Dynamic effects of communication delay, failure rates, and speed on UAV swarm formation

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Abstract. *This study, focusing on Unmanned Aerial Vehicles (UAVs) in a leader/follower network architecture, addresses the increasing reliance on UAVs operating in groups - or swarms - for applications like reconnaissance and target surveillance. This study tackles the problem on how the swarm dynamics and its coordination, i.e. the drone's movement synchronization, is impacted by varying operational conditions such as leader speed, communication delay and failures. Utilizing an advanced Python-based simulation framework, the research evaluates the impact of different parameters on swarm dynamics in various UAV formation scenarios, specifically in relation to networking and communication issues. The study's principal contribution lies in its systematic investigation of how these parameters influence key performance metrics like Leadership Error and Formation Error. Experimental results reveal critical insights into UAV swarm behavior, demonstrating that while high speeds and communication failures impact formation integrity and leader-following accuracy, the systems show resilience to extended communication delays.*

1. Introduction

Unmanned Aerial Vehicles (UAVs), commonly known as drones, have emerged as a pivotal technology in numerous applications, such as reconnaissance and target surveillance [Zhu et al. 2019]. The ability of UAVs to work in coordinated groups or swarms has further expanded their potential, enabling complex tasks to be executed more efficiently and safely.

This study delves into the dynamics and the coordination of UAV swarms, particularly focusing on the challenges and strategies associated with their coordinated operations. Employing an advanced Python-based network simulation framework, this research simulates and evaluates various scenarios involving UAV formations. These scenarios are designed to assess the impact of critical operational parameters such as leader speed, communication delay, and failure rates on the effectiveness of UAV swarm formations.

Through a series of simulations spanning scenarios, the study systematically investigates how these parameters influence two key performance metrics: Leadership Error and Formation Error. Each scenario presents a unique set of conditions, thereby providing insights into the operational dynamics of UAV swarms under different communication and movement constraints. By analyzing these scenarios, the research aims to contribute to the growing field of UAV technology, particularly in understanding and optimizing the coordination mechanisms in UAV swarms. This study not only enhances our knowledge of UAV operational dynamics but also lays the groundwork for future advancements in autonomous aerial systems.

The following sections will provide a detailed account of the related works, theoretical background, simulation methodology, scenario-specific results, and a comprehensive discussion on the implications of our findings.

2. Related Works

This section reviews existing literature, focusing on three main areas crucial for understanding the challenges and solutions in UAV swarm formation: formation control and synchronization, impact of communication delays, and coordination strategies in complex environments. We used specific search keywords to identify relevant studies in the field. The keywords we chose were 'UAV', 'formation', 'control', 'latency', and 'communication delay'. We prioritized the most recent articles to ensure that the review reflects the latest advancements and findings in this area of study.

Formation Control and Synchronization: Several studies explore formation control in multi-UAV systems. [Olivieri et al. 2016] and [Xue and Cai 2016] investigate the use of smartphones and distributed control protocols to manage UAV swarms, respectively. They highlight the importance of communication latency in the accuracy of swarm formation. Comparatively, our study also addresses communication efficiency in UAV swarms, but focuses on the influence of communication latency on leadership and formation errors. [Ji et al. 2023] and [Lu et al. 2022] introduce advanced control schemes for formation flight and collision avoidance, addressing challenges like communication delays and input saturation. These studies underscore the need for robust algorithms to maintain formation integrity under various operational conditions. Our work aligns with these researches by investigating how communication delays influence the effectiveness of maintaining formation in UAV swarms.

Impact of Communication Delays: The influence of communication delays on UAV swarms is a recurring theme. [Daniel et al. 2010] and [Liu et al. 2023] discuss the importance of considering delays and round trip time (RTT) in network and protocol design for UAV swarms, especially in high mobility scenarios. Our study complements these works by quantifying the specific impact of these delays on the accuracy of UAV swarm formations. [Edwards et al. 2020] experimentally demonstrate how communication delays induce bifurcations in spatiotemporal patterns of robot swarms, a crucial finding for understanding swarm dynamics under delays. Our study extends this line of research by analyzing how these delays impact specific metrics such as Leadership Error and Formation Error.

Coordination Strategies in Complex Environments: Effective coordination of UAVs in complex tasks is addressed by [Chatterjee and Dutta 2022], focusing on autonomous coordination of UAVs for hazardous material identification. While they concentrate on algorithms for coordinated decision-making, our work examines how communication delays affect the precision and integrity of UAV swarm formations in similar critical tasks. [Zhang et al. 2019] and [Pham et al. 2023] explore finite-time formation control and cooperative formation guidance algorithms for UAVs, emphasizing challenges associated with communication delays and switching topology. These researches provide valuable context for our study, which examines how communication delays and failure rates affect the efficacy of these methods in maintaining formation integrity and precision in leadership. [Kang et al. 2023] and [Feng et al. 2021] present robust formation control strategies for UAV swarm systems. These works highlight the complexity of maintaining effective coordination in dynamic and uncertain scenarios.

In summary, these studies offer valuable insights into the challenges and solutions for UAV swarm formation and coordination, particularly emphasizing the importance of considering communication delays, robust control algorithms, and effective strategies for coordination in challenging environments. Complementary to our study, each work contributes unique perspectives focused on the specific dynamics of UAV swarms under varied operational conditions. We aim to better understand how various factors, especially communication delays, influence the effectiveness of formation and accuracy in leadership, thereby addressing a gap in the existing literature.

3. Theoretical Background

This section explores the theoretical background that determines the characteristics of UAV leader/follower swarm formation as they move through a mission while attempting to maintain their exact formation and minimize errors over time. The four fundamental aspects to be examined are: Mission, Formation, Leadership Error, and Formation Error.

3.1. Formation

The formation of Unmanned Aerial Vehicles (UAVs) is designed in a circular configuration. In this formation, a specific number of follower UAVs, denoted as 'n', are uniformly distributed along the circumference of a circle. The circle has a radius labeled as 'Rf', ensuring that each UAV is equidistant from the center point (i.e., the leader) and from each other along the curve of the circle. See Figure 1.

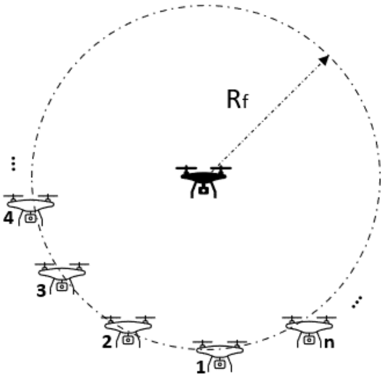

Figure 1. Formation

This equidistant spacing is critical for the formation's integrity, allowing for synchronized movements and a cohesive unit as the group navigates through the airspace. The circular formation also facilitates a 360-degree field of operation, enabling the UAVs to cover areas or execute tasks that require a well-organized and systematic approach. The radius 'Rf' plays a vital role in defining the scale of the formation, impacting the UAVs' spatial distribution and the overall footprint of the group in flight. It is important to note that in this work, the focus was on the formation of the UAVs; hence, collision avoidance between individual UAVs was not a primary concern.

3.2. Mission

The mission involving a formation of UAVs follows a unique and challenging flight path characterized by two circles that are tangent to one (figure-eight pattern). Each of the circles have a radius of Rm, and intercept at a single point called Starting Point (SP) where the two halves of the eight meet. See Figure 2.

The selection of a figure-eight pattern for the mission serves multiple purposes. The UAV formation is capable of executing maneuvers in both clockwise and counterclockwise directions, which enhances their agility and adaptability in varying flight conditions. SP serves as a critical juncture for direction reversal, allowing the UAVs to seamlessly switch from traversing one circle to the other and effectively invert their direction.

The flight path in a figure-eight pattern requires precise coordination and control. The UAVs must maintain formation integrity while navigating the complex trajectory, which demands synchronized timing and spatial awareness from each UAV in the formation. This mission tests not only the maneuvering capabilities of the individual UAVs but also their ability to operate as a cohesive unit in a dynamically changing environment.

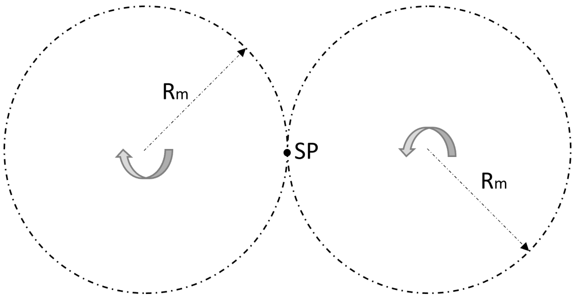

Figure 2. Mission path (figure-eight pattern)

During the upcoming simulation, the leader UAV will follow the pre-defined mission trajectory closely. The trajectory is laid out in a figure-eight pattern. The simulation will run for a specific duration to assess the formation's performance in navigation and maneuverability within the mission's parameters. The designated leader will maintain formation and control throughout the simulation. The simulation will run for a specific duration to assess the formation's performance in navigation and maneuverability within the mission's parameters.

3.3. Performance Metrics

In the context of UAVs formation movement, two principal normalized error metrics are proposed: Leadership Error and Formation Error. These metrics are fundamental in quantifying the accuracy of the formation in flight.

Leadership Error is defined to assess the average distance of the follower UAVs from the leader, providing an indication of the followers' positional accuracy with respect to the leader. The error is normalized between 0 and 1, where 0 denotes no error (perfect follower-leader alignment), and 1 denotes infinite error (maximum possible deviation from the leader). The Leadership Error at any given time instant t during the mission is calculated through a sequence of steps to evaluate the positional precision of follower UAVs with respect to the leader. These steps are as follows:

1. Compute the actual distance d_i for each of the n follower UAVs, using their 3-dimensional coordinates $(x^i_{follower}, y^i_{follower}, z^i_{follower})$ and $(x_{leader}, y_{leader}, z_{leader})$:
$$d_i = \sqrt{(x^i_{follower} - x_{leader})^2 + (y^i_{follower} - y_{leader})^2 + (z^i_{follower} - z_{leader})^2} \quad (1)$$
2. The ideal distance for each follower from the leader is the formation radius R_f.
3. Calculate the dimensionless absolute error e_i for each follower UAV:
$$e_i = \frac{|d_i - R_f|}{R_f} \quad (2)$$
4. Obtain the average error E_{avg} by averaging all e_i for the n followers:
$$E_{avg} = \frac{1}{n}\sum_{i=1}^{n} e_i \quad (3)$$
5. Normalize the average error E_{avg} using the formula:
$$E_{norm} = \frac{E_{avg}}{1 + E_{avg}} \quad (4)$$
It scales the error between 0 (no error) and 1 (infinite error).

Formation Error assesses the uniformity of the formation's shape. It gauges the extent to which the formation deviates from the predetermined geometric configuration. This error is also normalized between 0 and 1, with 0 indicating no deformation (ideal formation shape maintained), and 1 representing infinite deformation (complete loss of formation shape). The Formation Error at any given time instant t of the mission is determined to measure the fidelity of the UAV formation structure. The sequence of steps for this calculation is as follows:

1. For each combination of two out of the n follower UAVs, compute the actual distance d_{ij} based on their three-dimensional coordinates (x_i, y_i, z_i) and (x_j, y_j, z_j):
$$d_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2} \quad (5)$$
2. The ideal distance D_{ij} between two follower UAVs i and j, derives from the Law of Cosines:
$$D_{ij} = R_f \times \sqrt{2 - 2\cos(\frac{2\pi}{n} \times |i - j|)} \quad (6)$$
3. Assess the dimensionless absolute error e_{ij} for each UAV pair:
$$e_i = \frac{|d_{ij} - D_{ij}|}{D_{ij}} \quad (7)$$
4. Obtain the mean error E_{mean} by averaging all e_{ij} for the UAV pairs:
$$E_{mean} = \frac{1}{\binom{n}{2}}\sum e_{ij} \quad (8)$$
5. Normalize the mean error E_{mean} utilizing the normalization formula:
$$E_{norm} = \frac{E_{mean}}{1 + E_{mean}} \quad (9)$$
It constrains the error between 0 (perfect formation) and 1 (max deformation).

3.4. Key Parameters in UAV Formation Mission

In the UAV formation mission, several critical parameters are pivotal to the mission's success and efficiency. This sub-section details the following key parameters: communication delay, leader speed, and communication failure rate. Understanding and evaluating these parameters is essential for assessing the robustness and operational efficacy of the UAV formation under various conditions.

Communication Delay (s): This parameter measures the time lag in the communication network among the UAVs. The delay in transmitting and receiving commands or data is a significant factor that can impact the coordination and responsiveness of the UAVs, influencing the formation's overall performance. The delay can be caused by network congestion, signal interference, distance, obstructions, resource constraints, and dynamic topology.

Leader Speed (m/s): The speed at which leader operates is critical for the timing and efficiency of the mission. This simulation parameter will be varied to evaluate the formation's ability to maintain structural integrity and coordination at different speeds, which is vital for adapting to diverse mission scenarios. It is assumed that the followers can always operate at its speed limit of 25 m/s.

Communication Failure Rate (0 to 1): This parameter represents the probability of a communication breakdown occurring between the leader and the followers, scaled from 0 (no failure) to 1 (complete failure). Testing different failure rates is crucial to understand how the UAV formation responds to communication disruptions, thereby assessing the resilience of the system to such challenges.

4. Methodology

Simulation is a fundamental tool for understanding and improving performance in the field of distributed systems analysis. This study utilizes a state-of-the-art simulation platform to conduct tests on UAV networks across various operational scenarios. This section provides an in-depth description of the simulation tool used, the mission and formation design, and the simulation scenarios conducted.

4.1. The Simulation Tool

GrADyS-SIM NextGen[1] has been employed as the foundational tool for all simulations of this work. GrADyS-SIM NextGen, a Python-based advanced network simulation framework, has been crucial for analyzing and evaluating scenarios with networked nodes, such as UAVs. Its protocol-centric approach enables the simulation of real-world communication challenges, making it a reliable tool for accurate simulations. This simulator excels in flexibility, allowing the testing of decentralized algorithms for coordinating autonomous systems. Protocols, as its core component, dictate node behavior and allow diverse environmental interactions, enhancing the framework's adaptability and reusability across different simulations.

A key feature of GrADyS-SIM NextGen is its ability to configure communication mediums, critical for developing resilient distributed systems and simulating challenges like delays and failures. This functionality enables developers to validate their protocols in

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[1] https://project-gradys.github.io/gradys-sim-nextgen/

varied conditions. Its event-based network simulation module, implementing nodes with protocol-defined behaviors, is central to running prototype simulations in Python. This module's flexibility in creating scenarios that resemble real-world conditions enhances its effectiveness for testing and development in networked environments.

The use of GrADyS-SIM NextGen in this work involved leveraging its capabilities to simulate and analyze key parameters such as communication delay, leader speed, and communication failure rate. The framework's ability to simulate different environments and its protocol-centric approach were instrumental in assessing the robustness and operational efficacy of UAV formations under varying conditions. By manipulating these parameters, the study could understand the impact of each on the performance and reliability of the UAV networks, thus contributing valuable insights into the design and operation of autonomous vehicle systems.

4.2. Mission and Formation Design

Mission Parameters In this work, the mission is defined with a specific radius R_m of 20 meters and comprises 36 waypoints on each half of the figure-eight pattern. See Section 3.2. This configuration tests the UAVs' navigation skills over a complex trajectory. A radius of 20 meters allows for significant maneuverability, while 36 waypoints ensure coverage of various angles and directions, simulating real-world operational scenarios.

Formation Parameters The formation for the UAVs is designed with a radius R_f of 10 meters, including 10 follower UAVs. See Section 3.1. This radius balances compact formation for efficient communication and sufficient spacing for safety. The choice of 10 followers aims to test the scalability of communication protocols in a moderately sized group, representing realistic operational scenarios like surveillance or search and rescue operations. In summary, the mission and formation parameters were chosen to reflect the dimensions of urban streets and to ensure that the UAV formation can effectively navigate city-like environments, making this setup not only practical, but also an ideal option for future testing in real urban environments.

4.3. Simulation Scenarios

The simulation is executed over a period of 30 s, enabling the evaluation of the system's performance under different conditions. This duration was chosen because it is sufficient for the system to either reach a steady state or exhibit permanent oscillation, providing a clear picture of its behavior. In the **base case**, the parameters are set as follows: leader speed at 1 m/s, communication failure rate at 0.0 (no failure), and communication delay at $0\,\text{s}$. This setup represents ideal operating conditions. Conversely, the **worst case** is designed to test the system's limits, with a leader speed of 20 m/s, a communication failure rate of 0.9, and a communication delay of $5\,\text{s}$. These two simple cases provide valuable insights into the system's performance across a spectrum of conditions.

Between the base case and the worst-case scenario, various evaluation scenarios will be established. These scenarios serve a crucial function: to test the variation of one parameter while holding the others constant. This approach affords a clear understanding of the singular effect each parameter has on the system's overall performance. By systematically altering a single factor at a time, the direct consequences and interplay of specific changes on the system can be accurately discerned, providing an in-depth assessment of the UAV's.

The Table 1 summarizes the parameters for a series of simulations conducted to evaluate the performance of UAVs under different operational scenarios. These scenarios, labeled A through E, have been designed to test various aspects of UAV behavior, including speed, communication delay, and failure rate in communication. Each scenario is examined over three separate runs to ensure consistency and to capture a range of outcomes.

- Scenario A is intended to test the influence of leader speed in an environment devoid of communication delay and failure.
- Scenario B focuses on the impact of communication failure rates when the leader speed is low and constant at 1 m/s, with no communication delay present.
- Scenario C is designed to evaluate the effects of communication delays, which vary from 1 to 5 s, in the absence of communication failures and at a low leader speed of 1 m/s.
- Scenario D exists to examine the influence of communication failures at a higher leader speed of 10 m/s, considered standard for UAV operations, again without any communication delays.
- In Scenario E, the analysis is directed towards the influence of communication failure rates under conditions of a longer communication delay of 5 s and a low leader speed.

Scenario D is formulated to contrast with Scenario B, with the objective of testing the influence of communication failure rate in the presence of a higher leader speed. This allows for a comparative analysis of the failure rate's effect at different speeds. Scenario E also stands in opposition to Scenario B by testing the impact of the failure rate in the presence of a longer communication delay; it is crucial to understand how increased communication delays can compound the effects of failure rates in UAV operations.

Scenario	**Parameter**	**Run 1**	**Run 2**	**Run 3**
A	Speed (m/s)	2.0	10.0	20.0
	Delay (s)	0.0	0.0	0.0
	Failure Rate	0.0	0.0	0.0
B	Speed (m/s)	1.0	1.0	1.0
	Delay (s)	0.0	0.0	0.0
	Failure Rate	0.5	0.7	0.9
C	Speed (m/s)	1.0	1.0	1.0
	Delay (s)	1.0	2.0	5.0
	Failure Rate	0.0	0.0	0.0
D	Speed (m/s)	10.0	10.0	10.0
	Delay (s)	0.0	0.0	0.0
	Failure Rate	0.5	0.7	0.9
E	Speed (m/s)	1.0	1.0	1.0
	Delay (s)	5.0	5.0	5.0
	Failure Rate	0.5	0.7	0.9

Table 1. Simulation Parameters for Various Scenarios

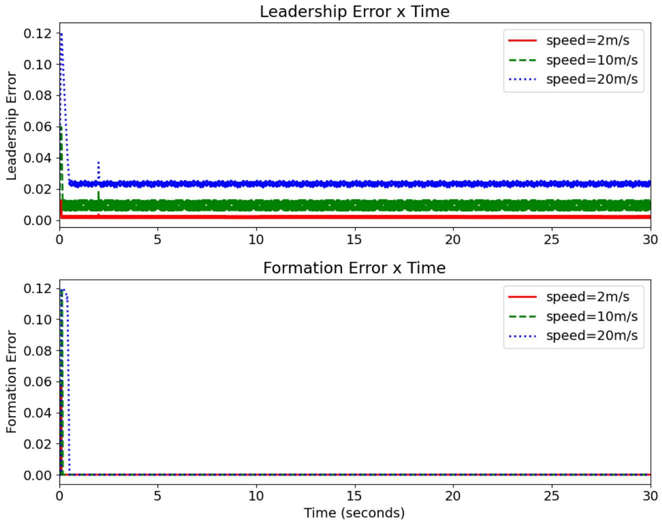

Figure 3. Scenario A - Leader Speed Variation, Failure=0, Delay=0

5. Results and Discussions

This section discusses the outcomes of the simulations, showcasing a variety of scenarios.

The base case scenario involves parameters set at a leader speed of 1m/s, a failure rate of 0, and a delay of 0s. The errors recorded are minimal and close to zero. Results from this simulation revealed that errors within the UAV network were negligible. Both Leadership Error and Formation Error were extremely low, indicating a high level of coordination and formation integrity among the UAVs. This performance aligns with the expectations for a scenario characterized by an absence of communication delays and failure rates, coupled with a leader speed of 1m/s, which is conducive to maintaining stable formation dynamics.

In our simulation, the broadcast interval, set at 0.02 s, plays a critical role in coordination, with a key aspect being that a smaller broadcast interval leads to less interference from communication failure rates. Frequent updates of the leader's position reduce the impact of communication delays. Thus, the shorter the broadcast interval, the more minimized the effects of communication failures.

Scenario A Results Scenario A, depicted in Figure 3, involved testing UAVs at different leader speeds to observe their impact on formation dynamics. The data revealed that the Formation Error was consistently low, indicating that changes in the leader's speed did not significantly affect the overall structure of the UAV formation. This low error suggests the effectiveness of the formation in adapting to speed variations. The Leadership Error demonstrates a correlation with the leader's speed, remaining low but exhibiting a slight increase as the speed escalates. At a speed of 2 m/s, the error is nearly negligible, suggesting tight control and coordination. As the speed increases to 10 m/s and further to 20 m/s, a modest upward shift in the Leadership Error is observed. This trend indicates that while the followers are generally capable of maintaining formation, there is a marginal challenge in tracking the rapidly moving leader with absolute precision. The consistent yet slightly elevated pattern of Leadership Error at higher speeds hints at the followers' efforts to continuously adjust their positions in relation to the fast-moving leader.

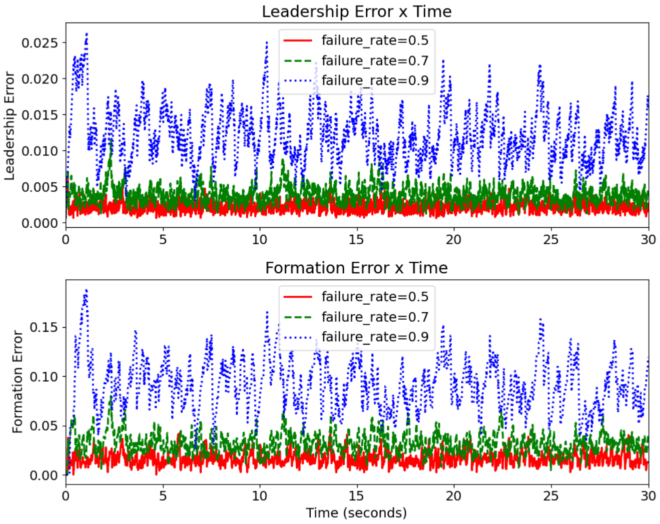

Figure 4. Scenario B - Failure Variation, Leader Speed=1, Delay=0

Scenario B Results Scenario B (Figure 4) aimed to analyze the impact of different communication failure rates on UAV behavior, with a specific focus on Leadership and Formation Errors. The results revealed intriguing patterns. Firstly, the Leadership Error remained relatively low across different levels of communication failure rate. The results indicate that the ability of followers to track the leader is not significantly affected by the communication failure rate, which aligns with expectations. This indicates that the leadership-following structure is somewhat resilient to communication interruptions. However, the Formation Error showed a different trend. Although the values were not significantly different, a gradual increase in Formation Error was observed as the communication failure rate increased. However, these increases were not significant enough to indicate a substantial deterioration in formation integrity. This suggests that while communication failures do have an impact on formation maintenance, the effect is not critically detrimental under the tested conditions.

Scenario C Results Scenario C (Figure 5) aimed to assess the impact of varying communication delays, from 1 to 5 s, on the dynamics of UAV formation. The results provided insights into the influence of delayed communication on UAV coordination. Notably, the Formation Error remained relatively minor regardless of increasing communication delays, indicating that the UAVs' ability to maintain formation is not significantly impaired by communication lags. The formation maintained its integrity despite time lags, demonstrating resilience to delays. This is expected as the accuracy of follower UAVs in tracking the leader depends on receiving commands promptly. On the other hand, delays can cause followers to act on outdated positional data, hindering their ability to occupy the correct positions in a timely manner. This delay disrupts the synchronization between the leader's maneuvers and the followers' reactions, amplifying the Leadership Error; the greater the delay, the larger the Leadership Error becomes.

Scenario D Results Scenario D (Figure 6) was particularly insightful as it involved a higher leader speed of 10 m/s combined with varying levels of communication failure rates. The scenario results show a significant trend in Leadership and Formation Errors, with both increasing as the communication failure rate rises. This trend is different from

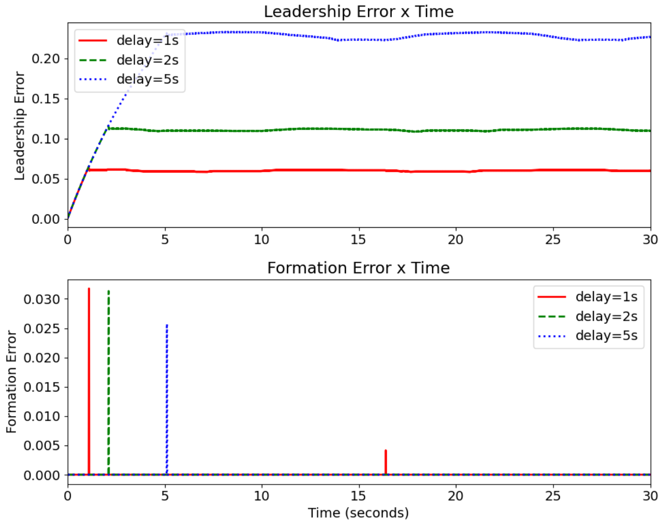

Figure 5. Scenario C - Delay Variation, Leader Speed=1, Failure=0

Scenario B (Figure 4), where the leader speed was much lower (1m/s). The higher leader speed in Scenario D had a significant impact on the communication failures. The challenges in maintaining both the formation and the tracking of the leader were exacerbated by the increased leader speed. It was evident that the UAVs' ability to follow the leader and maintain their formation was more adversely affected at higher leader speeds in the presence of communication failures. This highlights the compounded challenges that arise in high-velocity scenarios when communication reliability is compromised.

Scenario E Results In Scenario E (Figure 7), the simulation involved a 5s communication delay with varying communication failure rates. This study aimed to evaluate the impact of communication failures and substantial delays on UAV performance. The results showed that the Leadership Error was not significantly affected by the increased failure rates, despite the presence of a 5-second delay in communication. The UAVs were able to track the leader effectively. Similarly, the Formation Error did not show significant deviations, with noticeable effects only emerging after the full 5-second delay period. This outcome contrasts with Scenario B, where there was no communication delay. The presence of a 5-second delay did not worsen the impact of rising failure rates on UAV formation and leadership tracking capabilities. The statement implies that UAV systems can handle delays and communication failures up to a certain point without compromising their operational integrity.

Worst Case Results The worst-case scenario (Figure 8) was designed to test the limits of the UAV system by setting all operational parameters to their most challenging levels. This included a high leader speed of 20 m/s, a maximum communication failure rate of 0.9, and a significant communication delay of 5s. It was observed that both the Leadership Error and the Formation Error were significantly impacted in this scenario. The high values for speed, communication failure, and delay collectively contributed to exacerbating both types of errors. The rapid speed of the leader, combined with frequent communication failures and substantial delays in command transmission, severely hindered the UAVs' ability to maintain formation and accurately follow the leader. This outcome underscores the critical challenges faced by UAV systems in high-stress environments.

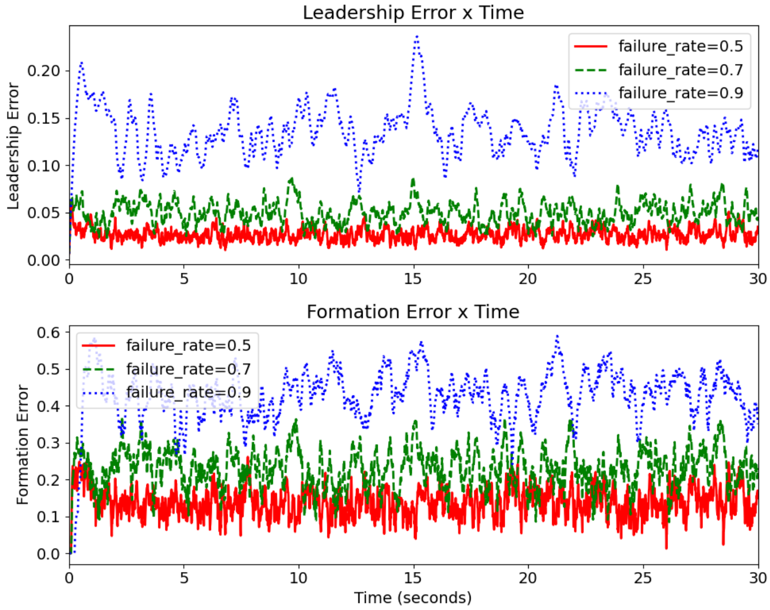

Figure 6. Scenario D - Failure Variation, Leader Speed=10, Delay=0

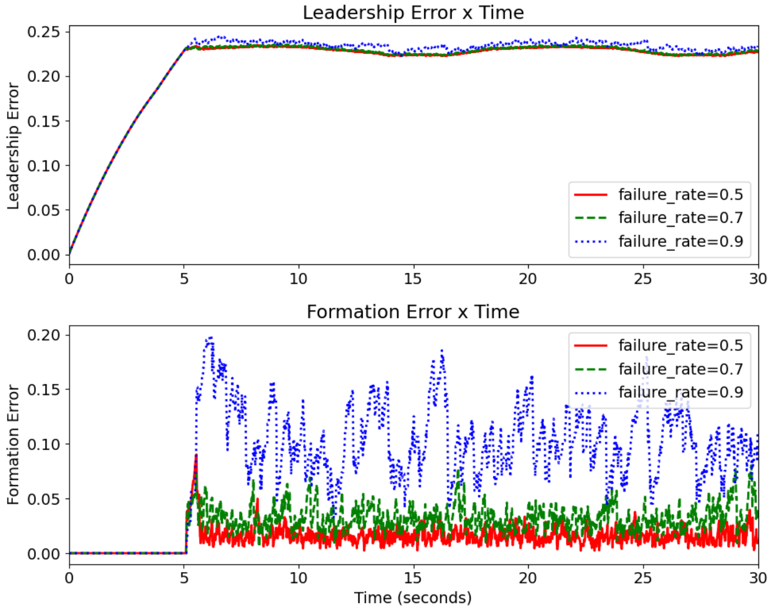

Figure 7. Scenario E - Failure Variation, Leader Speed=1, Delay=5

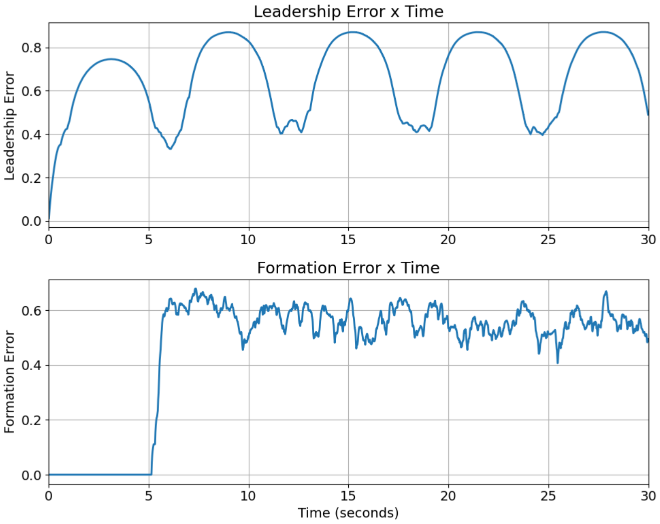

Figure 8. Worst Case - Leader Speed=20, Failure=0.9, Delay=5

6. Conclusion

This study provides a comprehensive analysis of the operational dynamics of UAV swarm systems under varying communication and movement conditions. The scenarios were designed to test the impact of different factors, such as leader speed, communication delay, and communication failure rate, on the performance of UAV formations. It is important to note that the parameters examined are only a subset of the potential influences on UAV formation. Environmental factors such as wind, barometric pressure, obstacles, and the acceleration capabilities of UAVs play a significant role in swarm behavior dynamics and should be considered in future research.

Our study offered insights into UAV swarm dynamics. High leader speeds do not significantly compromise formation integrity, but they can slightly affect leader-following accuracy. Low leader speeds can mitigate the impact of communication failures on formation stability, although they can still have an effect. Extended delays primarily affect leader-following accuracy, but do not significantly impact formation maintenance. High-speed operations combined with communication failures present significant challenges. Prolonged communication delays, even when accompanied by failure rates, do not necessarily exacerbate leader-following or formation errors beyond certain thresholds.

Overall, this study's findings contribute to a deeper understanding of the dynamics of UAV formations and provide a foundation for future research and development in UAV operational algorithms and communication protocols. Future research avenues include using a more precise simulator, such as OMNET+, to capture nuanced dynamics of UAV interactions, which could yield richer insights. Additionally, simulating environmental effects and conducting field tests would be invaluable. It will be also crucial to explore other formation shapes and mission patterns beyond the eight-figure format currently adopted such as V-shapes, lines, or grids. Investigating the influence of broadcast interval on the performance and reliability of UAV communication networks will also be a significant area of study. These approaches strive to bridge the gap between theoretical models and real-world applicability, enhancing UAV swarm effectiveness in diverse conditions.

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