphasis on sustainability in technological developments.

In conclusion, while considerable progress has been made in MASs consensus control, future research should focus on refining these strategies to address the practical and theoretical gaps that still exist. Emphasis should be placed on real-world implementation and testing, as well as the continuous integration of advanced technologies to ensure that MASs are not only efficient and secure but also capable of adapting to the rapidly evolving technological landscape.

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