

Rafting Towards Consensus: Formation Control of Distributed Dynamical Systems

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Abstract—In this paper, we introduce a novel adaptation of the Raft consensus algorithm for achieving emergent formation control in multi-agent systems with a single integrator dynamics. This strategy, dubbed "Rafting," enables robust cooperation between distributed nodes, thereby facilitating the achievement of desired geometric configurations. Our framework takes advantage of the Raft algorithm's inherent fault tolerance and strong consistency guarantees to extend its applicability to distributed formation control tasks. Following the introduction of a decentralized mechanism for aggregating agent states, a synchronization protocol for information exchange and consensus formation is proposed. The Raft consensus algorithm combines leader election, log replication, and state machine application to steer agents toward a common, collaborative goal. A series of detailed simulations validate the efficacy and robustness of our method under various conditions, including partial network failures and disturbances. The outcomes demonstrate the algorithm's potential and open up new possibilities in swarm robotics, autonomous transportation, and distributed computation.

Index Terms—Distributed Dynamical Systems, Multi-Agent Systems, Raft, Consensus, Formation Control, Fault Tolerant

I. INTRODUCTION

Distributed Dynamical Systems (DDSs) consist of multiple interacting agents collaborating to achieve complex goals that exceed the capabilities of individual agents [1]. Distributed systems allow tasks to be divided across spatially dispersed agents, enhancing robustness, scalability, and effective resource allocation [2]. In recent decades, multi-agent systems (MAS) and distributed systems have risen to prominence in cooperative tasks, such as formation control [3] and collaborative computation [4]. Formation control enables agents to achieve predetermined geometric arrangements, which is vital for applications in swarm robotics [5], Unmanned Aerial Vehicle (UAV) networks [6], and sensor arrays [7].

By leveraging the potential of MAS and distributed systems, new solutions for a wide variety of applications, including traffic management, smart grids, distributed data mining, and disaster response can be devised [8]. The importance of MAS and distributed systems will only increase as technology advances and the demand for more efficient, cooperative systems rises, leading to further developments in the field [9].

For handling replicated logs in fault-tolerant systems, Ongaro and Ousterhout [10] introduced a distributed consensus technique called Raft. It distinguishes itself from the

conventional Paxos algorithm [11] by providing simplicity, readability, and robust consistency guarantees. Raft is based on a leader-follower paradigm, employing leader election, log replication, and state machine application to maintain consistency across nodes [12]. Raft plays a crucial role in cooperative tasks and distributed systems by guaranteeing that system components perform coherently and consistently, despite failures or delays. Its properties make it suited for allowing robust multi-agent collaboration across a variety of areas, from IoT networks to distributed computing systems [13].

Utilizing the Raft consensus algorithm for formation control in dynamical multi-agent systems presents a novel approach to address coordination challenges. The leader-follower paradigm of Raft ensures fault tolerance and strong consistency, critical for MAS reliability [10]. By adapting Raft to single integrator MAS, the algorithm can promote resilient collaboration across spatially separated agents, enabling them to achieve desired geometric configurations despite network failures or communication delays [14].

This paper is organized into five sections to describe the application of the Raft consensus algorithm for formation control in MAS. The Background section provides a thorough introduction to the Raft consensus algorithm and formation control in MAS, detailing their fundamentals, characteristics, and relevance to the problem domain. The Method section elaborates on the employment of the Raft algorithm for formation control, outlining the integration of single integrator dynamics with Raft's inherent mechanisms. In the Simulation section, we present a series of carefully designed simulations that validate the efficacy and resilience of our proposed approach under varying conditions. The Discussion section analyzes the results, highlighting the advantages and potential challenges of the presented approach. Finally, the Conclusion section summarizes the key findings and contributions of our study, while also exploring future research directions to advance the field.

II. BACKGROUND

The Raft consensus algorithm, introduced by Ongaro and Ousterhout [10], revolutionized the landscape of distributed consensus protocols by providing a more understandable and accessible alternative to the Paxos algorithm [11]. Since its

inception, numerous studies have been conducted to evaluate, extend, and apply the Raft algorithm in various domains.

One of the earliest evaluations of the Raft consensus algorithm was presented by Howard et al. [12]. The authors investigated its key characteristics, assessed its performance, and compared it with other consensus algorithms. Their study contributed to the validation and acceptance of Raft in the distributed systems community. Moraru et al. [13] extended Raft to Egalitarian parliaments, a more generalized consensus model. Their work, "There is more consensus in Egalitarian parliaments," presented a novel approach to consensus decision-making and demonstrated the versatility of the Raft algorithm.

Fu et al. [15] optimizes the Raft consensus algorithm for the Hyperledger Fabric platform in terms of both log replication and leader election. Liu et al. [16] proposes a new leader selection scheme based on the distributed consensus algorithm RAFT to facilitate the use of blockchain on resource-constrained IoT end devices. Wang et al. [17] discusses a Raft-like consensus algorithm that preserves the logic of part of Raft consensus algorithm and optimizes leader election and consensus process through the established K-Bucket node relationships in the Kademlia protocol and demonstrated the applicability of Raft in the burgeoning field of blockchain technology.

Overall, these studies exemplify the adaptability and robustness of the Raft consensus algorithm across diverse applications. Each study contributed to the understanding and advancement of Raft, highlighting its potential for enabling reliable and efficient distributed systems.

Table I summarizes and compares a few recent articles and researches on the Raft consensus algorithm:

TABLE I
COMPARISON OF RAFT-RELATED WORK

Reference	Key Contributions	Domain/Application
Ongaro and Howard et al.[10, 12]	Introduced and Evaluated Raft	Distributed systems
Moraru et al.[13]	Extended Raft	Egalitarian parliaments
Liu et al.[16]	Applied Raft	IoT networks
Wang and Fu et al.[17, 15]	Used Raft	Blockchain systems
Gonzalez et al.[18]	Raft for Software-Defined Networking (SDN)	Software-defined networking
Deyeri et al.[19]	Scalable Raft	Distributed systems
Hou et al.[20]	Raft for edge computing	IoT and Edge computing
Nasimi et al.[21]	Raft in vehicular networks	Vehicular Ad-Hoc networks (VANETs)

Formation control and consensus in dynamical multi-agent systems have gained significant attention over the past decade due to their wide applicability in various domains, including

robotics, distributed computing, and swarm intelligence. This literature review highlights ten recent studies that have contributed to the field in unique ways.

One study by Chen et al. [22] studies the formation control problem for general linear multi-agent systems constrained with unavailable states and event-triggered communications. Li et al. [23] considers the leader-following formation control problem for second-order multiagent systems with time-varying delay and nonlinear dynamics. Xiao et al. [24] explore the consensus problem in high-dimensional systems, presenting a scalable solution that can be adapted to different applications.

In the area of robotic swarms, Kartal et al. [25] proposes a backstepping-based, distributed formation control method that is stable independent of time delays in communication among multiple unmanned aerial vehicles (UAVs).

For practical applications, Nair et al. [26] presents a comprehensive literature review on the application of Multi-agent systems (MAS) to Economic Dispatch (ED) and Unit Commitment (UC) in smart grids, ensuring efficient and reliable operation. Qian et al. [27] apply formation control techniques to mobile sensor networks for environmental monitoring, using a consensus-based approach to improve the sensing quality.

In the realm of connected vehicles, Wang et al. [28] reviews researches regarding different aspects of Cooperative adaptive cruise control (CACC) systems. CACC is one promising technology to allow connected and automated vehicles (CAVs) to be driven in a cooperative manner and introduces system-wide benefits.. Liu et al. [29] proposes a novel robust cubature Kalman filter (CKF) for cooperative localization of connected vehicles under a GNSS/DSRC integrated architecture. The CKF is enhanced using the Huber M-estimation technique to improve the performance of data fusion under uncertain sensor observation environments. Finally, in the context of social network analysis, Karimi et al. [30] introduce proposes a consensus-based community detection approach (CBC) for finding communities in multilayer networks.

III. PROBLEM FORMULATION AND MAIN RESULTS

The Raft consensus algorithm is typically used for achieving consensus in distributed systems, particularly in applications like distributed databases and configuration management.

Applying Raft to dynamical systems such as robots can be beneficial in certain scenarios. For example, if you have a group of robots that need to coordinate their actions and maintain a consistent state, Raft could help ensure that all robots agree on the state of the system and the actions to be taken. This can be particularly useful in environments where communication is unreliable, or where there is a risk of individual robot failures.

In a formation control scenario, the Raft consensus algorithm allows agents to communicate with each other through a graph, share their states, and adjust their behavior based on the received information. In other words, the Raft algorithm manages the agents' states as the replicated log entries and updates and synchronizes the states across all nodes. Whenever

TABLE II
SUMMARY OF KEY CONTRIBUTIONS AND DOMAIN/APPLICATIONS OF
FORMATION CONTROL STUDIES

Reference	Key Contributions	Domain/Application
Cheng et al.[22]	Distributed formation control via output feedback event-triggered coordination	Robotics, multi-agent systems
Li et al.[23]	Leader-following formation control for second-order multiagent systems with time-varying delay and nonlinear dynamics	Multi-agent systems
Xiao et al.[24]	Consensus in high-dimensional multi-agent systems	Distributed computing, swarm intelligence
Kartal et al.[25]	Distributed formation control for UAV swarms with communication delays	UAV swarms, robotics
Nair et al.[26]	Distributed consensus algorithm for smart grid applications	Smart grids, energy management
Qian et al.[27]	Formation control for mobile sensor networks using consensus-based approach	Environmental monitoring, sensor networks
Wang et al.[28]	Formation control for cooperative adaptive cruise control	Connected vehicles, traffic management
Liu et al.[29]	Distributed consensus algorithm for cooperative localization in connected vehicle systems	Connected vehicles, localization
Karimi et al.[30]	Consensus-based methodology for detection communities in multilayered networks	Network analysis, community detection

an agent updates its state, the Raft algorithm would be used to replicate the new state across all nodes. The agents would then adjust their behavior based on the received state information.

The Raft consensus algorithm is not used to solve the formation control problem in a traditional sense. Instead, it is used to synchronize the states (i.e., positions) of the agents across different nodes in a distributed system.

We assume that each agent is on a different node in the Raft algorithm. In this case, each agent will be managed by a separate node in the Raft cluster, and these nodes will use the Raft algorithm to reach a consensus on the agents' states.

When each agent is on a separate node, it means that each agent's state is managed independently within its associated node. The Raft algorithm is responsible for ensuring that the agent's state is consistent across all nodes. This will allow the agents to cooperate and reach the desired formation on a regular polygon.

Let's consider a group of N agents, and let their positions in a 2D plane be denoted as $x_i = (x_i, y_i)$ for $i = 1, 2, \dots, N$.

The desired formation can be represented as a formation graph $G = (V, E)$, where V is the set of vertices (each vertex represents an agent), and E is the set of edges (each edge represents the desired relationship between two agents).

The formation control problem can be posed as a consensus problem:

Define the relative position vector d_{ij} for each pair of connected agents (i, j) in the graph G as:

$$d_{ij} = x_j - x_i$$

Define the desired relative position vector d_{ij}^* for each pair of connected agents (i, j) in the graph G as:

$$d_{ij}^* = x_j^* - x_i^*$$

where (x_i^*, y_i^*) represents the desired position of agent i in the formation.

Define the formation error e_{ij} for each pair of connected agents (i, j) in the graph G as:

$$e_{ij} = d_{ij} - d_{ij}^*$$

The formation control objective is to design a control law u_i for each agent i such that:

$$u_i = -k \sum_{\substack{j=1 \\ j \neq i}}^N L_{ij} e_{ij}$$

where k is a positive control gain, and L_{ij} is the ij -th element of the Laplacian matrix L of the formation graph G . The Laplacian matrix L can be computed as $L = D - A$, where D is the degree matrix (a diagonal matrix with the degree of each vertex on the diagonal) and A is the adjacency matrix (with $A_{ij} = 1$ if (i, j) is an edge in E and $A_{ij} = 0$ otherwise).

The dynamics of agent i can be described by a set of differential equations:

$$\frac{dx_i}{dt} = u_i$$

The overall formation control problem can be expressed as finding a control law u_i for each agent i that minimizes the global formation error:

$$E = 0.5 \sum_{(i,j) \in E} e_{ij}^2$$

The control laws designed with the above approach will ensure that the formation error converges to zero, meaning the agents will maintain the desired formation while moving. The choice of control gain k and the structure of the formation graph G determine the performance and stability of the formation control system.

Integration of the Raft communication steps:

- 1) Agent i updates its position x_i and/or control input u_i , and sends the update to the Raft leader.
- 2) The Raft leader appends the update to its log and replicates the log to all followers.
- 3) Followers receive the log, apply updates to their state machines, and send acknowledgments back to the leader.

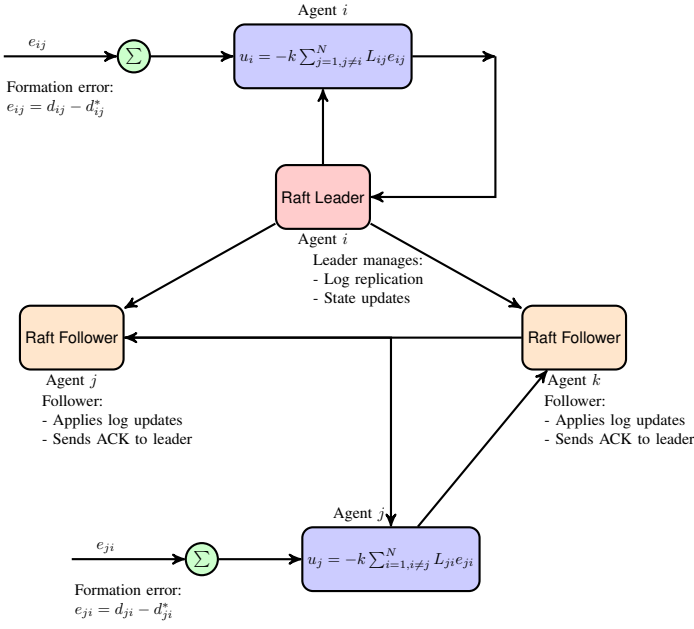


Fig. 1. Integration of Raft consensus algorithm with formation control of multi-agent systems.

- 4) The leader ensures a majority of agents have applied the update before considering it committed.

The Raft algorithm mainly deals with the communication and state replication process, while the formation control uses the equations to compute the control inputs and maintain the desired formation. By combining the communication infrastructure provided by Raft with the formation control equations, the multi-agent system can achieve the desired formation while ensuring fault-tolerance and consistency in the presence of communication or agent failures.

IV. SIMULATIONS

For the simulation, we assume that the center of regular polygon is at origin and agents' positions are initialized randomly. One of the agents will be selected as the leader, and it will be responsible for calculating the next positions for all agents, including itself. The other agents will follow the leader's instructions. Through Scenario IV-A to IV-C, the leader changes periodically every 20 frames. So the original Raft's leader election mechanism is not used.

The agents collaborate by following the updates provided by the leader, and the leader is responsible for maintaining the formation. The targets (goal positions) for each agent are set based on the formation shape, which is determined by the leader. So, the agents are working together to maintain the formation, and their targets are set according to the overall objective of the system, which is to maintain the desired formation.

A. Scenario A

When the current leader gets disconnected, a new leader is elected automatically by the Raft algorithm to ensure the

continued operation of the system. In this process, nodes can vote for a leader based on their unique identifier (address). This way, you can ensure that a new leader will be elected if the current leader gets disconnected.

To demonstrate the effects of changing the leader or handling leader failure, the leader is periodically switched or upon the failure of a leader, agents vote to select the new leader.

Below is an example of periodically switching the leader, the leader node is switched every 20 frames, and a leader failure is simulated at frame 35. Then a new leader is elected by incrementing the failed leader index. In this example it should be noted that the leader failure simulation only prevented the failed leader from updating the positions of other agents, but the failed leader's position was still updated by the new leader.

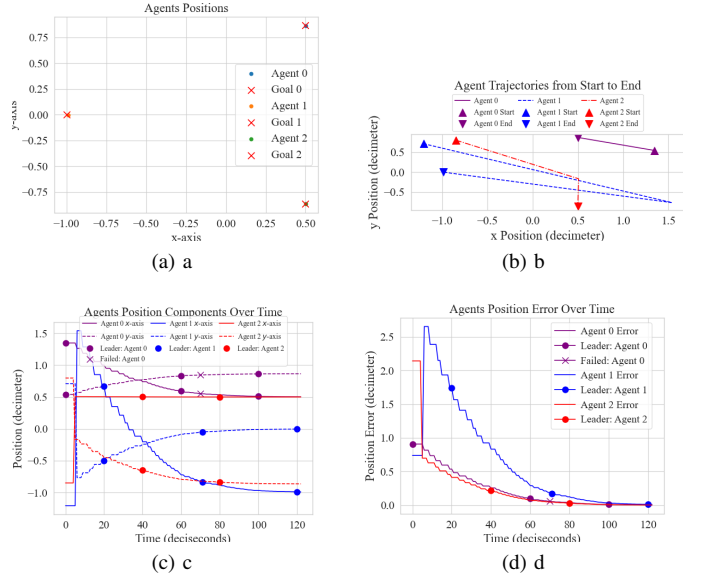


Fig. 2. Scenario A: Leader is periodically switched or upon the failure of a leader, agents vote to select the new leader. Leader node is switched every 20 frames, and a leader failure is simulated at frame 35. Then a new leader is elected by incrementing the failed leader index. (a): Agents' final position. (b): Agents trajectories from start to end. (c): Agents position components (x and y) over time. (d): Agents position errors over time.

B. Scenario B

In this scenario, when an agent or nodes fails as a leader at a specific time, the position of the failed leader should not be updated anymore showing that the agent is disconnected from the rest. The other agents make a formation on a regular n -sided polygon even if some agents fail and get disconnected from the rest. Figure 3 shows that Agent 1 will be stationary after its failure.

C. Scenario C

In this scenario, when an agent or nodes fails as a leader at a specific time, the position of the failed leader should not be updated anymore showing that the agent is disconnected from the rest. The other agents make a formation on a regular $n - m$ -sided polygon where m is number of fail agents (Figure 4).

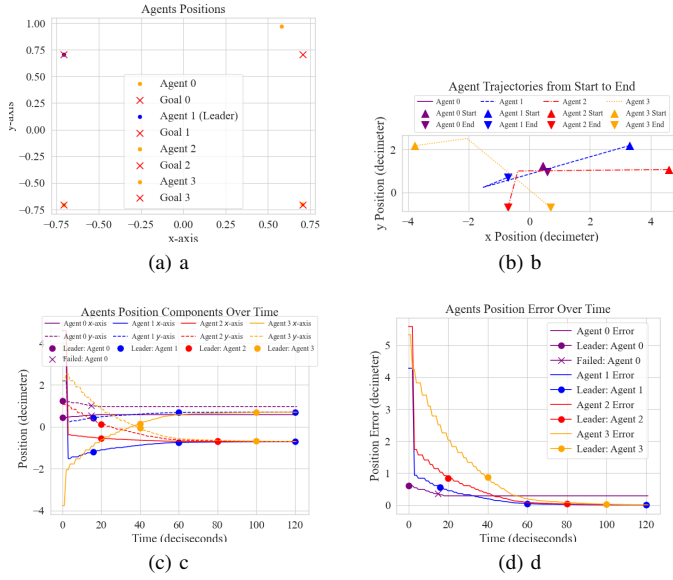


Fig. 3. Scenario B: When an agent or nodes fails as a leader at a specific time, the position of the failed leader should not be updated anymore showing that the agent is disconnected from the rest. Agent 1 will be stationary after its failure. (a): Agents' final position. (b): Agents trajectories from start to end. (c): Agents position components (x and y) over time. (d): Agents position errors over time.

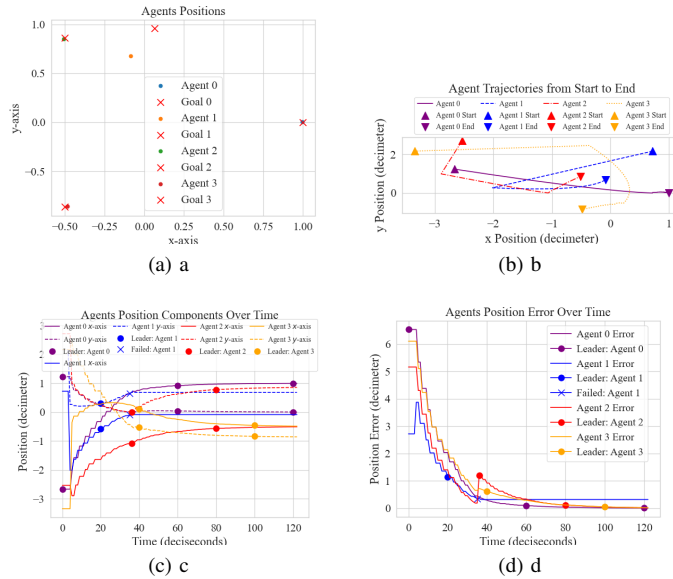


Fig. 4. Scenario C: When an agent or nodes fails as a leader at a specific time, the position of the failed leader is not updated anymore showing that the agent is disconnected from the rest. Other agents make a formation on a regular $n - m$ -sided polygon where m is number of fail agents. (a): Agents' final position. (b): Agents trajectories from start to end. (c): Agents position components (x and y) over time. (d): Agents position errors over time.

D. Scenario D

The Raft algorithm ensures that all nodes in the system maintain a consistent state by replicating logs across all nodes. This feature can be leveraged to maintain a consistent view of the agent positions and goals across all nodes. Instead of updating the positions only on the leader node and then broadcasting the updated positions to the other nodes, the leader node can propose position updates and let the Raft algorithm replicate the new state across all nodes.

In Figure 5, by plotting the error between each agent's position and its goal position over time. This will allow to observe if there are any significant inconsistencies or jumps in the error when the leader changes or fails. Since the error plots show smooth transitions without any abrupt changes, this indicates that the state is consistent across all nodes, even during leader changes or failures.

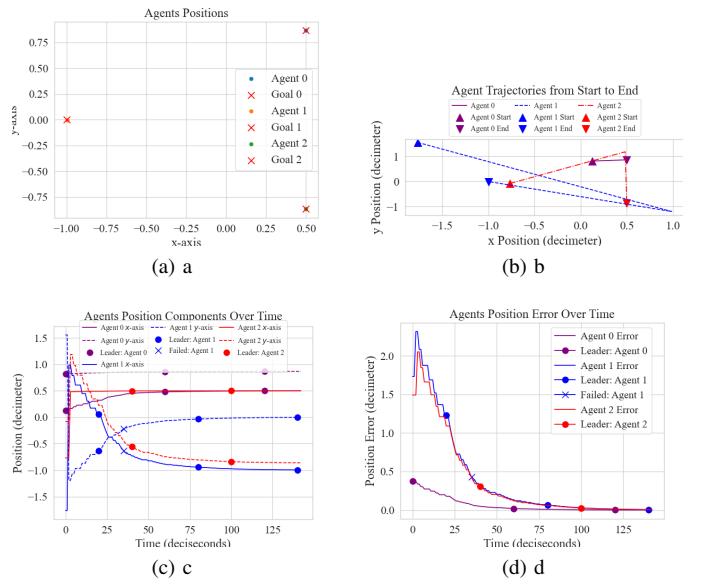


Fig. 5. Scenario D: Instead of updating the positions only on the leader node and then broadcasting the updated positions to the other nodes, the leader node can propose position updates and let the Raft algorithm replicate the new state across all nodes. (a): Agents' final position. (b): Agents trajectories from start to end. (c): Agents position components (x and y) over time. (d): Agents position errors over time.

In Scenario IV-D, we replace the current leader selection process with Raft's leader election and introduce a randomized election timeout for each agent, which will trigger a new election if no leader is detected within that time. Finally, we ensure that agents vote for a leader and manage their votes according to the Raft algorithm.

E. Scenario E

The agents have three possible statuses: follower, candidate, and leader. The leader is responsible for updating the positions of all agents to maintain the desired formation. If an agent does not receive a heartbeat from the leader for a certain duration, it starts an election and becomes a candidate.

In Figure 6, each circle represents the position of an agent according to one of the nodes. Since you have three agents

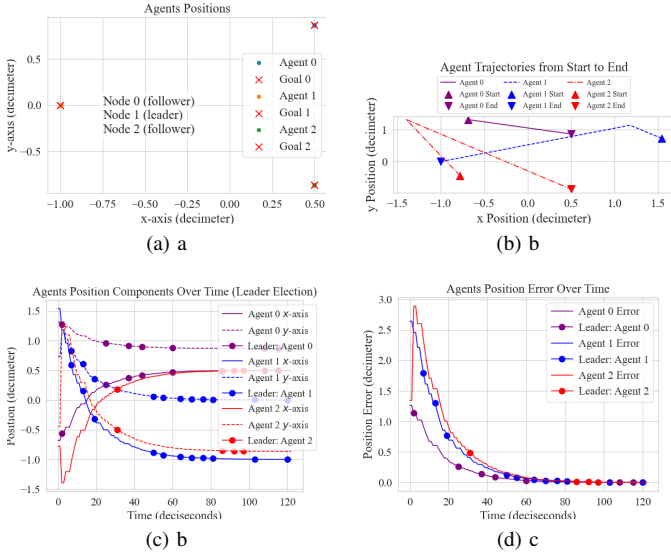


Fig. 6. Scenario E: (a): Agents' final position. (b): Agents trajectories from start to end. (c): Agents position components (x and y) over time. (d): Agents position errors over time.

TABLE III
STATUS OF NODES IN DIFFERENT TIMES AND ELECTION TERMS IN SCENARIO F

type	node	term	frame
candidate	1	1	6
leader	1	1	6
simulate failure	localhost:4322	1	10
failure	localhost:4322	1	12
candidate	0	2	15
leader	0	2	15
failure	localhost:4322	1	15
failure	localhost:4322	1	18
simulate recovery	localhost:4322	1	20
candidate	1	2	21
leader	1	2	21
candidate	1	3	27
leader	1	3	27
candidate	1	4	33
leader	1	4	33
candidate	1	5	45
leader	1	5	45
candidate	1	6	54
leader	1	6	54
candidate	2	7	60

and three nodes, you get a total of $3 \times 3 = 9$ circles at the beginning.

F. Scenario F

Now we implement a mechanism to detect and handle node failures, such as timeouts or unreachable nodes. This method checks for failed nodes based on their status and the time passed since the last heartbeat received. If a follower node has not received a heartbeat for more than the specified timeout, it is marked as failed. To show the effectiveness of the proposed method, we manually simulate node failures and recovery. In the simulation as shown in Figure 7, we make node 1 to fail at frame 10 and recover at frame 20.

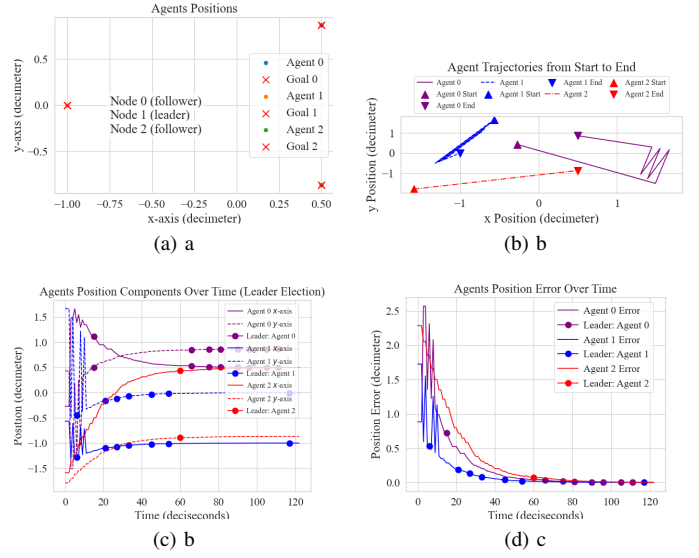


Fig. 7. Scenario F: Implementing a mechanism to detect and handle node failures, such as timeouts or unreachable nodes. (a): Agents' final position. (b): Agents trajectories from start to end. (c): Agents position components (x and y) over time. (d): Agents position errors over time.

G. Scenario G

In the last scenario that we consider here, the focus is on implementing dynamic membership changes, allowing to add or remove agents at runtime. Raft supports membership changes through a joint consensus approach, which guarantees that the system remains operational during configuration changes. The agent or node removal is discussed in IV-B and IV-C, therefore, we modify the approach and simulate a scenario that a node, i.e., an agent is added to the current cluster at runtime. The results are shown in Figure 8

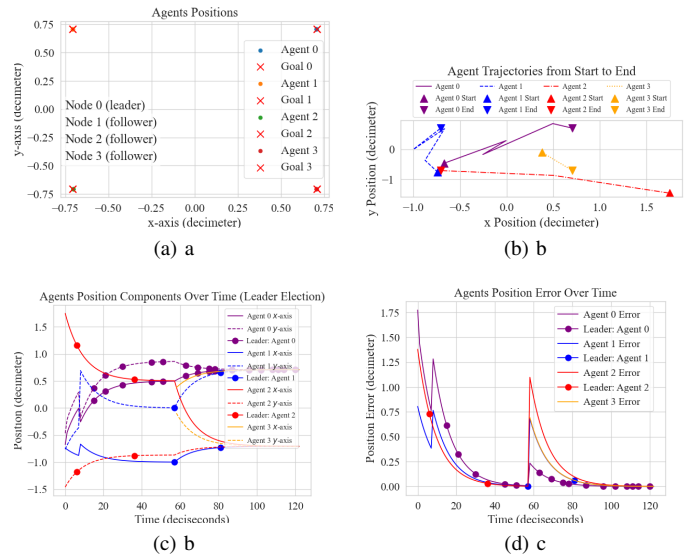


Fig. 8. Scenario G: Implementing dynamic membership changes, allowing to add or remove agents at runtime. (a): Agents' final position. (b): Agents trajectories from start to end. (c): Agents position components (x and y) over time. (d): Agents position errors over time.

V. DISCUSSION AND CONCLUSIONS

In this study, we address distributed formation control of multi-agent systems, combining leader election and node failures. The decentralized algorithm allows the system to function despite node failures or recoveries. The Election-Timer class prevents simultaneous elections with a randomized timeout, while the DistributedFormation class manages agent positions and goals. Agents autonomously adjust their formation based on the leader's goals, which change with leader elections.

The formation control algorithm ensures agents form the desired shape, while the Raft algorithm provides a distributed, fault-tolerant method for maintaining consistent state across nodes. By synchronizing agents' states, the Raft algorithm allows the system to handle node failures while achieving desired formation control.

The implementation is robust against node failures, supports adding new agents during runtime, and allows for failed node recovery. However, the leader election process is not optimized for large-scale networks, potentially causing increased latency, and the simulation assumes a 2D environment.

However, while applying Raft to dynamical systems offers exciting possibilities, there are inherent challenges and limitations that should be addressed, such as latency, scalability, complexity, overhead, and use-case fit. Raft, for instance, is not initially designed for real-time systems, potentially introducing latency that could affect rapid response times. This is an area where future work could focus on optimizing the algorithm, specifically the leader election process, for quicker response times even in large-scale systems.

Moreover, Raft's performance may degrade with an increase in node numbers, and its implementation can add complexity, potentially increasing development time and costs. This identifies another opportunity for future enhancements, possibly through exploring different communication models for more realistic simulations and extending the algorithm's applicability to complex 3D environments.

Raft also necessitates communication and computational resources, which might not suit resource-constrained systems, and may not fit all robotic use cases. This calls for additional research to examine the impact of various network topologies and communication delays on the system's performance.

In conclusion, the challenges with using Raft in dynamical systems are complex, but they give us a clear path for future work. This study reveals these challenges, yet it lays the groundwork for more research on distributed control and leader selection in systems with many agents. The limitations we've discussed aren't barriers, but signs showing us the way forward in this exciting area of study.

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