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Design and Fabrication of a Multirotor UAV for Heavy-lift Applications

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ABSTRACT
This research delineates the design and execution of an Unmanned Aerial Vehicle (UAV) specifically tailored for heavy-lift applications. A thorough examination of the current literature on UAVs was conducted to guide the selection of cost-effective and efficient components, subsequently leading to a requirements analysis for the delivery UAV to design an appropriate airframe. The properties of the UAV system were modeled utilizing parameters derived from the chosen materials. A power system was engineered to satisfy the energy requirements of the UAV, predicated on a proposed maximum payload of 10 kg. PID tuning was carried out for flight stability using PID Toolbox software. The outcomes of the diverse tests conducted indicate a highly functional and stable prototype for cost-effective heavy-lift applications up to 7kg, and provide access to challenging terrains previously deemed inaccessible by conventional methods.

KEYWORDS: Unmanned Aerial Vehicle, Drone, Heavy-lift, PID Toolbox, Flight Stability,Flight Control System.

I. INTRODUCTION

1.1 Background

Unmanned Aerial Vehicles (UAVs) are remotely or autonomously operated pilotless aircraft. They differ in dimensions, design, and function, ranging from compact versions to extensive, advanced drones employed in military, commercial, and scientific contexts. They provide benefits in delivery logistics, including expedited delivery times, enhanced efficiency, and reduced costs. Nonetheless, its effective execution encounters technological, regulatory, and safety obstacles.

Delivery constitutes a significant aspect of our daily existence. Efficient delivery logistics is essential in contemporary industry, acting as a vital connection between production and consumption. Nonetheless, obstacles such traffic congestion, complications in last-mile delivery, and the necessity for economical, eco-friendly solutions present considerable barriers. To resolve these challenges, there is an increasing necessity to construct and deploy Unmanned Aerial Vehicles (UAVs) specifically for delivery purposes. To tackle contemporary delivery issues, there is an increasing need for UAVs specifically designed for delivery purposes. These UAVs provide a carbon-neutral, traffic-evading solution that ensures swift and eco-friendly delivery. This study seeks to develop and execute a UAV tailored for short-range parcel delivery.

1.2 Heavy-lift UAVs for Delivery

The advancement of Unmanned Aerial Vehicles (UAVs) for delivery has emerged as a pivotal focus of research and development within engineering, possessing considerable potential for economic and societal influence. The advantages of utilizing recent technological breakthroughs to develop UAVs capable of safely and efficiently transporting items are substantial. Notwithstanding the difficulties inherent in developing UAVs for delivery, the prospective advantages are substantial. Utilizing the newest technological breakthroughs, it is feasible to develop UAVs that can securely and effectively transfer products between locations. The advancement of UAVs for delivery has emerged as a crucial focus in engineering research and development, possessing considerable potential for economic and societal influence.

The manufacturing process is not deemed complete until the goods have been delivered to the final consumer. While considerable focus is placed on improving manufacturing conditions and maximizing automation, equal attention must be given to the complexities of product logistics throughout its delivery to the ultimate consumer. The deployment of Unmanned Aerial Vehicles (UAVs) for delivery presents a revolutionary resolution to the previously described logistical issue. UAVs provide a rapid and eco-friendly solution for connecting manufacturers with end-consumers, thanks to their carbon-free operation and capacity to circumvent traffic bottlenecks. UAVs boost efficiency and minimize delivery times by adeptly traversing intricate urban environments and optimizing delivery routes. This breakthrough signifies a fundamental change in production logistics, guaranteeing the efficient and prompt delivery of goods while adhering to sustainability objectives.

1.4 Research Contributions

II. 2. LITERATURE REVIEW

Unmanned Aerial Vehicles (UAVs), generally known as drones, have emerged as a transformative technology with significant consequences across multiple domains. These aerial platforms have gained significant appeal owing to their versatile applications, including surveillance, environmental monitoring, disaster response, and package delivery. With the growing interconnectivity and reliance on technology, UAVs have emerged as vital instruments for enhancing efficiency, accessibility, and safety across several industries [1].

The incorporation of UAVs into daily operations and sectors demonstrates significant potential, prompting researchers and professionals to investigate several essential elements concerning their design, functionality, and efficiency. To fully harness the potential of UAVs, it is essential to comprehend the intricate network of subsystems that collectively facilitate their operation [2].

2.1FlightControl Systems for Unmanned Aerial Vehicles

The flight control system (FCS) of Unmanned Aerial Vehicles (UAVs) is crucial for maintaining stability, mobility, and safe operation. It consists of an amalgamation of hardware and software elements that jointly regulate the vehicle's conduct during flight. Essential elements comprise sensors for attitude determination, gyroscopes, accelerometers, magnetometers, and GPS modules. The sensors deliver real-time data to the flight controller, which analyzes the information to determine control inputs for the vehicle's actuators. The FCS must guarantee precise stabilization, altitude regulation, trajectory monitoring, and obstacle evasion to achieve successful payload delivery.

UAV flight control systems face challenges such as inclement weather, communication signal interference, and dynamic environmental influences, all of which can affect flight stability and control. To mitigate these issues, redundant sensor systems, fault-tolerant control algorithms, and adaptive control strategies have been suggested [3]. Furthermore, investigations have concentrated on formulating resilient control principles to guarantee UAV stability and efficacy in unpredictable and demanding environments [4]. With the increasing need for UAV delivery systems, researchers are investigating novel methods to improve flight control capabilities. This encompasses the investigation of energy-efficient propulsion systems [5].

2.1.1 Components of a Flight Control System

The flight control system of a delivery drone consists of several components such as GPS modules, accelerometers, gyroscopes, barometers, and magnetometers, which are used to measure and track the drone's position, velocity, altitude, and orientation. These components provide essential data to the drone's flight controller, which uses this information to make real-time adjustments to the drone's movement and keep it on course.

2.1.2 Classifications of Flight Control Systems

Flight Control Systems are classified based on the level of automation, the type of UAV they are used in, and the control system.

1. Manual Flight Control System: Requires a human operator to control the UAV's movements using a remote controller or a ground control station. This type of FCS is typically used in small UAVs, such as hobby drones, where the operator maintains direct line-of-sight with the UAV.
2. Autonomous Flight Control System: Relies on sensors, algorithms, and pre-programmed instructions to control the UAV's movements without direct human intervention. This type of FCS is commonly used in UAVs for delivery and other commercial applications.
3. Hybrid Control Systems: Combine manual and automated control systems to provide a flexible and adaptable approach to flight control, commonly used in military drones and other specialized aircraft.

2.2 Payload Systems

The payload system of UAVs is an essential element, comprising diverse equipment and cargo necessary for executing particular jobs or transporting items. The drone's payload configuration is customized to its mission objectives, including medical supplies delivery and extensive field surveys. Effective payload distribution requires meticulous route design, trajectory optimization, and precise release mechanisms. Researchers have concentrated on creating advanced payload attachment systems, modular payload configurations, and optimization algorithms to improve delivery efficiency while maintaining safety and accuracy.

Payload system design challenges encompass weight distribution, aerodynamic factors, and payload safeguarding during flight. Researchers have developed sophisticated structural optimization approaches, lightweight materials, and robust control algorithms to stable UAVs during payload operations in order to overcome these problems. Emerging trends influencing payload systems encompass the incorporation of artificial intelligence and machine learning for autonomous payload evaluation, secure payload compartments, and progress in energy-efficient propulsion systems. The payload types for UAVs are varied, encompassing image, communication, sensing, delivery, sampling, weaponry, and entertainment payloads, each designed for certain mission specifications and purposes. UAV delivery methods include many technologies and systems engineered for the precise and efficient transportation and discharge of payloads. These techniques encompass drop, winch, cable sling, parachute deployment, landing pads, winch-and-lower systems, and human-guided payload retrieval, each tailored to particular cargo attributes and delivery specifications. The selection of payload and delivery system is contingent upon particular mission goals and industry applications, underscoring the adaptability and potential of UAVs to transform diverse sectors.

2.3 UAV Propulsion System

The propulsion system is a crucial and complex component of Unmanned Aerial Vehicles (UAVs) designed for delivery tasks. It includes many mechanisms and technologies that work together to produce the necessary thrust, allowing the UAV to counteract gravitational forces and navigate through the air. Key elements of the propulsion system comprise engines or motors, propellers or rotors, and corresponding power sources, which function collaboratively to generate the necessary force. The efficiency, power output, and design complexities of this system substantially affect multiple performance indicators of the UAV, including flight capabilities, cargo capacity, range, endurance, and overall operating efficacy.

As UAVs increasingly play a crucial role in various delivery tasks, from medical supplies to consumer goods, ongoing advancements in propulsion technology are essential for the secure, accurate, and efficient execution of aerial delivery missions in diverse environments.

Chen and Wang [6] present an extensive assessment emphasizing power-to-weight ratios, energy efficiency, and thrust generation as critical factors in the field. They delineate the evolutionary path from traditional internal combustion engines to the emerging domain of electric propulsion, emphasizing its advantages in emissions reduction, enhanced mobility, and versatility for diverse mission requirements. Khan, Khan, and Rahman [2] thoroughly investigate the issues inherent in UAV propulsion systems, including complexities such as energy density, battery technology, and thermal management. They promote creative solutions, presenting insights into upcoming trends, such as hybrid propulsion systems and sophisticated energy storage technologies, thereby clarifying the future direction of propulsion paradigms. These studies provide a comprehensive understanding of the propulsion system's diverse functions in heavy-lift UAV applications. UAV propulsion systems serve as the foundation for precise, efficient, and ecologically sustainable airborne navigation.

2.2.1 Types of Propulsion Systems used in UAVs

Diverse propulsion systems are essential for powering Unmanned Aerial Vehicles (UAVs) in delivery applications, each designed for particular operating needs and mission profiles. These systems include a variety of technologies, from traditional internal combustion engines to advanced electric and hybrid-electric propulsion, each presenting unique benefits and challenges.

1. Internal Combustion Engines (ICE): Traditionally utilized in UAV propulsion, these engines have great power-to-weight ratios; nevertheless, they generate pollutants and noise, constraining their applicability in ecologically sensitive and noise-restricted regions.
2. Electric Propulsion Systems: Electric motors driven by batteries are gaining significance due to their efficiency, reduced emissions, and versatility, offering clean and quiet operation, which is especially advantageous for urban air transportation and short-range delivery missions [7].

Hybrid-Electric Propulsion: This system integrates electric and internal combustion engines to improve energy efficiency, expand range, and minimize emissions, allowing for the transition between power sources to maximize performance.

4. Solar-Powered Propulsion: Utilizing energy from sunlight via solar panels, these systems provide limitless endurance for prolonged missions, ideal for continual monitoring or surveillance activities.

The selection of propulsion type for the UAV is contingent upon payload, power specifications, and efficiency.

The Electric Propulsion System

In recent years, electric propulsion systems have been a favored and promising option for UAVs utilized in delivery applications, owing to their efficiency, precision, and environmental sustainability in aerial delivery operations [8].

2.3 The UAV Airframe

The airframe of an Unmanned Aerial Vehicle (UAV) serves as the cornerstone of flight, exemplifying engineering proficiency and incorporating aerodynamics, materials science, and design innovation [9]. It is essential for enabling UAV missions, such as delivery operations, and exemplifies the integration of innovation, robustness, and performance. Chen and Wang [6] investigate UAV airframe designs, highlighting the relationship between aerodynamics, structural integrity, and weight optimization, with specific emphasis on customized airfoil designs and the incorporation of innovative materials. These studies underscore the intricacy of UAV airframe design and its crucial function in facilitating effective and dependable UAV operations, hence advancing innovation and operational viability in heavy-lift UAVs.

In Multirotor UAVs, the significance of aerodynamics is somewhat limited owing to their flight characteristics. In contrast to fixed-wing UAVs, multi-rotors depend on rotor propulsion for both lift and maneuverability, as opposed to the aerodynamic lift produced by wings. Consequently, the design of the UAV's fuselage and arms prioritizes weight distribution, balance, and stability over aerodynamics [10]. Nonetheless, the design of Multirotor UAV bodies can influence their performance by minimizing drag and enhancing overall efficiency.

Aluminum, a multifaceted and extensively utilized material in aerospace engineering, is an advantageous option for UAV airframe fabrication owing to its numerous mechanical and structural benefits. This pick is supported by its exceptional combination of qualities that distinguishes it from other materials.

III. HEAVYLIFT UAV SYSTEM DESIGN

This chapter explores the fundamental components of our UAV design for delivery. This document examines the selected materials based on their strength and performance, as well as the sequential techniques employed to mold and construct these elements into a functional UAV. This chapter elucidates the behind-the-scenes procedure that actualizes our UAV, emphasizing how judicious material selection and adept techniques culminate in an effective delivery vehicle.

3.1 Materials

Significant emphasis is placed on the weight of the materials utilized in the manufacturing of the heavy-lift drone. This is implemented to mitigate the impact of the drone's weight on the total payload capacity. Therefore, it is advisable to utilize the lightest material alternatives in UAV development. The materials utilized in the development of the UAV for this project are delineated in Table 3.1 below:

Table 3.1 Octo-X Heavy-lift UAV Materials

S/N	Material	Quantity	Description
1	Carbon fiber Propeller 1755	8	1755 –17.5inch (diameter) x 5 inches (pitch) propellers
2	Red and Black 10AWG Silicone Wire	10 meters	High temperature resistant wire

3	5010 750KV Brushless DC Motors	8	Two motors per UAV arm for an Octo-X configuration
4	Radiomaster RP3 Diversity ExpressLRS Receiver	1	Radio receiver module
5	Power Distribution Board	1	Board to distribute power to entire UAV circuitry
6	Dji O3 Air unit	1	FPV camera and Video Transmitter
7	HolybroKakute H7 FC	1	Flight controller supports up to 8 motor PWM outputs needed for an octocopter
8	Holybro Tekko32 4in1 55A ESC	2	Electronic Speed Controllers containing four ESCs in one board. One ESC per motor, total of 8 ESCs
9	Matek Systems GNSS M10-5883 U-Blox GPS	1	Global positioning system module for flight stability and autonomous navigation
10	6S 20000mAh 25C batteries	2	Batteries are connected in parallel22.2V at nominal voltage

3.2 System Architecture

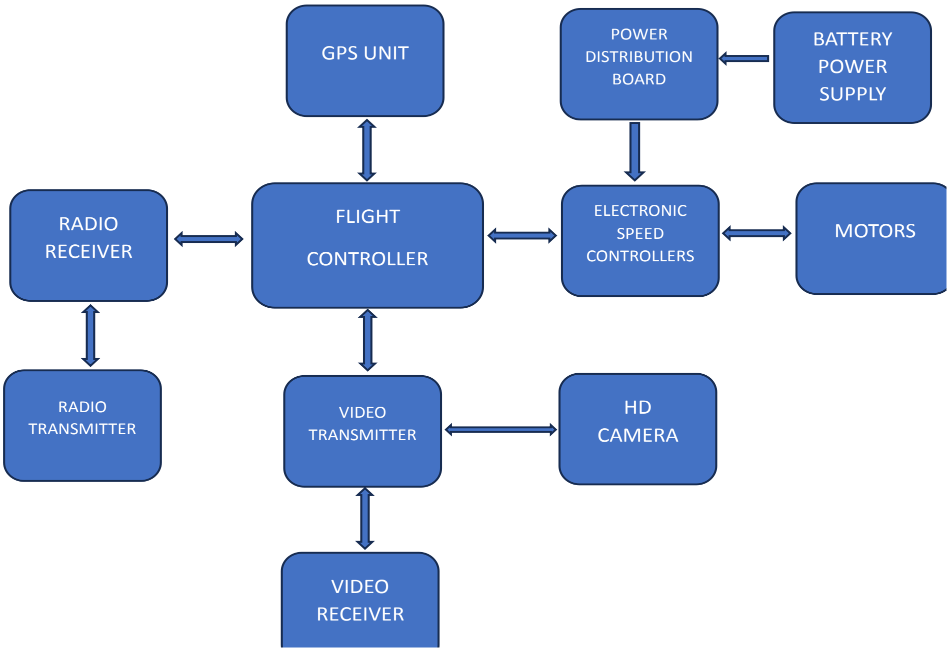

Fig 3.1: UAV Embedded System Architecture

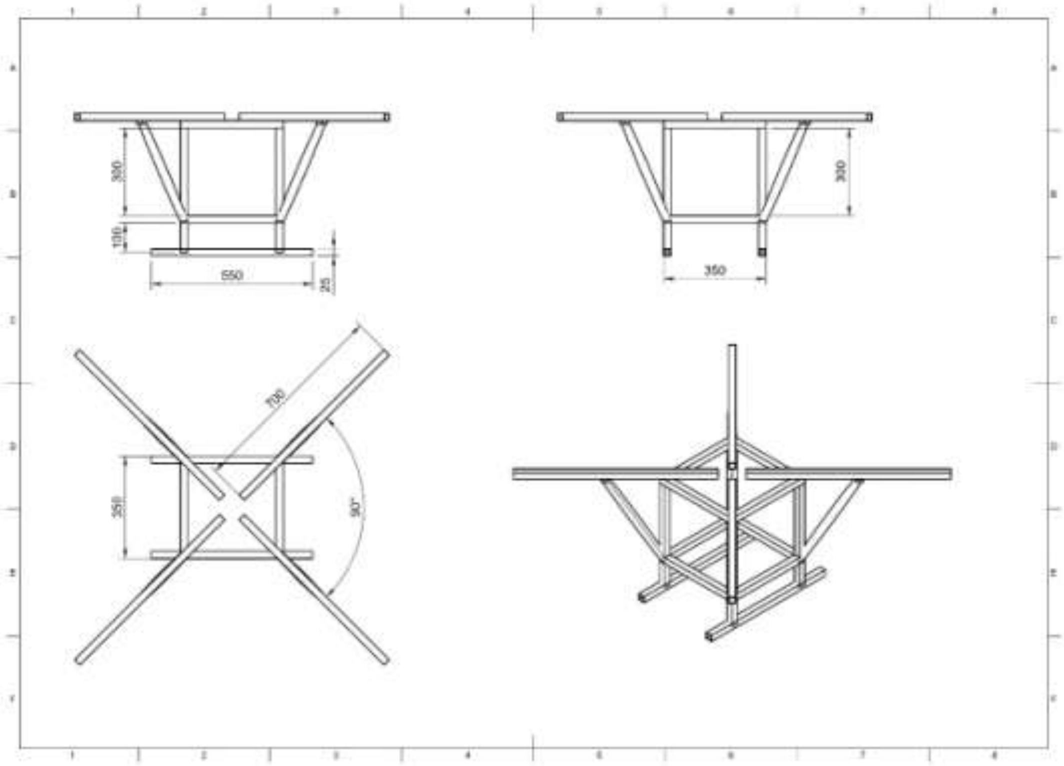

Fig 3.2: UAV CAD design withdimensions

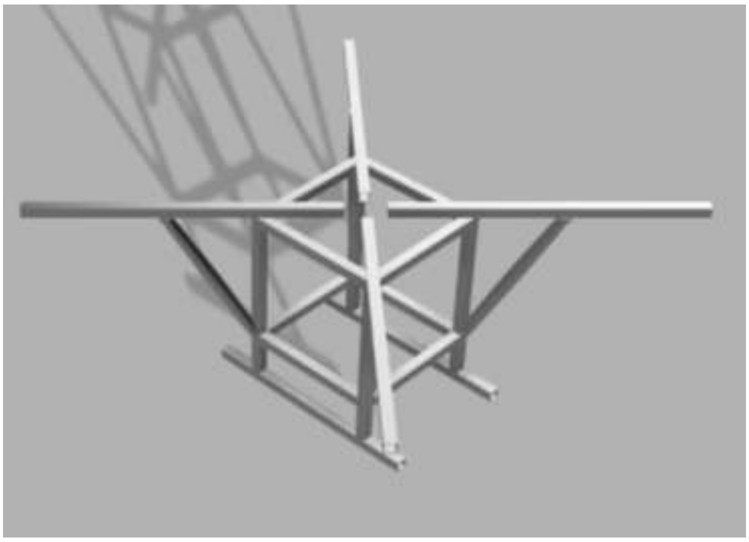

Fig 3.3: UAV Airframe 3D model

3.3SYSTEM CALCULATIONS

3.3.1 Thrust to Weight Ratio

To calculate the **thrust-to-weight ratio (TWR)** of your **Octo-X UAV**, follow these steps:

Step 1: Given Parameters

- **Configuration**: Octo-X (8 motors)
- **Motors**: 750 kV
- **Propellers**: 17x5.5 (1755)
- **Batteries**: Two **6S** (connected in parallel)
- **AUW (All-Up Weight)**: **7 kg** (including battery and all components)

Since the batteries are in parallel, the **voltage remains 6S (22.2V nominal, 25.2V fully charged)**, but the capacity (2 x 20000mAh) doubles.

Step 2: Estimating Thrust per Motor

To estimate thrust per motor, we need thrust test data for **750kV motors with 17x5.5 props on 6S**. Based on similar setups:

Voltage (V)	**Current (A)**	**Thrust (g) (per motor)**
22.2V (Nominal)	~30A	~2500g
25.2V (Full)	~35A	~2800g

We use **2.5 kg (2500g) per motor** as a safe estimate at **nominal voltage (22.2V)**.

Step 3: Calculating Total Thrust

Since there are **8 motors**, the total thrust is:

Total Thrust = 8×2500g = 20,000g = 20kg

3.1

Step 4: Calculating the Thrust-to-Weight Ratio (TWR)

$$\text{TWR} = \frac{\text{Total thrust}}{\text{AUW}} \quad 3.2$$

$$\text{TWR} = \frac{17429.44}{7000} = 2.86 \quad 3.3$$

Therefore thrust to weight ratio **TWR** = **2.86:1**

This value is ideal for liftoff with extra room for payload as the UAV produces more than twice more thrust than its own weight.

3.3.2 Maximum Power Output

Power output of one motor: P = V·I

Given that the motors are 1510 750kv, and a typical current draw under load is around 35A per motor.

$$P = 22.2V \times 35A = 777W \quad 3.4$$

Total power output of all 8 motors: $P_{total} = 8 \times 777 = 6216W$ 3.5

3.3.3Maximum Flight Time

Efficiency of multirotor drones typically ranges from 70% to 90%. We assume 80% efficiency for this calculation.Effective power consumption:

$$P_{effective}=P_{total}\times efficiency \quad 3.6$$

$$P_{effective}=6216\times 0.8=4972.8W\approx 5kW \quad 3.7$$

Now, we can estimate the maximum flight time using the battery capacity:

$$\text{Flight timet}=\frac{\text{Battery Capacity}}{\text{P}-\text{effective}} \quad 3.8$$

$$\text{Flight time t}=\frac{20\text{Ah} * 2}{5000}\approx 8 \text{ mins} \quad 3.9$$

This time is however expected to vary under load, environmental conditions, flight maneuvers, and other power losses.

3.4SYSTEM TESTS

3.4.1 Flight Stability Test

The aim of this test is to ensure the flight stability of the Heavy-lift UAV. This test is performed under no load conditions.

Test Procedure

1. Connect the UAV to Betaflight software and setup the black box configuration
2. Disconnect the UAV and power on the radio transmitter
3. Connect the battery to the UAV 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 Betaflight software
6. Retrieve the black box logs from the UAV and save in a specified folder on the PC
7. Perform impulse response tests on the logs using PID Toolbox software
8. Observe results and repeat steps 4 – 7 as necessary.

3.4.2Maximum Payload Lift Test

The UAV was tested to determine its maximum payload in hover position. The procedure is outlined as follows:

1. Perform preflight checks and make sure battery is fully charged
2. Start with a payload of 0.5kg (500g)
3. Arm the drone and take off about 2 meters above the ground
4. Hover for about 10 seconds and land
5. Repeat steps 1 – 4 with increments of 0.5kg to the payload until the drone can no longer take off
6. Record maximum payload for which the drone was able to liftoff and hover for 10 seconds.

3.4.3Maximum Flight time Test

The maximum flight time test was carried out under three scenarios as follows:

1. Maximum flight time on no load and moderate flight
2. Maximum flight time at 50% maximum payload from the payload test
3. Maximum flight time at 100% maximum payload from the payload test

Each of the scenarios is carried out in an open and controlled airspace (a football field) without unwanted human presence to ensure safety and observe regulations.

IV. RESULTS AND DISCUSSION

Figures 4.1a to 4.1d are images of the finished UAV

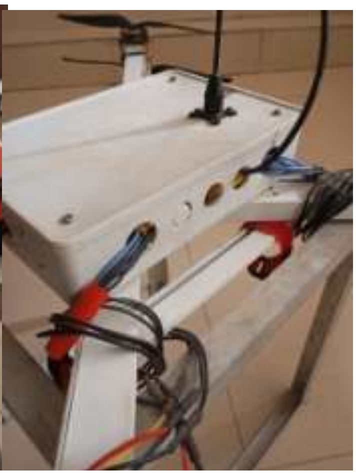

Fig 4.1a Parallel xt60 Connection Fig 4.1bElectronics housing

Fig 4.1c GPS module attached

Fig 4.1d X8 Motor mounting

4.1 Flight Stability Test Results

Figure 4.2 below show the flight stability test results. We consider only the roll and pitch axis as we do not use a lot of yaw input during flight, hence we have insufficient yaw data for PID tuning. The result shows that the UAV gyro attains critical stability at roll P = 45, I = 40, D = 54 with a feed forward value = 187, and pitch P = 47, I = 42, D = 55 with a feed forward value of 194.

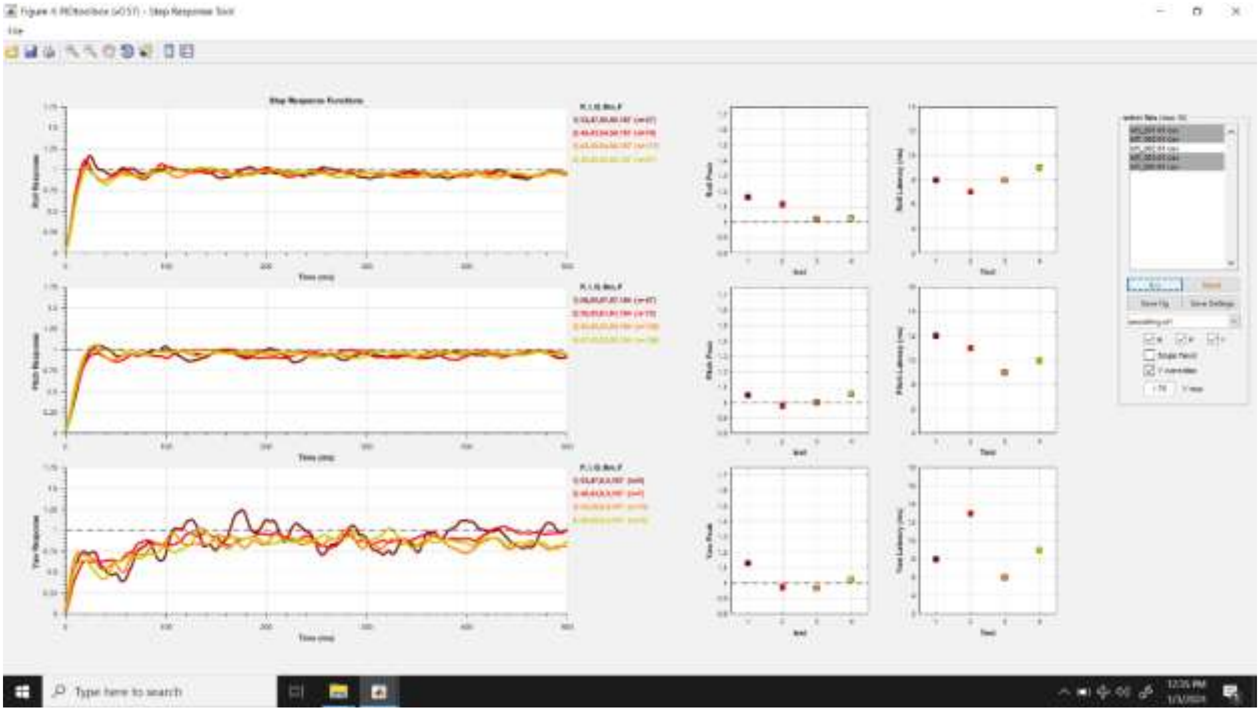

Fig 4.2. Flight Stability Test Result in PID Toolbox

4.2Maximum payload Lift Test Result

Results from the maximum payload lift test show the UAV was able to hover 2 meters above the ground for 10 seconds at a maximum load of 7kg. beyond this weight, the UAV struggled to take off. This result makes the UAV better suited for carry payloads such as cinema cameras which fall within this range and require agility on movie sets.

4.3Maximum Flight time Test Results

Below is the summary of results from the maximum flight time tests performed.

Table 4.1 Flight time Test Results

Test No	Test Description	Flight Time Recorded
1.	Max. flight time on no load and moderate flight	10 mins
2.	Max. flight time at 50% Max payload	6 - 7 mins
3.	Max. flight time at 100% Max payload	3 – 4 mins

The results show a decrease in flight time as payload increases just as expected. 50% payload (3.5kg) mark seems to be the most practical use case which gives up to 7 mins of flight time.

V. CONCLUSION

This research has effectively delineated the design and execution of an Unmanned Aerial Vehicle (UAV) tailored for medium to heavy-lift applications. A thorough literature review facilitated the selection of cost-effective and efficient components, while needs were assessed to design an appropriate airframe. Comprehensive evaluations were conducted on flying speed, stability, payload, and flight duration across various conditions, yielding a functional prototype that markedly decreases, carbon emissions, and facilitates access to previously unreachable areas. The establishment of a power system to fulfill energy requirements and a navigation system for secure autonomous delivery significantly improves the practicality and efficacy of the proposed UAV system.

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