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RESEARCH ARTICLE

# Formation Control of Heterogeneous Multi–Agent Systems Under Fixed and Switching Hierarchies

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**ABSTRACT** Modern information technology is driving the rapid development of the information and automation industry through the combination of computer technology, communication technology, and control technology. Inspired by nature's cluster movement, such as birds, people proposed the concept of *Multi–Agent Systems (MASs)*. This paper deals with the formation control problem for a class of *heterogeneous multi–agent systems* with time-delays. First, the formation control of heterogeneous multi–agent systems with communication delay in fixed and switching topologies is investigated. A *heterogeneous multi–agent system model* with input delay and communication delay is established. Furthermore, based on this model, the formation control protocol is designed and the stability of the proposed control protocol in *fixed* and *switched topologies* is analyzed. The first– and second–order multi–agent control system was formulated for both *fixed* and *switched topology*, respectively. Then, using the new *LMI toolbox*, the feasibility of the parameters is obtained and the example is created by *MATLAB*. The simulation results show that the proposed formation control protocol with delay in this paper can make the systems converge to the expected value under *fixed* and *switched* hierarchies.

**INDEX TERMS** Heterogeneous multi–agent systems, Lyapunov functionals, formation control, resource constraints.

## I. INTRODUCTION

In the realm of artificial intelligence and control engineering, the emergence of *multi–agent systems (MASs)* marks a paradigm shift from traditional individual autonomous control to a cooperative structure. This approach, inspired by collective animal behaviors and extensively explored in research [1] and industrial applications [2], offers enhanced robustness and efficiency. Key characteristics of an agent in this context include the ability to sense the environment, make decisions, and actuate movement or interaction [3].

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The evolution of *MASs*, influenced by advances in robotics [4], *micro–grids*, and traffic control systems Chen et al. 2003), demonstrates significant benefits such as improved task efficiency, energy savings, and increased fault tolerance in system redundancy [5]. These attributes collectively contribute to the growing prominence and application of *MASs* in modern technological landscapes. The readers may also be directed to the published papers listed in Table 1, which provide additional historical evaluations of diverse control systems implemented on *multi–agent systems (MAS)*.

In the actual network communication between agents, the input delay and communication delay caused by the limited network resources and the non–ideal state of the actual environment can not be ignored, including the influence of switching topology on consistency convergence, which has also attracted the attention of scholars, and has achieved fruitful research results in the research of consistency under switching topology and time–varying topology [6], [7]. Among them, literature [8], [9] mainly studies the consistency of continuous-time systems with time delay and switching topology, literature [10], [11], [12] mainly studies the stability of discrete–time multi-agent systems with time delay, interference or both, and literature [13] studies the average consistency of discrete-time Markov switched *linear multi–agent systems (L-MAS)* with fixed topology and time delay, and proposes a time–delay switching. By improving the new signal mode, the switching signal of the system and the time delay signal of the controller are combined into one signal. By using *Lyapunov method*, two *LMIs standards* of average consistency are given, and it is proved that the consistency of *multi–agent system* is related to the spectral radius of the Laplacian matrix. Literature [14] studies the distributed consistency of a class of *multi–agent complex systems* with unknown time delay under switching topology and intermittent communication. Each agent is modeled as a general nonlinear system. Based on *Lyapunov stability theory* and *graph theory*, the sufficient conditions for exponential convergence are proved. Literature [15] studies the grouping consistency of *discrete–time multi–agent systems* with switching topology and bounded time delay. Based on non–negative matrix theory and graph theory. It is proved that the packet consistency condition is solvable under the assumption that the communication topology in any time interval of a given length contains the group–spanning tree.

*Multi–agent system control*, specifically containment control, has drawn increasing attention from scholars in the modern era. The inclusion control problem has been discovered to be apply in many practical situations inspired by some natural phenomena, such as multi–mobile robots or vehicle fleets. Incorporating control can allow an agent to act as the leader so that a group of robots or autonomous vehicles does not enter the dangerous zone by guiding the vehicle or multiple–mobile robot into the safe areas that the leader crosses. The use of containment control in practical applications can be seen as playing a significant role in [16] and [17]. The inclusion control problem has been studied in great detail in recent years, and Ref. studies the inclusion control problem for a dynamic switching topology with communication delay in the case of a *leader–following multi–agent system*. In [18], the problem of inclusion control is studied. *First–order* and *second–order dynamic systems* are considered containment control algorithms, and modern control theory and algebraic graph theory are applied to analyze the stability of the two containment control algorithms using the *Lyapunov–Rasovskii method*. An undirected/directed network topology was examined in [19] and [20] when sampling data inclusion was needed from a linear multiagent system with multiple leaders. Refer to [20] for the decomposition of the closed–loop control problem into multiple subsystem stability analysis problems. The Lyapunov function was combined with sufficient conditions to ensure all followers entered the leader's convex hull. Several agents are under different leaders in [21] and [22]. The authors discusses distributed containment control strategies for multiple leaders both in static and dynamic situations in his published kinds of literature [21], [23]. It is mainly the study of alpha-asymptotically convergent followers in *first–order network* models of *multi–agent systems* that refers to [24], in which the *alpha–asymptotically convergent* followers follow the strategy of *alpha–asymptotically* convergent followers. Refer to Figure 1 for more information about the behavior-based formation control model.

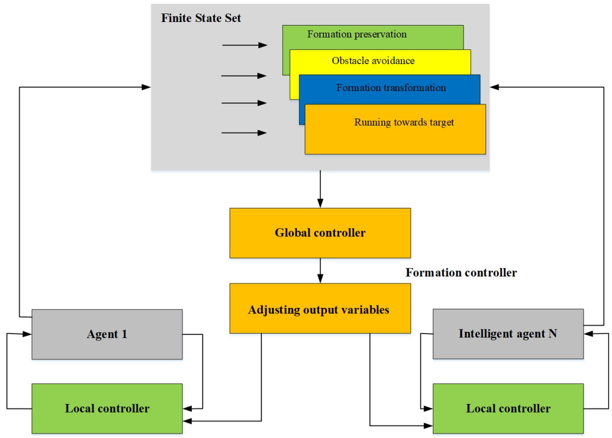



**FIGURE 1. Behavior–based formation control model.**

The above research results all consider that agents have the same dynamic characteristics, but in reality, there are differences between *multi–agents*. In recent years, *heterogeneous multi–agent systems* have gradually attracted the attention of scholars [25], [26], [27], and literature [25] has studied the consistency of *heterogeneous multi–agent systems* under *directed topology*. A new consistency algorithm is proposed for continuous–time systems with fixed and switched topologies. Based on the method of system transformation, the consistency problem of *heterogeneous multi–agent system* is transformed into the consistency problem of *homogeneous multi–agent system*. And enough conditions are given. Literature [26] considers the problem of *leader–follower* output consistency of a *heterogeneous multi–agent system* with uncertain dynamic performance under the conditions of lead time delay and input saturation restriction. Combining neural network, graph theory, mean value theorem and *dynamic surface control (DSC)* technology, a distributed adaptive control scheme is constructed of the *nonlinear multi–agent systems*. For a class of *MIMO* time–delay systems with strict feedback, Li et al. [27] proposed an adaptive control scheme through *dynamic surface control (DSC)* technology, neural network and

*Lyapunov–Krasovskii function*. In a control design scheme, *heterogeneous multi–agent systems* plays a crucial role by enabling decentralized decision–making, collaboration, and coordination among agents with diverse capabilities and expertise. System performance, reliability, and scalability are enhanced by this ability to adapt and respond effectively to complex and dynamic environments. It is also possible to continue functioning if some agents fail or are unavailable during *heterogeneous multi–agent systems*, which promotes flexibility and fault tolerance. *Heterogeneous multi–agent systems* also increases system resilience since multiple agents accomplish control tasks, resulting in a reduced dependence on one entity. Control schemes incorporating *heterogeneous multi–agent systems* facilitate distributed intelligence and decision–making since agents are capable of exchanging information, sharing knowledge, and cooperating to achieve goals [28]. *Heterogeneous multi–agent systems* optimize and allocate resources efficiently by leveraging the diverse abilities and knowledge of individuals. Generally, *heterogeneous multi–agent systems* can enhance control design schemes in multiple ways, including decentralized decision–making, collaboration, adaptation to dynamic environments, fault tolerance, resilience, and distributed intelligence.

Based on the above analysis,

1) In this research, the *consistency problem* of *heterogeneous multi–agent systems* under switching topology has been investigated with communication delay to the formation control problem.
2) For the formation control problem, both scenarios (*second–order and first–order heterogeneous multi-agent systems*) has been developed with *new Lyapunov function*.
3) This research designs a *new formation control protocol* with *input delay* and *communication delay*. Considering that the communication between agents will be restricted by the geographical environment, the stability of the system is affected in two cases: *fixed topology* and *time–varying topology* and *convergence* were analyzed.

The succeeding portions of this document are structured in the subsequent fashion: *Section 2* investigates the creation of a deferred diverse *multi–agent system model*. *Section 3* outlines the development of a formation control protocol in both fixed and switched topologies. *Section 4* delves into the examination of the results obtained from simulations, while *Section 5* provides a concise summary of the proposed system and offers potential paths for future research.

## II. FORMATION OF DELAYED HETEROGENEOUS MULTI–AGENT SYSTEM MODEL

Consider a heterogeneous multi-agent system consisting of $q$ first–order and second–order agent nodes and a second-order virtual leader. Firstly, $p(p < q)$ agents are second–order multi–agent systems, and $q$ agents are first–order multi-agent systems. The dynamic models of second-order and first-order multi-agent systems are as follows:

$$\begin{cases} \dot{s}_i(t) = v_i(t), \\ \dot{v}_i(t) = u_i(t), \; i = 1, 2, \ldots, p \\ \dot{s}_i(t) = u_i(t), \; i \in p+1, p+2, \ldots, q \end{cases} \tag{1}$$

where

- $s_i(t) \in \mathbb{R}^{\mathcal{N}}$ presents the position of the $i^{th}$ agent.
- $v_i(t) \in \mathbb{R}^{\mathcal{N}}$ denotes the speed of the $i^{th}$ agent.
- $u_i(t) \in \mathbb{R}^{\mathcal{N}}$ shows the control inputs of the $i^{th}$ agent.

In the existing literature, many control protocol algorithms have been proposed for different multi-agent system consistency control problems. For example, in literature [29], the first-order integral system consistency protocol is adopted for the dynamic model with only one order integral system:

$$u_i(t) = \sum_{j \in \mathcal{N}_i} b_{ij}(s_j(t) - s_i(t)), \; i = 1, 2, \ldots, q \tag{2}$$

In [30], aiming at the dynamic model of the second–order integral system, the consistency protocol of the second–order integral system is adopted:

$$u_i(t) = \sum_{j \in \mathcal{N}_i} b_{ij}(s_j(t) - s_i(t)) - \mathbb{K}_1 v_i, \; i = 1, 2, \ldots, q \tag{3}$$

On the basis of the above research results, in [6], the authors proposed a consistency control protocol for heterogeneous systems (1):

$$u_i(t) = \begin{cases} -\mathbb{K}_1 v_i + \sum_{j=1}^{q} b_{ij}(t)(s_j - s_i), \; i = 1, 2, \ldots, p \\ \mathbb{K}_2 \sum_{j=1}^{q} b_{ij}(t)(s_j - s_i), \; i = p+1, p+2, \ldots, q \end{cases} \tag{4}$$

Based on the above consistency control protocol, considering the formation control problem of heterogeneous multi-agent systems under switching topology, a new formation control protocol for system (1) is proposed:

$$u_i(t) = \begin{cases} -\mathbb{K}_2 v_i(t) + \mathbb{K}_1 \sum_{j \in \mathcal{N}_i} b_{ij}(s_j(t) - s_{dj}) \\ -(y_i(t) - s_{di}) + d_{i0}(s_i(t) - s_0 - s_{d_i}), \\ i = 1, 2, \ldots, p \\ \sum_{j \in \mathcal{N}_i} b_{ij}(s_j(t) - s_i(t)) \\ +d_{i0}(s_i(t) - s_0 - s_{d_i}), \\ i = p+1, \ldots, q \end{cases} \tag{5}$$

where $\mathbb{K}_1$, and $\mathbb{K}_2$ are the values to be designed. $y_i(t)$ is the position information of the desired agent node and its neighboring agent nodes respectively with $y_i(t) = s_i(t) + v_i(t)$, $(s_{d_i}, s_{d_j}) \in s^q$. Let $D = \text{diag}\{d_{i0}\}$, is a communication

**TABLE 1. Different Controllers Schemes for Multi–agents systems.**

| References | Parameter | Value |
|---|---|---|
| Fault–Tolerant Control for Heterogeneous Multiagent Systems [33], [35], [38] | • Cooperative fault–tolerant output regulation approaches.<br>• Formation control under fixed topologies.<br>• Fixed–time optimization control algorithm.<br>• Fractional–order sliding–mode control strategy. | • Avoids fault propagation.<br>• Efficient convergence time.<br>• Cooperative tracking errors. |
| Tracking Control of Nonlinear Multi–Agent Systems [34], [36], [37] | • Fixed–time formation control for multi–agent systems.<br>• Overcome the bounded disturbance of communication.<br>• New adaptive *FixF* control protocol is provided.<br>• New protocol for faults, uncertainties, and disturbances. | • Leader agent to change desired formation at runtime.<br>• Control protocol with fewer parameters and reduces control cost.<br>• Bounded error of MASs. |
| $H_\infty$ Control for Heterogeneous Multi–Agent Systems [39], [40], [42] | • Robust fault–tolerant output formation.<br>• Tracking control for heterogeneous multi–agent systems.<br>• Data dropout is modelled using homogeneous Markov chain. | • Development of fault–tolerant output formation.<br>• Use of finite–time observers control.<br>• To derive leader's information for each follower. |
| Event–triggered scheme for multi–agent systems [41], [43] | • Distributed fixed–time consensus control protocol.<br>• Reduce the number of triggering events.<br>• Neural network–based fixed–time controller is formulated.<br>• Estimated leader commands to achieve the desired control. | • Reducing calculation costs.<br>• Settling time can be specified according to specific requirements.<br>• Output–constrained fixed–time problem is solved. |
| Time-varying output Control of Heterogeneous Systems [44], [46] | • Control protocol for time–varying formation of multi–agent systems.<br>• Convergence of the observer controller.<br>• Position and velocity information for direct topology.<br>• Non–uniform communication delay and switching topology. | • Optimal tracking control design.<br>• Achieve the time–varying formation under switching topologies.<br>• To derive leader's information for each follower. |
| Adaptive control design with unknown inputs for Multi-agent Systems [45], [47] | • Adaptive consensus control of leader–following system.<br>• Functional uncertainties, external disturbances, and unknown control directions.<br>• Adverse impact of filtered errors formulated.<br>• Addressing controller design for fractional-order systems with unknown control. | • Distributed algorithms for tracking problem.<br>• To overcome the unknown faults and directed graphs.<br>• To derive leader's information for each follower.<br>• Estimate and reconstruct the leaderŠs state. |

link between the agent node $i$ and the virtual leader, $d_{i0} = b_{i0}$, otherwise $d_{i0} = 0$.

**Definition 2.1** For the heterogeneous multi–agent system (1), as long as the following conditions are met, we say that the system realizes formation, and the conditions are as follows:

$$\lim_{t\to\infty} \left\| s_i(t) - s_j(t) - s_{d_i} \right\| = 0 \quad \text{for} \quad i, j \in I_q$$
$$\lim_{t\to\infty} \left\| v_i(t) - v_j(t) \right\| = 0 \quad \text{for } i, j \in I_p$$

Considering the existence of input time-varying delay $\hbar(t) > 0$ and communication delay between agents $\lambda(t) > 0$, the control protocol (2) can be written as:

$$u_i(t) = \begin{cases} \mathbb{K}_1 \sum\limits_{j\in\mathcal{N}_i} b_{ij}(s_j(t-\lambda(t)-\hbar(t)) - s_{dj}) \\ -(y_i(t-\hbar(t)) - s_{di}) + d_{i0}(s_i(t) - s_0 - s_{d_i)} \\ -\mathbb{K}_2 v_i(t-\hbar(t)), \qquad i = 1, 2, \ldots, p \\ \sum\limits_{j\in\mathcal{N}_i} b_{ij}(s_j(t-\lambda(t)-\hbar(t)) - s_{dj}) \\ -(s_i(t-\hbar(t)) - s_{di})) \\ +d_{i0}(s_i(t) - s_0 - s_{d_i}), \\ i = p+1, \ldots, q \end{cases} \tag{6}$$

According to the system (1) and the formation control protocol (3), the agent node can be expressed as:

$$\begin{cases} \dot{s}_i(t) = v_i(t), \\ \dot{v}_i(t) = -\mathbb{K}_2 v_i(t-\hbar(t)) + \mathbb{K}_1 \sum\limits_{j\in I_q} b_{ij}[(s_j(t-\digamma(t)) - s_{d_j}) \\ \qquad -(y_i(t-\hbar(t)) - s_{d_i})] \\ \qquad + d_{i0}(s_i(t) - s_0 - s_{d_i}), \quad i = 1, 2, \ldots, p \\ \dot{s}_i(t) = \sum\limits_{j\in I_q} b_{ij}[(s_j(t-\digamma(t)) - s_{d_i}) \\ \qquad -(s_i(t-\hbar(t)) - s_{d_j})] + d_{i0}(s_i(t) - s_0 - s_{d_i}) \\ \qquad i = p+1, \ldots, q \end{cases} \tag{7}$$

where $\digamma(t) = \hbar(t) + \lambda(t)$, Define formation error of agent node $i$:

$$\begin{cases} \bar{s}_i(t) = s_i(t) - s_0 - s_{d_i}, \\ \bar{v}_i(t) = v_i(t) - v_0. \end{cases} \tag{8}$$

Then equation (7) can be rewritten as:

$$\begin{cases} \dot{\bar{s}}_s(t) = \bar{v}_s(t), \\ \dot{\bar{v}}_s(t) = -\mathbb{K}_2 I_p \bar{v}_s(t-\hbar(t)) + \mathbb{K}_1[\mathbb{A}_{22}\bar{s}_s(t-\digamma(t)) \\ +\mathbb{A}_{21}\bar{s}_f(t-\hbar(t)-\lambda(t)) \\ -\mathbb{D}_2\bar{s}_s(t-\hbar(t)) - \mathbb{D}_2\bar{v}_s(t-\hbar(t))] - \mathbb{C}_s\bar{s}_s(t), \\ \dot{\bar{s}}_f(t) = \mathbb{A}_{12}\bar{s}_s(t-\digamma(t)) + \mathbb{A}_{11}\bar{s}_f(t-\digamma(t)) \\ -\mathbb{D}_1\bar{s}_f(t-\hbar(t)) - \mathbb{C}_f\bar{s}_f(t) \end{cases} \tag{9}$$

where

$$\bar{s}_s = \left[\, \bar{s}_1^T \ \bar{s}_1^T \ \ldots \ \bar{s}_p^T \,\right]^T$$
$$\bar{v}_s = \left[\, \bar{v}_1^T \ \bar{v}_1^T \ \ldots \ \bar{v}_p^T \,\right]^T$$
$$\bar{s}_f = \left[\, \bar{s}_{p+1}^T \ \bar{s}_{p+2}^T \ \ldots \ \bar{s}_q^T \,\right]^T$$

Furthermore, $\mathbb{A}_{11} \in \mathbb{R}^{(q-p)\times(q-p)}$, and $\mathbb{A}_{22} \in \mathbb{R}^{p\times p}$ are the adjacency matrix between the second-order agents and the adjacency matrix between the first–order agents respectively. $\mathbb{A}_{21} \in \mathbb{R}^{p\times(p-q)}$, and $\mathbb{A}_{12} \in R^{(q-p)\times p}$ are the adjacency matrix between the second–order agent and the first–order agents are with the proper definitions:

$$\mathbb{D}_2 = diag\left\{\sum\nolimits_{j=1}^{q} b_{ij}, i \in 1, 2, .., p\right\},$$
$$\mathbb{D}_1 = diag\left\{\sum\nolimits_{j=1}^{q} b_{ij}, i \in p+1, p+2, .., q\right\},$$
$$\mathbb{C}_s = \mathrm{diag}\{d_{10}, \ldots, d_{p0}\},$$
$$\mathbb{C}_f = \mathrm{diag}\{c_{(p+1)0}, \ldots, d_{q0}\}$$

Then a closed–loop multi–agent system can be obtained with augmented matrix.

$$\begin{aligned} &e(t) = \left(\bar{s}_s \bar{v}_s \bar{s}_f\right). \\ &\dot{e}(t) = \mathbb{G}_1 e(t) + \mathbb{G}_2 e(t-\hbar(t)) + \mathbb{G}_3 e(t-\hbar(t)-\lambda(t)) \end{aligned} \tag{10}$$

where

$$\mathbb{G}_1 = \begin{bmatrix} 0 & I_m & 0 \\ -\mathbb{C}_s & 0 & 0 \\ 0 & 0 & -\mathbb{C}_f \end{bmatrix}$$
$$\mathbb{G}_2 = \begin{bmatrix} 0 & 0 & 0 \\ -\mathbb{K}_1\mathbb{D}_2 & -\mathbb{K}_2 I_p - \mathbb{K}_1\mathbb{D}_2 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$
$$\mathbb{G}_3 = \begin{bmatrix} 0 & 0 & 0 \\ \mathbb{K}_1\mathbb{A}_{22} & 0 & \mathbb{K}_1\mathbb{A}_{21} \\ \mathbb{A}_{12} & 0 & \mathbb{A}_{11} \end{bmatrix}$$

Then, the formation control problem of multi–agent (1) is transformed into the stability problem of the closed–loop system (10). Before proceeding to the principal theorem, the authors shall establish certain fundamental assumptions and lemmas.

*Assumption 1 ( [31]):* $0 \le \hbar(t) \le \delta_1, \ 0 \le \dot{\hbar}(t) \le \rho_1 < 1, \quad \delta_1 > 0, \quad t \ge 0$

*Assumption 2 ( [31]):* $0 \le \lambda(t) \le \delta_2, \ 0 \le \dot{\lambda}(t) \le \rho_2 < 1, \quad \delta_2 > 0, \quad t \ge 0$

*Lemma 1 ( [32]):* Suppose $0 \le \lambda(t) \le \delta_2$, $\delta_2 > 0$ is a piecewise continuous function. For any differentiable vector function $s(t) : [-\delta_2, \infty) \to \mathbb{R}^q$ and any positive definite matrix $\mathbb{M} \in \mathbb{R}^{q\times q}$, the following inequality holds:

$$\left(\int_{t-\lambda(t)}^{t} \dot{s}^T(\vartheta)d\vartheta\right)\mathbb{M}\left(\int_{t-\lambda(t)}^{t} \dot{s}(\vartheta)d\vartheta\right) \le \delta_2 \int_{t-\delta_2}^{t} \dot{s}^T(\vartheta)\mathbb{M}\dot{s}(\vartheta)d\vartheta, \ t \ge 0.$$

*Remark 1:* Due to the diversity of characteristics and dynamic interactions between the agents in heterogeneous multi–agent systems, formation control poses significant challenges. Coordinating effectively and communicating effectively is crucial for maintaining the stability of these complex systems, especially the positions and velocities among the agents. Decentralized control, consensus protocols, and optimization techniques have been developed to address these challenges. Taking into account heterogeneous agents' different capabilities, constraints, and objectives, our proposed methods aim to achieve coordination and cooperation between them. Optimizing coordination and communication strategies in heterogeneous multi–agent systems requires consideration of diverse characteristics and the dynamic interactions of agents. In addition, robustness and flexibility in an unpredictable network configuration depend on the ability to adapt to changing topologies. An understanding of agent dynamics, effective coordination and communication strategies, and robust and adaptable control algorithms are necessary for the development and control of heterogeneous multi-agent systems under fixed and switching topologies.

## III. DESIGN OF FORMATION CONTROL PROTOCOL IN FIXED AND SWITCHED TOPOLOGIES

Formation control in a *multi–agent model* refers to the coordinated behavior of a group of agents to achieve and maintain a desired geometric formation or pattern. In fixed topologies, the agents maintain a specific arrangement relative to each other throughout the entire operation. This can be done by following a set of predefined rules and communication protocols. On the other hand, in switched topologies, the communication links between agents change dynamically over time. This creates additional challenges in achieving and maintaining the desired formation, as the agents must adapt and synchronize their actions based on the changing communication topology. In fixed topologies, the formation control protocol involves agents maintaining a specific arrangement relative to each other throughout the operation using predefined rules and communication protocols. In switched topologies, the formation control protocol requires agents to dynamically adapt and synchronize their actions based on the changing communication topology, ensuring that they continue to achieve and maintain the desired geometric formation or pattern.

### A. FIXED COMMUNICATION TOPOLOGY

In this section, the authors will present the basic conditions for the asymptotically stability in the Theorem 1.

*Theorem 1:* For heterogeneous multi–agent systems (1), the closed-loop system (10) is globally uniformly asymptotically stable, if $\hbar(t), \lambda(t)$ satisfy Assumptions 1 and 2 respectively. In a fixed communication topology, if there are real numbers $\mathbb{K}_1$, $\mathbb{K}_2$ and a series of positive definite matrices $\mathbb{P}$, $\mathbb{Q}_j$, $\mathbb{R}_j$, $j = 1, 2, 3$, the following linear matrix inequalities hold:

$$\begin{bmatrix} \Xi_{11} & \Xi_{12} & \Xi_{13} \\ \diamond & \Xi_{22} & \Xi_{23} \\ \diamond & \diamond & \Xi_{33} \end{bmatrix} < 0 \tag{11}$$

where

$$\Xi_{11} = \mathbb{G}_1^T\mathbb{P} + \mathbb{P}\mathbb{G}_1 + \mathbb{Q}_1 + \sigma\mathbb{G}_1^T\mathbb{R}_1\mathbb{G}_1 + \delta_2\mathbb{G}_1^T\mathbb{R}_2\mathbb{G}_1 - \sigma^{-1}\mathbb{R}_1,$$
$$\Xi_{12} = \mathbb{P}\mathbb{G}_2 + \delta_1\mathbb{G}_1^T\mathbb{R}_1\mathbb{G}_2 + \delta_2\mathbb{G}_1^T\mathbb{R}_2\mathbb{G}_2 + \sigma^{-1}\mathbb{R}_1,$$
$$\Xi_{13} = \mathbb{P}\mathbb{G}_3 + \sigma\mathbb{G}_1^T\mathbb{R}_1\mathbb{G}_3 + \delta_2\mathbb{G}_1^T\mathbb{R}_2\mathbb{G}_3,$$
$$\Xi_{22} = (1-\rho_1)(\mathbb{Q}_2 - \mathbb{Q}_1) + \sigma\mathbb{G}_2^T\mathbb{R}_1\mathbb{G}_2 + \delta_2\mathbb{G}_2^T\mathbb{R}_2\mathbb{G}_2 - \sigma^{-1}\mathbb{R}_1 - \delta_2{}^{-1}\mathbb{R}_2,$$
$$\Xi_{23} = \sigma\mathbb{G}_2^T\mathbb{R}_1\mathbb{G}_3 + \delta_2\mathbb{G}_1^T\mathbb{R}_2\mathbb{G}_3 + \delta_2{}^{-1}\mathbb{R}_2,$$
$$\Xi_{33} = (\rho_1 + \rho_2 - 1)\mathbb{Q}_2 + \sigma\mathbb{G}_3^T\mathbb{R}_1\mathbb{G}_3 + \delta_2\mathbb{G}_3^T\mathbb{R}_2\mathbb{G}_3 + \delta_2{}^{-1}\mathbb{R}_2.$$

**Proof:** Consider a Lyapunov–Krasovskii function as follows:

$$W(t) = e^T(t)\mathbb{P}e(t) + W_1(t) + W_2(t) \tag{12}$$

where

$$W_1(t) = \int_{t-\hbar(t)}^{t} e^T(\theta)\mathbb{Q}_1 e(\theta)d\theta + \int_{t-\lambda(t)-\hbar(t)}^{t-\hbar(t)} e^T(\theta)\mathbb{Q}_2 e(\theta)d\theta$$
$$W_2(t) = \int_{-\sigma}^{0}\int_{t+\vartheta}^{t} \dot{e}^T(\theta)\mathbb{R}_1\dot{e}(\theta)d\theta d\vartheta + \int_{-\delta_2-\sigma}^{-\sigma}\int_{t+\vartheta}^{t} \dot{e}^T(\theta)\mathbb{R}_2\dot{e}(\theta)d\theta d\vartheta$$

Derive the formula (12).

$$\begin{aligned}\dot{W}(t) = {} & \dot{e}^T(t)\mathbb{P}e(t) + e^T(t)\mathbb{P}\dot{e}(t) \\ & + (1-\rho_1)e^T(t-\hbar(t))(\mathbb{Q}_2 - \mathbb{Q}_1) \\ & e(t-\hbar(t)) + (\rho_2 + \rho_1 - 1)e^T(t-\hbar(t) \\ & - \lambda(t))\mathbb{Q}_2 e(t-\hbar(t)-\lambda(t)) + \sigma\dot{e}^T(t)\mathbb{R}_1\dot{e}(t) \\ & - \sigma^{-1}(e^T(t) - e^T(t-\hbar(t)))\mathbb{R}_1(e(t) - e(t-\hbar(t))) \\ & + \delta_2\dot{e}^T(t)\mathbb{R}_1\dot{e}(t) - \delta_2{}^{-1}(e^T(t-\hbar(t)) - e^T(t-\hbar(t) \\ & - \lambda(t)))\mathbb{R}_2(e(t-\hbar(t)) - e(t-\hbar(t)-\lambda(t)))\end{aligned}$$

According to Lemma 1:

$$\dot{W}(t) \le \xi^T(t)\Xi\xi(t)$$

where

$$\xi^T(t) = [e^T(t), e^T(t-\hbar(t)), e^T(t-\hbar(t)-\lambda(t))]$$

Therefore, if equation (11) holds, the system (10) is globally asymptotically stable. And thus, the demonstration of this theorem can be easily finalized. □

*Remark 2:* Robotic systems in complex manufacturing environments benefit from multi–agent systems because they enhance efficiency, flexibility, and adaptability. By utilizing multiple autonomous agents that can communicate and collaborate, multi-agent systems enable robots to perform tasks more effectively. As a result of these systems, resource allocation and coordination can be optimized, movement can be coordinated, and information can be shared, resulting in improved efficiency and productivity. By distributing decision–making and task execution among multiple agents, multi–agent systems in industrial robotics encourage fault tolerance and resilience. In this way, a single robot is not dependent on a single mechanism, and system robustness is enhanced. Multiple robots can be coordinated, collaborated, and made to make decisions using multi–agent systems. Manufacturing processes become more efficient, adaptable, and productive by collaborating and coordinating multiple robots in multi-agent systems in industrial robotics.

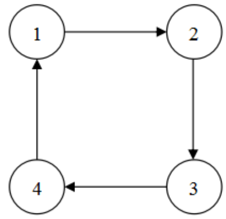



**FIGURE 2.** Communication topology diagram of multi-agent system.

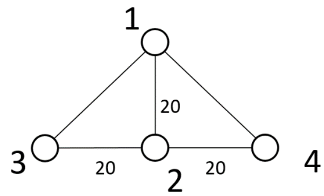
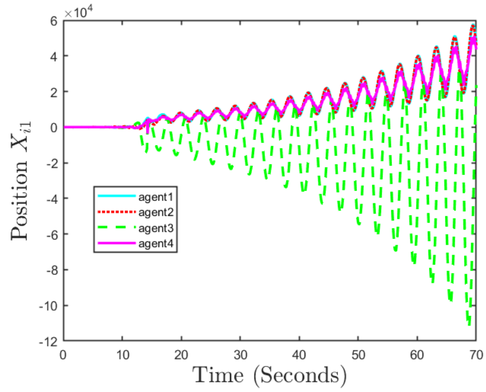



**FIGURE 3.** Expected formation.

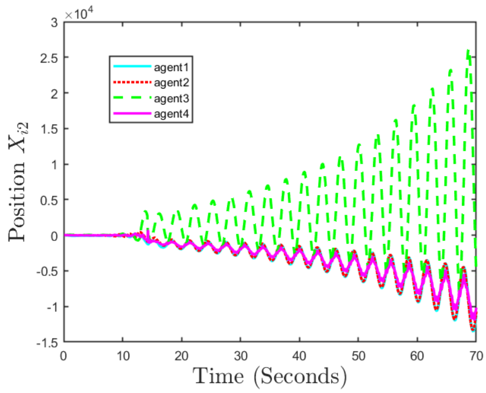
### B. SWITCHING COMMUNICATION TOPOLOGY

In practice, due to the change of the agent's environment, the communication of the whole network will be disturbed, so the topological structure will also change. Therefore, designing a communication topology that changes with time can effectively solve the communication obstacle problem. This section mainly studies the formation control problem of heterogeneous multi–agent systems under switching topology. The definition of $\mho = \{\bar{\mathbb{G}}_\Phi,\ \Phi = 1, 2, \ldots, \mathcal{N}\}$ represents a set of switching topologies. Then the system (7) with time-varying delay in switched topology can write:

$$\begin{cases} \dot{\bar{s}}_s(t) = \bar{v}_s(t), \\ \dot{\bar{v}}_s(t) = -\mathbb{K}_2 I_p^\Phi \bar{v}_s(t-\hbar(t)) + \mathbb{K}_1[A_{22}^\Phi \bar{s}_s(t-F(t)) \\ +\mathbb{A}_{21}^\Phi \bar{s}_f(t-F(t)) - \mathbb{D}_2^\Phi \bar{s}_s(t-\hbar(t)) \\ -\mathbb{D}_2^\Phi \bar{v}_s(t-\hbar(t))] - \mathbb{C}_s^\Phi \bar{x}_s(t), \\ \dot{\bar{s}}_f(t) = \mathbb{A}_{12}^\Phi \bar{s}_s(t-F(t)) + \mathbb{A}_{11}^\Phi \bar{s}_f(t-F(t)) \\ -\mathbb{D}_1^\Phi \bar{s}_f(t-\hbar(t)) - \mathbb{C}_f^\Phi \bar{s}_f(t) \end{cases} \tag{13}$$

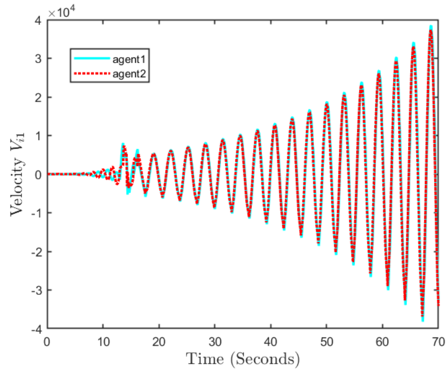



(a) Position of Agent on $X$–axis in Fixed Directed Topology.

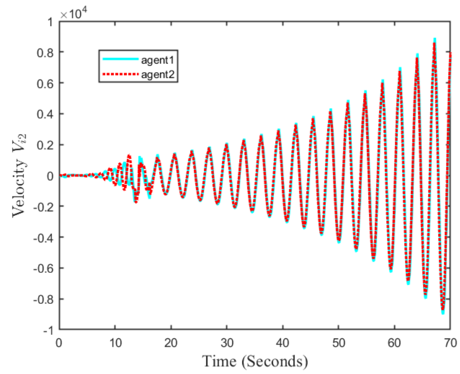



(b) Position of Agent on $Y$–axis in Fixed Directed Topology.

**FIGURE 4. Positions of Agent on $X$–axis and $Y$–axis in fixed Directed Topology without control inputs.**




(a) The velocity trajectory of the agent on the $X$–axis under fixed directed topology.




(b) The velocity trajectory of the agent on the $Y$–axis under fixed directed topology.

**FIGURE 5. The velocity trajectory of the agent on the $X$-axis and $Y$-axis under fixed directed topology without control inputs.**

The system (13) with augmented matrix can be rewritten as:

$$\dot{\zeta}(t) = \mathbb{G}_1^\Phi \zeta(t) + \mathbb{G}_2^\Phi \zeta(t-\tau(t)) + \mathbb{G}_3^\Phi \zeta(t-\hbar(t)-\lambda(t)) \tag{14}$$

where

$$\mathbb{G}_1^\Phi = \begin{bmatrix} 0 & I_p^\Phi & 0 \\ -\mathbb{C}_s^\Phi & 0 & 0 \\ 0 & 0 & -\mathbb{C}_f^\Phi \end{bmatrix}$$

$$\mathbb{G}_2^\Phi = \begin{bmatrix} 0 & 0 & 0 \\ -\mathbb{K}_1\mathbb{D}_2^\Phi & -\mathbb{K}_2 I_p^\Phi - \mathbb{K}_1\mathbb{D}_2^\Phi & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$\mathbb{G}_3^\Phi = \begin{bmatrix} 0 & 0 & 0 \\ \mathbb{K}_1\mathbb{A}_{22}^\Phi & 0 & \mathbb{K}_1\mathbb{A}_{21}^\Phi \\ \mathbb{A}_{12}^\Phi & 0 & \mathbb{A}_{11}^\Phi \end{bmatrix}$$

*Theorem 2:* For heterogeneous multi-agent systems (1), the closed–loop system (10) is globally uniformly asymptotically stable, if $\hbar(t)$, and $\lambda(t)$ satisfy assumptions 1 and 2 respectively. In the switching communication topology, if there are real numbers $\mathbb{K}_1$, and $\mathbb{K}_2$ and a series of positive definite matrices $\mathbb{P}$, $\mathbb{Q}_j$, $\mathbb{R}_j$, $j = 1, 2, 3$, the following linear matrix inequalities hold:

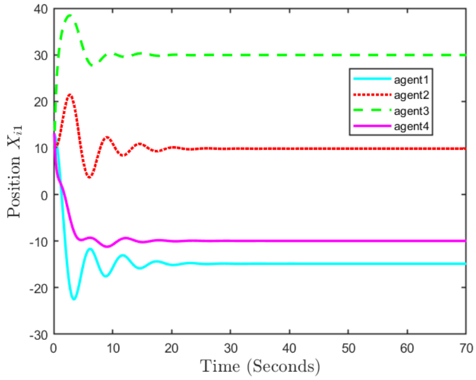
$$\begin{bmatrix} \Xi_{11}^s & \Xi_{12}^s & \Xi_{13}^s \\ \diamond & \Xi_{22}^s & \Xi_{23}^s \\ \diamond & \diamond & \Xi_{33}^s \end{bmatrix} < 0 \tag{15}$$

where

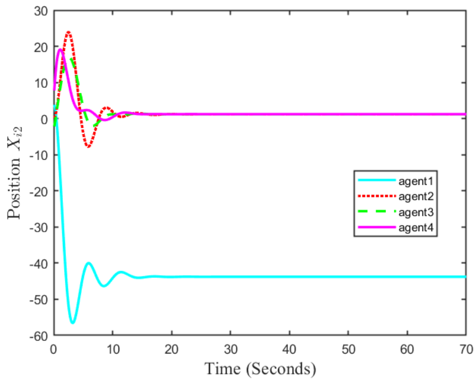
$$\begin{aligned}
\Xi_{11}^s &= \mathbb{G}_1^{\Phi T}\mathbb{P} + \mathbb{P}\mathbb{G}_1^\Phi + \mathbb{Q}_1 + \mathbb{Q}_2 + \sigma\mathbb{G}_1^{\Phi T}\mathbb{R}_1\mathbb{G}_1^\Phi \\
&\quad + (\rho_2+\sigma)\mathbb{G}_1^{\Phi T}\mathbb{R}_2\mathbb{G}_1^\Phi - \sigma^{-1}\mathbb{R}_1 - (\rho_2+\sigma)\mathbb{R}_2, \\
\Xi_{12}^s &= \mathbb{P}\mathbb{G}_2^\Phi + \sigma\mathbb{G}_1^{\Phi T}\mathbb{R}_1\mathbb{G}_2 + (\rho_2+\sigma)\mathbb{G}_1^{\Phi T}\mathbb{R}_2\mathbb{G}_2^\Phi + \sigma^{-1}\mathbb{R}_1, \\
\Xi_{13}^s &= \mathbb{P}\mathbb{G}_3^\Phi + \sigma\mathbb{G}_1^{\Phi T}\mathbb{R}_1\mathbb{G}_3^\Phi \\
&\quad + (\rho_2+\sigma) + \mathbb{G}_1^{\Phi T}\mathbb{R}_2\mathbb{G}_3^\Phi + (\rho_2+\sigma)^{-1}\mathbb{R}_2, \\
\Xi_{22}^s &= (\rho_1-1)\mathbb{Q}_1 + \sigma\mathbb{G}_2^{\Phi T}\mathbb{R}_1\mathbb{G}_2^\Phi + (\rho_2+\sigma)\mathbb{G}_2^{\Phi T}\mathbb{R}_2\mathbb{G}_2^\Phi \\
&\quad - \sigma^{-1}\mathbb{R}_1, \\
\Xi_{23}^s &= \sigma\mathbb{G}_2^{\Phi T}\mathbb{R}_1\mathbb{G}_3^\Phi + (\rho_2+\sigma)\mathbb{G}_1^{\Phi T}\mathbb{R}_2\mathbb{G}_3^\Phi, \\
\Xi_{33}^s &= (\rho_1+\rho_2-1)\mathbb{Q}_2 + \sigma\mathbb{G}_3^{\Phi T}\mathbb{R}_1\mathbb{G}_3^\Phi \\
&\quad + (\rho_2+\sigma)\mathbb{G}_3^{\Phi T}\mathbb{R}_2\mathbb{G}_3^\Phi - (\rho_2+\sigma)^{-1}\mathbb{R}_2.
\end{aligned}$$

**Proof**: Consider a Lyapunov–Krasovskii function as follows:

$$U(t) = \zeta^T(t)\mathbb{P}\zeta(t) + U_1(t) + U_2(t) \tag{16}$$

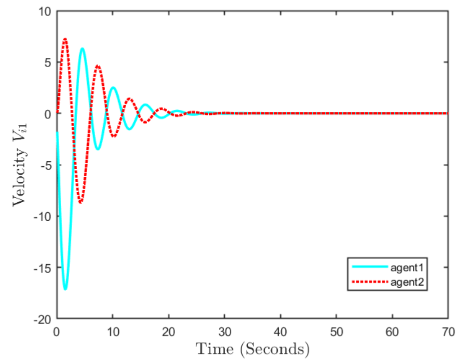



(a) Position of Agent on $X$–axis in Fixed Directed Topology.

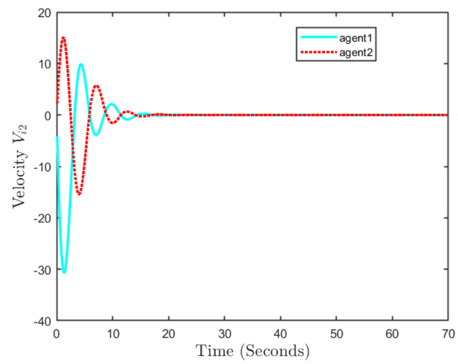



(b) Position of Agent on $Y$–axis in Fixed Directed Topology.

**FIGURE 6. Positions of Agent on $X$–axis and $Y$–axis in fixed Directed Topology with control inputs.**




(a) The velocity trajectory of the agent on the $X$–axis under fixed directed topology.




(b) The velocity trajectory of the agent on the $Y$–axis under fixed directed topology.

**FIGURE 7. The velocity trajectory of the agent on the $X$–axis and $Y$–axis under fixed directed topology with control inputs.**

where

$$U_1(t) = \int_{t-\hbar(t)}^{t} \zeta^T(\psi)\mathbb{Q}_1\zeta(\psi)d\psi + \int_{t-\lambda(t)-\hbar(t)}^{t-\hbar(t)} \zeta^T(\psi)\mathbb{Q}_2\zeta(\psi)d\psi$$

$$U_2(t) = \int_{-\sigma}^{0}\int_{t+\theta}^{t} \dot{\zeta}^T(\psi)\mathbb{R}_1\dot{\zeta}(\psi)d\psi d\theta + \int_{-\delta_2-\sigma}^{-\sigma}\int_{t+\theta}^{t} \dot{\zeta}^T(\psi)\mathbb{R}_2\dot{\zeta}(\psi)d\psi d\theta$$

Derive the formula (16).

$$\begin{aligned}
\dot{U}(t) &= \dot{\zeta}^T(t)\mathbb{P}\zeta(t) + \zeta^T(t)\mathbb{P}\dot{\zeta}(t) \\
&\quad + (1-\rho_1)\zeta^T(t-\hbar(t))(\mathbb{Q}_2-\mathbb{Q}_1)\zeta(t-\hbar(t)) \\
&\quad + (\rho_1+\rho_2-1)\zeta^T(t-\hbar(t)-\lambda(t))\mathbb{Q}_2\zeta(t-\hbar(t) \\
&\quad - \lambda(t)) + \sigma\dot{\zeta}^T(t)\mathbb{R}_1\dot{\zeta}(t) \\
&\quad - \sigma^{-1}(\zeta^T(t)-\zeta^T(t-\hbar(t)))\mathbb{R}_1(\zeta(t)-\zeta(t-\hbar(t))) \\
&\quad + \rho_2\dot{\zeta}^T(t)\mathbb{R}_1\dot{\zeta}(t) - \rho_2{}^{-1}(\zeta^T(t-\hbar(t))-\zeta^T(t-\hbar(t) \\
&\quad - \lambda(t)))\mathbb{R}_1(\zeta(t-\hbar(t))-\zeta(t-\hbar(t)-\lambda(t)))
\end{aligned}$$

According to Lemma 1.

$$\dot{U}(t) \leq \varphi^T(t)\Xi^s\varphi(t)$$

where

$$\varphi^T(t) = [\zeta^T(t), \zeta^T(t-\hbar(t)), \zeta^T(t-\hbar(t)-\lambda(t))]$$

Therefore, if equation (15) holds, the system (14) is globally asymptotically stable. And thus, the demonstration of this theorem can be easily finalized. □

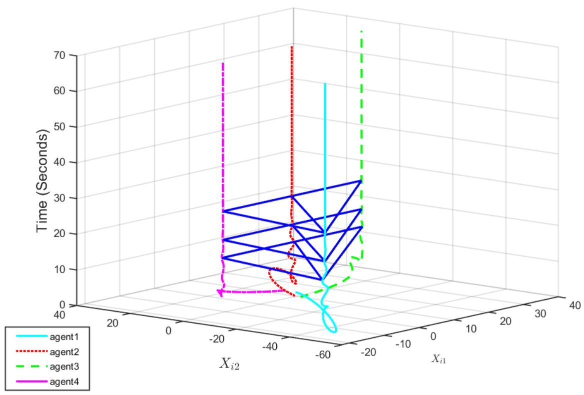
## IV. SIMULATION EXAMPLE

### A. FORMATION CONTROL OF MULTI-AGENT SYSTEM UNDER FIXED DIRECTED TOPOLOGY

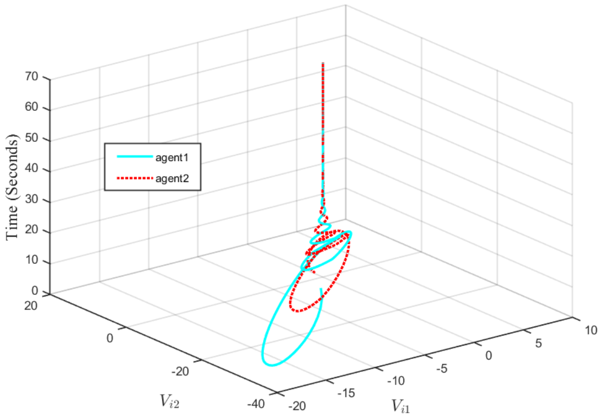
A heterogeneous multi-agent system consisting of four first–order and second–order agent nodes and a virtual leader is considered. First, the two numbers 1 and 2 are second–order multi–agent systems, and the two numbers 3 and 4 are first–order multi–agent systems. The dynamic models of the second–order and first–order multi–agent systems are as follows:

$$\begin{cases} \dot{s}_i(t) = v_i(t), & \\ \dot{v}_i(t) = u_i(t), & i \in I_p \\ \dot{s}_i(t) = v_i(t), & i \in I_p/I_q \end{cases}$$

The communication topology diagram of a heterogeneous multi-agent system based on fixed directed topology is shown in Figure 2. The desired formation is shown in Figure 3. The sampling period of the sensor is $h = 0.1s$. The authors can




(a) Position response of multi-agent system based on directed topology.




(b) Velocity response of multi-agent system based on directed topology.

**FIGURE 8.** **The position and velocity trajectory of the agent on the *X*–axis and *Y*–axis under fixed directed topology with control inputs.**

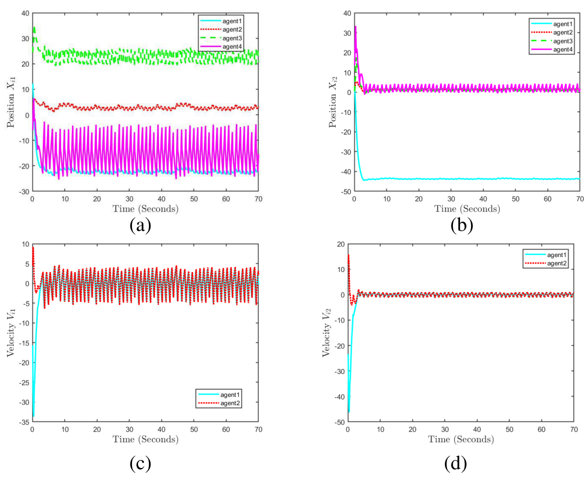



**FIGURE 9.** **Different views of position and velocity of Multi-agent on different time-varying delays.**

choose communication delay and input time–varying delays are as follows:

$$\lambda(t) = 3\,|\sin(0.8t)|\,(s)$$
$$\hbar(t) = 0.5\,|\sin t|\,(s) \tag{17}$$

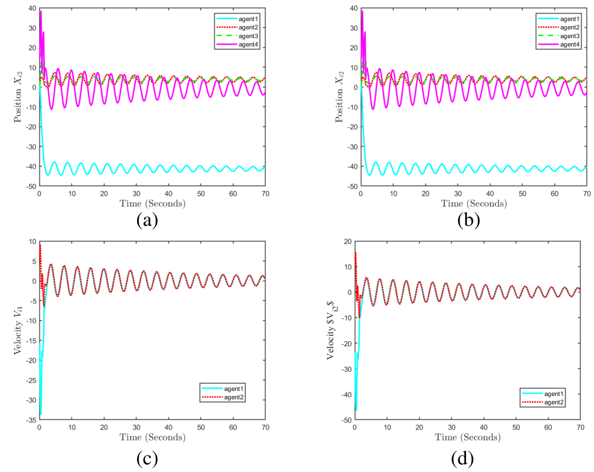



**FIGURE 10.** **Different views of position and velocity of Multi-agent on different time-varying delays.**

After solving the equation (11) by *LMI toolbox* with $\hbar(t) < 0.816$. In a heterogeneous multi–agent system, where agents with different capabilities and requirements collaborate and interact, the maximum upper bound delay plays a crucial role in ensuring efficient communication and coordination among the agents. This is because the maximum upper bound delay represents the maximum time it takes for a message or information to be transmitted from one agent to another within the system. If the maximum upper bound delay is too large, it can lead to delays in decision–making, slower response times, and potential synchronization issues among the agents. On the other hand, if the maximum upper bound delay is small and well–controlled, it allows for timely and seamless communication between agents, enabling efficient coordination and collaboration in the multi–agent system. Furthermore, the maximum upper bound delay is especially important in real–time applications or critical systems where timely communication is crucial for achieving desired outcomes. Now, the maximum allowable upper bound delay tau derived from the methodologies outlined in [48], [49], [50], [51], [52], [53], [54], [55], and [56] and our study is juxtaposed. This evaluation is illustrated in Table 2, with $h(t) = \lambda(t)$ being equal to $\bar{\tau}$. The tabulated data reveals that our approach yields more generalized results for varying maximum allowable upper bounds compared to the methodologies presented in [48], [49], [50], [51], [52], [53], [54], [55], and [56]. Consequently, the methodology introduced in our paper demonstrates superior efficiency in this comparative analysis relative to the approaches in [48], [49], [50], [51], [52], [53], [54], [55], and [56].

Then, the simulation results are shown in Figures 4–8, where Figure 4 and Figure 5 show that the position components of four agents converge to the expected formation respectively, Figure 6 and Figure 7 show that the velocity components of two second-order multi-agents converge to zero, respectively.

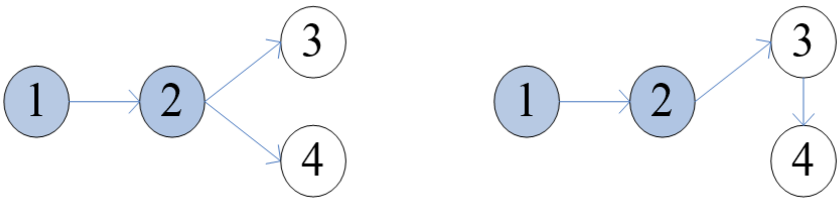



**FIGURE 11.** Topology diagram of multi-agent system communication.

**TABLE 2.** Maximum upper bound delay with different values of $h(t) = \lambda(t) = \bar{\tau}$.

| Fixed Topology | | | | | | |
|---|---|---|---|---|---|---|
| Method | [48] | [49] | [50] | [51] | [52] | Theorem 1 |
| $\bar{\tau}$ | 0.325 | 0.516 | 0.698 | 0.834 | 0.938 | 1.265 |
| Switch Topology | | | | | | |
| Method | [53] | [54] | [50] | [55] | [56] | Theorem 2 |
| $\bar{\tau}$ | 0.147 | 0.288 | 0.364 | 0.487 | 0.615 | 0.837 |

**TABLE 3.** Initial conditions for the heterogeneous multi–agent systems.

| Agent | Initial Conditions | Initial Conditions |
|---|---|---|
| Agent 1 | $e_{10}(1,1) = 13$ | $s_{10}(1,1) = 13$ |
| | $e_{10}(2,1) = 4$ | $s_{10}(2,1) = 4$ |
| | $e_{10}(3,1) = 0.5$ | $v_{10}(3,1) = -0.5$ |
| | $e_{10}(4,1) = 0.1$ | $v_{20}(4,1) = 0$ |
| Agent 2 | $e_{20}(1,1) = 10$ | $s_{20}(1,1) = 3$ |
| | $e_{20}(2,1) = 0$ | $s_{20}(2,1) = -0.1$ |
| | $e_{20}(3,1) = -0.5$ | $v_{20}(3,1) = 0.5$ |
| | $e_{20}(4,1) = 0.15$ | $v_{20}(4,1) = 0.15$ |
| Agent 3 | $e_{30}(1,1) = 5$ | $s_{30}(1,1) = -3$ |
| | $e_{30}(2,1) = -3$ | $s_{30}(2,1) = 1$ |
| | $e_{30}(3,1) = 1$ | $v_{30}(3,1) = 1.5$ |
| | $e_{30}(4,1) = -3$ | $v_{30}(4,1) = 0$ |
| Agent 4 | $e_{40}(1,1) = 15$ | $s_{40}(1,1) = -1.5$ |
| | $e_{40}(2,1) = 5$ | $s_{40}(2,1) = 2.5$ |
| | $e_{40}(3,1) = 1.5$ | $v_{40}(3,1) = -3$ |
| | $e_{40}(4,1) = 5$ | $v_{40}(4,1) = 0$ |

The Laplace matrix of the communication topology diagram of the multi–agent system is:

$$L = \begin{bmatrix} 4 & 0 & 0 & -2 \\ -2 & 2 & -2 & 0 \\ -2 & 0 & 4 & 0 \\ 0 & -2 & -2 & 2 \end{bmatrix}$$

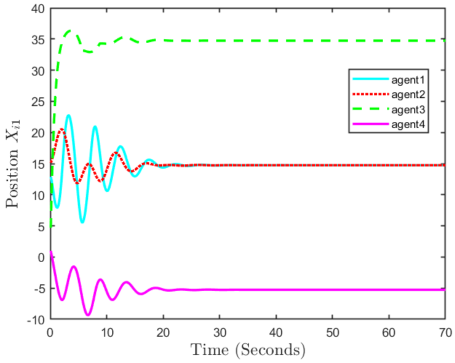
The initial state of each agent is:

$$s_1 = (1.5, 0.35), \quad s_2 = (-20, -10), \quad s_3 = (21, 18)$$
$$s_4 = (10, 50), \quad v_1 = (0.8, 0), \quad v_2 = (0.5, 0.15)$$

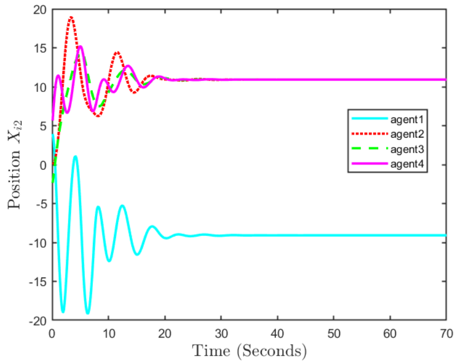
Get $(\mathbb{K}_1, \mathbb{K}_2) = (0.95, 3.75)$ with *LMI toolbox*. The simulation results of formation control under fixed directed topology are as follows:

In Figures 4(a) and 4(b), the authors present the positions of agents on both the $X$-axis and $Y$-axis in fixed fixed–directed topology without control inputs, respectively. On the other hand, the position and velocities of agents are presented on the $X$-axis and $Y$-axis in fixed directed topology in Figures 5(a) and 5(b). From the Figures 4 and 5, one can observe that the multi-agent system states are highly unstable. In control theory, it is important to consider the effect of closed-loop systems on nonlinear systems. Various effects can be caused by closed–loop systems on nonlinear systems. As a result, it can enhance stability by providing feedback and adjusting inputs accordingly. For this, the authors also presented the closed-loop system with the help of controller gains and showed the efficiency in Figures 6(a) and 6(b).

Heterogeneous multi–agent systems depend on position and velocity to determine the locations and movements of individual agents. Agents' positions are determined by their spatial coordinates, which indicate where they are in a system. An agent's velocity refers to its speed and direction, while its speed refers to how quickly it is moving. In order for agents to navigate their environment effectively, establish communication with other agents, and coordinate their actions, they need to know their position as well as their velocity. In order to avoid collisions, reach consensus, and control motions, this information is crucial. A system's overall behavior and dynamics are also influenced by the

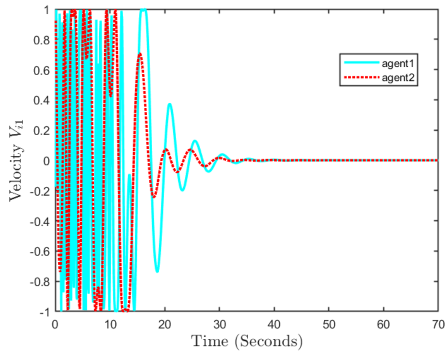



(a) Location Trajectory of Agent Nodes on $X$-axis under Switching Topology.

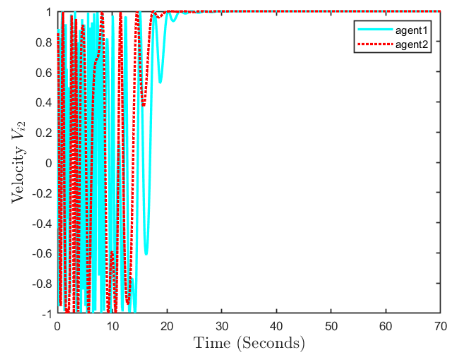



(b) Location Trajectory of Agent Nodes on $Y$-axis under Switching Topology.

**FIGURE 12. Location Trajectory of Agent Nodes on *X*-axis and *Y*-axis under Switching Topology.**




(a) The velocity trajectory of the agent on the $X$-axis under switching topology



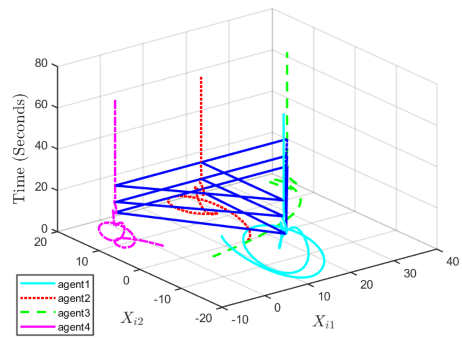

(b) The velocity trajectory of the agent on the $Y$-axis under switching topology.

**FIGURE 13. The velocity trajectory of the agent on the *X*–axis and *Y*–axis under switching topology.**

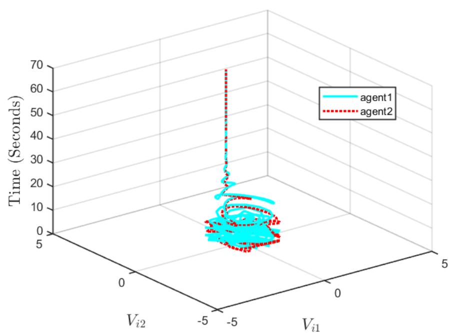
position and velocity of agents. A heterogeneous multi-agent system can be navigated accurately and coordinated, and avoid collisions by taking position and velocity into account. A system's overall performance and efficiency can also be affected by the position and velocity of agents. A system's global patterns and emergent behaviors can also be analyzed and predicted through the consideration of both position and velocity. The agent's velocity trajectory on the $X$-axis and $Y$-axis under fixed directed topology control inputs can be observed in Figures 7(a) and 7(b), respectively and *3D plotting* of the agent's velocity trajectory are given in Figures 8(a) and 8(b).

**Formation control of multi-agent system with different time varying delays:**

Robotics and control theory are interested in the formation control of multi-agent systems. Multi-agent systems can experience various effects of time-varying delays [57], and [58]. As a result, agents may be unable to synchronize and coordinate, resulting in errors in formation. To maintain desired formations, adaptive formation control strategies may be required because topology switching disrupts the connectivity between agents. The formation of the desired compound can also be hindered by external disturbances, which can introduce uncertainties and perturbations. To ensure reliable and robust formation control in real–world applications, it is crucial to understand and address different time–varying delays. Researchers have recognized the need for advanced




(a) Position response of multi-agent systems under switching directed topology.




(b) Velocity response of multi-agent systems with switched directed topologies.

**FIGURE 14. The position and velocity trajectory of the agent on the *X*–axis and *Y*–axis under switch directed topology.**

methods to tackle these challenges in multi-agent formation control by taking into account time–varying delays. In order

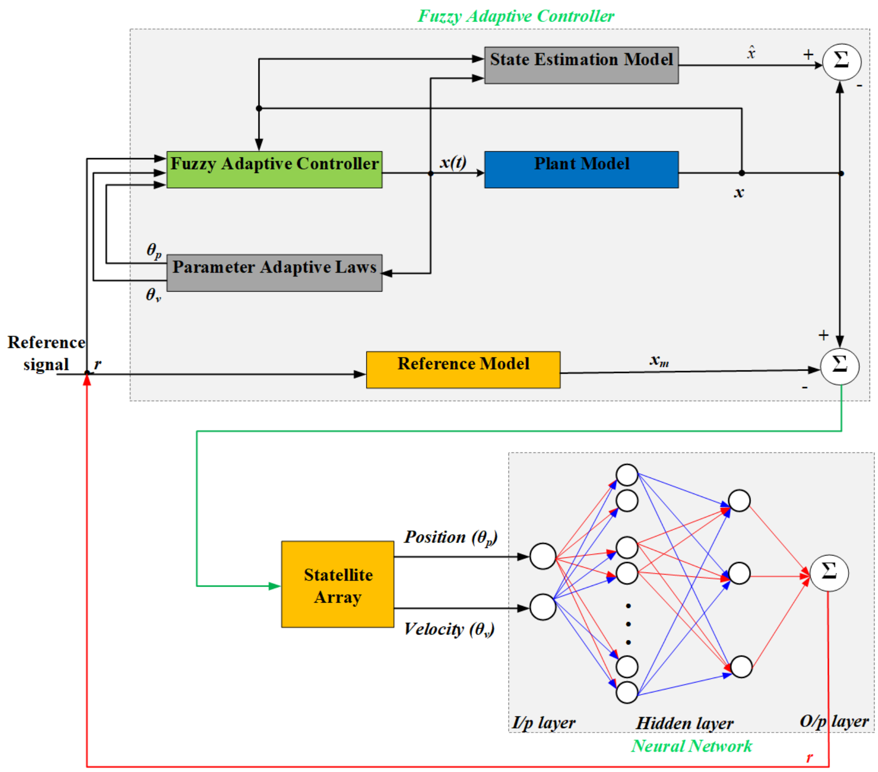



**FIGURE 15.** Fuzzy Adoptive controller based on neural networks for the satellite system.

to compensate for delay effects, distributed protocols are often developed, predictive control algorithms are used to compensate for delays or decentralized control strategies are implemented to mitigate formation control effects resulting from delays. To show time-varying delays for the multi–agent systems can be observed in Figures 9 and 10.

*Remark 3:* The practical implementation of heterogeneous multi–agent systems involves integrating different types of agents with varying capabilities, designs, and platforms to achieve a specific goal or task. This can be done by designing a communication protocol that allows agents to exchange information and coordinate their actions, allocating tasks to different agents based on their expertise and coordinating their communication and collaboration to achieve a common objective. Additionally, practical implementation may involve developing algorithms and rules for agent interaction, designing a suitable architecture for the system, and ensuring compatibility between different agent types. Moreover, real–world implementations of heterogeneous multi–agent systems require careful consideration of the potential challenges and trade–offs. Some of these challenges include managing the heterogeneity of agents, ensuring efficient communication and coordination among diverse agents, handling conflicts and resolving them effectively, designing mechanisms for agent adaptation and learning, and evaluating the overall performance and effectiveness of the system. Furthermore, practical implementation might also involve considering security aspects, scalability, and robustness of the system in order to ensure its successful deployment in various real–world scenarios. In summary, the practical implementation of heterogeneous multi-agent systems involves integrating different types of agents, designing communication protocols and coordination mechanisms, addressing challenges related to heterogeneity ensuring compatibility, and evaluating the performance and robustness of the system.

### B. FORMATION CONTROL OF MULTI-AGENT SYSTEM UNDER SWITCH DIRECTED TOPOLOGY

A heterogeneous multi-agent system consisting of four first–order and second-order agent nodes and a virtual leader is considered. First, the two numbers *1* and *2* are second–order multi–agent systems, and the two numbers *3* and *4* are first–order multi-agent systems. The dynamic models of the second-order and first-order multi-agent systems are as follows:

$$\begin{cases} \dot{s}_i(t) = v_i(t), \\ \dot{v}_i(t) = u_i(t), \quad i = 1, 2 \\ \dot{s}_i(t) = v_i(t), \quad i = 3, 4 \end{cases}$$

The communication topology diagram of a heterogeneous multi–agent system based on switch topology is shown in Figure 11. The desired formation is shown in Figure 3. The sampling period of the sensor is $h = 0.1s$. Based on the Assumptions 1 and 2, we can choose communication delay $\lambda(t) = 3\,|\sin(0.02\pi t)|\,(s)$, and we can get $\hbar(t) < 0.945$ by solving equation (15) in *LMI toolbox*. Assuming $\hbar(t) = 0.5\,|\sin(0.1\pi t)|\,(s)$, the simulation results are shown in Figures 12–14, in which Figure 12(a) and Figure 12(b) show that the position components of four agents converge to the expected formation, Figure 13(a) and Figure 13(b) show that the velocity components of two second-order multi–agents converge to zero. Figures 14(a) and 14(b) show the position trajectories of four agents and the speed changes of two second–order agents more intuitively.

The initial state of each agent, the reader can refer to the Table 3. After getting the $(\mathbb{K}_1, \mathbb{K}_2) = (0.62, 0.47)$ with *LMI toolbox*. The simulation results of formation control under switch directed topology are shown in Figures 12–14.

*Remark 4:* The simulation results under fixed directed topology showcase the positions and velocities of agents, revealing the system's inherent instability without control inputs. By presenting the system's behavior under a fixed directed topology, the authors emphasize the significance of closed–loop systems in enhancing stability through feedback mechanisms and input adjustments. This underlines the effectiveness of the proposed design method in improving system stability and performance. The simulation examples provide a visual representation of the system's dynamics, aiding researchers in understanding the impact of control inputs on the agents' trajectories under fixed communication topologies. This visual feedback enhances the comprehension of the proposed design method's ability to regulate agent movements and maintain formation integrity. In addition, the simulation results underscore the advantages of the proposed design method in achieving stability, enhancing control, and optimizing the formation control of heterogeneous multi–agent systems under fixed directed topologies.

## V. CONCLUSION

In this research, the problem of *heterogeneous multi–agent formation control* with input delay and communication delay in switching topology is studied. In order to solve the problem of time delay in network communication in the actual non-ideal environment, a *heterogeneous multi–agent system model* with input delay and communication delay is established, a new formation control protocol with time delay is designed, and the formation convergence of *heterogeneous multi–agent systems* in fixed and switched topologies is analyzed, respectively. The closed–loop system is proved to be stable by *new Lyapunov function*. Finally, through two simulation examples, it is verified that each agent can asymptotically converge to the desired formation under fixed and switched topologies through the formation control protocol designed in this research.

A state tracking controller can be implemented using our proposed methodology for *T–S fuzzy systems*. To track the states of a stable linear reference model, this controller provides attainable *plant–model* matching conditions. Using neural networks, two satellite variables will be trained. *Neural networks* play a crucial role in satellite arrays by enhancing data analysis and interpretation capabilities for various applications such as weather forecasting, earth observation, and communication satellite systems. For further understanding in detail, the researcher can refer the Figure 15.

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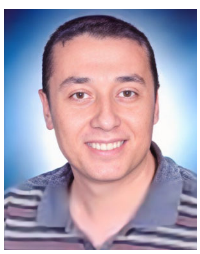

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