Mobility-Aware Graph Restructuring and Conflict-Minimizing Modeling for Autonomous Continuous Monitoring by Self-Organizing UAV Swarms

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***Abstract*— Continuous area surveillance with self-organizing UAV swarms is vital for applications such as environmental monitoring and emergency response. To support uninterrupted coverage, we propose a framework where each UAV follows a Eulerian graph path, and dynamically selects a new starting vertex after completing its task, avoiding downtime. This persistent monitoring model introduces two key challenges: unreliable data transmission and simultaneous drone arrivals at the same vertex, which lead to congestion and coordination conflicts.**

To address these issues, we present a two-fold solution:

1) **a mobility-aware modeling framework that incorporates probabilistic transmission and routing behavior to reduce communication failures, and**

2) **an adaptive graph restructuring algorithm that modifies UAV traversal sequences to minimize vertex-level conflicts. Simulation results demonstrate that our combined approach significantly enhances communication reliability, reduces operational risks, and supports scalable, autonomous UAV-based continuous monitoring in complex environments**

***Keywords*—Continuous area surveillance, adaptive graph, congestion reducing, data transmission.**

I. INTRODUCTION

Unmanned aerial vehicle (UAV) swarms are increasingly being used for tasks that require distributed, adaptable, and scalable operations. Drawing inspiration from the collective intelligence seen in nature, such as flocks of birds or colonies of ants, UAV swarms can coordinate autonomously to perform complex missions across large and changing environments. This approach offers notable benefits: it reduces the need for central control, increases system robustness, and allows multiple units to work together efficiently. Because of this, UAV swarms have become a compelling solution for a range of applications, including disaster assessment, precision farming, environmental monitoring, and search-and-rescue efforts.

One particularly valuable use case is continuous area surveillance, where drones must maintain constant coverage of a region. Unlike traditional missions where UAVs complete a route and return to base, continuous monitoring requires UAVs to immediately begin a new task once the previous one ends, ideally without downtime. In this study, we propose a framework where each UAV follows an Eulerian graph path, starting from assigned points. Rather than returning to a landing site after completing its assigned route, each drone dynamically selects a free vertex to begin the next monitoring cycle. This approach enables persistent coverage without operational pauses.

However, ensuring such uninterrupted, autonomous operation is not without its challenges. This continuous monitoring approach introduces two major technical obstacles. First, a high rate of failed data transmissions can significantly degrade communication reliability, particularly in decentralized systems. Second, multiple drones often arrive simultaneously at the same vertex, leading to communication congestion and conflicts in path coordination. These challenges, if unaddressed, result in monitoring gaps, inefficient resource usage, and reduced mission performance.

1) To tackle these limitations, we present a two-part solution: a modeling-based method that simulates swarm behavior under various routing and communication protocols, incorporating mobility-aware algorithms and probabilistic transmission models to reduce communication failures significantly; and

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2) an adaptive graph restructuring technique that alters the traversal order of drones at graph vertices, minimizing simultaneous arrivals and reducing congestion and path conflicts. Together, these contributions offer a practical and robust approach to enabling scalable, autonomous continuous monitoring by UAV swarms in complex and dynamic environments.

This paper addresses these limitations by presenting a modeling-driven framework that blends enhanced routing, adaptive communication, and decentralized reassignment. The first component is a conflict-aware extension of the rotor-router navigation algorithm that enables UAVs to handle path collisions through rollback logic. Second, we introduce a more responsive gossip protocol that adjusts its behavior based on nearby drone density. Finally, a mechanism for real-time route reassignment allows UAVs to autonomously select their next monitoring task, eliminating delays between cycles. Together, these strategies are implemented within a unified simulation platform that builds upon previous research in deterministic routing, swarm modeling, and fault-tolerant communication [1-9].

II. Related Work

The foundations for this study lie in a broad body of work focused on decentralized algorithms for graph traversal and communication within dynamic networks [8]. Among the most influential is the rotor-router model, which provides a deterministic way for agents to explore and revisit graph structures [4]. Unlike random walks, rotor-router traversal offers balanced node coverage over time, and with minor enhancements, can be made more resilient to congestion. For example, the concept of loop reversibility, as introduced in [1], allows agents to backtrack from potential deadlocks while still maintaining predictable movement.

On the communication side, gossip-based protocols have gained attention for their simplicity and scalability. These protocols work by having each node periodically transmit messages to nearby nodes. While effective under steady conditions, traditional gossip suffers when network links become unreliable or when drones drift out of range. To improve its fault tolerance, researchers have introduced structural enhancements and timing adjustments, leading to more resilient message propagation even in challenging environments [2].

Several recent efforts have extended these ideas into practical swarm control systems. A cloud-integrated swarm simulation platform was developed in [3], combining rotor-router routing with adaptive gossip in a cohesive framework. This platform enabled UAVs to operate autonomously while still allowing real-time monitoring and feedback from a central cloud system. Further evolution of this platform was seen in [6], where a multi-user interface was added. This allowed human operators to interact with and guide the swarm during mission execution, demonstrating how user-defined tasks and autonomous UAV behavior could co-exist.

In parallel, other works have explored how automata theory can be applied to swarm decision-making. For instance, [9] presents a finite-state machine model for drone behavior, showing how agents can respond to environmental triggers or mission updates without external input. These kinds of models provide a flexible base for adapting swarm behavior as conditions change.

Finally, the importance of real-time adaptability and persistent coverage has been emphasized in work such as [10, 13], which describes a mission preparation system for multi-user UAV platforms. This system supports autonomous reassignment, decentralized coordination, and live simulation feedback features that align closely with the goals of our approach.

Together, these studies offer a foundation for our framework, which extends prior models by combining deterministic routing, dynamic gossip control, and real-time path reassignment in a single, self-organizing UAV swarm system.

III. Problem Statement

Deploying autonomous UAV swarms in large-scale missions, especially those involving continuous area monitoring-poses several persistent technical challenges. Even when agents operate according to decentralized logic, certain limitations in routing and communication can lead to instability, inefficient coverage, or interrupted mission execution. This section outlines the key problems that motivated our proposed solution.

3.1 Vertex Conflicts and Navigation Clashes

In many UAV swarm systems, movement decisions are based on deterministic algorithms like rotor-router routing. This method works well when UAVs are spread out across a graph and allowed to move freely. However, issues arise when multiple drones choose the same destination vertex at the same time. Without a built-in way to arbitrate these collisions, agents may end up blocked, stuck in loops, or forced to take suboptimal detours.

As swarm density increases, the risk of these vertex conflicts grows, particularly at critical nodes or intersections. The original rotor-router framework offers no mechanism to detect or resolve simultaneous occupancy attempts. As a result, mission efficiency suffers, and in extreme cases, the entire system may become unbalanced. To ensure scalable, reliable operation, it’s essential to introduce a local mechanism for detecting and resolving such conflicts in real time.

3.2 Fragile Communication in Gossip-Based Networks

Communication in self-organizing UAV swarms often relies on gossip-style protocols. These decentralized schemes allow drones to share information with nearby agents by periodically broadcasting messages. While this approach is flexible and generally robust, it becomes fragile under certain conditions. For instance, if drones are spaced too far apart, signals may not reach their targets. On the other hand, if several drones are in close proximity and all transmit simultaneously, messages may collide or go unnoticed.

Traditional gossip protocols assume regular, fixed-interval communication, regardless of the swarm’s physical distribution. This can lead to wasted transmissions, dropped packets, or outdated information. To maintain reliable situational awareness and coordination, UAVs need a smarter approach-one that dynamically adjusts transmission timing based on the density of neighboring agents.

3.3 Disruptions in Continuous Monitoring Cycles

Another critical gap in current systems lies in how UAVs handle transitions between tasks. In most routing models, a drone completes its assigned path and then returns to a starting point or waits to be re-tasked. This “start-stop” behavior breaks the continuity needed for real-time surveillance. It introduces idle time, leads to blind spots in coverage, and consumes more energy than necessary.

For applications such as emergency response or environmental monitoring, interruptions like these are unacceptable. What’s needed is a method for allowing UAVs to autonomously continue their missions-without centralized control-by seamlessly assigning themselves new routes as soon as the current one ends. This requires local decision-making, awareness of graph coverage history, and the ability to distribute swarm effort evenly over time.

IV. System Model and Assumptions

System Mode To support persistent surveillance and self-organizing behavior, we define a decentralized system model that maps UAV swarm operations onto a directed graph structure. This section outlines the assumptions and basic architecture of our approach.

The mission space is represented as a graph $G = (V, E)$, where each node $v \in V$ corresponds to a geographic waypoint or task location, and each directed $e \in E$ defines an allowable transition between waypoints. Drones move through this network by following rotor-router traversal rules, making their decisions based on local rotor states at each vertex.

Each UAV is equipped with three essential components:

- A **rotor pointer** to guide routing decisions
- A **broadcast module** to enable communication with nearby agents
- A **synchronized internal clock** to coordinate actions with the swarm

The drones operate in discrete time steps, progressing through the environment without global oversight. Communication between agents relies on a **proximity-based gossip protocol**, where each UAV shares data only when others are within transmission range. Importantly, each drone also receives feedback about the success or failure of its most recent communication attempt, allowing it to adapt future broadcasts accordingly.

To facilitate **uninterrupted monitoring**, the system is designed for autonomous reassignment. Instead of returning to a base or waiting for new instructions after completing a route, a drone evaluates nearby nodes and selects an appropriate new starting point. This is based on recently visited areas, the local graph structure, and whether the selected node is currently occupied. The reassignment process is lightweight and happens locally, helping to avoid redundant coverage and balance swarm load over time. This model promotes decentralization, resilience, and efficiency-core requirements for long-term autonomous swarm missions in uncertain and dynamic environments.

V. Proposed Methodology

To overcome the challenges outlined earlier, such as path conflicts, unreliable communication, and mission discontinuity, we propose a unified approach composed of three lightweight, decentralized mechanisms. Each is designed to run independently on every UAV and work without central coordination. Together, they enable robust, scalable, and continuous operation of a self-organizing swarm.

5.1 Rotor-Router Rollback for Conflict Resolution

The first part of our solution enhances the classic rotor-router navigation model. In its original form, this algorithm guides UAVs through a graph by rotating a pointer at each node to direct movement. However, when two or more drones select the same destination simultaneously, the lack of coordination can lead to conflicts, blocking, or erratic backtracking.

To address this, we introduce a rollback mechanism. If a UAV detects that it cannot proceed because the next vertex is already occupied or another drone is also approaching, it returns to its previous location and rotates its pointer to try an alternative direction. If no alternatives are available, it temporarily pauses. This process is bounded by a predefined rollback depth, ensuring that drones do not enter infinite loops. The rollback strategy builds on earlier concepts of loop reversibility [1], adapting them for real-time spatial conflict resolution in a swarm setting.

5.2 Adaptive Gossip Timing

The second enhancement improves communication within the swarm by replacing static broadcast intervals with a dynamic strategy. Traditional gossip protocols assume that drones should transmit data at regular intervals, regardless of how many peers are nearby. This often results in wasted bandwidth when no agents are in range-or in congestion when too many are.

Instead, each drone monitors its neighborhood and only initiates a broadcast if the number of nearby peers exceeds a predefined threshold. If few or no agents are within communication range, the drone defers its transmission. On the other hand, if conditions are favorable, it proceeds to share its local state or mission update. This approach reduces unnecessary transmissions and improves overall message success rates [2, 3, 6].

5.3 Autonomous Route Reassignment for Persistent Coverage

Finally, to maintain uninterrupted monitoring, each UAV is equipped with logic for autonomous reassignment. When a drone completes its current path or monitoring segment, it immediately seeks a new location to continue its mission. Rather than returning to a depot or awaiting new instructions, it evaluates adjacent vertices in the graph to identify one that is unoccupied and underserved.

The reassignment logic considers several local cues, such as recent visitation frequency and current swarm density, to ensure that drones do not cluster unnecessarily or repeatedly visit the same regions. This continuous reassignment loop minimizes idle time and distributes swarm effort evenly across the task space, allowing the system to adapt fluidly to environmental changes or drone failures.

VI. Theoretical Insights

The strategies outlined above are grounded in both theoretical principles and validated modeling. They reflect a broader shift toward decentralized, rule-based control in complex systems, where agents rely on local interactions to produce stable, large-scale behavior. In what follows, we summarize the theoretical reasoning that supports each component of the framework.

6.1 Conflict Handling via Deterministic Rollback

Rotor-router algorithms are designed to ensure even graph traversal over time [4]. However, in the absence of conflict resolution, they fall short in multi-agent scenarios. Our rollback extension provides a way for UAVs to recover gracefully from collisions without randomization or global intervention. The idea builds on the concept of loop reversibility, introduced in [1], which showed that a system can deterministically reverse its steps and still maintain fairness.

Later studies involving swarm-scale simulations confirmed that this kind of rollback logic helps avoid starvation and preserves equitable access to shared routes, even in dense networks [3, 10]. Our version of this technique ensures that agents resolve navigation clashes efficiently while preserving overall coverage goals.

6.2 Communication Efficiency through Adaptive Gossip

Gossip protocols are well-known for their resilience and simplicity, but only when used under the right conditions. Fixed-interval broadcasting often becomes inefficient when drones are sparsely distributed or moving unpredictably. By introducing density-aware timing, each drone can regulate its transmissions based on real-time neighbor counts, avoiding both under-communication and flooding.

This concept builds on earlier work in fault-tolerant gossip structures [2], and was expanded in [3, 6] through simulation-based verification. These studies showed that adaptive gossip reduces redundancy while improving delivery accuracy, especially in swarms with changing topology.

6.3 Emergence of Self-Organized Stability

When rotor-router routing, adaptive gossip, and local reassignment are combined, the swarm tends to self-organize over time. Drones gradually redistribute themselves; coverage becomes balanced, and idle time decreases-all without centralized oversight. This behavior reflects a form of self-organized criticality (SOC), where local decision rules lead to stable global patterns [11, 12].

In [3], it was observed that such systems often settle into equilibrium states, where mission loads are distributed proportionally and agents adapt automatically to failures or congestion. These SOC-like properties allow the swarm to scale effectively and remain robust under stress.

6.4 Flexibility for Multi-User Environments

While the framework is fully autonomous, it also supports human interaction when needed. Multi-user simulation platforms like those described in [6, 10] demonstrate how UAVs can balance independent operation with real-time user input. For example, users can reassign targets or inject new mission goals, and the swarm will adjust without compromising its decentralized logic.

Our framework is designed to be compatible with such hybrid architectures. It preserves deterministic state transitions while remaining responsive to external commands, making it well-suited for practical deployments that require both autonomy and supervision [5, 9].

VII. Conclusion and Future Work

This work presented a lightweight and decentralized framework aimed at improving how UAV swarms coordinate during autonomous, continuous monitoring missions. The framework addresses three critical challenges faced by such systems: avoiding route conflicts, enhancing communication reliability, and ensuring persistent area coverage without interruption.

By extending the rotor-router routing algorithm with a rollback mechanism, UAVs can now resolve navigation conflicts deterministically and without needing central control. In parallel, the use of proximity-based adaptive gossip allows drones to share information more intelligently, broadcasting only when it matters, and conserving bandwidth when it doesn't. Finally, the autonomous reassignment strategy ensures that once a UAV completes a task, it immediately continues to the next, allowing the swarm to maintain high efficiency and full mission continuity.

All three components are designed to work independently and in combination, with minimal overhead. This makes the system not only scalable but also robust against agent failures and communication losses - two of the most common issues in real-world deployments.

Looking ahead, several areas are worth exploring. One direction involves developing mathematical proofs to better understand the convergence behavior of the system under different graph topologies. Another is the integration of learning-based methods, such as reinforcement learning or predictive modeling, to enable UAVs to anticipate conflicts before they occur. Lastly, we aim to validate the entire system on physical hardware, using real UAVs in outdoor testbeds, to assess performance under varying environmental conditions.

Together, these next steps will further enhance the system’s practicality and readiness for real-world missions in disaster response, environmental monitoring, and smart infrastructure surveillance.

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