Cloud-Based Self-Organizing UAV Swarm Simulation Platform

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***Abstract*—Unmanned aerial vehicle (UAV) swarms offer a cost-effective and time-efficient data collection and analysis solution across various applications. The study presents a cutting-edge self-organizing UAV swarm simulation platform empowered by collective artificial intelligence designed to facilitate terrain monitoring and optimize task performance using a fleet of UAVs. The cloud-based multi-user platform provides users with interactive features for seamless user collaboration and real-time video viewing for collective exploration of dynamic terrain imagery. This integrated data fuels the formation of essential swarm and target tasks, determining key parameters such as swarm participant count, initial relative coordinate positions, and statuses (imager and/or strike). The server employs advanced algorithms to achieve these functionalities, including the research road graph based on the rotor-router model and the comprehensive information exchange graph using the gossip/broadcast model. These algorithms work synergistically within the server environment, enabling efficient task planning and coordination among the UAV swarm. Furthermore, the platform allows for the seamless transmission of the formed target tasks to the memory of individual swarm participants, enhancing their decision-making capabilities and overall swarm performance.**

***Keywords*—swarm of UAVs, gossip/broadcast models, rotor-router walk, mathematical models.**

I. INTRODUCTION

In recent years, UAVs have become increasingly involved in various industrial-civilian applications performing tasks beyond manpower in a wide area, providing high performance, required flexibility, stability, and execution time while saving the traditionally consumed resources. UAV swarms in ad-hoc or other formations play a significant role in meeting high-demand and mission-specific goals. UAVs are designed with various key features depending on the mission, distinctive characteristics, and functionality. The use of a UAV swarm has many advantages, such as resilience against disruptions of individual drones, ease of removal or integration of devices, speed of mission performance due to parallelization of operations, and ability to self-organize.

A comparative UAV analysis is presented in [1], outlining key features and applications of well-known drone examples. The study covers UAV swarm management and control mechanisms. UAV swarm management protocols encompassing mission coordination and secure drone-to-drone communication are presented in [2]. Efficient swarm control methods are explored in [3-4]. Notably, [5-6] delve into UAV swarm security aspects, including collision avoidance, self-organization, and swarm intelligence modeling. This field extensively employs multi-agent system design, collective decision-making, and targeting algorithm development [7-9].

The UAV swarm is a mathematical multi-agent system, with each drone acting independently. A set of uncomplicated, logically designed drones, configured as a cellular automaton on a connected graph, creates a dependable setting for group decision-making. An essential trait of swarm intelligence lies in its capacity to surpass the individual capabilities of isolated UAVs. Within a UAV swarm, localized uncertainties, errors, or malfunctions in individual drones are resolved by transferring responsibilities from impaired drones to neighboring swarm members. On the other hand, UAV swarm modeling is a relatively new and actively evolving domain referring to the study of collective behavior in decentralized self-organizing systems. UAV swarms are increasingly involved in topological and video surveillance, agricultural operations, climate monitoring, disaster management, civil security, and other emergency procedures/operations, which exclude the human factor.

UAV swarm missions are classified into separate problems of task and motion planning in robotics with the

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adoption of well-defined strategies for building individual trajectories of UAVs. The trajectory construction involves collecting data on the area surveyed by the UAV and identifying points of interest for simple geometric flights up to providing more complex network solutions. The frequency characteristics of UAV swarm and their location in space can be determined with the required accuracy, ensuring the formation of a complete, continuous image of the area under investigation. UAVs may operate independently from the swarm while targeting and exchanging information with neighbors via logical links.

In this context, developing a cloud platform of self-organizing UAV swarm with the involvement of multi-agent systems (optimal gossip broadcast schemes, sandpile, and rotor-router models) and algorithms is a novelty in the field of logically linked and decentralized intelligent networks. Also, designing a software toolkit for self-organizing UAV swarms is complex and costly. Therefore, the involvement of cloud technologies, virtual environments, and computing resources in one platform creates realistic opportunities to overcome challenges on-field. The proposed platform will reduce the time and cost of completing UAV swarm missions and promote the achievement of autonomous missions over a wide range of tasks and situations.

The study aims to design and analyze a secure cloud-based mathematical model for self-organizing UAV swarms. The proposed platform is intended to facilitate the deployment of UAV swarms that can adapt and self-organize in real-time, even in changing environments. Development of decentralized and self-organizing swarms of logically linked UAVs involves the design of optimal and fault-tolerant schemes (gossip/broadcast models) enabling dynamic snapshotting and full exchange of captured images of surveilled areas during the swarm quasi-random walk (rotor-router model). The construction is given below regarding essential definitions, concepts, and mathematical models [10].

Premises for the design and implementation of the cloud platform following modern requirements are our offered and approved solutions in building high-performance computing infrastructures [11-12], AI-based big data gathering, classification, and processing [13-14], optimizing cloud computing environments [15], optimizing energy consumption in electronic infrastructures [16], efficiently using HPC resources in linear arithmetic calculations [17] and disposing of cloud services [18].

II. CLOUD PLATFORM

The cloud platform comprises a self-organized UAV-based computing area, cloud computing environment, and QT service layers (see Fig. 1). This architecture enhances the platform's computing power and capabilities, resulting in a seamless and efficient user experience. The UAV-based computing area utilizes a network of low-cost Raspberry Pi-equipped UAVs to collect and transfer data to a ground station via Wi-Fi or cellular networks.

The collected data received from the UAV cameras is transferred to the ground station in real-time. The UAVs communicate through decentralized gossip protocols, eliminating the need for a central control node. Cloud computing has gained traction in UAV image-processing tasks due to its computational resources and storage capacity. The proposed cloud-based mathematical models for self-organizing swarms of UAVs consist of client and server components.

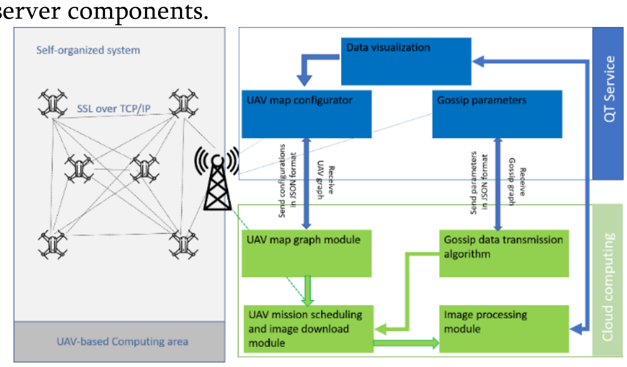

Fig.1. Cloud platform

The QT service layer is vital for user interaction with the proposed cloud platform. It provides tools and functionalities to visualize, configure, and manage the self-organized UAV swarm. The UAV map configurator is a critical tool for creating and modifying maps for the UAV swarm's navigation and task performance. It enables users to define obstacles, points of interest, and flight paths and optimize the swarm's behavior. The parameter gossip system enables communication and coordination between the UAV swarm, allowing it to operate as a cohesive unit. Additionally, the QT service layer provides visualizations and analytics for users to monitor and understand the UAV swarm's behavior, track its movement, observe its interactions with the environment, and analyze its performance. The QT service layer uses the Internet TCP protocol for secure communication with virtual servers in the cloud infrastructure, utilizing security encryption techniques to protect data transfer from malicious attacks.

The proposed cloud platform incorporates several modules and algorithms to support the selforganized UAV swarm. These modules and algorithms work together seamlessly to provide users with a powerful and efficient computing platform for managing and controlling the UAV swarm.

The UAV map graph module allows users to create and manage maps for the UAV swarm's navigation and task completion. This module reads a JSON file with the client's drone map specifications, generates a graph representing the map with nodes and edges, and removes any cycles to avoid infinite loops. The Drone Map Processor verifies that the graph meets all the client's specifications, including clear paths between starting and ending positions and safe navigation around obstacles. If verification fails, the module alerts the client and suggests map modifications.

The cloud platform's second module is the UAV mission scheduling and image download module, allowing users to schedule tasks for the swarm and download images for analysis. The module also lets users download images captured by the swarm during their missions, allowing them to analyze and process the data.

The third module is the Gossip data transmission algorithm, enabling coordinated communication between the self-organized UAV swarm. This module calculates and selects transmission parameters, creates a node graph, and verifies the validity of the chosen gossip algorithm. The module alert the system administrator if the graph fails.

The fourth module is the image processing module, providing users with tools for analyzing and interpreting swarm data, including object detection, image classification, and data visualization. An Image Pixel to WGS Converter software program is also used for georeferencing, and Opendronemap can be used for image processing. The proposed cloud platform could also utilize Opendronemap as a powerful tool for processing the images captured by the UAV swarm during their missions.

A serverless high-performance computing (HPC) cloud platform is used to load the swarm's HPC tasks to address the timely behavior of the swarm [19]. It is based on the container technology abstract force, such as Singularity and Docker, combined with the Kubernetes used for deploying and operating containerized applications. The platform facilitates the intensive tasks' performance without installing the conventional HPC complex infrastructure, thus effectively managing resources and avoiding constraint violation.

III. CONCLUSION

Utilizing UAV swarms presents an economical and efficient approach to data collection and analysis across diverse fields. This study introduces an innovative self-organizing UAV swarm simulation platform based on optimal gossip broadcast schemes, sandpile, and rotor-router models. Through this collaborative data exchange, essential swarm and target tasks are formulated, determining vital parameters such as swarm size, initial coordinates, and operational statuses. Leveraging advanced algorithms, the server orchestrates these tasks seamlessly, ensuring efficient planning and coordination within the UAV swarm.

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