# UAV Technology (UE22EC42BA)

# 7th semester Special Topic

# (Aug – Dec 2025)

## Project Title:

## Bio-Inspired Decentralized UAV Swarm


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# Introduction

The rapid development of Unmanned Aerial Vehicles (UAVs), in particular, UAV swarms has led to them being increasingly employed in a variety of applications such as agriculture, search and rescue, and defence. The conventional approach to swarm architectures relies on centralized control, leading to rigid models that lack scalability and robustness in dynamic environments. These approaches become inefficient in scenarios where swarm sizes continue to increase.

For scalability, adaptability, and fault tolerance, decentralized architectures have emerged as competitive alternatives. Bio-mimicry is an approach that has yielded successful design strategies for this kind of system. It takes inspiration from nature such as flocks of birds [3][5], packs of wolves [1], and schools of fish [2]. These biological systems exhibit coordination without relying on a single leader; hence, they are adequate models for autonomous distributed decision-making.

However, it is challenging to maintain completely decentralized systems when swarm sizes reach very big numbers. Often, centralized components are brought back to lead or coordinate subgroups of UAVs. In this work, we overcome this limitation by equipping each UAV with the capability of independently deciding its trajectory based on the positions and velocities of its neighbours. The system will promote local, autonomous decision-making and thus eliminate the use of a central controller, which enhances scalability and robustness in complex environments.

# Literature Survey

**[1] H. Jinqiang, W. Husheng, Z. Renjun, M. Rafik and Z. Xuanwu, "Self-organized search-attack mission planning for UAV swarm based on wolf pack hunting behavior," in *Journal of Systems Engineering and Electronics*, vol. 32, no. 6, pp. 1463-1476, Dec. 2021, doi: 10.23919/JSEE.2021.000124.**

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| **Objective** | The paper's goal is to create a self-organized, distributed algorithm for UAV (UAV) swarms that can search and attack multiple targets efficiently in unknown environments. |
| **Methodology** | Each UAV acts like a scout wolf, exploring areas and avoiding already searched regions using a "stimulus" (interest) map that fades over time. Once targets are found, UAVs self-organize like wolves assigning roles (leader, hunter, support). |
| **Hardware / Simulation Platform** | All experiments were performed in MATLAB. Monte Carlo simulations were used to verify consistency and reliability across random trials. |
| **Dataset / Test Environment** | The environment was modeled as a 2D grid, representing a 2000 m × 2000 m battlefield divided into small cells. |
| **Results** | High search coverage (UAVs efficiently explored the whole area without redundancy).Faster task allocation compared to traditional algorithms (like ant colony or genetic algorithms).Better adaptability, UAVs could dynamically re-assign roles when conditions changed. |
| **Limitations** | Only simulation-based targets were stationary, not moving or hiding, which limits combat realism. Perfect communication was assumed between UAVs, no obstacles or delays were assumed. |

**[2] M. Verdoucq, G. Theraulaz, R. Escobedo, C. Sire and G. Hattenberger, "Bio-inspired control for collective motion in swarms of UAVs," 2022 International Conference on Unmanned Aircraft Systems (ICUAS), Dubrovnik, Croatia, 2022, pp. 1626-1631, doi: 10.1109/ICUAS54217.2022.9836112.**

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| Objective | Develop a simulator for a fish school model and implement it for UAVs in a circular arena. |
| Methodology | Social interactive "bust and coast" model where only the next two neighbours and obstacles were accounted for checking for collisions. |
| Hardware / Simulation Platform | DJI TELLO EDU 2 UAVs were used with ROS2. |
| Dataset / Test Environment | Upto 5 UAVs in a circular area with a radius of 6m. |
| Results | UAVs were able to form a swarm formation in a short time when spawned at random locations in the circle. |
| Limitations | Needs motion capture to work.<br>2D planning only. |

**[3] M. Verdoucq, C. Sire, R. Escobedo, G. Theraulaz and G. Hattenberger, "Bio-Inspired 3D Flocking Algorithm with Minimal Information Transfer for Drones Swarms," 2023 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Detroit, MI, USA, 2023, pp. 8833-8838, doi: 10.1109/IROS55552.2023.10341413.**

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| Objective | To develop a 3D flocking algorithm and implement it in a swarm of UAVs and validate it in an indoor arena. |
| Methodology | A novel algorithm on an agent based 3D model as an extension of a previous 2D model with minimal information sharing. |
| Hardware / Simulation Platform | ROS2 for the simulation and TELLO EDU UAVs for real-time validation. |
| Dataset / Test Environment | An indoor arena that is 5 m in height and 3.25 m in radius with 2-3 UAVs for a duration of 8 minutes per test. |
| Results | The UAVs produced stable, coordinated collective behaviors (schooling, swarming, and milling) in both simulations and real UAV tests. |
| Limitations | The model has to be tested for a large swarm of UAVs.<br>The environment was ideal, i.e., there were no obstacles in the arena. |

**[4] Q. Zeng and F. Nait-Abdesselam, "Multi-Agent Reinforcement Learning-Based Extended Boid Modeling for Drone Swarms," ICC 2024 - IEEE International Conference on Communications, Denver, CO, USA, 2024, pp. 1551-1556, doi: 10.1109**

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|---|---|
| Objective | To enable autonomous, adaptive, and efficient swarm-based UAV sensing using nature-inspired, distributed intelligence. |
| Methodology | A Swarm coordination algorithm. Each UAV interacts only with nearby UAVs and adjusts its altitude or area coverage locally, based on simple reward system. |
| Hardware / Simulation Platform | Python simulation. |
| Dataset / Test Environment | A 2D flat grid divided into discrete cells. Each cell has a resolution requirement and coordinates. |
| Results | The swarm responds dynamically and continuously to environmental changes, demonstrating adaptive behavior similar to natural systems.The algorithm finds near-optimal configurations quickly and maintains them with minimal disruption. |
| Limitations | Fixed Trajectory<br>2D grid only. |

**[5] Chia-Hsuan Lai, Chian-Yu Lu, Chun-Liang Lin, and Yang-Yi Chen. 2025. Enhancing drone swarm efficiency through a high-flexibility**

**biomimetic formation algorithm.** ***Drone Systems and Applications*****. 13: 1-26. https://doi.org/10.1139/dsa-2024-0066**

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|---|---|
| Objective | Focus is on incorporating biomimetic features into UAV swarms to make them more decentralized, adaptable and scalable. |
| Methodology | The UAV closest to the target coordinates acts as the leader. Its plane is divided into left, right and center regions, forming three clusters. Each cluster gets assigned a reference UAV, which in turn follows the leader until the target is reached. |
| Hardware / Simulation Platform | RTK GPS module for accurate communication with the base station. ROS on a self-developed flight controller. NVIDIA Jetson Xavier NX embedded computer for enhanced computations. |
| Dataset / Test Environment | Real-world tests with a set of three UAVs. They followed a cruising path set for UAV swarms. |
| Results | Improved performance compared to traditional centralized approaches, showing improved responsiveness, better adaptability to environmental variations,and enhanced robustness under mission conditions. |
| Limitations | Advanced on board computers required, which lead to a very high cost when incorporated into swarm UAVs. |

**Research gaps** identified via the literature survey includes:

- Most decentralized algorithms end up needing some form of centralized control either via motion capture/ lighthouse systems.

- There is a range limit that occurs due to centralization. The UAVs have to be within the communication range of the GCS.
- The tracking of objects happens in 2D not 3D.There is a limit to how the UAVs can be simulated in 2D as it doesn't take into account a height range as UAVs layered on top of each other in 3D are as good as one object in 2D.

# Proposed Methodology & Implementation Details

Given below is a flowchart that describes the proposed methodology:

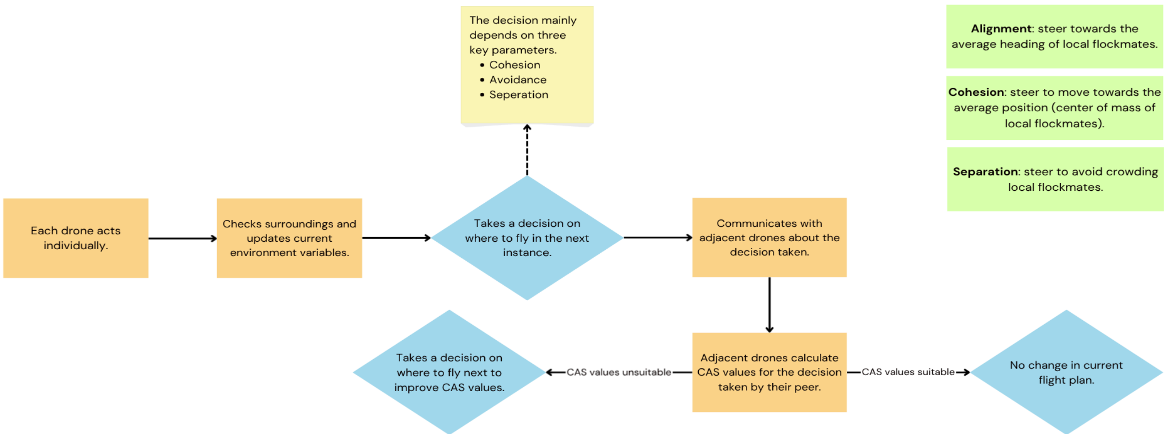



Fig 1. Methodology

Attempting to configure a swarm of drones in real life can be expensive , dangerous when tested in public spaces with people, so we rely on using Ardupilot SITL (Software in The Loop) as a virtual flight controller which provides us with an autopilot that commands the drone to perform the tasks necessary. We also use Gazebo Harmonic which is a physics simulator , to simulate a swarm of five drones tracing a path , Gazebo provides us with a safe virtual environment to test our swarm, though the physics engine in gazebo is very realistic, it is simulates a virtual environment that is ideal, with no disturbances and noise from environmental factors such as wind.

A swarm of UAVs is referred to as a flock, with each UAV operating autonomously. Once airborne, every UAV senses and updates the environment variables relevant to its operation. After initialization, it communicates with its nearest neighbours and obtains their coordinates.

Using this information, the UAV computes three key parameters: Cohesion (C), Alignment (A), and Separation (S) as seen in figure 1. In the proposed architecture, each UAV makes decisions independently, relying entirely on these three parameters:

- Cohesion (C): This parameter ensures that the flock remains united. Based on the value of C, a UAV determines whether it should move closer to its neighbours or maintain its current trajectory. Cohesion prevents a UAV from drifting too far from the average position of its local flockmates, maintaining the overall structure and integrity of the swarm.
- Alignment (A): The Alignment parameter steers the UAV toward the average heading or direction of nearby UAVs. A high A value ensures that all UAVs orient themselves toward a common direction, enabling the flock to move cohesively as a group.
- Separation (S): This parameter prevents collisions within the flock. Depending on the value of S, a UAV decides whether to increase distance from nearby UAVs or continue on its current path. Separation ensures safe spacing and avoids overcrowding within the flock.

# Implementation:

To initiate the system, the Gazebo simulation environment is first launched with five iris drone models. Subsequently, five corresponding instances of ArduPilot SITL instances are started to provide flight control for each simulated drone. Once the SITL instances are active, MAVSDK connects to each UAV and is individually connected, armed, and commanded to take off. After reaching a stable hover, the flight mode is switched to Offboard, enabling the drones to externally receive velocity commands. A position script then continuously subscribes to the Gazebo pose topics of the UAVs to obtain real-time positional data for all UAVs. This information is then processed by the BOIDS algorithm, which computes the required velocity vectors based on flocking rules such as separation, alignment, and cohesion. The resulting velocity commands are transmitted back to each drone through the offboard interface, enabling coordinated swarm behavior within the simulation environment.

The distance between each drone is calculated with the help of Euler's distance formula as stated:

$$d = ||u_{i,t} - u_{j,t}||_2, \forall j \in N_i$$

The centroid of the “Flock” is calculated with the following formula

$$Uc_t = \frac{U_{1,t} + U_{2,t} + \cdots + U_{N,t}}{N}$$

The UAVs compare the flocks' centroid with their own centroid and adjust accordingly.

The alignment of the drone with its leader is done with the following equation

$$dL_t = ||UL_t - U_{i,t}||_2$$

This ensures that the drone is properly aligned with the rest of the Flock and the leader. This is necessary for the entire flock to move in a particular direction.

# Results and Conclusions

The selected parameter values for separation, cohesion, alignment, and migration provide stable behavior in simulation where the UAV swarm is tightly grouped but the UAVs don't collide with each other. The unusual higher than standard separation constant was required because the classical BOIDS algorithm models each agent as a point mass, whereas our UAVs have a physical dimension of 685.8mm across that must be accounted for to prevent overlap and ensure realistic spacing.

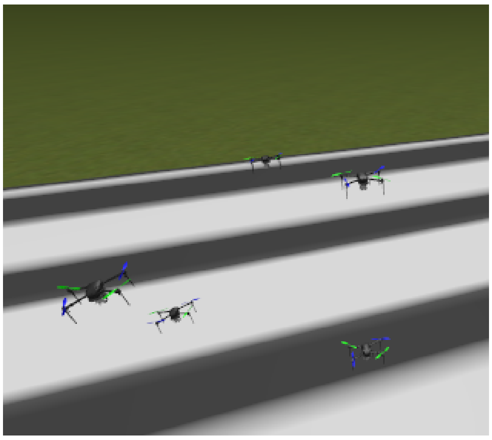


fig 2. Parameter values for CAS

Using MAVSDK, the system successfully generated and transmitted velocity commands to each UAV, enabling precise swarm control as illustrated in Figures 3, 4 and 5. The drones consistently responded to the BOIDS-based velocity vectors, maintaining formation and adjusting dynamically to the positions of neighboring UAVs.

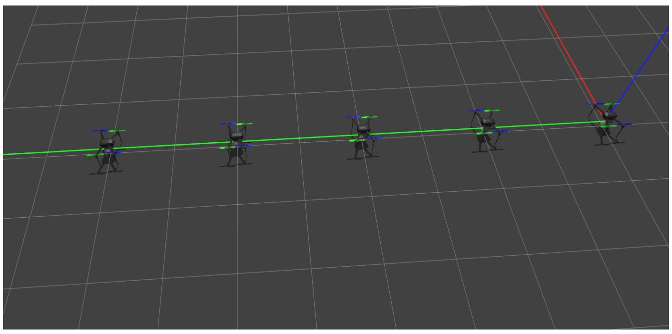


fig 3. UAVs in Gazebo with 2m separation

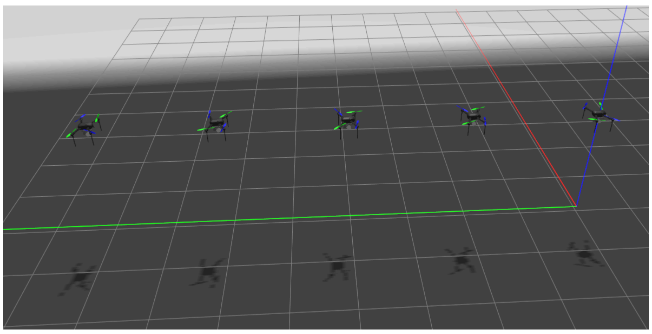


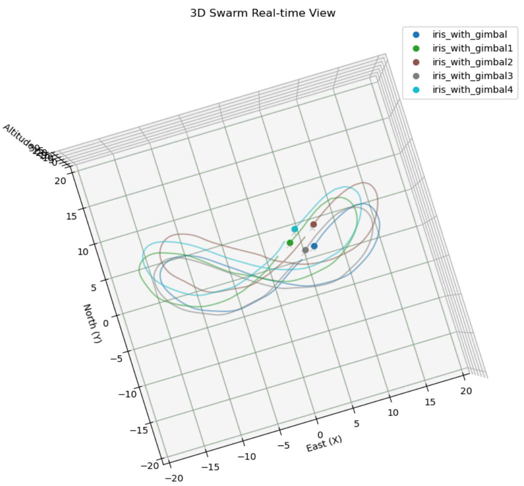
fig 4. UAVs takeoff in offboard control

```
W_SEPARATION = 2.5
W_COHESION = 2.0
W_ALIGNMENT = .6
W_MIGRATION = 2.5      #

PERCEPTION_RADIUS = 8.0
PROTECTED_RANGE = 4.0
MAX_SPEED = 4.5        #
```

fig 5. UAVs following boids algorithm using velocity commands

The swarm demonstrated the capability to follow predefined trajectories, including a figure-eight flight path, as shown in Figure 5. This confirms that the integration of the BOIDS algorithm with MAVSDK and ArduPilot SITL provides a reliable framework for decentralized swarm navigation.



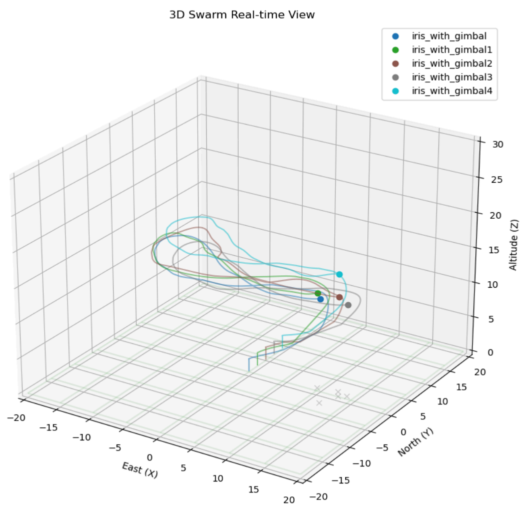




fig 6. Top view of the UAVs flying in figure 8 fig 7. Perspective view of figure 8 pattern

Overall, the results validate the effectiveness of the implemented approach, showing that decentralized coordination can be achieved with stable flocking, smooth control, and the ability to execute complex maneuvers. These outcomes reinforce the potential of such bio-inspired algorithms for scalable multi-UAV systems.

# Future Enhancements

- Implement the system in real-world conditions to validate performance beyond simulation.
- Integrate LiDAR sensors to improve localization accuracy and reliability.
- Add advanced obstacle avoidance capabilities for safer autonomous navigation.
- Enable inter-UAV communication to support collaborative mapping and information sharing.
- Scale the framework to accommodate a larger number of UAVs.
- Explore additional bio-inspired algorithms to enhance decentralized control and adaptability.

# References


- [1] H. Jinqiang, W. Husheng, Z. Renjun, M. Rafik and Z. Xuanwu, "Self-organized search-attack mission planning for UAV swarm based on wolf pack hunting behavior," in *Journal of Systems Engineering and Electronics*, vol. 32, no. 6, pp. 1463-1476, Dec. 2021.

- [2] M. Verdoucq, G. Theraulaz, R. Escobedo, C. Sire and G. Hattenberger, "Bio-inspired control for collective motion in swarms of drones," *2022 International Conference on Unmanned Aircraft Systems (ICUAS)*, Dubrovnik, Croatia, 2022, pp. 1626-1631.

- [3] M. Verdoucq, C. Sire, R. Escobedo, G. Theraulaz and G. Hattenberger, "Bio-Inspired 3D Flocking Algorithm with Minimal Information Transfer for UAVs Swarms," *2023 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Detroit, MI, USA, 2023, pp. 8833-8838.

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- [5] Chia-Hsuan Lai, Chian-Yu Lu, Chun-Liang Lin, and Yang-Yi Chen. 2025. Enhancing Drone swarm efficiency through a high-flexibility biomimetic formation algorithm. *Drone Systems and Applications*. 13: 1-26.