

Design and Simulation of UAV Swarm Systems with Focus on Centralized Control using SITL and Gazebo

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Abstract- Unmanned Aerial Vehicle (UAV) swarming has become an important research area for coordinated aerial operations. Multiple UAVs can complete surveillance, mapping, monitoring, and search tasks more efficiently than a single vehicle. This work presents the design and simulation of a three-UAV swarm system based on a centralized control strategy using ArduPilot SITL, Gazebo, Mission Planner, and WSL2. In the proposed model, UAV1 acts as the leader, while UAV2 and UAV3 perform follower operations. The simulation was tested through waypoint missions, altitude control, telemetry observation, and formation monitoring. Results indicate that centralized swarm control offers a practical and simple solution for small UAV groups in simulation environments.

Keywords - UAV Swarm, Centralized Control, SITL, Gazebo, Mission Planner, Leader-Follower

INTRODUCTION

A UAV swarm refers to a coordinated group of multiple unmanned aerial vehicles that operate together to complete a common mission. **Swarming is inspired by natural systems such as birds flying in formation, fish schooling, and ant colonies.** These biological systems demonstrate coordinated movement, distributed intelligence, and efficient group behavior.

Centralized Control-

Centralized control is a swarm coordination method in which one controller, ground station, or leader UAV is responsible for making decisions and sending commands to all other UAVs.

SITL (Software In the Loop)

Software In the Loop (SITL) is a simulation technique where autopilot software runs on a computer without physical flight hardware.

Gazebo -

Gazebo is a robotics simulation platform used to create realistic 3D environments for testing autonomous systems. In UAV research, Gazebo is commonly integrated with SITL to

visualize drone motion, physics response, sensors, and formation behaviour.

Mission Planner-

Mission Planner is a ground control station software used for configuring, monitoring, and controlling ArduPilot-based UAV systems. It supports waypoint mission creation.

LITERATURE REVIEW

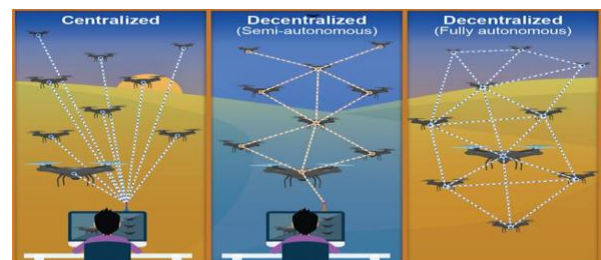
Types of swarm-

Swarming systems are mainly divided into three types

Centralized Swarming (One central controller (GCS/leader) controls all UAVs)

Decentralized Swarming (Each drone makes its own decisions)

Hybrid Swarming (Combination of centralized + decentralized)



[Fig.1-shows in image UAV Swarm Type]

Swarm technology is widely applied in surveillance, mapping, disaster monitoring, and military operations. Researchers have focused on improving communication, coordination, and autonomous decision-making among UAVs for reliable swarm behaviour.

Centralized Swarm Control

Centralized swarm control is a coordination approach in which a single controller manages all UAVs in the network. The controller generates commands and distributes them to follower drones through communication links.

Leader-Follower Formation Studies

Several researchers have implemented leader–follower formation strategies for multi-UAV coordination. In this approach, one UAV acts as the leader and follows the predefined mission path, while follower UAVs maintain fixed relative distances from the leader.

SITL and Gazebo Based Simulation

Simulation platforms are widely used in UAV research before real flight testing. ArduPilot SITL allows autopilot firmware to run on a computer without physical hardware, while Gazebo provides a realistic three-dimensional environment for observing UAV movement and formation behaviour.

METHODOLOGY

Centralized Swarm Architecture (Leader to follower)-

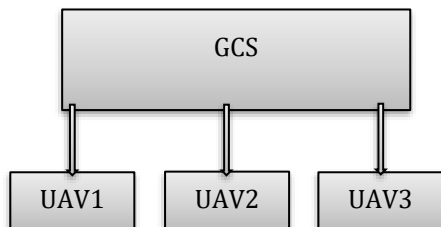
Centralized swarm architecture is a control framework in which a single controller manages the movement and coordination of all UAVs in the swarm network. The controller may be a ground control station, onboard computer, or leader UAV that continuously sends commands to follower vehicles. This method is commonly used in small swarm systems because mission planning, communication, and monitoring can be handled from one source.

The implemented swarm uses a leader–follower model:

- UAV1**- executes the main waypoint mission.
- UAV2** -follows the leader with left-side offset.
- UAV3** -follows the leader with right-side offset.

The controller continuously monitors telemetry data and mission Planner status.

Block diagram of UAV Swarm setup –



Major Architecture Components-

Ground Control Station (GCS)

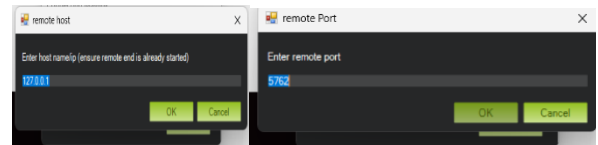
The central controller is the main decision-making unit of the complete swarm system. It is responsible for generating movement commands, assigning missions, and monitoring all UAVs during operation.

Main functions of the controller include:

- Sending waypoint and movement commands to UAVs
- Monitoring flight parameters of all vehicles
- Managing leader and follower behaviour
- Observing mission progress in real time
- Maintaining coordinated swarm movement

Communication Protocol-

Reliable communication between the controller and UAV nodes is necessary for successful swarm operation. In this work, the MAVLink protocol has been used for data exchange between the controller and UAV instances. MAVLink is a lightweight communication protocol commonly used in autopilot systems. It supports command transmission as well as telemetry feedback.



[Fig.2-shows in image TCP Port and IP address]

During connection setup, the loopback IP address 127.0.0.1 was entered as the host address, which represents the local machine. This configuration allowed Mission Planner to receive data from the SITL simulator running on the same system.

A dedicated TCP port such as 5762 was assigned for telemetry communication. Separate ports were used for multiple UAV instances to maintain independent. The successful connection confirmed that the centralized controller was able to monitor and command multiple UAVs through MAVLink communication.

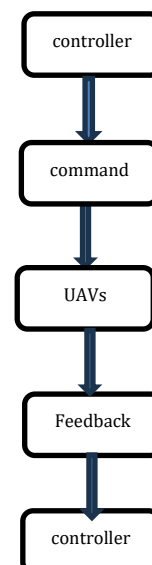
UAV Nodes (SITL Instances)-

Each UAV in the swarm was generated through separate ArduPilot SITL instances. Three independent quadcopters were launched using the multi-vehicle simulation command. Command in WSL for 3 drone command in SITL-
`sim_vehicle.py -v ArduCopter --count 3 --auto-sysid --location CMAC --auto-offset-line 90,8 --console`

System Data Flow-

The complete swarm system follows a closed-loop control mechanism in which command and feedback signals continuously circulate between the controller and UAVs.

BLOCK DIAGRAM OF DATA FLOW-



Software and Hardware Configuration

The complete UAV swarm simulation framework was developed using Software-in-the-Loop (SITL) technology integrated with Mission Planner. The simulation environment was configured on Ubuntu 22.04 running through Windows Subsystem for Linux 2 (WSL2). ArduPilot firmware version 4.5.0 was used for quadcopter UAV simulation and autonomous mission execution. Mission Planner version 1.3.xx was used as the Ground Control Station (GCS) for mission monitoring, telemetry analysis, waypoint management, and parameter configuration

SOFTWARE SETUP-

Windows Subsystem for Linux (WSL) Installation-

A Linux-based environment was required to execute ArduPilot. SITL tools and simulation packages. Since the experimental work was performed on a Windows laptop, Windows Subsystem for Linux (WSL) was selected to run Ubuntu without installing a separate operating system. The installation was completed through PowerShell using administrator privileges. After successful installation, the system was restarted and Ubuntu was initialized with a user account. This environment was later used for simulation commands, source compilation, and swarm execution.

```
wsl --install
wsl -l -v
```

ArduPilot SITL Setup

Software-In-The-Loop (SITL) was used to simulate UAV flight controllers without physical hardware. This approach allows firmware testing, mission planning, and swarm validation in a virtual environment.

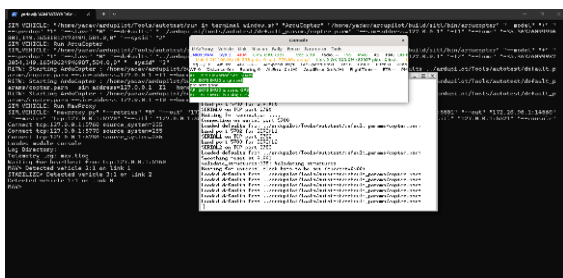
The ArduPilot source code was cloned from the official repository, and prerequisite scripts were executed to install required libraries and build tools. After successful installation, the simulator was tested using a sample vehicle launch command.

SITL Test Command-

```
C:\Users\yadav>wsl
(venv-ardupilot) yadav@NARRATAYADAV:~/mnt/c/Users/yadav$ cd ~
(venv-ardupilot) yadav@NARRATAYADAV:~$ cd ardupilot/
(venv-ardupilot) yadav@NARRATAYADAV:~/ardupilot$ sim_vehicle.py -v ArduPlane --console
```

[Fig.3-shows in image SITL test commands]

SITL running terminal, Console and map opened



[Fig-04 shows in images sitl running and console map opened.]

Gazebo Integration

Gazebo was integrated as the three-dimensional simulator for visual observation of UAV motion. While SITL simulated the autopilot logic, Gazebo provided the virtual world where UAV movement, spacing, and swarm formation could be observed. This setup helped verify leader-follower behavior and formation movement during mission execution.



[Fig.5-shows in image 3 UAVs in 3d]

Mission Planner Setup-

Mission Planner was used as the Ground Control Station (GCS) for mission planning, telemetry monitoring, parameter observation, and swarm supervision. It was installed on Windows and connected to the SITL vehicles through TCP ports.

Multi-UAV monitoring screen-



[Fig.6- Mission Planner interface showing three connected UAVs with separate telemetry ports for centralized swarm monitoring and control.]

Mission Planner was used as the centralized monitoring interface for observing multiple UAVs simultaneously. The software successfully detected three simulated vehicles connected through separate TCP telemetry ports. Each UAV could be selected individually using the vehicle list available in the top-right corner.

The map interface displayed the real-time location of all UAV nodes, while the HUD section provided status indicators such as arming condition, flight mode, GPS state, and altitude. This setup confirmed that Mission Planner can supervise multiple SITL vehicles within a centralized swarm environment.

Software Workflow Summary:

1. WSL created Linux support inside Windows
2. Ubuntu provided the development workspace
3. ArduPilot SITL simulated UAV firmware
4. Gazebo provided 3D visualization.

IMPLEMENTATION-

Overview

This chapter describes the detailed implementation of the centralized UAV swarm system using ArduPilot SITL and Gazebo. A three-UAV swarm is implemented based on a leader-follower formation under a centralized control mechanism.

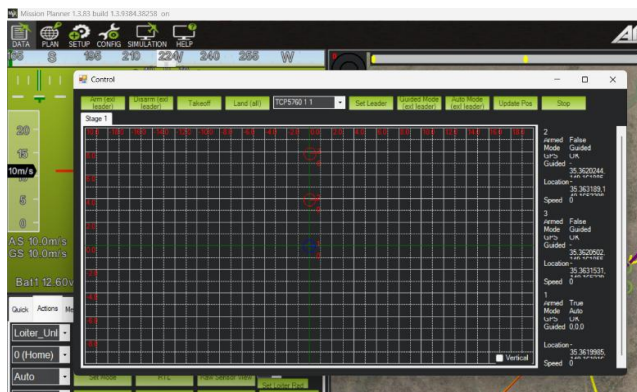
The pictures show the three UAVs positioned at the launch location after successful startup. Individual vehicle markers are visible, indicating that the instances were active and ready for further commands.

The left-side control panel also confirms that the selected vehicle was connected **in Guided mode**, which is commonly used for controlled startup, arming, and take-off procedures. MAVLink communication links were established between Mission Planner and all SITL vehicles, enabling command transfer and real-time feedback. This initialization stage was necessary before executing formation control, waypoint navigation, and swarm mission operations.

In the developed system, the UAV communication structure was configured as follows:

- UAV1 → Port 5760 (Leader)
- UAV2 → Port 5770 (Follower 1)
- UAV3 → Port 5780 (Follower 2)

Three-UAV Swarm Formation with Leader Selection-



[Fig. 07- Three-UAV swarm control interface showing UAV1 as leader and UAV2-UAV3 as follower vehicles under centralized supervision.]

In the displayed formation graph, three UAV nodes are visible with separate identifiers. UAV1 was assigned as the leader vehicle, while UAV2 and UAV3 operated as follower drones. The leader UAV served as the reference point for swarm motion, whereas the follower UAVs maintained fixed relative spacing based on centralized commands.

The blue marker indicates the currently selected leader UAV, and the red markers represent follower nodes positioned at predefined offsets. This arrangement demonstrates a leader-follower strategy in which follower drones continuously adjust their positions according to the movement of the leader.

The right-side status panel shows independent telemetry information for each UAV, including arming condition, flight mode, GPS state, speed, and location coordinates. At the shown moment, UAV1 was active in Auto mode, while the follower vehicles remained in Guided mode awaiting coordinated motion commands. This mixed-mode operation is commonly used during mission execution, where the leader follows a predefined route and followers track the leader positions.

The successful display of all three UAVs confirms that the centralized swarm controller can monitor multiple vehicles simultaneously and maintain coordinated formation behaviour in the SITL environment.

Waypoint Mission Planning and Altitude Configuration-



[Fig.08- Mission Planner waypoint mission setup showing five waypoints at 5 m altitude with final Return-to-Launch command uploaded to the UAV.]

In the presented setup, the flight altitude for each waypoint was configured to 5 meters using the relative altitude frame. A low operational height was selected to safely validate navigation logic, path tracking, and follower coordination within the simulation environment.

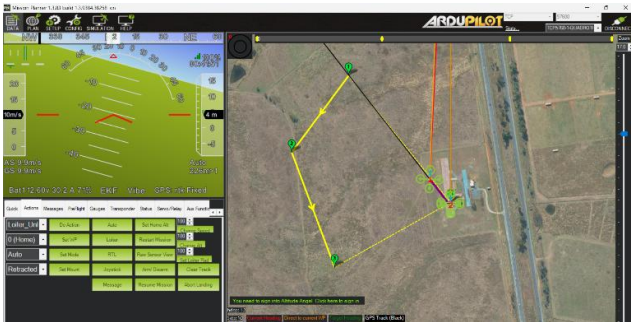
A total of five mission commands were prepared in the mission list. These commands consisted of multiple waypoint locations followed by a final recovery command. The waypoint markers visible on the map represent the route that the leader UAV was required to follow sequentially.

At the final stage of the mission, the RTL (Return to Launch) command was inserted. This command instructs the UAV to automatically return to the original take-off position after completing all assigned waypoints. The use of RTL improves mission safety and ensures automatic recovery after route execution.

Once the route, altitude, and mission sequence were finalized, the Write function in Mission Planner was used to upload and save all parameters to the selected UAV. After this step, the vehicle became ready for autonomous mission execution.

This mission planning process demonstrates how waypoint navigation can be integrated with centralized swarm control, where the leader follows the uploaded route and follower UAVs maintain formation during movement.

Autonomous Leader Flight with Follower Tracking at 5m. Altitude-



[Fig 09 -Leader UAV executing autonomous mission at 5 m altitude while follower drones track the leader in swarm formation.]

The figure illustrates the mission execution stage of the proposed three-UAV swarm system. In this condition, the leader drone was armed successfully and was performing autonomous waypoint navigation under centralized control. The Mission Planner interface confirms that the selected UAV was operating in Auto mode, indicating that the uploaded mission commands were being executed automatically.

The HUD panel on the left shows an altitude of approximately 5 meters, which was the predefined mission height used during testing. Maintaining a fixed altitude helped evaluate path tracking accuracy and stable swarm movement in the simulation environment.

On the map interface, the leader UAV followed the planned route marked by yellow waypoint lines and directional arrows. The visible path indicates that the drone was moving sequentially between mission waypoints according to the uploaded autonomous mission.

The follower UAVs were positioned near the leader and continuously adjusted their locations to maintain formation. Their movement was based on the real-time position of the leader vehicle, demonstrating leader-follower swarm coordination. As the leader advanced along the route, the follower drones responded by preserving relative spacing and synchronized motion.

The right-side telemetry section displays live parameters such as speed, GPS lock, battery condition, and flight mode. This confirms that all required data were available for real-time swarm supervision.

The result verifies that the proposed centralized architecture can support autonomous leader navigation while follower UAVs maintain formation at the same operational altitude.

RESULTS AND DISCUSSION

The developed centralized UAV swarm system was successfully implemented in the SITL and Gazebo simulation environment. Three UAVs were connected simultaneously

through Mission Planner using separate communication ports. All vehicles were detected correctly and real-time telemetry data such as mode status, GPS lock, altitude, and coordinates were received continuously.

During testing, UAV1 was assigned as the leader drone, while UAV2 and UAV3 were configured as follower UAVs. The leader completed the predefined waypoint mission smoothly at an altitude of 5 meters. Followers maintained their relative positions with respect to the leader and responded properly during directional changes.

The results confirmed that centralized control is effective for small swarm groups where one controller supervises multiple UAVs. Mission Planner provided stable monitoring and command execution for all vehicles.

Performance Parameter Observation-

Formation Error	1.2 m
Position Offset Accuracy	$\pm 0.8m$
GPS Deviation	0.5 m
Communication Latency	110–120 ms
Path Tracking Accuracy	95%
Operational Altitude	5 m

- Three UAV nodes connected successfully through different TCP ports.
- MAVLink communication remained stable during simulation.
- Leader drone executed waypoint mission accurately.
- Followers maintained fixed offsets and formation discipline.
- Auto mode and Guided mode switching worked properly.
- RTL command returned the UAV safely to home location.
- Centralized monitoring simplified swarm supervision.

CONCLUSION

This paper is presented the design and simulation of a three-UAV swarm system based on centralized control using ArduPilot SITL, Gazebo, WSL2, and Mission Planner. A leader-follower strategy was implemented in which one UAV acted as the mission leader and the remaining UAVs maintained formation offsets.

Simulation results showed that the proposed framework can perform waypoint navigation, altitude maintenance, formation tracking, and multi-vehicle monitoring successfully. The leader completed autonomous missions while followers maintained synchronized movement.

The work demonstrates that centralized swarm architecture is practical, low-cost, and easy to implement for small UAV groups in simulation environments.

FUTURE SCOPE

The present work can be extended in several directions for advanced swarm applications:

- Increase the swarm size from three UAVs to multiple drones.
- Implement decentralized or hybrid swarm control methods.
- Add obstacle avoidance and collision prevention algorithms.
- Integrate computer vision for target tracking applications.
- Use real hardware drones instead of only simulation.
- Apply swarm systems in agriculture, surveillance, and disaster response.
- Introduce AI-based path planning and adaptive formation control.
- Improve communication security and fault tolerance

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ABOUT THE AUTHOR'S -

Namrata Yadav is currently pursuing the MTech degree in Electronics and Communication Engineering. She completed the Bachelor of Technology (B.Tech) degree in Electronics and Communication Engineering in 2022 with 76% from Veer Bahadur Singh Purvanchal University, Jaunpur, Uttar Pradesh, India. She also completed the Diploma in Electronic Engineering in 2019 with 80% from Government Polytechnic Jaunpur, Uttar Pradesh, India. She is presently working as a **UAV System Engineer** in the Research and Development Department, where she is involved in UAV integration, system testing, operational support, and flight-related activities. Her current research interests include UAV swarm systems, autonomous aerial control, centralized coordination strategies, simulation platforms, embedded systems, and advanced aerospace technologies. Her present work focuses on the design and simulation of UAV swarm systems using centralized control with SITL and Gazebo.

Mrs. Aashu Kori is a professional in Electronics and Communication engineering with solid academic and technical expertise in electronic. Systems, communication technologies, and engineering education. She completed her Master of Engineering from DAVV University, Indore in 2015, securing 69%. She earned her Bachelor of Engineering degree from RGPV, Bhopal in 2012 with 66%. She possesses a strong background in analog and digital circuit design, VLSI fundamentals, and basic electrical engineering, which has helped her build both theoretical insight and practical skills in communication systems and networking technologies. At present, she is working as an Assistant Professor in the Department of Electronics and Communication Engineering at RITM, Lucknow, where she is actively involved in teaching, guiding students, and supporting academic development. Earlier, she served as an Assistant Professor at AITRC, Chinaware, where she enhanced her teaching and research experience. In addition, she completed professional training at Bharat Sanchar Nigam Limited (BSNL), Indore, with a focus on digital communication system further.