

Optimization and Control of Autonomous UAV Swarm for Object Tracking

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Abstract—Unmanned Aerial Vehicles (UAVs) swarms are emerging technologies with the ability to carry out a wide range of military missions aiming to avoid human casualties. The UAVs’ ability to access remote and inaccessible territories while gathering critical intelligence can be critical. Therefore, swarm real-time coordination on the fly is vital for information exchange and dynamically updating the flying hierarchy without failing the mission. Nevertheless, coordinating UAV swarms to execute maneuvers poses a complex challenge. In our Demonstration, we execute an on-the-fly swarm update based on unexpected or urgent events during the missions to avoid collisions and ensure mission safety. This demo shows a “find and rescue” military mission for security operations using a swarm of UAVs to track other adversaries’ UAVs in a restricted area, which requires advanced swarm synchronization and on-the-fly decisions. For this demo, we conducted a successful flying swarming coordination for dynamic on-the-fly maneuvers with a reliable collision avoidance mechanism.

Index Terms—Ad-hoc network, Decentralized communication, FMCW radar, MAVLink, UAV swarming, UAV testbed.

I. INTRODUCTION

A battle space is a complex environment, and multiple events occur simultaneously over wide areas. Here, situation awareness is critical, and Unmanned Aerial Vehicles (UAVs) or drones (as commercially known) can play an essential role in collecting that information and carrying out missions. UAVs’ swarming is considered an adequate solution for a temporary or short-term solution to carry out critical missions. Data processing and decision-making through the UAV swarm are vital, especially in unexpected events and weather conditions that can occur during critical missions. In such urgent events, it may not be practical or efficient to rely solely on ground stations to make decisions for the UAVs, as it can cause delays in response time and potentially lead to severe consequences.

Therefore, an autonomous environment of a UAV’s swarm is necessary for mission safety. In an autonomous swarm, UAVs share information and make decisions as a group, making them more efficient and effective than individual UAVs. UAVs are usually utilized in critical applications such as emergency applications, military setups, or Intelligent Transportation Systems (ITS) where additional connectivity is required [1], [2].

With all the anticipated potentials of UAVs, the UAVs’ configuration and coordination are the most crucial parameters when considering a UAV swarm. This coordination requires

extensive and synchronized information exchange between all the UAVs in the swarm. In this demo scenario, we propose a “find and rescue” mission using a number of UAVs operating as a swarm that moves in synchronization to track an out-of-control object. The privilege of the proposed scenario is the ability to decouple it into two separate components or stages. The first stage in this scenario is where drones communicate and maintain a stable formation without crashing. Second, a real-time target-tracking operation is required with high, fast, and reliable data collection algorithms for the targeted object.

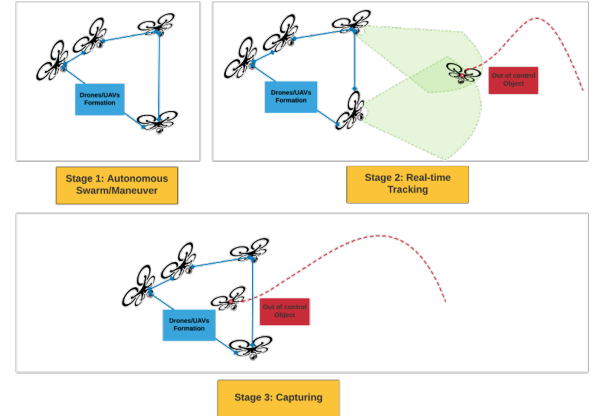


Fig. 1. The swarm UAV find and rescue demo scenario

II. AUTONOMOUS SWARM

A. UAVs’ Swarming

A swarm is generally defined as a group of behaving entities that together coordinate to produce a significant or desired result or behavior. There are multiple examples of swarming in nature, such as bees working in a coordinated manner to accomplish their tasks, fish schooling to appear larger than their individual sizes and protect themselves from prey, or migratory birds flying in patterns to fly efficiently over long distances. Similarly, a swarm of UAVs is a coordinated unit of UAVs that effectively communicate with one another to complete a set of tasks.

In most cases, each individual UAV in a swarm is simultaneously controlled by a single ground control station

(GCS). The GCS is referred to as an infrastructure-based swarm architecture and is typically done using a computer acting as a GCS running ground control swarming software. Those computers are required to be equipped with some telemetry module to maintain constant communication with the individual UAVs. Command and Control data is generally sent over these links, which includes the UAV's Unique ID, GPS coordinates, ground speed, and heading in the downlink while it carries waypoint data and flight mode control packets in the uplink. These telemetry transceivers use unlicensed frequency bands in the 900MHz spectrum to send and receive data.

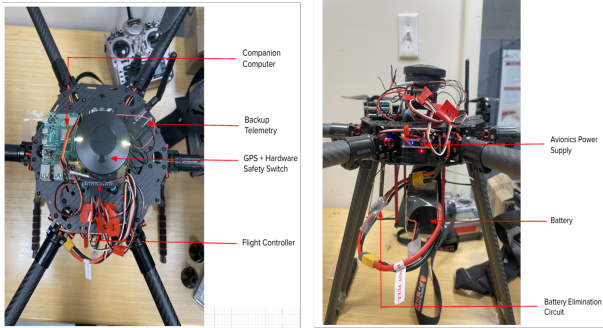


Fig. 2. UAVs equipment top view used for swarming operations.

The advantages of such an architecture are that it requires a much simpler communication architecture, and the GCS can communicate with each UAV in real time, providing navigation commands directly to the flight controller on each UAV. Further, the navigation and collision avoidance computations can be done on a much more powerful ground-based computer. Such an architecture would also have a much simpler communication architecture with data being transmitted in unicast between individual UAVs and the GCS, requiring minimal networking, which generally reduces the amount of payload that can be supported in a link. However, an infrastructure-based swarm is entirely dependent on the GCS to enable swarming, leading to what is essentially a single point of failure and all UAVs to be within the propagation range of the GCS. This can also lead to higher latency in receiving GPS coordinates, especially in scenarios where the swarm is operating at the edge of propagation range from the GCS, as the GPS data from a publishing UAV needs to travel all the way to the GCS and back. This also unnecessarily occupies the links between the UAVs with command and control data that could otherwise have been better utilized to transmit video streams or other sensor data.

A better approach would be to transmit command and control data for swarming directly between the UAVs. This, however, would require a higher level of autonomy that would enable the UAVs to make decisions using onboard computers. This is generally referred to as Flying ad-hoc network architecture. Rather than the UAVs communicating with the

GCS, all command and control data in the swarm can be relayed to a gateway onboard a UAV that then shares the information with the rest of the UAVs either through multicast or broadcast. Since the communication network is ad-hoc in nature, it does not rely on existing infrastructure to establish the network. The gateway UAV can also be connected to the GCS using a separate high throughput communication link to make telemetry data available at the GCS and allow mission planning, monitoring, and manual intervention and control of the UAVs in case of an emergency.

B. Leader Follower Architecture

The first stage of our demonstration is managing the synchronized movement of a set of UAVs with no crashes. The real challenge here is the synchronization between the UAVs with low latency communication and almost zero error tolerance. In order to accomplish this, we use a leader-follower architecture, where each follower requests the leaders' position and velocity information, then each follower UAV coordinates its motion with the leader UAV in two different ways:

- **Position Updates:** Each follower UAV places itself at a predefined position offset from the leader in the North-East-Down (NED) coordinate system with respect to the leader UAV.
- **Velocity Update:** Each follower UAV initially positions itself at a certain distance from the leader; following this, it requests the velocity information of the leader and then predicts the position of the leader and positions itself accordingly to maintain a fixed offset from the leader.



Fig. 3. The swarm UAV find and rescue demo scenario

Initially, all the UAVs are given initial coordinates as a starting point, and both the leader UAV and the follower groups are assigned. The leader UAV is loaded with a flight plan that contains waypoints and desired altitudes that are provided by the mission director. Once all the UAVs are in place, each UAV location within the swarm will update each t_u period to a new position while maintaining the swarm formation. Each

follower UAV will trigger the swarm formation by requesting the leader UAV's position and velocity. Then, each follower UAV calculates its required coordinate position to maintain the swarming formation. This information is then passed to each individual follower UAV flight controller, where those follower UAVs use GNSS navigation to reach the desired coordinates.

Once all the follower UAVs have reached their desired positions, they will issue an ACK message to the leader. On receiving ACK messages from all the follower UAVs, the leader UAV will start flying its custom mission, sequentially going to each individual waypoint loaded in the flight computer before returning to its launch site and landing.

As the leader UAV goes to each waypoint, the follower UAVs, maintain the issued position offset and fly along with the leader UAV to maintain the swarm formation. Once the leader UAV completes its preloaded mission and is prepared to land, it issues a message to all the follower UAVs that trigger the follower UAVs to land and disarm, completing the mission.

C. Communication Architecture

Communication is vital in operation and coordination within a UAV swarm. In most cases, each UAV is simultaneously controlled by a ground control station. The computers are equipped with a transceiver that sends and receives telemetry data from connected UAVs. Our initial implementation used such architecture with unicast links between every UAV and the ground station. This architecture, however, severely limits the swarm's capabilities to operate beyond visual line-of-sight conditions and hampers the ability of the swarm to make decisions autonomously.

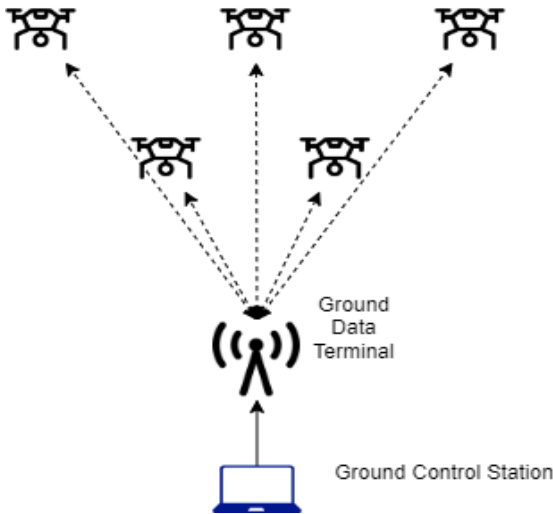


Fig. 4. Centralized communication architecture for swarm operations.

Hence, we opt for decentralized communication [3] with a leader-follower architecture to allow direct communication within the swarm without the need to reach out to the ground station. In this architecture, every follower UAV is responsible

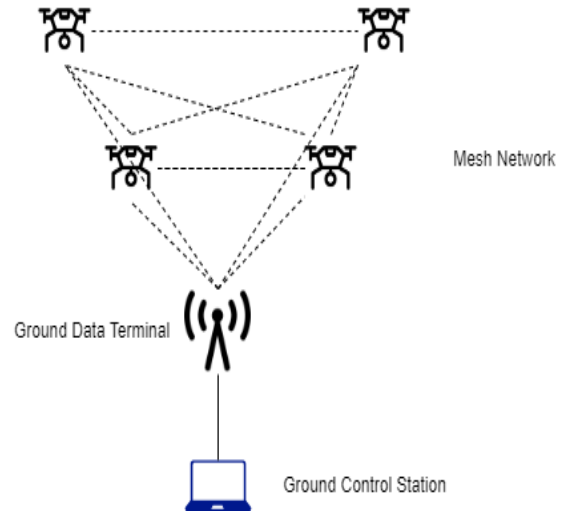


Fig. 5. Decentralized communication architecture for swarm operations.

for making its own position and updating decisions based on periodic information from the leader. This allows the swarm to operate without needing a ground control station.

For our demonstration, a decentralized architecture is used with an ad-hoc network being developed between the various drones. The ad-hoc network is built on WiFi standards and operates on the 2.4 GHz spectrum. The network is set up on the Raspberry Pi (RPI) companion computer on each drone and allows each drone to request or share mission-critical data among the UAVs in the swarm. Apart from the ad-hoc network, there is also a backup telemetry link between each UAV and ground station operating at 900 MHz to issue emergency commands in case of ad-hoc network failure.

The protocol used for communication between the UAVs in the swarm and the ground control station (GCS) is done using MAVLink [4]. MAVLink is a lightweight messaging protocol for communicating with drones and between onboard drone components. The MAVLink is an open-source protocol using hybrid publish-subscribe and point-to-point models [5]. The MAVLink simulator supports sending waypoints, control commands, and telemetry data, switching flight modes, as well as adjusting parameters remotely. While data streams are published as "topics", mission parameters such as waypoints and configuration parameter files are sent point-to-point with re-transmissions. Another advantage of the MAVLink protocol is that it supports different types of communication technologies such as WiFi, LTE, Serial, etc. Our MAVLink implementation can be employed for both Internet Protocol (IP) network User Datagram Protocol (UDP) and Transport Control Protocol (TCP).

The MAVLink packets that contain the command and control information for the drones are sent between the drones and the ground control station using UDP sockets. The leader UAV hosts multiple UDP servers that are used to store critical

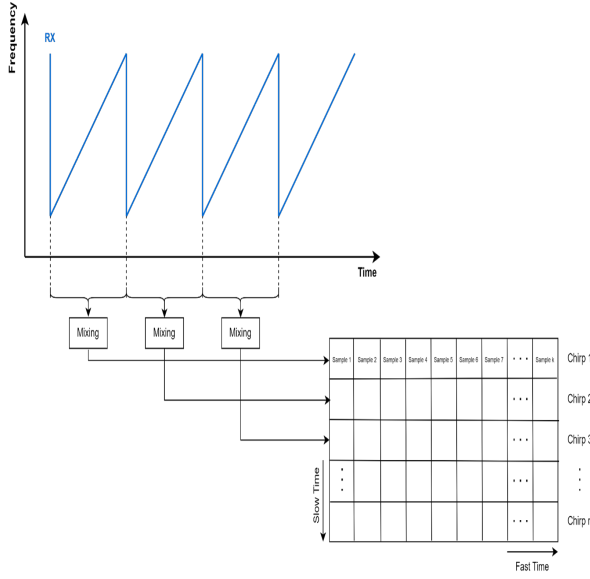


Fig. 6. Sampling by ADC of the received signal post mixing with transmit signal

telemetry data about the leader, such as latitude and longitude information, velocity information, battery information, etc. Each follower UAV has a UDP client socket running that periodically requests the leader UAV's telemetry. UDP was chosen as the transport layer protocol to reduce the overhead due to ACK messages and ensure that the data available at the client is always the latest.

D. Software-in-the-Loop (SITL) Simulations

Software-in-the-Loop (SITL) simulations are used to validate all control algorithms by running the flight controller firmware on a computer directly without any special hardware. This makes it possible to make quick changes to the control algorithms, allowing for rapid prototyping and development, increased safety by reducing the number of experimental flights required to validate the control algorithm, and reduced human resources required for effective development, thus lowering developmental costs. All swarming missions demonstrated are initially tested on the SITL simulator before the actual UAVs' flying tests.

When running in SITL, the sensor data comes from a flight dynamics model in a flight simulator. A significant advantage of ArduPilot on SITL is it gives access to the full range of development tools, such as interactive debuggers, static analyzers, and dynamic analysis tools.

In this demonstration, we can showcase the use of SITL in the development process of actual swarming missions.

E. Target Tracking using FMCW Radar

The second stage of our proposed UAVs' demo is monitoring and tracking an out-of-control target, such as a defective

UAV. Here, we aim to detect and classify a rogue multi-rotor vehicle from backscatter. Although there are multiple research works on dynamic target tracking and obstacle avoidance in drones, they are not designed for critical missions as our objective in this demo [6], [7]. In this work, we design a target tracking mechanism using Frequency Modulated Continuous Wave (FMCW) radars, where a high-frequency signal is linearly modulated in frequency, and the return echo signal is processed to capture target information such as range and velocity. The FMCW Radars perform well even in non-line-of-sight (NLOS) conditions [8], and with millimeter waves, they also allow the estimation of the micro-Doppler signature from the energy backscattered by UAV propellers. Such signatures allow us to classify drones, detect the presence of additional payloads, and distinguish them from other flying objects or obstacles, such as birds or trees [9].

The transmit signal consists of "chirps" where each chirp is the cycle between the minimum and maximum transmitted frequency. A group of chirps constitute a "frame" and are processed together at the receiver. The FMCW radar works by sending the frame and then mixing the transmitted frame with the frame received after reflection by the target. This mixed signal is called the Intermediate Frequency (IF) signal. The IF signal is then digitized using an analog-to-digital converter (ADC), and the samples are stored as indicated in Fig. 6.

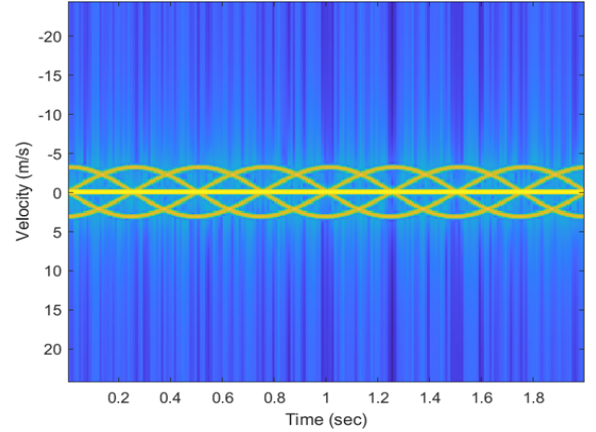


Fig. 7. Doppler-Time response from FMCW radar operating at 77GHz when tracking a UAV target with 4 blades

Following data acquisition, a Fast Fourier Transform (FFT) operation is performed across "Fast Time" first to extract the range data and then subsequently over the "Slow Time" to extract the Doppler/Velocity data to form a range-Doppler plot. Following this, with the range-Doppler plot from a single frame, the coherent sum is taken across the range bins to plot the variation in Doppler from one frame. This is performed across multiple frames and stacked together to form a Doppler-time plot that illustrates the micro-Doppler effect brought about by the rotation of the propellers as depicted in Fig. 7.

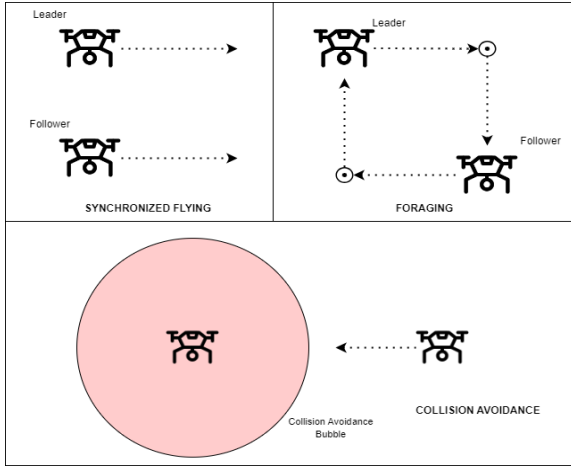


Fig. 8. UAV Swarm Demonstrations

III. DEMONSTRATION

The demonstration consists of two parts - the autonomous swarm demonstration and the target tracking demonstration. In this autonomous swarm demonstration, we showcase a leader-follower swarm using 2 UAVs. Our designed UAV swarm demonstrations are as follows,

- **Synchronization:** Demonstrates the leader-follower architecture, where we check the ability of the follower to communicate with the leader and follow the commands provided by the leader UAV. The leader follows forward and backward motions with the follower repeating the leader's movement while maintaining a 20-meter distance to the leader UAVs right.
- **Foraging:** Ability to survey a designated area of importance. Two UAVs follow a square pattern where the leader dictates the points of interest or corners of the square. The follower then follows the leader's UAV around this square pattern, flying over the area of interest. This is critical to performing Intelligence, Surveillance, and Reconnaissance (ISR) and detecting targets in an area of interest.
- **Collision Avoidance:** A critical aspect of a swarm is to perform real-time tracking of other UAVs in the vicinity and ensure collision avoidance between two UAVs.
- **Radar based Target Tracking:** In this demonstration, through simulation, we aim to showcase the use of an FMCW radar to detect the presence of another UAV through peak detection on the range-Doppler plots and the ability to classify objects with rotating propellers such as UAVs from other objects.

All tests were conducted in a 90×40 m enclosure at the Virginia Tech Drone Park. The detection and classification of drones are demonstrated through simulations conducted using MATLAB. The target was modeled as individual point

scatterers for each blade with a Radar Cross-Section (RCS) value of 0.01m^2 .

IV. CONCLUSION AND FUTURE WORK

Moreover, we finalized our autonomous swarm successfully and moved to our next stage, real-time tracking. For the real-time tracking stage, we have showcased proof of concept MATLAB simulations utilizing the micro-Doppler effect to detect and classify rogue UAVs using FMCW radars.

ACKNOWLEDGEMENT

The support of ONR under MURI Grant N00014-19-1-2621 and US NSF (Grant CNS-1923807) is gratefully acknowledged.

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