Real-Time Swarm Behavior Simulation and Dynamic Role Assignment in Decentralized UAV Coordination Platforms

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***Abstract*— This paper introduces a next-generation simulation and a coordination platform for decentralized UAV swarms, with an emphasis on real-time behavior validation and adaptive role-based mission execution. Building upon our previously established rotor-router and gossip-based communication algo- rithms, the enhanced system offers a robust software layer that enables pre-deployment simulation, persistent UAV tracking, and live deviation correction. The platform maintains a full simulation state, including GPS traces for each UAV, and con- tinuously monitors live drone telemetry during missions. Upon detecting positional deviations from predefined paths, the system triggers automatic corrective commands to ensure mission integrity. Furthermore, a dynamic role reassignment module allows any UAV to be designated as an "attacker/rescue", en- abling it to temporarily leave the swarm, execute a high-priority mission, and reintegrate into the formation autonomously. These features, integrated within a modular microservice architecture, elevate the platform's capabilities in mission planning, reliability assurance, and adaptive autonomous behavior, offering a com- prehensive environment for testing and deploying complex UAV swarm operations in both simulated and real-world scenarios.**

***Keywords*— UAV swarm simulation, decentralized coordina- tion, real-time telemetry, GPS path correction, dynamic role assignment, rotor-router algorithm, autonomous systems, mi- croservice architecture.**

I. INTRODUCTION

Decentralized coordination of UAV swarms is gaining increasing importance in scenarios where robustness, fault tolerance, and edge autonomy are critical. Traditional cen- tralized control models, although effective under controlled conditions, often fail in dynamic, disconnected, or adversarial environments due to their dependence on high-bandwidth communication and a single point of control.

Recent advances in deterministic path planning, decentral- ized communication, and simulation-driven mission prepa- ration have laid the foundation for scalable UAV swarm systems. In our previous work [1], [2], we introduced a multi- user platform for mission planning and control that supports rotor-router-based traversal and gossip-based communication among UAVs. The system was architected as a cross-platform Qt/C++ client-server application capable of secure multi-user collaboration, mission graph definition, and live telemetry monitoring.

We further enhanced the model in [3], introducing formal cloud-based mathematical representations for self- organizing swarm behavior, enabling improved theoretical guarantees on convergence and role stability. In our most recent im- plementation [4], we demonstrated a simulation environment that integrates graph-based terrain modeling with live swarm visualization and telemetry feedback.

Building upon this foundation, the present work focuses on three key advancements:

1) Real-time validation of UAV behavior using a con- tinuously running simulation engine that mirrors the physical swarm and triggers corrective actions upon deviation;
2) Dynamic role reassignment capabilities, enabling UAVs to switch between mission-critical functions (e.g., at- tacker, rescue) in-flight based on telemetry and mission context;
3) Full integration of GPS-based path correction mecha- nisms that validates UAV positioning against the mis- sion plan and enforce coordinated fallback strategies when deviations are detected.

This paper presents the architecture, design, and imple- mentation of these enhancements, illustrating how they ele- vate the reliability, autonomy, and mission flexibility of the UAV swarm deployments in both simulated and real-world conditions.

II. COMPARISON WITH RELATED WORK

Numerous research efforts have focused on UAV swarm coordination, but most existing systems rely heavily on cloud infrastructure and static mission logic, which limit their adaptability in real-world environments. Our work introduces

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key advancements that address these limitations through decentralized coordination, real-time simulation, and role-adaptive control mechanisms.

Traditional cloud-based coordination platforms, such as the system proposed by Itkin et al. [5] and the platform by Sousa et al. [6], provide effective mission management in connected environments, but fail to support autonomous adaptation in disconnected or adversarial contexts. Unlike these centralized frameworks, our system supports offline-first deployments, real-time path correction through a telemetry-driven simula- tion engine, and in-flight dynamic role reassignment, making it highly resilient to communication loss and environmental uncertainty.

Recent studies on swarm intelligence and UAV collaboration, including Zhou et al. [7] and Tang et al. [8], have surveyed algorithmic frameworks for collective UAV behavior but lack integration with live simulation and corrective feedback mechanisms. In contrast, our platform combines rotor-router traversal [9], gossip-based consensus [10], and shadow simulation for proactive error correction, significantly enhancing mission continuity and reliability.

Compared to vision-based drone coordination sys- tems [11], [12], our approach does not depend solely on image processing or AI inference. Instead, it blends determin- istic graph-based planning with real-time telemetry validation and decentralized decision-making, reducing computational load on UAV nodes and increasing reliability under con- strained processing conditions.

Furthermore, unlike mission planning frameworks with limited interactivity and feedback [13], our platform provides a full-featured microservice-based environment with pre-deployment validation, live telemetry monitoring, dynamic graph editing, and secure encrypted communication [14]. These features ensure robustness in mission-critical scenarios such as disaster response [14], where adaptability and autonomous fault handling are essential.

Our previous work [1]–[4] laid the foundation for se- cure multi-user swarm mission planning, rotor-router-based traversal, and gossip synchronization. This paper builds upon that work by integrating a dual-mode simulation system for live mission validation and a dynamic role management engine. These advancements distinguish our platform as a comprehensive, autonomous coordination solution that remains effective in disconnected, hostile, or infrastructure-less environments.

In summary, this research presents a transformative step in UAV swarm autonomy by merging formal algorithmic guarantees, live mission monitoring, and decentralized adaptability—features rarely found in existing UAV coordination systems.

III. System Architecture

The architecture of the proposed UAV swarm coordination system is designed for modularity, cross-platform interoperability, and resilience in dynamic field conditions. As shown in Figure 1, the system follows a client-microservice pattern consisting of a graphical mission planning client, a decentralized coordination backend, and lightweight drone-side agents deployed on physical UAVs.

The mission planning client, developed in Qt/C++, enables users to define graph-based exploration zones, assign initial roles to UAVs, and monitor mission progress in real time. It communicates securely with the backend using AES-256 encrypted TCP channels and TLS protocols, ensuring integrity and confidentiality of control data [1]. The backend manages telemetry aggregation, task dispatching, and mission lifecycle events using a set of microservices that can operate on both cloud and edge nodes.

UAVs are equipped with Raspberry Pi 4B+ units and Pixhawk flight controllers. These agents receive their navigation instructions based on the rotor-router traversal policy and periodically broadcast telemetry and image metadata via gossip protocols [2]. This enables distributed synchronization of swarm behavior without requiring a persistent connection to a central server.

A key advancement in this architecture is the integration of a continuously running real-time simulation module that mirrors UAV behavior based on live telemetry, allowing the system to validate task execution, detect positional drift, and apply automated corrective measures when needed. The architecture also supports dynamic role reassignment and run-time graph modifications—capabilities absent in our earlier platforms [2]–[4].

Together, these components form a robust and extensible framework for orchestrating decentralized UAV swarm missions under constrained or disconnected conditions.

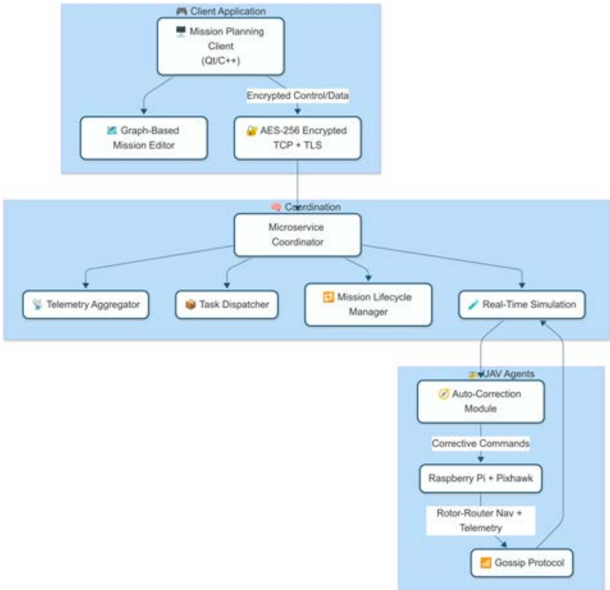

Fig. 1. System architecture of the UAV swarm coordination platform

IV. Real-Time Simulation and Deviation Correction

A defining feature of the proposed platform is its dual-mode simulation engine, which supports both pre-mission behavior validation and real-time in-mission correction. This engine is tightly integrated with telemetry and mission control services, enabling the system to detect and respond to path deviations dynamically.

As illustrated in Figure 2, each UAV in the swarm periodically transmits its current GPS position, heading, and task status to the server. These telemetry updates are processed by the simulation engine, which maintains a live ”shadow state” of the mission by mirroring expected rotor-router traversal paths. The system compares the incoming telemetry with the expected node visitations derived from the mission graph.

A deviation is flagged when a UAV’s live GPS position diverges from its expected position beyond a configured spatial tolerance ϵ. In such cases, the simulation engine triggers a validation routine and issues correction commands back to the deviating UAV. These commands may include re-aligning the UAV to the correct graph node, steering it toward a nearby unvisited node, or offloading its remaining tasks to neighboring agents via gossip-based coordination [2].

The path alignment is continuously monitored through a timestamped deviation function $E(t)$, defined as the Euclidean distance between the UAV’s reported GPS coordinate and its current logical node assignment. When $E(t) > \epsilon$, the following correction strategies are applied:

1) **Soft correction:** a minor navigational adjustment to steer the UAV back to its expected path;
2) **Hard correction:** reallocation of traversal to a nearby valid node and updating its rotor state;
3) **Role reassignment:** if the UAV cannot proceed (e.g., due to failure or obstruction), nearby UAVs dynamically inherit its responsibilities.

Before mission deployment, the simulation engine also offers full-path emulation for planning validation. Users can simulate UAV traversal, gossip convergence, and area coverage to identify mission flaws early—such as disconnected subgraphs or unbalanced role distribution—that were previously difficult to predict [1], [4].

This dual-mode simulation and correction approach significantly enhances swarm reliability, allowing the system to self-correct mid-flight and maintain mission continuity even in the presence of environmental uncertainty, GPS drift, or partial node failure. Where node failures, unexpected obstacles, or mission priority shifts may occur.

The role assignment engine operates in two modes: static initialization and dynamic reassignment. During mission planning, users can define initial roles such as *Monitoring*, *Attacker*, or *Rescue* for each UAV. These roles govern the UAV’s responsibilities, traversal behavior, and interaction priorities within the swarm. However, during flight, role assignments are not fixed. Based on incoming telemetry, environmental triggers, or task overload, the system evaluates whether a UAV should temporarily or permanently switch roles.

For example, if a UAV detects a distressed unit or a communication blackout in a sector, it may assume the *Rescue* role, leave its path, and move toward the target zone autonomously. Upon completion, it reintegrates into its original mission with an updated traversal state. This reactive role switching is coordinated using the gossip-based broadcast system, ensuring swarm-wide consistency without relying on a central coordinator [2].

In parallel, the platform supports live graph modifications. If new zones are discovered, obstacles arise, or partial mis- sion failures occur, users—or automated subsystems—can inject new nodes or remove unreachable edges from the mission graph. These changes are propagated in real time across the swarm and the simulation engine, maintaining a synchronized and consistent mission state.

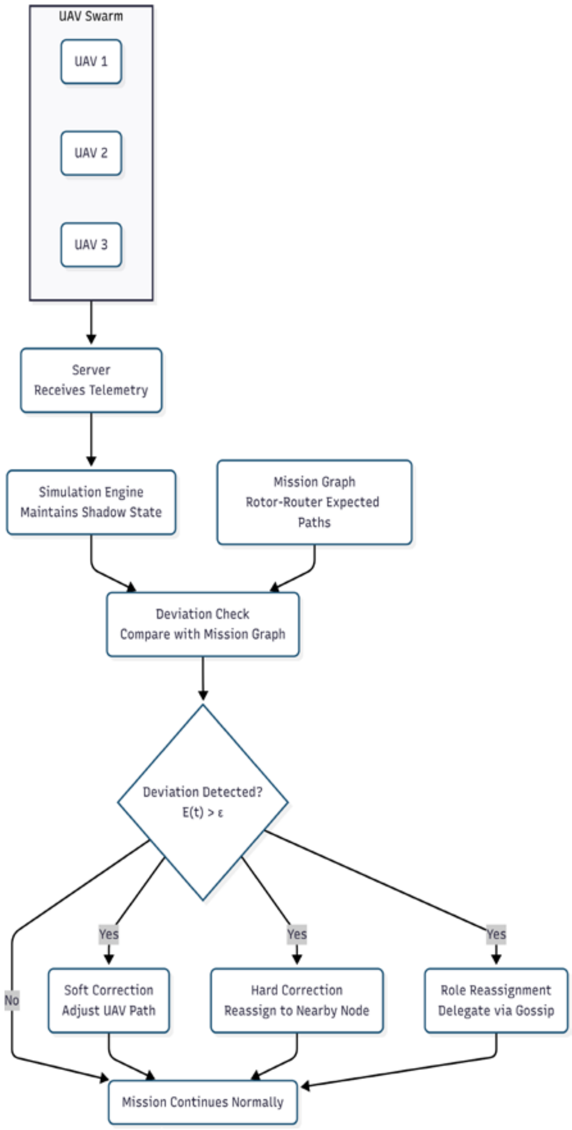

Fig. 2. Dual-mode simulation system: pre-mission validation (top) and real- time deviation correction (bottom)

Figure 3 illustrates a typical dynamic role reassignment scenario where a UAV departs from the swarm to execute an emergency task and later rejoins its path. This ability to fluidly shift roles and reconfigure paths mid-mission significantly enhances swarm resilience and mission coverage in dynamic field conditions.

Fig. 3. Dynamic role reassignment and mission graph update during live swarm operation

Importantly, the reliability of this dynamic behavior is underpinned by theoretical properties of the rotor-router model. When new traversal paths or cycles emerge due to graph modifications, the system maintains deterministic convergence through local loop reversibility. Based on weak reversibility principles [15], a UAV can eliminate rotor cycles by locally traversing and reorienting them, ensuring convergence even under structural change. Furthermore, due to the Abelian nature of rotor-router dynamics, the final traversal configuration remains stable regardless of the order in which updates occur. This provides strong guarantees for correctness and consistency during mid-mission path reassignment and graph evolution.

V. Conclusion and Future Work

This paper presented a significant extension to our previously developed UAV swarm coordination platform by introducing real-time simulation, path deviation correction, and dynamic role management. These features enable robust, autonomous swarm operation in uncertain environments, addressing limitations of static mission logic and centralized control.

By maintaining a synchronized shadow simulation of live UAV behavior, the system can detect and correct execution errors as they occur. Its dynamic graph and role update engine ensures swarm adaptability in response to real-world challenges such as node failure, communication loss, or shifting priorities.

Future work will focus on integrating AI-based path prediction, optimizing correction strategies using reinforcement learning, and expanding the system for inter-swarm collaboration across separate UAV clusters.

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