International Journal of Advances in Engineering and Management (IJAEM)
Volume 7, Issue 02 Feb. 2025, pp: 276-284 www.ijaem.net ISSN: 2395-5252

Embedded System Design and Implementation for a Heavy-lift Agricultural UAV

Nwaokolo Ikechukwu Frank
Federal University of Technology, Owerri

Date of Submission: 05-02-2025 Date of Acceptance: 15-02-2025

ABSTRACT

The increasing demand for automation in agriculture has driven the development of unmanned aerial vehicles (UAVs) capable of performing complex tasks such as precision spraying, seed dispersal, and crop monitoring. However, the design of embedded systems for heavy-lift agricultural UAVs presents significant challenges, including power efficiency, flight stability, payload management, and real-time data processing. This paper proposes a specialized embedded system tailored for a heavy-lift agricultural UAV, integrating advanced microcontrollers, sensor fusion techniques, and adaptive flight control algorithms to enhance operational efficiency. The system incorporates optimized power management, real-time navigation, and wireless communication frameworks to ensure reliable performance in diverse agricultural environments. Experimental testing and simulations validate the embedded system's effectiveness in maintaining flight stability, optimizing energy consumption, and handling heavy payloads. The results demonstrate significant improvements in UAV endurance, control accuracy, and autonomous operation, making the proposed system a promising solution for enhancing large-scale agricultural productivity.

Keywords: Embedded Systems, UAV, Heavy-Lift Drone, Precision Agriculture, Flight Control, Power Management, Sensor Fusion

I. INTRODUCTION

The integration of unmanned aerial vehicles (UAVs) into modern agriculture has revolutionized precision farming, enabling more efficient crop monitoring, pesticide application, and data collection. However, the demand for heavy-lift agricultural UAVs—capable of carrying substantial payloads for seed dispersal, fertilizer application, and irrigation support—has introduced new challenges in embedded systems design. These challenges include optimizing power efficiency, ensuring real-time flight control, and integrating advanced sensors and communication protocols to enhance operational safety and autonomy (Ganesh et. al., 2022).

One key challenge in designing embedded systems for heavy-lift agricultural UAVs is ensuring that they can handle the complex algorithms and computations required for tasks such as autonomous navigation and obstacle avoidance. Additionally, these systems must be able to operate in harsh environmental conditions, including extreme temperatures and high levels of dust and debris. Another important consideration is the need for redundancy and fault tolerance to ensure the safe and reliable operation of the UAVs, especially when carrying heavy payloads or flying long distances. By addressing these challenges and leveraging advancements in technology, the design of embedded systems for heavy-lift agricultural UAVs can help revolutionize the way farming is done, improving efficiency, productivity, and sustainability in the agricultural industry (Spot & Henrik, 2019).

This paper explores the design and implementation of an embedded system tailored for a heavy-lift agricultural UAV. The proposed system incorporates real-time processing capabilities, robust fault-tolerant mechanisms, and efficient energy management strategies to maximize flight endurance and operational effectiveness. By leveraging a combination of high-performance microcontrollers, sensor fusion techniques, and adaptive control algorithms, the system aims to enhance flight stability and payload management while ensuring seamless integration with existing agricultural technologies.

The remainder of this paper is structured as follows: Section 2 reviews related work in agricultural UAV design and embedded system integration. Section 3 details the hardware and software architecture of the proposed system.

Section 4 presents experimental results and performance evaluations, followed by a discussion in Section 5. Finally, Section 6 concludes the paper with key findings and potential future developments in heavy-lift UAV technology for agricultural applications.

1.1 Background

The use of unmanned aerial vehicles (UAVs) in agriculture has grown significantly over the past decade, driven by advancements in automation, sensor technology, and embedded system design. Traditional agricultural UAVs are primarily used for aerial imaging, crop health assessment, and precision spraying. However, the increasing need for high-capacity payload delivery, such as large-scale fertilizer and seed dispersal, has led to the development of heavy-lift UAVs capable of carrying greater loads while maintaining stability and efficiency in flight.

1.1.1 Evolution of Agricultural UAVs

Early agricultural UAVs were predominantly fixed-wing or lightweight multirotor platforms, designed for data collection rather than direct intervention. While these UAVs provided valuable insights into crop health through multispectral imaging, their limited payload capacity restricted their practical use for material transport and spraying applications. The introduction of heavy-lift UAVs has addressed these limitations by incorporating high-thrust propulsion systems, extended battery life, and advanced control mechanisms to support payloads exceeding 10kg.

1.1.2 Challenges in Heavy-Lift UAV Design

The shift toward heavy-lift UAVs presents several technical challenges, particularly in embedded systems design. These challenges include:

- **Power Management:** Large payloads significantly impact flight endurance, requiring efficient energy distribution and battery management solutions.
- **Flight Stability and Control:** Increased weight alters flight dynamics, necessitating sophisticated control algorithms and real-time sensor fusion to maintain stability.
- **Autonomous Navigation:** Heavy-lift UAVs must integrate high-precision GPS, inertial measurement units (IMUs), and obstacle avoidance systems to ensure accurate delivery of agricultural materials.
- **Environmental Resilience:** Agricultural UAVs operate in diverse and often harsh environments, requiring robust embedded systems capable of handling variable weather conditions, dust, and moisture.

1.1.3 Embedded Systems in UAVs

Embedded systems play a crucial role in UAV performance, enabling real-time data processing, sensor integration, and adaptive flight control. Recent advancements in microcontroller technology, field programmable gate arrays (FPGAs), and machine learning algorithms have improved UAV autonomy and responsiveness. Additionally, wireless communication protocols such as LoRa, Wi-Fi, and 5G are enhancing remote monitoring and fleet management capabilities, allowing for more efficient agricultural operations.

Given these challenges and technological advancements, the need for a specialized embedded system tailored to heavy-lift agricultural UAVs has become apparent. This paper aims to design and implement an embedded system that addresses these challenges while optimizing energy efficiency, flight stability, and payload handling for practical agricultural applications.

II. AIM AND OBJECTIVES

Aim

The primary aim of this research is to design and develop an efficient embedded system for a heavy-lift agricultural UAV, optimizing flight stability, energy consumption, and payload management to enhance its operational effectiveness in large-scale agricultural applications.

Objectives

To achieve this aim, the study focuses on the following key objectives:

1. **Design an Embedded System Architecture:** Develop a robust embedded system integrating high performance microcontrollers, real-time operating systems (RTOS), and sensor fusion techniques for precise flight control.
2. **Optimize Power Management:** Implement an efficient energy distribution and battery management system to maximize flight endurance while carrying heavy payloads.
3. **Enhance Flight Stability and Control:** Develop adaptive flight control algorithms that compensate for payload-induced variations in UAV dynamics, ensuring stable and efficient operation.
4. **Integrate Advanced Sensing and Navigation Systems:** Incorporate GPS, inertial measurement units (IMUs), LiDAR, and

computer vision techniques to enhance autonomous navigation and obstacle avoidance.

5. **Develop a Wireless Communication Framework:** Implement real-time data transmission and remote monitoring capabilities using low-latency wireless communication protocols such as LoRa, Wi-Fi, or 5G.
6. **Validate Performance Through Experimental Testing:** Conduct flight tests and simulations to evaluate the embedded system's effectiveness in real-world agricultural scenarios, assessing flight duration, stability, and payload handling.

By addressing these objectives, this research aims to contribute to the development of advanced UAV technologies that improve the efficiency, precision, and scalability of agricultural operations.

III. SYSTEM DESIGN

3.1 Materials

The materials used for this project are listed below

Table 3.1 System Material List

Item No	Item
1	2.5mm Galvanized Steel UAV frame
2	Hobbywing X11 Plus 85kv 11118 motors (x4)
3	4313 reinforced Plastic foldable Propellers (x4)
4	Hobbywing 120A Electronic Speed Controllers (x4)
5	Holybro Pixhawk 6X Autopilot H753 Flight Controller
6	M10 GPS Module
7	6S 20000mAh 25c LiPo batteries (x2)
8	10m 10AUG Silicone wire
9	Radiomaster ELRS Radio Transmitter and Receiver RP3 Diversity
10	Walksnail HD Video Transmitter and Receiver
11	HD Video Monitor
12	Mission Planner IDE
13	PID Toolbox Software

3.2 System Architecture

The UAV embedded system plays a crucial role in ensuring the smooth operation of heavy-lift agricultural UAVs, which often operate in harsh environmental conditions. These systems need to be designed with redundancy and fault tolerance in mind to guarantee the safety and reliability of the UAVs, particularly when they are carrying heavy payloads or flying long distances. Key components within the architecture of heavy-lift agricultural UAVs include redundant flight control systems, backup power sources, advanced sensors for navigation and obstacle avoidance, and robust communication systems. These components work in tandem to ensure that the UAVs can operate effectively even in challenging situations. Figure 3.1 is an overview of the system architecture.

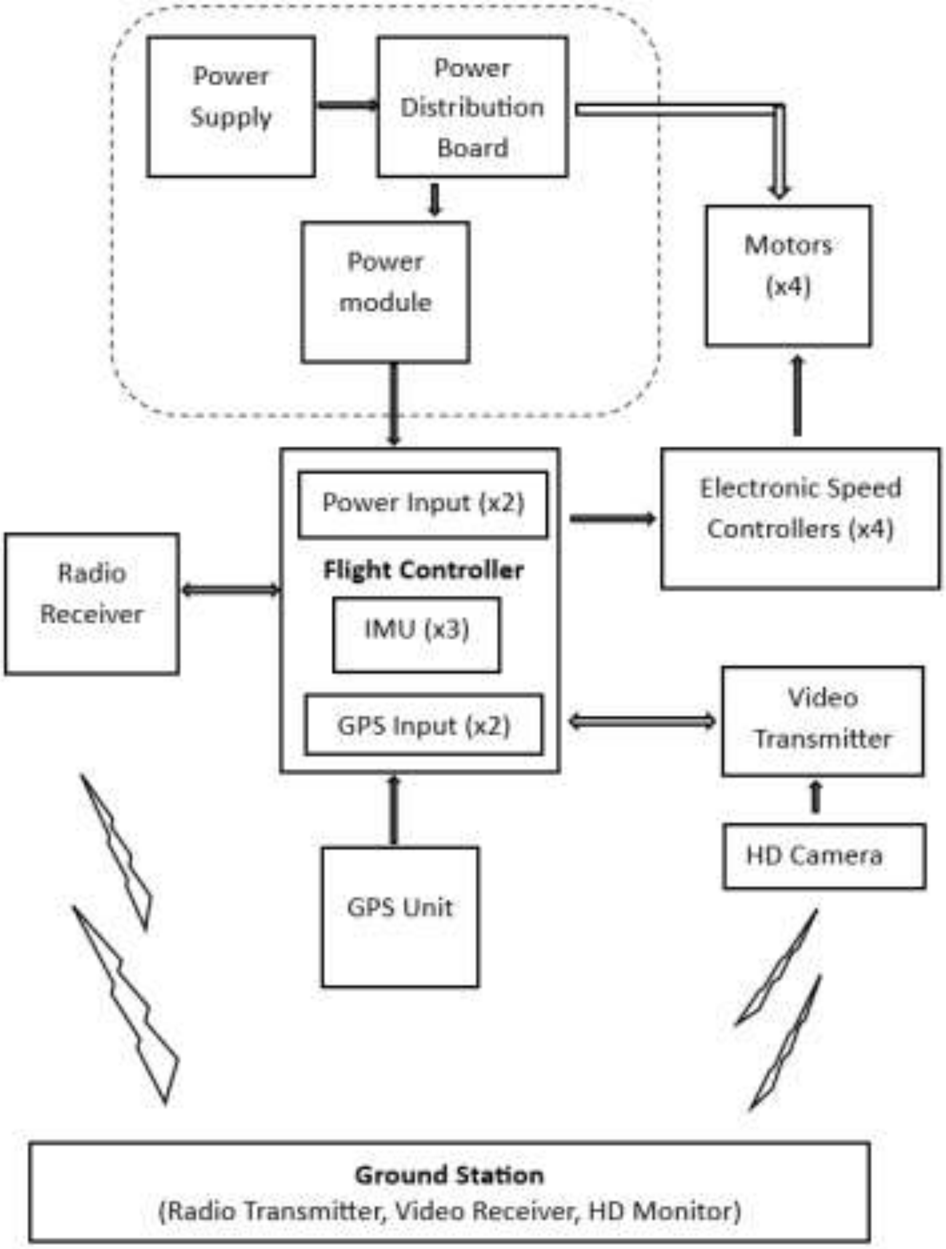


Fig 3.1 UAV Embedded System Architecture

3.2.1 Flight Controller

At the heart of every UAV embedded system design is the flight controller. The flight controller chosen for this project is the Holybro Pixhawk 6X Autopilot H753 Flight Controller, a high-performance module designed for advanced autonomous vehicle applications. It is based on the Pixhawk® FMUv6X Open Standard and the Pixhawk® Autopilot Bus Standard, ensuring compatibility and flexibility for various use cases.

Key Features:

- **High-Performance Processor:** Equipped with an ST Microelectronics® STM32H753 microcontroller, featuring an Arm® Cortex®-M7 core running at up to 480 MHz, with 2MB of flash memory and 1MB of RAM. This provides substantial computational power for complex flight operations.
- **Triple Redundant IMUs and Dual Redundant Barometers:** The flight controller includes three Inertial Measurement Units (IMUs) and two barometers on separate buses. Two of the IMUs are industrial-grade, enhancing reliability and accuracy in sensor data.

- **Modular Design:** Features a modular architecture with separated IMU, Flight Management Unit (FMU), and base system connected via 100-pin and 50-pin Pixhawk® Autopilot Bus connectors. This design allows for flexibility and ease of maintenance.
- **Advanced Vibration Isolation:** Incorporates a newly designed vibration isolation system to filter out high-frequency vibrations and reduce noise, ensuring accurate sensor readings and improved flight performance.
- **Temperature-Controlled IMUs:** The IMUs are temperature-controlled by onboard heating resistors, maintaining optimal operating temperatures for consistent performance across varying environmental conditions.
- Table 3.2 gives the specifications for the flight controller.

Table 3.2 Holybro 6X Specifications

Processors	1. FMU Processor: STM32H753 32-bit Arm® Cortex®-M7, 480 MHz, 2MB flash memory, 1MB RAM 2. IO Processor: STM32F103 32-bit Arm® Cortex®-M3, 72 MHz, 64KB SRAM
Onboard Sensors	1. Accelerometer/Gyroscope: ICM-20649 or BMI088 2. Accelerometer/Gyroscope: ICM-42688-P 3. Accelerometer/Gyroscope: ICM-42670-P 4. Magnetometer: BMM150 5. Barometer: 2x BMP388
Electrical Data	Maximum Input Voltage: 6V USB Power Input: 4.75~5.25V Servo Rail Input: 0~36V
Mechanical Data	Dimensions: 38.8 x 31.8 x 14.6 mm Weight: 23g

3.2.2 Electronic Speed Controllers

Electronic Speed Controllers are responsible for supplying the current needed by the motors to function. The Hobbywing XRotor X11 Plus system integrates a high-performance Electronic Speed Controller (ESC) with its motor, designed specifically for industrial and agricultural drone applications. This integration ensures seamless communication and optimal performance between the ESC and motor. The ESCs are rated at 120A which is typical for heavy-lift applications due to the large current demand from the motors.

Key Features of the Integrated ESC:

- **Field-Oriented Control (FOC):** The ESC employs FOC technology within a Permanent Magnet Synchronous (PMS) system, enhancing motor efficiency and providing smoother operation.
- **Comprehensive Protection Mechanisms:** To ensure system reliability and longevity, the ESC includes multiple protection features:

o **Power-On Self-Test:** Verifies system integrity upon startup.

o **Over-Current Protection:** Prevents damage from excessive current flow.

o **Stall Protection:** Safeguards the motor in the event of a stall condition.

o **Power-On Voltage Abnormality Protection:** Detects and responds to irregular voltage levels during startup.

- **Data Communication:** The ESC supports data output to the flight controller in real-time, providing critical operational parameters such as input and output throttle, motor speed, bus current, phase current, bus voltage, capacitor temperature, and MOSFET temperature. This data transmission is facilitated through CAN or serial communication protocols, enhancing system integration and monitoring capabilities.
- **Firmware Upgradability:** Users can update the ESC's firmware via the Hobbywing DataLink data box, ensuring access to the latest features and improvements. This can be accomplished through a computer connection or remotely via compatible flight controllers.
- **Environmental Resilience:** The ESC boasts an IPX6 protection rating, indicating a fully sealed design that enhances resistance to

environmental factors such as moisture and dust.

3.2.3 Global Positioning System

The GPS module employed in this project is the M10 GPS. It is a high-performance Global Navigation Satellite System (GNSS) receiver that leverages the u-blox M10 series chipset to provide precise and reliable positioning data. Designed for applications such as unmanned aerial vehicles (UAVs), robotics, and other systems requiring accurate navigation, the M10 GPS module offers several notable features.

The M10 GPS module can concurrently receive and track multiple GNSS systems, including GPS, Galileo, GLONASS, and BeiDou. This multi-band capability enhances positioning accuracy and reliability by utilizing a broader range of satellite signals.

Built on the u-blox M10 ultra-low-power platform, the module consumes less than 15mW in continuous tracking mode. This efficiency makes it ideal for battery-powered applications where energy conservation is crucial.

The M10 platform's high RF sensitivity reduces the time required to establish a position fix, ensuring rapid and accurate location data even in challenging environments. Features like Super-S technology boost performance in weak signal conditions or when used with small antennas, making it suitable for compact product designs.

3.2.4 Video Transmission System

The video transmission system provides a real time view for the UAV operator which aids in navigation and other essential operations that require video feedback. The video system chosen for this project is the Walksnail Avatar HD system, a high-definition digital video transmission solution designed for First-Person View (FPV) applications, offering pilots enhanced image quality, low latency, and reliable performance.

Key Features:

- **High-Definition Video:** Utilizing H.265 compression technology, the system delivers crisp 1080p video at 60 frames per second, ensuring detailed and smooth visuals during flight.
- **Low Latency:** The system achieves minimal latency, providing real-time video feedback essential for responsive control in FPV operations.
- **Dual Antenna Configuration:** Equipped with a dual-antenna setup, the Avatar HD system enhances signal stability and range, reducing the likelihood of video dropouts in challenging environments.
- **Integrated DVR:** The system features a built-in Digital Video Recorder (DVR) with 32GB of internal storage, allowing pilots to record their flights without the need for external devices.

Components:

- **Avatar HD Pro Kit V2:** This kit includes a high-definition camera, video transmitter (VTX), and antennas. The VTX features mounting holes with a 25.5x25.5mm pitch for easy installation and operates on a voltage range of 6-25V, accommodating 2-6S LiPo batteries.
- **Avatar VRX Module:** This supports HDMI output, making it compatible with various display devices, including large-screen monitors for an immersive viewing experience.

3.2.5 Radio Transmission System

The radio transmission system used in this project is ExpressLRS which is an open-source radio control system engineered for high-performance applications, including FPV (First-Person View) drone racing, long-range flying, and other rigorous remote control situations. It is recognized for its minimal latency, extensive range capabilities, and community-oriented development, rendering it a cost-efficient substitute for proprietary systems. A primary benefit of ExpressLRS is its elevated refresh rates, with the 2.4 GHz variant accommodating packet rates of up to 1000 Hz. This guarantees little latency and exceptional responsiveness, rendering it a favored option for pilots necessitating accurate inputs. The device functions on 900 MHz and 2.4 GHz frequencies, enabling users to select the optimal solution according to their range and penetration needs. The 900 MHz frequency offers superior signal penetration through barriers, but the 2.4 GHz frequency facilitates quicker response times and elevated refresh rates. The module chosen for this task is the Radiomaster 2.4 GHz ELRS system.

3.2.6 The UAV Power System

The UAV is powered with a 12s battery configuration by connecting two 6s LiPo batteries in series. Each battery is a 6s 2000mAh 25c battery. A single cell is 3.7v at nominal voltage and 4.2v at full charge. For the 12s configuration we have: 12s x 3.7v = 44.4v 3.1

Note the use of nominal voltage levels for calculations as the battery is not assumed to stay at full charge all through the UAVs operations. This voltage is connected the power distribution board which in turn distributes power to the entire UAV circuitry (i.e. motors, flight controller etc.). The flight controller makes use of a power module which serves as a Battery Elimination Circuit (BEC) which steps down the voltage to the 6s (22.2v) rating of the flight controller.

3.3 System Calculations

To calculate the **thrust-to-weight ratio** of the given quadcopter configuration

Given Parameters

Battery Voltage: 12S LiPo (Each cell is 3.7V nominal, 4.2V fully charged)
Nominal voltage = 12 × 3.7V = 44.4V 3.2
Fully charged voltage = 12 × 4.2V = 50.4V 3.3
Motor KV Rating: 85 KV (RPM per volt)
Propeller Size: 4314 (43-inch diameter, 14-inch pitch)
Total Weight (AUW): 15 kg
Number of Motors: 4 (Quadcopter)
Motor RPM = KV × Voltage 3.4
For nominal voltage (44.4V): RPM = 85 × 44.4 = 3,774 RPM 3.5

From the manufacturer’s datasheet, the 85KV motor with a 43-inch propeller at 44V can produce 20-25 kg of thrust per motor at full throttle. We'll assume an average thrust per motor of 22.5 kg at full power.

Total Thrust = Thrust per Motor × Number of Motors = 22.5 × 4 = 90kg 3.6

3.3.1 Thrust-to-Weight Ratio

Thrust-to-Weight Ratio = Total Thrust/Total Weight = 90kg/15kg = 6.0 3.7

The thrust-to-weight ratio for this quadcopter is **6:1**, meaning the drone has six times more thrust than its weight, providing excellent flight performance, high payload capacity, and strong maneuverability.

3.4 Flight Stability Test and Tuning

The aim of this test is to ensure the flight stability of the Heavy-lift UAV. This test procedure is performed under 50% expected load conditions (15kg).

Test Procedure
1. Connect the UAV to Mission Planner software and setup the black box configuration 2. Disconnect the UAV and power on the radio transmitter
3. Connect the battery to the UAV, wait for GPS lock, and arm the drone
4. Perform short 20 second test flights with several roll and pitch movements on the radio transmitter.
5. Disarm the drone, disconnect the battery and connect to Mission Planner software 6. Adjust PID parameters in small steps and save the new configuration
7. Repeat steps 4 – 6 until UAV is moderately stable.
8. Retrieve the black box logs from the UAV and save in a specified folder on the PC 9. Perform impulse response tests on the logs using PID Toolbox software
10. Observe results and repeat steps 4 – 10 as necessary.

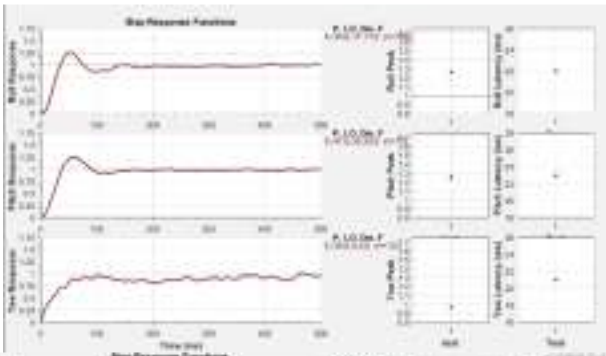
IV. RESULTS AND DISCUSSIONS

Figure 4.1a and 4.1b show the complete heavy-lift agricultural UAV.

Fig 4.1a UAV Setup Fig 4.1b Preflight Checks

4.1 Flight Tuning and Stability Results

Figures 4.2a – 4.2d show the progressive tuning results for the UAV. It can be seen that initial results (4.2a) show an overshoot beyond the setpoint margin. This overshoot is however dampened critically as we get to figure 4.2d therefore yielding a more stable flight performance.



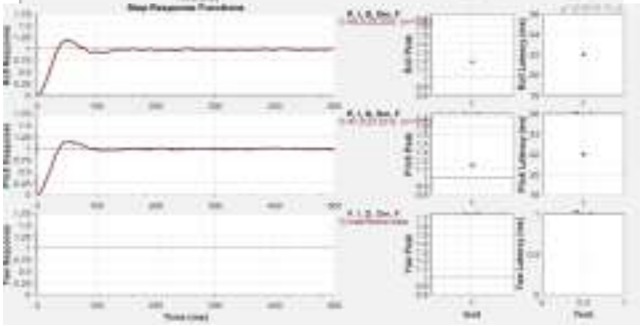
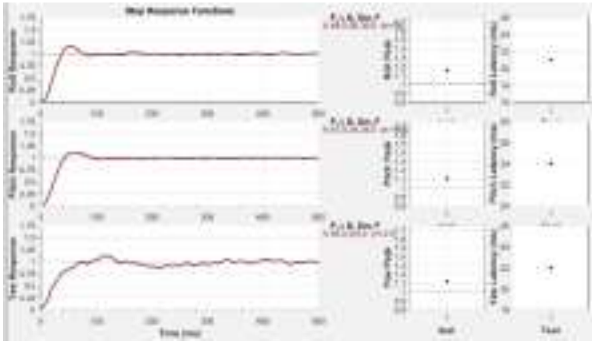


Fig 4.2a Underdamped system response Fig 4.2b



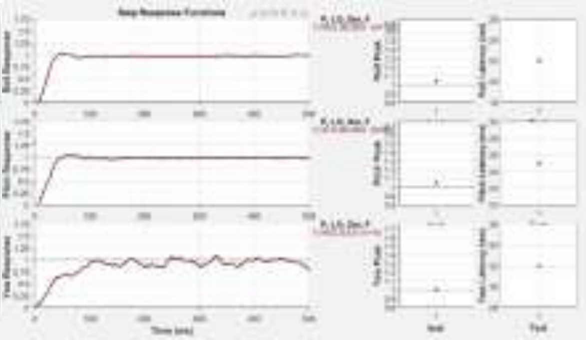


Fig 4.2c Fig 4.2d Critically Damped response Figure 4.3 is a superposition of all the tuning responses to show the damping progress.

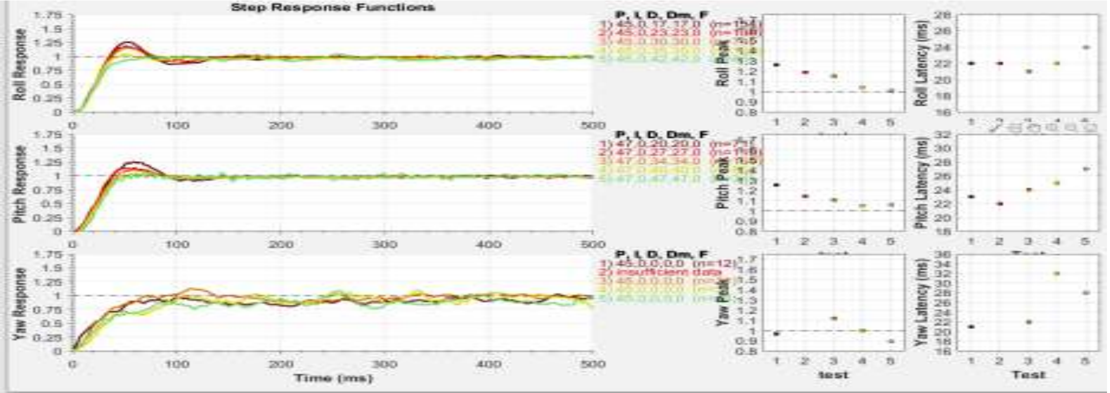


Fig 4.3 UAV PID Tuning Progress result

V. CONCLUSION

In conclusion, the development of an embedded system for a heavy lift agricultural UAV has proven to be a challenging yet rewarding endeavor. By integrating advanced sensors, control algorithms, and communication systems, the UAV is capable of efficiently and accurately performing tasks such as crop spraying and soil analysis. The successful implementation of this design has the potential to revolutionize the way agricultural tasks are carried out, leading to increased efficiency, reduced costs, and improved crop yields. Overall, the embedded system design for a heavy lift agricultural UAV represents a significant step forward in the field of precision agriculture.

However, the use of UAVs in agriculture raises concerns about privacy, safety, and potential negative impacts on the environment. Additionally, the high initial cost and maintenance requirements of these systems may limit their accessibility to small-scale farmers.

Despite these challenges, the benefits of using UAVs in agriculture cannot be overlooked. The ability to collect real-time data on crop health, soil conditions, and pest infestations allows for more precise and targeted interventions, ultimately leading to better outcomes for farmers. Furthermore, the use of UAVs can help reduce the reliance on chemical pesticides and fertilizers, promoting more sustainable farming practices. As technology continues to advance and costs decrease, it is likely that UAVs will become more accessible to a wider range of farmers, further driving innovation in the agricultural industry. In order to address concerns about privacy and safety, regulations and guidelines will need to be established to ensure responsible and ethical use of UAVs in agriculture.

REFERENCES

[1]. Angela. (2017). Analysis of preliminary design requirements of a heavy lift multirotor drone for agricultural use. Retrieved from: https://www.academia.edu/download/112071462/105.pdf

[2]. E. Ebeid. M. Skriver. and I. Jin. (2017). 'A survey on open-source flight control platforms of unmanned aerial vehicle." Euromicro conference on Digital system Design (Dov), pp. 396-402.

[3]. Ganesh, Chaitanya, & Sachin. (2022). Application of drone systems for spraying pesticides in advanced agriculture: A Review. IOP Conf. Ser.: Mater. Sci. Eng. 1259 012015

[4]. Hafeez, A., Husain, M. A., Singh, S. P., Chauhan, A., Khan, M. T., Kumar, N., & Soni, S. K. (2023). Implementation of drone technology for farm monitoring & pesticide spraying: A review. Information Processing in Agriculture, 10(2), 192–203.

[5]. Ju, C., & Son, H. I. (2018). Multiple UAV systems for agricultural applications: Control, implementation, and evaluation. Electronics, 7(9), 162.

[6]. Khanna, A., & Kaur, S. (2019). Evolution of Internet of Things (IoT) and its significant impact in the field of precision agriculture. Computers and Electronics in Agriculture, 157, 218–231.

[7]. Spot, & Henrik. (2019). Design methodology for heavy-lift unmanned aerial vehicles with coaxial rotors. Retrieved from: https://arc.aiaa.org/doi/pdf/10.2514/6.2019-2095

[8]. Tatale, O., Anekar, N., Phatak, S., & Sarkale, S. (2018). Quadcopter: Design, construction, and testing. International Journal of Research in Engineering and Applied Management, 4, 1–7.