UAV Swarm Management Platform for Autonomous Area and Infrastructure Inspection

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***Abstract*—Swarms of cooperative Unmanned Aerial Vehicles (UAVs) have emerged as a new promising solution for accomplishing complex and large scale tasks, that would be challenging or even impossible for a single UAV. Coordinating multiple UAVs towards a common mission is quite challenging, as multiple operational factors must be ensured in terms of flight reliability, safety, resource allocation and ubiquitous communications. This paper presents an integrated UAV swarm management platform for autonomous area and infrastructure inspection and proposes a novel network architecture for relaying swarm communications in underserved areas. Real trials and measurements were performed on the field, providing preliminary results and proof-of-concept insights.**

Keywords—UAV, swarm management, 5G, aerial relay, area and infrastructure inspection

I. Introduction

Unmanned Aerial Vehicles (UAVs) have rapidly expanded their applications in today's world as they have been well adopted by diverse technological and societal sectors. From military missions to industry and hobbyist enthusiastics, UAVs perform complex and innovative tasks, contributing to enhanced accuracy and security, fast deployment and cost effectiveness of a mission. In the majority of the applications, a single UAV is dedicated on performing specific tasks and it is controlled by a ground pilot in close proximity, who preserves a Line-of-Sight (LoS) with the flying aircraft.

However, as cutting-edge technology on processing power, materials and communications advances, the boundaries of what is possible, are continuously redefined, allowing industries and consumers to push for more data collection and expanded services. Thus, the utilization of not only a single UAV, but multiple UAVs in a collaborative swarm attracts the attention of the scientific community, aiming at collective intelligence and cooperation of multiple devices that act as a cohesive unit for accomplishing complex tasks [1].

Orchestrating a swarm of UAVs towards efficient and secure mission accomplishment, requires a holistic management and implementation approach that considers both technological and operational aspects (e.g. dynamic swarm formation, collision avoidance, endurance, autonomous flight etc.). Furthermore, each use case differs in terms of risk level, operation area size, network coverage or response time, so the system architecture should be able to adapt and support diverse requirements, with maximum safety and efficiency.

In scenarios of aerial infrastructure inspection (e.g. antenna masts, buildings, bridges, power lines etc.) the swarm of UAVs needs to cover long distances for inspecting a group of infrastructure components, sometimes in remote and hard to reach areas (e.g. mountain peaks, dense forests, isolated areas etc.), transmitting images/videos to the operational center or even detecting an anomaly and engaging an alarm. Thus, appropriate swarm formation, route optimization, autonomous flight and seamless and fast communications are critical aspects for the task accomplishment.

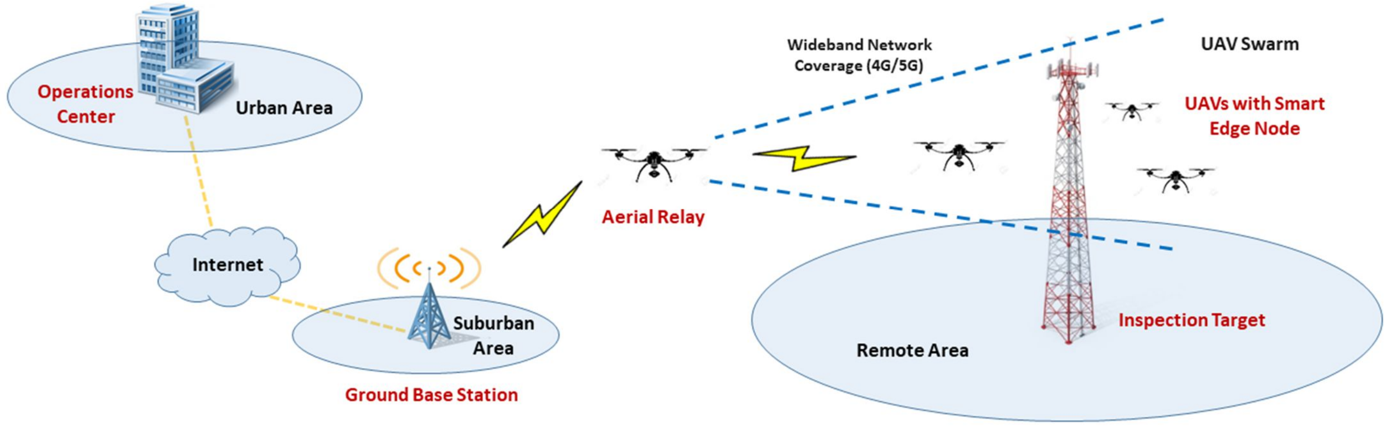

Fig. 1. Conceptual diagram

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Authors in [2], design a UAV swarm system for power lines inspection. They use a companion computer connected with the UAV autopilot and develop algorithms for autonomously flight and power lines detection. They combine Artificial Intelligence (AI) techniques, cloud networking and communication protocols to achieve collaborative flight and data transmission and analysis. The developed system is validated by performing small scale indoor and outdoor trials with two quadcopters. Researchers in [3], study the special use case of inspecting a tunnel using a swarm of UAVs. A mathematical model is firstly used for solving the energy optimization problem, offering greater inspection distance, while an intelligent algorithm is introduced, based on Genetic Algorithm (GA) and equipped with probabilistic, adaptive, and supervised operations (PA-SMC-GA) for solving the tunnel inspection problem. Authors in [4], present a multiple UAV system for real-time surface inspection. Communication is based on Internet of Things (IoT) devices, formation and flight path algorithms have been developed and high accuracy defects detection is realized implementing a histogram-based segmentation algorithm. Field tests have been conducted, with three UAVs in triangle formation, successfully inspecting their target. In [5], a cooperative target searching method is proposed for UAV swarm, based on an improved Bean Optimization Algorithm (BOA) called Robot Bean Optimization Algorithm (RBOA), taking account the limitations and characteristics of each UAV. The performance of the proposed algorithm has been evaluated using simulations, leading to promising results for inspection in unknown and complex environments. Authors in [6], study the consistency in swarm formation during complex missions and propose a coordination protocol for maintaining the appropriate UAV formation during flight. The system is based on a "master and slaves" architecture, where the master UAV synchronizes and corrects the positioning of each slave UAV when they reach at an intermediate waypoint. The proposed system has been validated on a simulation platform for both optimum and lossy communications conditions.

While the aforementioned publications and most of the existing literature on UAV swarms focus on single aspects of a problem, such as individual components or algorithms development, considering other dependencies as solved, our research follows a more holistic approach by proposing a versatile system architecture with an embedded integrated platform for autonomously coordinating a swarm of UAVs for areas or infrastructure inspection. Our proposed system addresses the complex challenges of such a use case while ensuring the seamless wideband communications between the swarm and the operation center, in underserved remote areas or blind spots. The system is showcased both with simulations and real preliminary trials and measurements.

Section II presents the platform architecture and analyzes its basic components, section III describes the tests and field trials conducted to validate the platform and provide a proof-of-concept, while section IV concludes the paper summarizing the work and suggesting future platform development and further evaluation/validation tests.

II. System Architecture

A. Overview

Figure 1 shows the conceptual architecture of the proposed system. Multiple UAVs dynamically organized in a swarm formation (e.g. triangle, circle, line etc.), fly autonomously to their waypoints, scan the target area and collect data. Data transmission (e.g. UAVs telemetry, sensors data etc.) is realized through the cellular network. For the use case of target inspection, high resolution images and high definition video (even 4K for detailed zoom option) are often required to be transmitted, so wideband network (i.e. 4G/5G and beyond) availability is required. However, fast network coverage is not guaranteed in all the cases, as the environment and the landscape around the inspected targets is often diverse. In the proposed system, the network coverage is ensured by dedicating one UAV (either in the swarm formation or a follower) as an aerial communications relay. Finally, the data analysis is performed at the edge of the network, for better performance in terms of latency and network offloading.

B. Autonomous Swarm Management Platform

The UAV swarm is coordinated by the Autonomous Swarm Management Platform (ASMP). The platform facilitates dedicated algorithms and real time data exchange and processing functions, enabling collaboration and synchronized actions among multiple UAVs, transforming them into a cohesive and highly efficient swarm. Furthermore, it provides mission monitoring and option of manual control of swarm when it is required. ASMP is hosted in the infrastructure owner premises or in a third-party operation center, while part of it may also be realized on the companion computer of one of the swarm members for moving the swarm management to the edge of the network. Figure 2 shows the architecture layers of the platform. The input layer collects all the mission specific initialization data for the mission that are generated outside of the platform (e.g. optimized route planning, required formation shape etc.). The processing layer facilitates all the functions and algorithms for analyzing the input data and transform them into swarm commands and navigation. This layer is also responsible for managing the swarm behavior during the flight and the communications

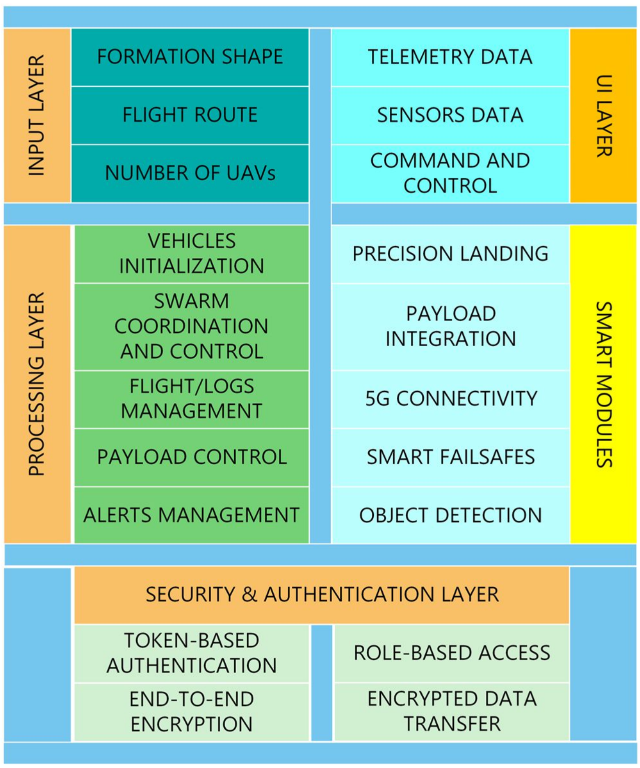

Fig. 2. Architecture of the Autonomous Swarm Management Platform

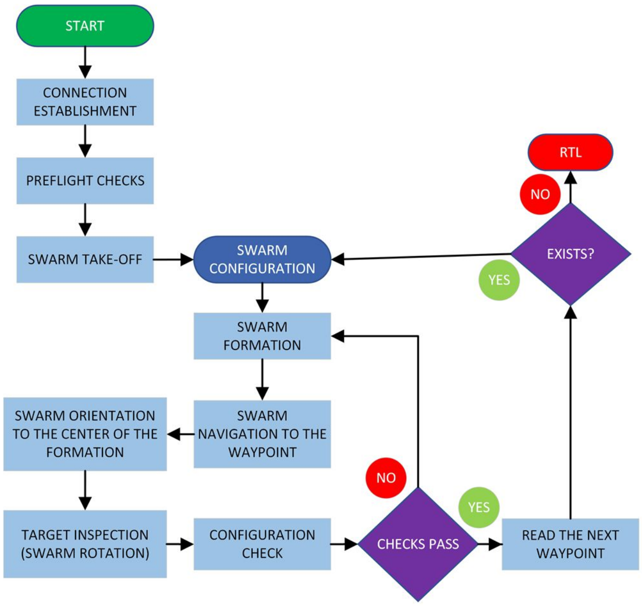

Fig. 3. Autonomous Swarm Algorithm flowchart

modes. The user interface layer visualizes all the data coming from the swarm (UAVs telemetry, sensors data, video stream, alarms etc.) offering real time monitoring and situational awareness to the operators. This layer also offers the option of interaction between the ground user and the UAVs in the swarm, in case this action is needed. Finally, the security and authentication layer facilitates all the necessary functions for secure data transmission, authenticated user access to the platform, as well as user rights assignment.

C. Autonomous Swarm Algorithm

The Autonomous Swarm Algorithm (ASA) is the heart of the ASMP. It regulates the formation and flight plan of the swarm and performs all the necessary checks and swarm behavior adjustments, both prior and during the flight, for ensuring secure and successful mission accomplishment. ASA flowchart is depicted in Figure 3. Connection to the swarm members, preflight checks and swarm take off are first performed and then, based on the ASMP input data (e.g. flight route, formation shape, swarm members number etc.) the swarm formation and navigation to the inspection targets is realized. The algorithm checks the swarm configuration in real time, re-adjusting it in case of misalignment and proceeding to the next inspection target. When all the targets have been successfully inspected, the swarm enters in Return-to-Launch (RTL) mode and returns back to base and lands.

D. Smart Edge node

During the inspection process, real time images/video are analyzed, defects are detected and swarm flight and formation is coordinated, while prior to the start of the mission, each member of the swarm is authenticated and authorized to join the swarm, for security reasons. The proposed system runs the smart edge node on a companion computer embedded on the UAVs, for mitigating all the aforementioned processes at the edge of the network, avoiding data transfer latency and network overloading.

E. Aerial Relay

In cases where the inspection target is located in an underserved area, in terms of wideband network connectivity, a dedicated UAV (either from the inspecting swarm or outside of it) may act as a communication relay, providing network coverage extension. The relay UAV may either enable an onboard WiFi6 router that connects to the internet with a 5G link (preliminary field measurements may be found in [7]) or provide a pure 5G link end-to-end utilizing an onboard Base Station (BS). In the latter case, the UAV carries a portable and lightweight 5G BS and a companion computer. The BS accesses each UAV of the swarm as a simple User Equipment (UE) and connects it to the backhaul network, while the companion computer is used for data traffic routing. The novelty in this relay architecture is that the backhaul link between the aerial BS and the public network is realized by enabling one more ground UE as a dedicated gateway to the public network. The Uplink (UL) and Downlink (DL) of the ground UE acts as a backhaul connection for the aerial BS to the internet, transforming the 5G BS to an aerial relay node, independent of a permanent ground gateway. This relay architecture offers flexibility and simplicity, without requiring heavy and complicated hardware onboard the UAV. This network setup has been tested on the field and the performance measurements are presented and analyzed in chapter III.

III. Field Trials

Preliminary system implementation and measurements were performed on the field for showcasing the feasibility and providing a proof of concept of the proposed architecture. Two basic functions were assessed, the autonomous infrastructure inspection and the 5G communications relay.

A. Autonomous Infrastructure Inspection

The scenario of multiple antennas masts inspection was performed. Prior to the field trial, the algorithms for the autonomous swarm flight formation were tested in the lab, using a simulation software. The swarm, after receiving the flight plan, took off from distributed locations, autonomously formed an equilateral triangle, and flew to the waypoints. After arriving at each waypoint, the algorithm turned the swarm towards the center of the triangle, where the antenna

Fig. 4. Field trial of an autonomous quadcopter

mast was and performed a 360° turn to inspect the infrastructure. After the successful inspection, the swarm headed to the next antenna mast, preserving the formation and oriented it to the new target. After the completion of the mission, the swarm returned to base and landed.

One custom made quadcopter (Figure 4) was used for the real field trial, loaded with a companion computer with wireless wideband connectivity. The purpose of this field trial was not only to validate the autonomous flight and formation algorithm, but also to test the autonomous route authenticated reception, calculated by a quantum algorithm [8] and its execution. The trial was performed with one UAV for security reasons, while trials with multiple UAVs will follow in the near future. The UAV was also connected to a ground pilot with a secondary link for security, but all the flight was performed autonomously without the pilot to intervene. The system completed successfully the following steps:

1. The optimized swarm route was calculated from the quantum algorithm, taking as an input the antennas masts locations.
2. The optimized route was transmitted to the swarm platform after the authentication check from the platform.
3. The swarm platform autonomously processed the route and fed it to the UAV.
4. The UAV, as soon as it received the route, autonomously took off from its base and started navigating to each waypoint.
5. After reaching to 4 waypoints the UAV headed back to its base and landed.
6. Throughout the flight an onboard camera was transmitting real time video to the infrastructure owner through the available public cellular network.

B. 5G Network Relay-edge node

In order to evaluate the suggested 5G communications relay architecture, preliminary measurements were performed on the ground. Figure 5 shows the testbed architecture. The relay node consisted of a lightweight portable 5G BS and a raspberry Pi for data routing. The ground gateway was a raspberry PI with a 5G HAT and the UEs were commercial 5G mobile phones. The 5G BS that was used, supported stand-alone (SA) mode and a flexible Time Division Duplex (TDD) transmission scheme [9]. The latter offered the ability of allocating different time slots to the DL and UL channels, for asymmetrical deployment option and different enhanced Mobile Broadband (eMBB) slicing requirements [10].

In this first set of preliminary measurements, three TDD schemes were used. The first TDD scheme allocated 7 timeslots to the DL and 1 to the UL, the second one allocated 6 timeslots to the DL and 3 to the UL, while the last one was symmetrical, allocating 2 timeslots to both the DL and UL. Figure 6 shows the achievable throughput of the UEs for each TDD scheme, while the reference (i.e. no relay node) 5G system throughput is also depicted.

As expected, the reference performance of the UL increases from 40.61Mbps to 91.5Mbps when more timeslots are assigned to it and the DL throughput decreases from the maximum of 137.93Mbps to 91,5Mbps when the TDD is symmetrical. In the latter case the throughput of both the DL and UL is of the same level, as 2 timeslots are assigned to each link.

However, the performance pattern of the system differs, when the relay node is activated. As the access link (i.e. the link between the aerial BS and the ground UEs) highly depends on the backhaul link between the relay node and the ground gateway UE, the performance of both the DL and UL of the access part of the system clearly optimizes, when a symmetrical TDD scheme is applied. When more timeslots are assigned to the UL, although the backhaul link is faster, the overall performance is not maximum, as the DL of the access side has been decreased.

The measurements show that in the case of a symmetrical TDD scheme, the system throughput is almost 75% and 79% of the reference BS performance, for the access DL and UL respectively, proving the capabilities and potentials of the proposed relay architecture.

IV. Conclusions

Multiple UAVs, forming a swarm, that cooperate and combine their individual functions and sensors data offer a significant enhancement to complex and demanding missions, such as large scale area and infrastructure inspection (e.g. power lines, forests, antennas masts etc.). Significant research

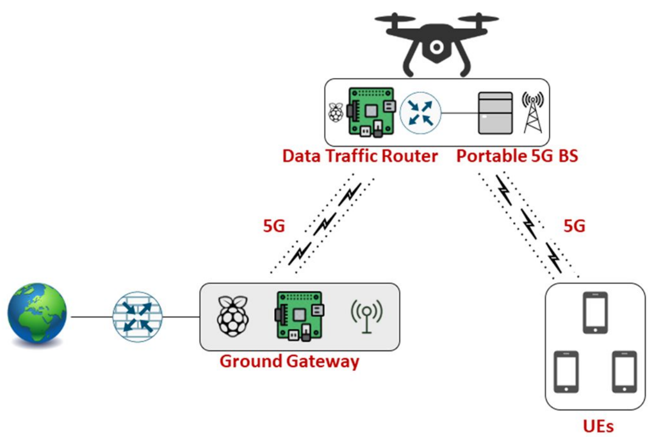

Fig. 5. Communications relay testbed

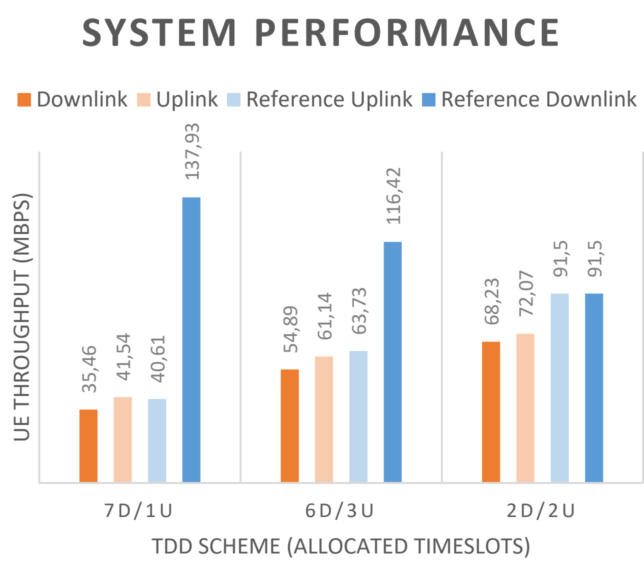

Fig. 6. DL and UL throughput of the UE for different TDD schemes

is being conducted for efficiently addressing the open issues in swarm management, safety and efficiency.

This paper, proposes an integrated platform for UAV swarm management, including a novel network relay architecture, contributing not only to the development of advanced aerial inspection capabilities, but also to the broader practices in the implementation and coordination of autonomous vehicles. The developed platform, after consuming the initialization data from the operator or another autonomous entity, processes the information and autonomously coordinates the swarm members towards an optimized operation. The appropriate formation, flight plan, UAVs individual reactions and mission oriented data transmission are realized and validated throughout the whole operation. Broadband and seamless communications, even in underserved areas, are ensured implementing a novel aerial relay system architecture, offering simplicity and flexibility to the overall swarm implementation.

Field trials were conducted where an individual UAV was successfully coordinated autonomously through the developed platform, after receiving the optimized route calculated by a quantum algorithm. Inspection and telemetry data were also transmitted from the UAV to the operational center. A set of measurements was also performed to evaluate the proposed communications relay architecture, providing preliminary but promising results for the system performance.

The planned future work includes integration of the developed platform in a Decentralized Autonomous Organization [11] for security and automation enhancement, as well as new measurements, in various propagation conditions with more complex setup, in the context of aerial communications relays.

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