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Research Article

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Design and Development of a Low-Cost Swarm UAV Platform for Intelligent Data-Driven Security Applications

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ABSTRACT

Intelligent data-driven security systems increasingly rely on distributed sensing, real-time communication, and autonomous decision-making to provide effective surveillance and situational awareness. Swarm robotics has emerged as a promising paradigm for such applications by enabling multiple unmanned aerial vehicles (UAVs) to collaboratively monitor dynamic environments and acquire security-relevant information. However, the widespread adoption of existing swarm UAV platforms is constrained by their high cost, complex system architectures, and dependence on specialized communication hardware. This paper presents the design and implementation of a low-cost swarm UAV platform for intelligent data-driven security applications. The proposed platform employs custom-built UAVs equipped with ESP32-S3 microcontrollers that utilize the ESP-NOW protocol to achieve reliable peer-to-peer communication without additional wireless communication modules. The system integrates custom-designed UAV frames, self-developed printed circuit boards (PCBs), and an independently developed flight control system, resulting in a modular, scalable, and cost-effective research platform. A Python-based monitoring dashboard developed using Streamlit provides real-time visualization, command transmission, and distributed data acquisition from multiple UAVs. Experimental validation demonstrates reliable multi-UAV communication and efficient real-time data exchange, enabling coordinated operation and continuous situational monitoring. The proposed platform offers a flexible and economical testbed for developing and evaluating swarm intelligence algorithms while supporting future research in distributed data fusion, autonomous swarm coordination, AI-driven threat detection, and next-generation aerial security systems.

Keywords: Swarm unmanned aerial vehicles (UAVs); Intelligent security systems; Distributed sensing; ESP-NOW communication; Multi-UAV communication; Swarm robotics; Data-driven security; Autonomous aerial surveillance.

1. INTRODUCTION

Recent advances in artificial intelligence (AI), the Internet of Things (IoT), wireless communication, and edge computing have fundamentally transformed conventional security systems into intelligent data-driven platforms capable of autonomous surveillance, real-time data processing, and adaptive decision-making. These technological developments have significantly enhanced the ability of modern security systems to perceive, analyze, and respond to dynamic environments with minimal human intervention [1-5]. Modern security applications demand continuous situational awareness through distributed sensing, reliable wireless communication, and intelligent analysis of large volumes of heterogeneous data generated in dynamic environments. Such systems are widely employed in smart cities, critical infrastructure protection, industrial automation, border surveillance, disaster response, and public safety, where the rapid detection of anomalies, accurate situational assessment, and timely decision-making are essential for maintaining operational resilience and ensuring public security [6-9]. Unlike traditional fixed surveillance infrastructures, intelligent data-driven security systems combine sensing, communication, and computational intelligence to provide scalable, resilient, and autonomous monitoring capabilities.

Among various sensing technologies, Unmanned Aerial Vehicles (UAVs) have emerged as one of the most effective platforms for intelligent surveillance because of their mobility, deployment flexibility, and ability to provide aerial observations over large geographical areas. Compared with ground-based surveillance systems, UAVs can rapidly access hazardous or inaccessible environments while collecting visual, thermal, positional, and environmental information in real time [10-13]. Consequently, UAVs have been widely adopted for applications including border patrol, traffic monitoring, environmental monitoring, precision agriculture, infrastructure inspection, search-and-rescue operations, military reconnaissance, and emergency response [11, 14, 15].

Although individual UAVs have demonstrated significant advantages, their operational capabilities remain constrained by limited sensing coverage, battery endurance, payload capacity, and susceptibility to single-point failures. These limitations have motivated extensive research into swarm robotics, where multiple autonomous agents cooperate to accomplish collective tasks more efficiently than a single robotic platform [16, 17]. Inspired by the collective behavior of biological systems such as ant colonies, honeybee swarms, bird flocks, and fish schools, swarm robotics enables decentralized coordination through local interactions among autonomous agents. Instead of relying on centralized control, swarm intelligence emphasizes distributed communication, self-organization, scalability, adaptability, and fault tolerance, making it particularly suitable for complex and dynamic operational environments [18, 19].

The integration of swarm robotics with unmanned aerial vehicle (UAV) technology has significantly enhanced the capabilities of intelligent security systems. By operating cooperatively, multiple UAVs can simultaneously monitor geographically distributed areas, exchange information in real time, coordinate surveillance tasks, and provide redundant sensing capabilities that improve mission reliability, fault tolerance, and operational efficiency. Furthermore, distributed sensing by UAV swarms enables comprehensive situational awareness through the fusion of information acquired from multiple aerial perspectives, thereby enhancing target detection, environmental perception, and event monitoring in dynamic and complex environments [20, 21]. Recent advances in AI, distributed computing, and cooperative communication further enable UAV swarms to support intelligent target tracking, autonomous navigation, cooperative exploration, distributed task allocation, and real-time data fusion for security applications. Recent surveys identify secure communication, AI-assisted decision making, and distributed autonomy as key research directions for future UAV swarm systems.

Reliable communication represents one of the fundamental requirements for effective swarm operation. Each UAV must continuously exchange state information, sensing data, and mission commands with neighboring agents or ground stations while operating under dynamic wireless network conditions. Consequently, various communication technologies, including Wi-Fi, ZigBee, LoRa, cellular networks, software-defined networking, Flying Ad Hoc Networks (FANETs), and peer-to-peer wireless protocols, have been investigated to support multi-UAV coordination [22, 23]. Furthermore, secure communication has become increasingly important because UAV swarms are vulnerable to cyber-attacks such as spoofing, denial-of-service attacks, jamming, false data injection, and man-in-the-middle attacks that may compromise mission performance. Recent surveys highlight lightweight communication protocols, secure authentication, and resilient networking as critical challenges in practical UAV swarm deployment.

Despite substantial progress in swarm robotics, most reported UAV swarm platforms are constructed using commercial flight controllers, proprietary autopilot systems, sophisticated navigation modules, expensive communication hardware, and high-performance embedded processors [24, 25]. Although these platforms provide excellent flight stability and autonomous capabilities, they often involve considerable financial investment and limited hardware flexibility. Their proprietary architectures restrict customization of embedded hardware, communication protocols, and control algorithms, making them less suitable for educational institutions, low-budget laboratories, and researchers interested in developing customized swarm intelligence algorithms. The high cost of commercial systems also limits large-scale experimentation involving multiple UAVs, particularly in developing countries where research budgets are constrained.

Motivated by these challenges, this paper presents the design and development of a low-cost swarm UAV platform to support intelligent data-driven security applications. Unlike conventional swarm UAV systems that rely on commercial flight controllers and dedicated communication hardware, the proposed platform integrates custom-designed UAV hardware, self-developed printed circuit boards (PCBs), and an independently developed embedded flight control architecture, providing a flexible and cost-effective research platform. In the initial design, inter-UAV communication was implemented using STM32 microcontrollers coupled with NRF24L01 radio modules. Although this architecture successfully established reliable wireless communication, experimental implementation revealed several practical limitations, including increased hardware complexity, additional communication circuitry, larger PCB dimensions, higher power consumption, and increased system cost. These constraints adversely affected the platform's scalability, payload capacity, and suitability for lightweight multi-UAV deployment.

To address these issues, the communication architecture was redesigned using ESP32-S3 microcontrollers implementing the ESP-NOW peer-to-peer communication protocol. By integrating wireless communication directly into the embedded controller, the proposed platform eliminates the requirement for dedicated RF communication modules, thereby reducing wiring complexity, simplifying PCB design, minimizing hardware cost, and improving system integration. In addition, a Python-based monitoring dashboard developed using the Streamlit framework provides a centralized interface for real-time identification of connected UAVs, wireless command transmission, and communication monitoring. This software infrastructure enables efficient management of multiple UAV nodes while providing the foundation for future distributed sensing and intelligent security applications.

Experimental validation demonstrates the feasibility of reliable communication and synchronization among multiple UAV nodes using the proposed ESP-NOW-based architecture. The developed platform successfully establishes a low-cost, custom embedded hardware framework for multi-UAV communication, providing the essential infrastructure for future swarm intelligence research. Although fully autonomous formation control and cooperative flight are beyond the scope of the present study due to the constraints of lightweight hardware, low-cost propulsion systems, and the absence of advanced flight stabilization mechanisms, the proposed platform offers a flexible, scalable, and cost-effective foundation for future research on distributed sensing, cooperative navigation, swarm coordination, distributed data fusion, AI-assisted threat detection, and intelligent data-driven security systems.

Multiple low-cost platforms have explored ESP-based swarm communication. Agrawal and Kumar [26] demonstrated master–slave swarm coordination using the low-cost ESP8266 Node MCU devices over IoT/cloud channels, while Drone Bridge-ESP32 provides an open-source ESP-NOW firmware layer for present commercial flight controllers. Porras Minaya et al. [27] presented a low-cost, ESP-NOW-based ground robot for trajectory tracking in swarm research. Unlike these works, which either target ground robots or add ESP-NOW on top of existing flight-controller hardware, the platform proposed in this paper is fully custom at every layer — frame, PCB, and flight control firmware — designed specifically for lightweight aerial swarm nodes, and is integrated with a dedicated monitoring dashboard for distributed data acquisition.

Table 1:Comparison table for different works

Platform	**Communication**	**Hardware Basis**	**Target Domain**
Agrawal & Kumar (2024)	ESP8266 + IoT/cloud	Off-the-shelf NodeMCU	Ground swarm robots
DroneBridge-ESP32	ESP-NOW (LR, up to ~1 km)	Add-on to commercial flight controllers	UAV telemetry/control
Porras Minaya et al. (2026)	ESP-NOW	Custom ground robot + camera	Trajectory tracking, education
Proposed Platform	ESP-NOW	Fully custom frame, PCB, flight control	Low-cost aerial swarm, security-monitoring foundation

The principal contributions of this work are summarized as follows. First, a fully customized low-cost swarm UAV platform is developed using self-designed hardware and embedded control architecture without relying on commercial flight controllers. Second, an ESP32-S3-based peer-to-peer communication framework utilizing the ESP-NOW protocol is implemented to provide efficient multi-UAV communication while reducing hardware complexity and cost. Third, a Python-based monitoring dashboard is developed for centralized communication management and command transmission. Finally, the proposed platform establishes a scalable experimental foundation for future research on swarm intelligence, distributed sensing, cooperative perception, and intelligent data-driven security applications.

2. MECHANICAL DESIGN

The mechanical structure of the swarm robotic system is designed with a focus on achieving a balance between strength, lightweight construction, and functional integration of all electronic components. The primary objective of the structure is to provide a stable platform for housing the microcontroller, sensors, power supply, communication modules, and motor system while ensuring reliable movement and coordination among multiple units. Initially, the robot body had a weight of approximately 19 grams, which was relatively high for efficient swarm operation due to increased power consumption and reduced maneuverability. Through iterative design optimization and material refinement, the structure was successfully reduced to around 12 grams without compromising mechanical integrity as shown in Figure 1. This weight reduction significantly improved flight/movement efficiency, responsiveness, and overall energy consumption of the system.

The frame design ensures proper alignment of motors and components to maintain balance and minimize vibration during operation. Careful attention has been given to weight distribution so that the center of gravity remains stable, allowing smooth directional control and better sensor accuracy. The structure also supports modular assembly, making it easier to integrate or replace components during testing and development phases. Additionally, vibration damping considerations have been included to reduce disturbances affecting sensitive sensors such as IMU units. Overall, the optimized mechanical design plays a crucial role in enhancing the performance and scalability of the swarm robotic system.

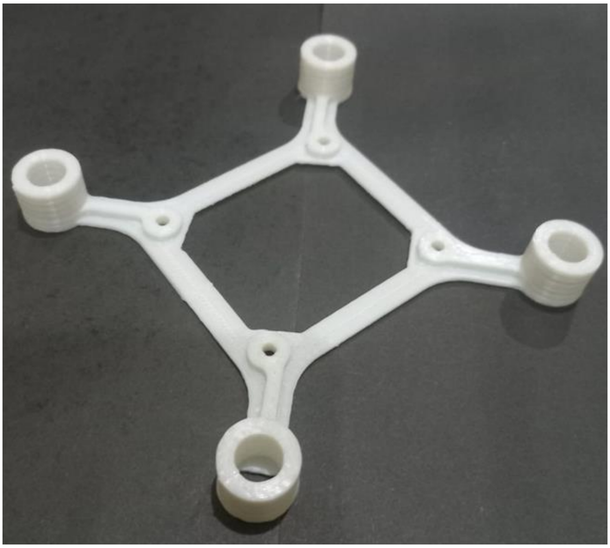

Figure 1 Frame

3. CIRCUIT DESIGN AND PCB FABRICATION

3.1. Design Software and Schematic Development:

The circuit design for the swarm robotic system was developed using EasyEDA, a web-based PCB design and schematic capture tool as shown in Figure 2. EasyEDA was chosen due to its ease of use, integrated component library, and direct support for generating Gerber files required for PCB fabrication. The schematic was first designed by defining all system-level connections between the microcontroller, motor drivers, sensors, power management circuitry, and communication modules. During schematic development, careful attention was given to signal integrity, power distribution, and modular connectivity. Separate functional blocks were created for control, power, and actuation systems to ensure clarity and ease of debugging during testing and iteration.

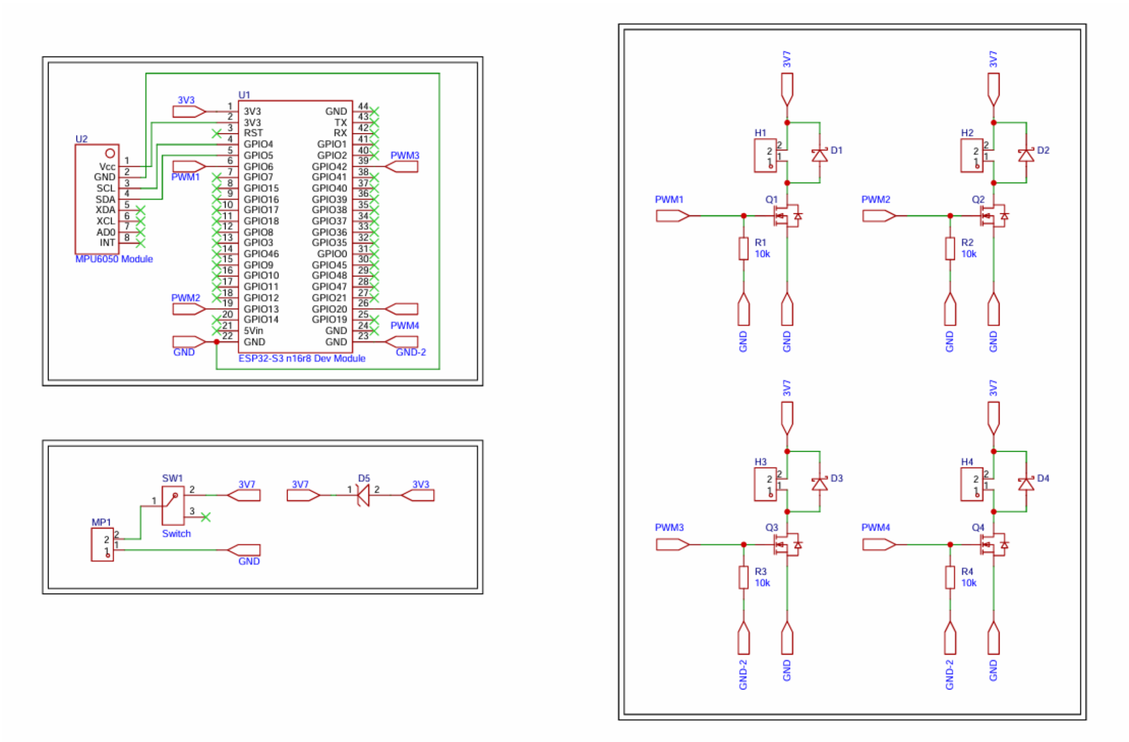

Figure 2 Schematic Diagram

3.2. Key Components and Circuit Architecture:

The PCB integrates multiple essential components required for stable operation of the swarm robot. The core control unit is connected with motor driving circuitry built using MOSFET-based switching stages, which allow efficient control of coreless motors. MOSFETs were selected due to their low switching losses, fast response, and ability to handle varying current demands of the motors. To ensure proper operation of the circuit, several resistors were used for current limiting, pull-up and pull-down configurations, and signal stabilization. These resistors play a critical role in protecting sensitive microcontroller pins and ensuring reliable logic level transitions. The PCB also includes multiple power rails, typically divided into regulated voltage lines such as 3.3V for the microcontroller and sensors, and higher voltage rails for motor operation. Proper decoupling capacitors were placed near power pins to minimize voltage fluctuations and noise during motor switching events. The communication and sensor interfaces were also routed carefully to avoid interference from high-current motor lines, ensuring stable data transmission and accurate sensor readings.

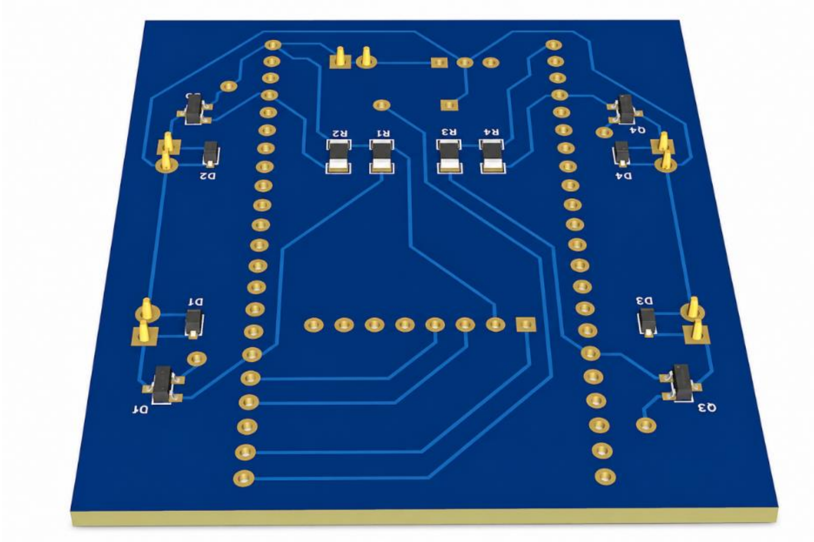

Figure 3 PCB Layout

3.3. PCB Layout and Design Considerations:

The PCB layout was designed with a compact structure to minimize size and reduce weight, which is crucial for swarm robotics applications. High-current motor traces were made wider to handle increased current flow, while signal lines were kept short and isolated from noise-prone areas. Grounding strategy was implemented using a common ground plane to reduce noise and ensure stable reference potential across the system. Component placement was optimized such that power components (MOSFETs and regulators) were placed away from sensitive communication and sensor circuits to avoid electromagnetic interference.

After finalizing the PCB layout in EasyEDA as shown in Figure 3, the design was exported into Gerber files, which contain all manufacturing data including copper layers, drill holes, and board outlines.

These files were then used for fabrication through multiple approaches. Due to high cost constraints in professional PCB manufacturing, alternative fabrication methods were explored.

Initially, CNC milling was used by converting Gerber files into machine-readable G-code. This allowed precise engraving of copper-clad boards for rapid prototyping and iterative testing. Chemical etching was also considered as an alternative method, where unwanted copper is removed using chemical solutions after transferring the PCB pattern. While etching provides good resolution, it requires careful handling and longer processing time compared to CNC-based fabrication.

Overall, the circuit design and PCB fabrication process ensured a compact, efficient, and modular electronic system for the swarm robotic platform. The use of MOSFET-based motor control, proper power distribution, and optimized PCB layout contributed to improved performance and reliability. The combination of EasyEDA design workflow and alternative fabrication methods like CNC milling enabled cost-effective and rapid development during iterative prototyping.

4. SENSORS INTEGRATION

The sensor integration in the swarm robotic system is primarily based on the use of an Inertial Measurement Unit (IMU) for balancing, specifically the MPU6050, which combines a 3-axis accelerometer and a 3-axis gyroscope in a single module. This sensor plays a crucial role in estimating the orientation, motion, and stability of each robot unit. It provides real-time data related to angular velocity and linear acceleration, which is essential for maintaining controlled movement and analyzing the dynamic behavior of the system. The MPU6050 is interfaced with the microcontroller using the I2C communication protocol, allowing efficient and fast data transfer with minimal wiring complexity. The accelerometer data is used to detect changes in position and motion, while the gyroscope data helps in understanding rotational movement and orientation drift. Together, these readings are used to improve stability control and ensure consistent movement behavior across all swarm units.

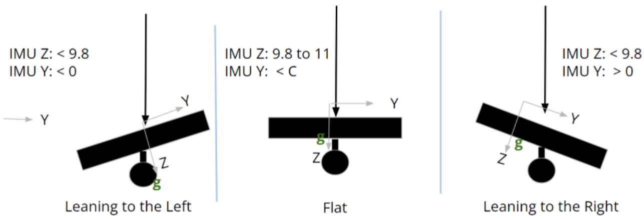

Figure 4 Balancing Diagram

The balancing diagram as shown in Figure 4 explains how the MPU6050's accelerometer output is interpreted for tilt estimation. When the robot is level, the Z-axis reads close to gravitational acceleration (~9.8 m/s²) with a near-zero Y-axis component. As the robot tilts left or right, the gravity vector readjusts between the Y and Z axes: a leftward lean produces Z < 9.8 with Y < 0, while a rightward lean produces Z < 9.8 with Y > 0. These thresholds have been derived empirically during calibration, allowing the firmware to classify the robot's instantaneous posture. Gyroscope data is integrated with the accelerometer using a complementary filter to reduce short-term noise and long-term drift, and the resulting orientation estimate is used to trigger corrective motor adjustments in the intended direction. Careful calibration of the sensor is required to reduce drift and noise errors as in Figure 4, especially in gyroscope readings. Filtering techniques such as complementary filtering or basic smoothing methods are applied in the firmware to improve data reliability. The sensor is also mounted securely on the PCB to minimize vibration-induced disturbances, which is critical in a mobile robotic platform. Overall, the MPU6050 serves as a foundational sensing unit for motion awareness and stability control in each robot, enabling better coordination and predictable behavior in swarm operations.

5. COMMUNICATION SYSTEM (NRF24L01 VS ESP-NOW)

Communication is one of the most critical aspects of the swarm robotic system, as the overall behavior of the swarm depends on fast, reliable, and synchronized data exchange between multiple robotic nodes. Unlike a single-robot system, swarm robotics requires continuous inter-device communication to maintain coordination, share states, and execute collective movement strategies. For this purpose, two wireless communication approaches were evaluated and implemented during development: NRF24L01 RF modules and ESP-NOW protocol (ESP-based communication).

5.1. NRF24L01 Based Communication Approach

Initially, the NRF24L01 module was selected due to its low cost, compact size, and wide usage in small-scale wireless robotic applications. It operates on the 2.4 GHz ISM band and supports multiple communication modes such as point-to-point and basic multi-node networking. In the early stage of development, NRF was used to establish basic transmitter receiver communication between the master and individual swarm units. However, during practical implementation, several limitations were observed. The communication reliability decreased when multiple nodes were introduced, leading to packet loss and synchronization issues. Additionally, managing addressing and routing for multiple robots required complex logic at the software level. The effective range was also inconsistent in indoor environments, and interference issues were observed when multiple NRF nodes operated simultaneously. These challenges made it less suitable for scalable swarm coordination.

5.2. Transition to ESP-NOW Communication

To overcome the limitations of NRF-based communication, the system was transitioned to ESP-NOW, a proprietary low-latency communication protocol developed for ESP32-based microcontrollers. ESP-NOW enables direct peer-to-peer communication without requiring a Wi-Fi router or internet connection, making it highly efficient for embedded robotic networks. One of the major advantages of ESP-NOW is its extremely low transmission latency, which is essential for real-time swarm coordination. Each robot node can act as both a sender and receiver, allowing flexible peer configuration. This decentralized structure aligns well with swarm intelligence principles, where there is no strict dependency on a central controller for every decision. Unlike NRF, ESP-NOW provides better stability, higher data reliability, and improved scalability when the number of nodes increases. It also simplifies the communication architecture, as pairing devices using MAC addresses eliminates the need for complex addressing schemes and packet routing logic.

5.3. Comparative Analysis (NRF24L01 vs ESP-NOW)

In terms of performance, NRF24L01 offers basic wireless communication capabilities but suffers in multi-node swarm environments due to packet collision and limited network management features. On the other hand, ESP-NOW provides a more robust and efficient communication framework optimized for ESP-based systems. NRF requires additional handling for synchronization and reliability, whereas ESP-NOW inherently supports faster data exchange with reduced overhead. From a development perspective, ESP-NOW significantly reduces software complexity and improves system responsiveness. In terms of scalability, ESP-NOW clearly outperforms NRF, making it more suitable for expanding swarm systems with multiple robots. During informal bench testing, the ESP-NOW-based architecture consistently delivered commands to connected UAV nodes with noticeably lower delay and fewer dropped packets compared to the earlier NRF24L01 setup, though systematic quantitative benchmarking (e.g., logged latency, range, and packet-loss statistics) was not performed at this stage and is identified as important future work.

Table 2 Comparison Between NRF24L01 Communication and ESP-NOW Protocol

Parameter	**NRF24L01**	**ESP-NOW**
Communication Hardware	Requires external RF module	Built-in wireless communication
System Complexity	Higher due to extra hardware	Lower and compact design
Circuit Size	Larger PCB integration	Smaller PCB footprint
Cost	Higher overall cost	Lower implementation cost
Latency	Moderate latency	Low-latency communication
Ease of Integration	Complex wiring and setup	Simple software-based setup
Communication Reliability	Faced implementation issues	Successfully implemented
Application in Project	Initially tested	Final communication system

5.4. Role in Swarm Intelligence

In the context of swarm robotics, communication is not merely data transmission but a foundation for collective behavior. Each robot shares essential information such as movement commands, status updates, and synchronization signals, enabling coordinated decision-making across the swarm. The transition to ESP-NOW significantly enhanced the system's ability to support real-time collaboration, making the swarm more stable, responsive, and scalable.

6. PROGRAMMING AND FIRMWARE DEVELOPMENT

The firmware development of the swarm robotic system was carried out in a structured and iterative manner, starting from basic hardware validation and gradually progressing toward full swarm-level control and remote dashboard integration. The complete software architecture was implemented on ESP32/ESP32-S3 microcontrollers, selected due to their built-in wireless capabilities, sufficient processing power, and compatibility with real-time embedded control applications.

6.1. Motor Control and Initial Hardware Testing

The development process began with the fundamental testing of coreless motors, which are used as the primary actuation system in the robotic platform. Initially, simple PWM (Pulse Width Modulation) signals were generated from the ESP microcontroller to verify motor response, rotation direction, and speed control behavior. During this stage, different duty cycles were tested to understand motor sensitivity and response characteristics. The focus was on ensuring stable and smooth actuation without sudden jerks or voltage instability. MOSFET-based switching circuits designed earlier in the PCB stage were used to drive the motors efficiently, as direct microcontroller driving is not possible due to current limitations. This phase validated the basic electromechanical interface between firmware and hardware.

6.2. IMU Integration and Stability Feedback

After successful motor testing, the next phase involved integration of the MPU6050 IMU sensor to enable motion awareness and stability feedback. The sensor provided real-time acceleration and angular velocity data, which was used to observe the orientation behavior of the robot. The IMU data was continuously read using the I2C protocol and processed in the firmware to monitor drift and movement deviations. Although full closed-loop stabilization was not implemented at this stage, sensor readings were used for analysis and future control improvements. Basic filtering techniques were applied to reduce noise and ensure more stable readings. This step helped in understanding how external disturbances and motor vibrations affect system stability. The independently designed flight control system consists of firmware running on the ESP32-S3 that reads IMU sensor data over I2C, estimates the system's orientation using a complementary filter, and generates differential PWM signals through MOSFET switching to adjust each motor's speed in response to detected tilt. This provides basic attitude-aware motor correction in place of a commercial flight controller, though full closed-loop stabilization was not yet achieved at this stage.

6.3. ESP-NOW Communication Development (Master–Slave System)

Once individual hardware modules were validated, the focus shifted toward wireless communication using ESP-NOW protocol. Master–slave architecture was implemented, where one ESP device acted as the central controller (master), and multiple robotic nodes acted as slaves. The master node was responsible for sending control commands such as movement direction, speed values, and synchronization signals. The slave nodes received these packets and executed corresponding motor actions in real time.

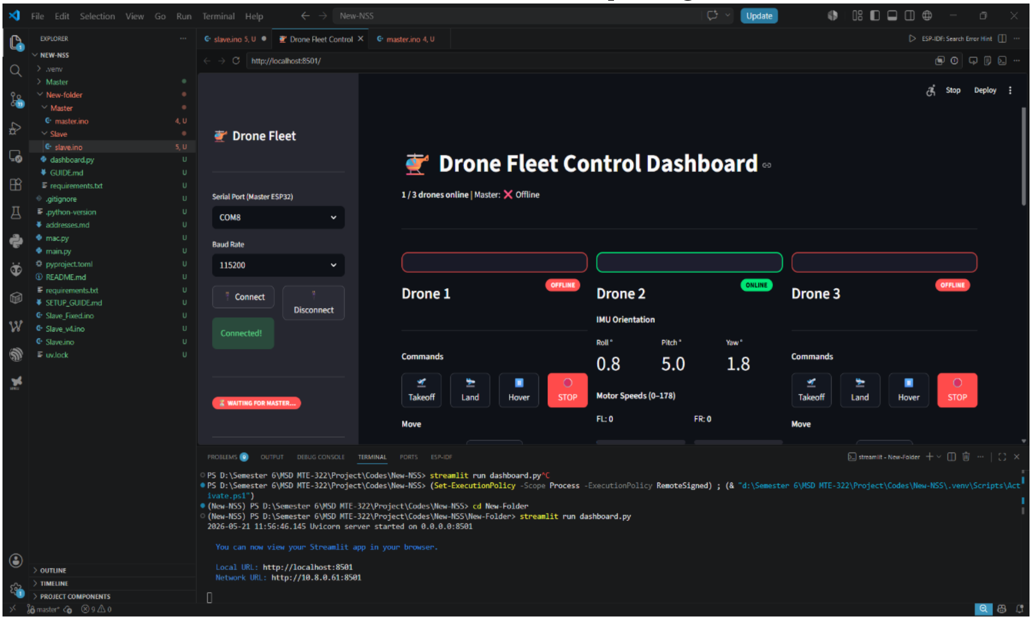

Figure 5 Streamlit Dashboard

Each node was identified using its unique MAC address, enabling direct peer-to-peer communication without requiring a router or internet connection. This significantly reduced latency and improved synchronization between swarm members. This stage marked the transition from single-robot control to multi-robot swarm coordination. It should be noted that the current implementation of the system follows a master–slave communication structure rather than fully decentralized swarm coordination. This was adopted as an intermediate validation step to confirm reliable multi-node communication; true peer-to-peer swarm behavior, including distributed decision-making without a central node, is identified as a direction for future work.

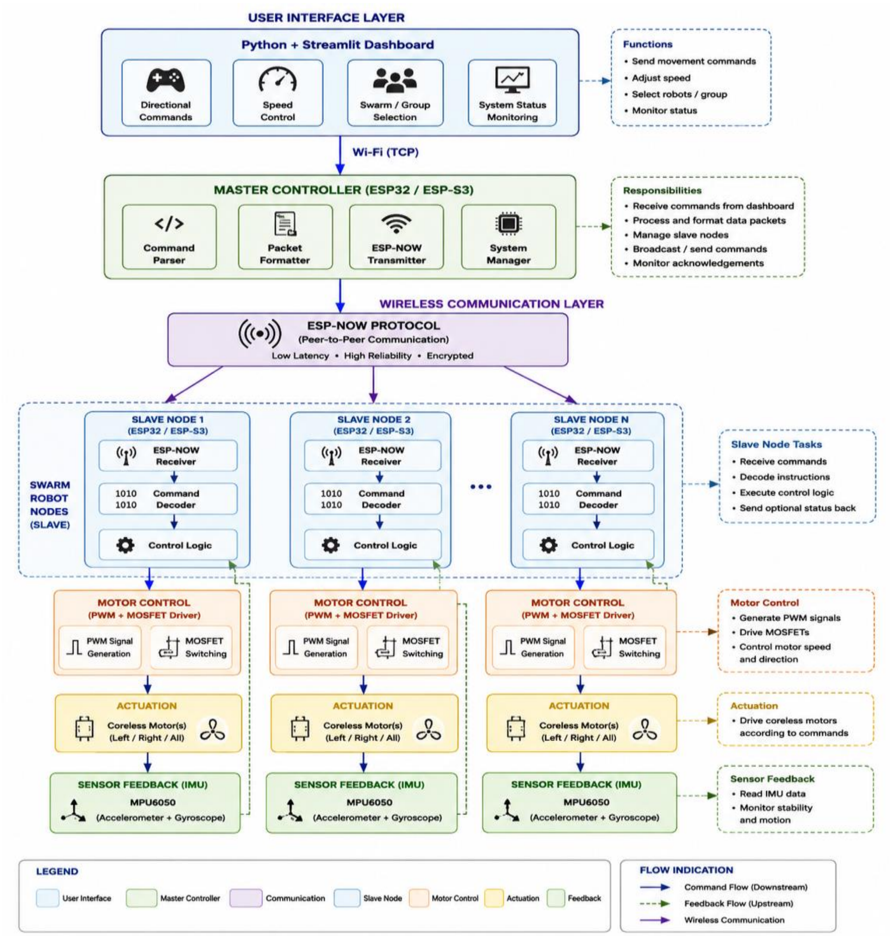

Figure 6 End to End Workflow

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7. Python + Streamlit Dashboard (User Control Interface)

To provide a user-friendly control system, a Python-based dashboard using Streamlit was developed, as shown in Figure 5. It can:

- Send directional movement
- Adjust speed parameters
- Monitor system status
- Control individual or group behavior of robots

Study develops a low-cost swarm UAV platform based on ESP32-S3 microcontrollers, coreless motor actuation, IMU-based sensing, and ESP-NOW wireless communication. The proposed system establishes modular and scalable hardware architecture for distributed UAV coordination while maintaining low implementation cost. The developed prototype successfully integrates embedded control, wireless communication, and onboard sensing into a unified swarm-ready platform, providing the fundamental infrastructure for future swarm robotics research. The overall system workflow is illustrated in Figure 6 and final view is shown in figure 7.

Figure 7 Final UAV view

CONCLUSION

Experimental validation confirmed the successful implementation of the embedded hardware and communication framework. Reliable inter-UAV communication was achieved using the ESP-NOW protocol, while the motor control subsystem demonstrated satisfactory performance during ground-based testing. Replacing conventional NRF modules with ESP-NOW improved communication reliability, reduced system complexity, and enhanced the platform's suitability for distributed UAV applications. The prototype also highlighted practical engineering challenges, including PCB fabrication constraints, payload limitations, and weight optimization, providing valuable guidance for future hardware improvements. Although the proposed platform establishes the essential foundation for swarm UAV development, it has been validated only underground-testing conditions. Autonomous flight, robust attitude stabilization, and cooperative aerial behaviors remain beyond the scope of the present work. Therefore, the developed system should be regarded as a proof-of-concept platform rather than a fully autonomous aerial swarm. Future work will focus on implementing closed-loop PID-based flight stabilization using IMU sensor fusion, followed by comprehensive in-flight experimental validation. Advanced swarm intelligence algorithms, including flocking, leader–follower, and consensus-based coordination, will be integrated to enable cooperative autonomous missions. Furthermore, communication scalability will be enhanced through optimized packet scheduling and collision avoidance, while sensor fusion, localization, and systematic benchmarking of communication latency, transmission range, packet delivery reliability, and network scalability will provide a comprehensive evaluation of the platform for intelligent multi-UAV applications.

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