Design and Implementation of a Remotely Operated Quadcopter with Integrated Image Capture for Surveillance Applications: A Case Study at the University of Nigeria, Nsukka

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Abstract: This paper details the design and implementation of a remotely operated unmanned aerial vehicle (UAV), specifically a quadcopter, integrated with image capture capabilities. Driven by Nigeria's over-reliance on foreign expertise and technology for drone applications in both civilian and military sectors, this project aimed to demonstrate a viable pathway for indigenous drone development using locally sourced materials where feasible. The methodology involved hardware selection based on empirical and mathematical analysis, software implementation for flight control using a PID controller, and the integration of a wireless transceiver system for remote operation. This document presents the design rationale, system architecture, and control principles, offering a foundational module for future enhancements in remote sensing, flight autonomy, and payload integration within the Nigerian context.

Keywords: *Unmanned Aerial Vehicle (Uav), Quadcopter, Indigenous Technology, Surveillance, Nigeria, Boko Haram, Pid Controller, Artificial Intelligence, Sensor Fusion, Drone Autonomy.*

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I. INTRODUCTION AND BACKGROUND

An unmanned aerial vehicle (UAV), commonly known as a drone, is an aircraft that operates without a human pilot onboard. Its flight is controlled either autonomously by onboard computer systems or via remote control from a ground station [1]. Drones are categorised based on their application, primarily falling into recreational, civilian/commercial, and military uses. Recreational drones serve hobbyist purposes, while civilian models are increasingly deployed for commercial applications such as infrastructure surveillance, goods delivery, and environmental monitoring. Military drones are employed for strategic operations, including reconnaissance, surveillance, and armed engagement [2], [3].

The core of this project lies in the integration of image capture and remote guidance technology. A drone functions as an integrated system of technologies [1]. Remote piloting relies on robust wireless transmissions, while modern autonomous systems often incorporate Internet of Things (IoT) devices and sophisticated algorithms for navigation. Image capture, enabling the collection of visual data, is dependent on the vehicle's payload capacity [4]. Advances in camera technology have facilitated equipping smaller drones with lightweight, high-definition cameras capable of object tracking and infrared surveillance.

The foundational technologies for UAVs—including motors, propellers, microcontrollers, and sensors—have existed for decades, with the specific configuration dictated by intended function [3], [4]. While the global history of UAVs is extensive, this research focuses on the specific context driving drone development within Nigeria.

The push for indigenous drone technology in Nigeria is intrinsically linked to the nation's pressing security challenges, including armed violence and insurgencies. The Nigerian government has identified advanced technology as a critical tool for enhancing national security, with President Bola Tinubu issuing a direct challenge to universities in early 2025 to focus research and development on producing security devices, particularly drones, for military and security agencies [5]. This directive underscores a strategic shift towards fostering local solutions, recognising that over-

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reliance on foreign technology is both costly and unsustainable.

This governmental impetus has been met with a surge of innovation from Nigerian universities and young engineers. Before this formal directive, students and hobbyists across the country demonstrated initiative, with notable examples including a LAUTECH student who built and flew a drone [6] [7], Federal University of Technology, Owerri (FUTO) students designing a campus surveillance drone [8], and Federal University of Technology, Akure (FUTA) students constructing a drone for project purposes [9]. The project by Egbujor *et al.* from Imo State University in 2021, which details the design and construction of a surveillance drone, further exemplifies these indigenous efforts [10]. Their work focused on a vertical take-off vehicle capable of sending visual feedback via a video transmitter, integrating electronic components and sensors for steady flight, and configuring an ArduPilot microcontroller with Mission Planner software. Key features included a calibrated compass, accelerometer, ESCs and radio-control systems, with the drone modelled in SolidWorks 2015. It demonstrated stable video surveillance and the ability to attain a height of 10 m. These early projects, similar to the one detailed in this paper, often began with the goal of solving a local problem or proving that complex technology could be built indigenously. However, unlike most prior implementations that rely on commercially available frames and preprogrammed control units, our approach constructs these critical components entirely from scratch.

These grassroots initiatives—frequently showcased on social media, in tech publications, and on television—underscore Nigeria's widespread enthusiasm and foundational aerospace engineering aptitude [11-13].

The ecosystem is evolving towards more structured, collaborative ventures, exemplified by the inauguration of the University of Lagos (UNILAG) and Nord Automobile Assembly Plant, a partnership aimed at manufacturing drones, among other technologies [14]. This collaboration signifies a critical step towards commercialisation and scaling production, bridging the gap between academic research and industrial manufacturing, and reflecting a maturing innovation landscape. Therefore, the development of drone technology in Nigeria is not merely an academic exercise but a national response to urgent security needs, fuelled by local talent and increasingly supported by strategic government and industry collaboration.

This paper details the design, implementation and initial testing of a quadcopter prototype, demonstrating a practical approach to indigenous drone development. The subsequent sections will elaborate on the problem statement, project objectives and scope, detailed methodology, experimental results and a discussion of findings, leading to conclusions and recommendations for future work.

II. PROBLEM STATEMENT

Nigeria has historically faced significant technological dependency, particularly in drone development and production. As of 2016, the assembly, programming and operation of UAVs for critical business and security functions were predominantly handled by foreign experts [5]. This over-reliance on external capabilities has limited local innovation and capacity building, creating a substantial gap in technological self-sufficiency. Our project addresses this gap by constructing a functional quadcopter primarily from locally sourced materials, thereby demonstrating the feasibility of homegrown solutions and fostering indigenous engineering talent.

Beyond the general aim of leveraging local resources, the nation's pressing security challenges—especially the Boko Haram insurgency in Northern Nigeria—demand advanced surveillance and security solutions [5].

III. AIMS AND OBJECTIVES

The primary goal of this project was to design and build a drone that bridges recreational and surveillance applications. The specific objectives were to:

- Construct a quadcopter capable of stable flight and image capture.
- Develop a remote-control system for the drone operated from a computer-based ground station.
- Provide comprehensive documentation to serve as a technical guide for future projects and improvements.
- Create a modular platform that allows for future enhancements to its remote sensing, flight, and imaging capabilities.

IV. PROJECT SCOPE

The project's scope was defined by practical constraints, including budget and available technology. The design targeted a maximum altitude of 10 meters with line-of-sight wireless communication. A quadcopter configuration was chosen for its balance of stability and cost-effectiveness compared to more complex hexa- or octa-copter models. The solution involved adopting a "cross" quadcopter module, utilising a locally sourced aluminium frame, XBee Trans-receiver for wireless communication, Arduino Uno as the microcontroller, and a PC for video display and control via Java programming language and Java API with a gamepad.

V. METHODOLOGY

The project was systematically structured into several stages: system architecture design, schematic development, material selection, hardware implementation, and software implementation for flight control.

➢ *System Architecture and Design*

The overall system comprises two main sections: the Quadcopter Controller and the Ground-Base. A simplified schematic illustrates the component integrations and communication pathways.

- *Quadcopter Controller:*

The Arduino Uno serves as the brain of the system, mounted on the quadcopter frame with an XBee shield [17]. A tri-axis L3G4200D gyroscope connects to the Arduino via I²C to provide real-time angular-rate feedback [18]. Four Electronic Speed Controllers (ESCs) compensate for motor voltage drop and independently regulate each brushless motor. A 3-cell LiPo battery supplies power to both the Arduino and the gyro. A First-Person View (FPV) camera is also integrated.

- *Ground-Base:*

A PC acts as the ground station, housing a transmitter mounted on an Arduino at one port and a gamepad at the other end for control. The PC receives data from the quadcopter, including video feedback via a transmitter integrated alongside the camera.

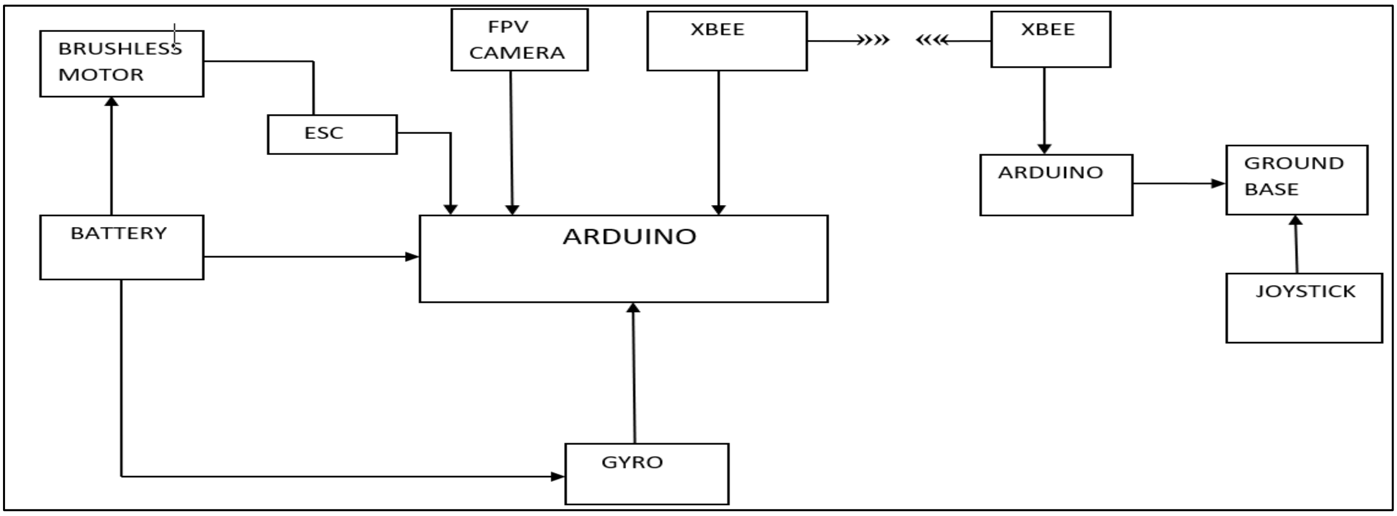

Fig 1 System Block Diagram Showing Quadcopter and Ground Station Communication

➢ *Hardware Selection and Implementation*

Material selection involved empirical and mathematical analysis, sticking to the original implementation carried out in 2016.

- *Frame Selection:*

A custom-made aluminium frame was chosen for its lightweight properties. The centre of mass was derived using a simple pontoon idea by attaching a string to the hub's centre and allowing the quadrotor to float freely. Battery packs were adjusted below the central hub to ensure balance in the x and y axes.

- *Propeller Selection:*

Carbon fibre was selected for the propellers based on natural frequency theory, by comparing the natural frequency of the propellers with that of the quadcopter, which is defined for the vortex shedding frequency. The Strouhal number (**S_t**) was used to determine the vortex shedding frequency of the propeller:

$$f_{shed} \approx St \times V / L \qquad (1)$$

$$S_t \approx \frac{(f \times L)}{V}$$

The Strouhal number is an experimentally determined quantity of 0.2, and the characteristic length (L) is analytically determined from propeller thickness and chord length multiplied by the sine of the angle of attack (thickness or chord × sin α) [20]. To determine the natural resonance frequency of the propellers, they were assumed as rigid bodies with carbon fibre spars representing cantilever beams with one free end and one fixed end. The effect of the propeller force on the spar was then determined:

The natural resonance frequency of a cantilever beam (representing the carbon fibre spar) is mathematically represented as:

$$f_n = \frac{\lambda_n^2}{2\pi L^2}\sqrt{\frac{EI}{\rho A}} \qquad (2)$$

where fn is the natural frequency for the n-th mode, λn is a dimensionless constant (e.g., for the fundamental mode λ1≈1.875), L is the effective length of the spar, E is the modulus of elasticity, I is the second moment of area, A is the cross-sectional area, and ρ is the density. By carbon fibre being lightweight and stiff means the term ρA will be small and E will be large, resulting in E/(ρA) being large, which invariably increases the frequency. Hence, resonance is avoided by ensuring the propeller's frequency is higher than the vortex shedding frequency.

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- *ESC Selection:*

A 30A ESC was chosen because the **maximum continuous discharge current** the battery can safely deliver is given by:

$I = C \times R_{mah}$---(3)

Where C is a dimensionless multiplier that rates how fast it can discharge in relation to its battery capacity, $\boldsymbol{R_{mah}}$.

The **Lithium Polymer battery** chosen is a 25C battery with a 10000mAh rating, and the drawn current was calculated as

$$\boldsymbol{I} = 25 \times 10000 = 250000\text{mah} = 250\text{A}$$

Since four 30A ESCs were used, totalling 120A, the 250A battery capacity was deemed sufficient. The battery is a 3-cell, 3.7V type.

- *The Hardware Components Utilised in the Project are Listed Below:*

✓ **Transmitting Section:** 2.4GHz XBee transmitter, 5.8GHz Transmitter

✓ **Sensory Section:** GYRO L3G4200D (5V), FPV HD camera (12V)

✓ **Receiving Section:** X-bee receiver (2.4 GHz), 5.8 GHz RC832 AV Camera Receiver with 4 channels, USB capture

✓ **Controller Section:** Arduino Uno, X-bee shield, XBee breaker board, 30A Opto ESC for multi-copters

✓ **Base Station:** Computer

✓ **Monitoring Section:** Computer

- *Power Supply (5 volts) Section:*

220Vac/12Vdc transformer, Bridge rectifier IC, 2200µF/25V electrolyte capacitor, Four diodes (full bridge rectification), Resistors (1kΩ), Choke resistor, Mica capacitor The physical circuit connection of hardware components with the Arduino code ensured lift for flight tests. An illustrative circuit diagram for the Arduino Uno connections to the gyro and ESCs is provided below.

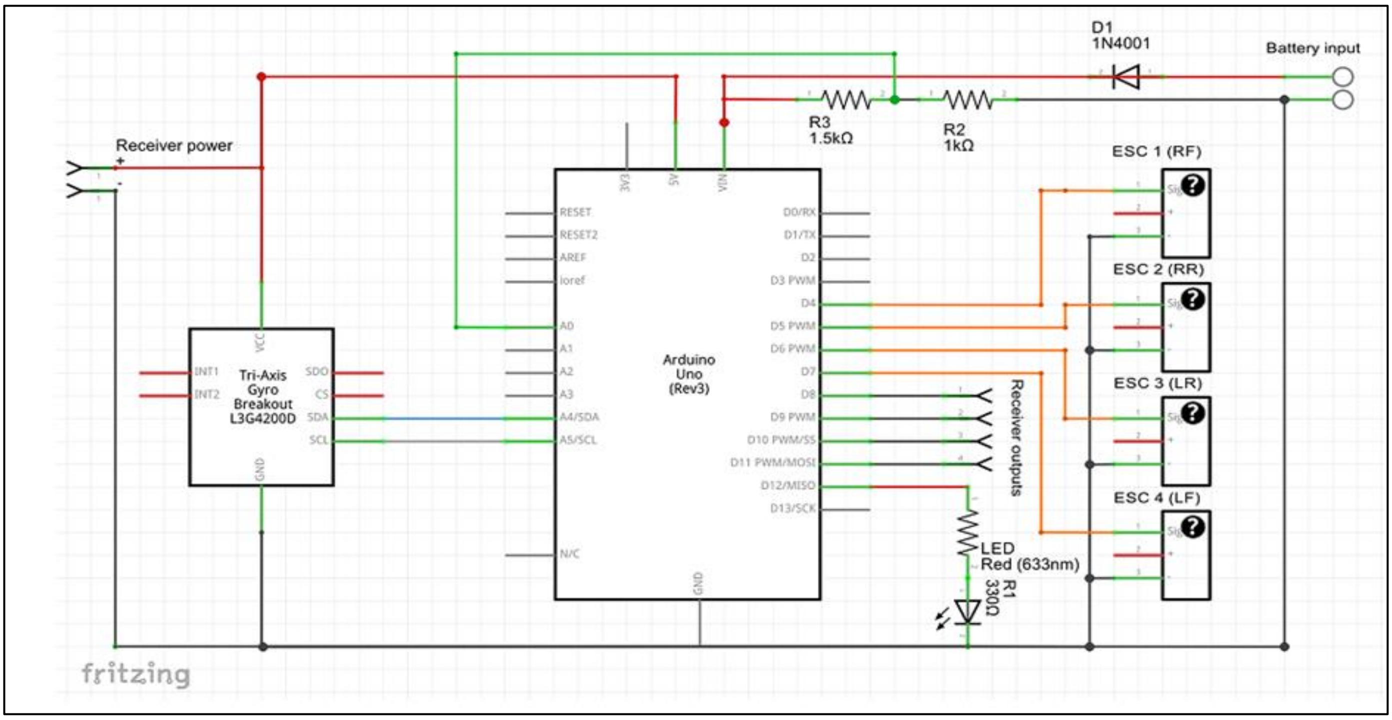

Fig 2 Arduino Uno Circuit Connections [15]

- *Power Supply and Protection Battery Input:*

The circuit is powered by a LiPo battery, which provides the necessary voltage for the motors and electronics.

✓ *Diode (D1):*

A 1N4001 diode is placed at the battery input to prevent reverse polarity. If the battery is connected incorrectly, the diode blocks the current, protecting the circuit.

✓ *Voltage Divider (R2 and R3):*

These resistors form a voltage divider to scale down the battery voltage to a level that the Arduino can safely read. This allows the system to monitor the battery voltage and prevent over-discharge.

✓ *Microcontroller (Arduino Uno):*

The Arduino Uno serves as the brain of the system. It processes sensor data, runs the control algorithms (like PID), and generates PWM signals to control the motors.

✓ *PWM Outputs:*

Digital pins 6, 9, 10, and 11 are configured to output PWM signals. These signals are sent to the ESCs (Electronic Speed Controllers) to control the speed of the motors.

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✓ *Electronic Speed Controllers (ESCs):*

The ESCs are connected to the Arduino via the PWM pins. They act as power amplifiers, taking the low-power PWM signals from the Arduino and using them to control the high-power current supplied to the brushless motors. Each ESC is connected to one motor, and the four ESCs correspond to the four motors of the quadcopter.

✓ *Gyroscope (L3G4200D):*

The L3G4200D is a tri-axis gyroscope used to measure angular velocity (how fast the quadcopter is rotating around its axes).

✓ *I²C Communication:*

The gyro communicates with the Arduino via the I²C protocol using the SDA and SCL lines. This allows the Arduino to receive real-time data about the quadcopter's orientation and movement.

✓ *Indicator LED:*

An LED is connected to the circuit via a current-limiting resistor (R1). This LED indicates that the system is powered and operational.

✓ *Ground Connections:*

All components share a common ground, ensuring a stable reference voltage for the entire system. The ground connections from the battery, Arduino, ESCs, gyro, and other components are tied together to form the ground bus.

✓ *System Operation Power Distribution:*

The battery provides power to the ESCs for the motors and to the Arduino for the control system. The voltage divider monitors the battery level.

✓ *Sensor Input:*

The gyro measures angular velocity and sends this data to the Arduino.

✓ *Control Algorithm:*

The Arduino processes the gyro data and calculates the necessary adjustments using a PID control algorithm to maintain stability.

✓ *Motor Control:*

The Arduino sends PWM signals to the ESCs, which adjust the speed of the motors to achieve the desired orientation and movement.

➢ *Software Design and Control System*

The stability of the quadcopter is modelled by simulating three distinct movements: Yaw (Left or Right), Roll (Tilt and turning), and Pitch (Up or down).

The generalised coordinates for a rotorcraft are:

Q = (x, y, z, θ, φ, ψ) [16]

Where (x, y, z) denote the position of the centre of mass of the rotorcraft relative to the frame, and (θ, φ, ψ) represent the three Euler angles that indicate the craft's orientation [16].

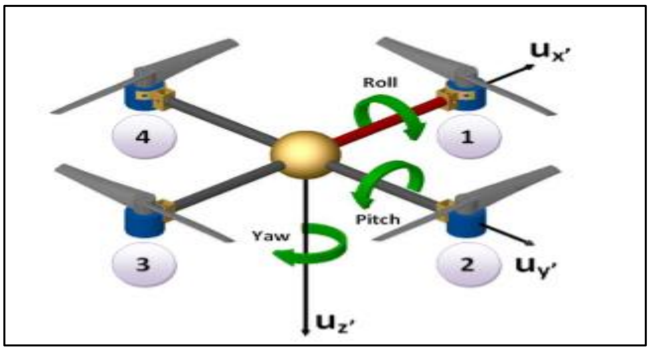

Fig 3 Axis of Rotation of a Quadcopter [16]

The essence of the control system is to compensate for angular rotation deviations (errors) to maintain quadcopter stability. This is achieved using a PID (Proportional-Integral-Derivative) controller, mathematically represented as:

$$w(t)=K_p\,e(t)+ K_i\int_0^t e(\tau)d\tau+K_d\,d/dt\,e(t) \text{ ---------------------(4)}$$

- *In Simpler Terms, the PID Components are Calculated as [15]:*

✓ **Proportional:** P-output = (gyro-receiver) × P_{gain}

✓ **Integral:** I-output = (I-output + (gyro-receiver)) x I-gain

✓ **Derivative:** D-output = [(gyro-receiver) - ($gyro_{prev}$ – $receiver_{prev}$)]x D_{gain}

The proportional section quickly compensates for wobbling, while the integral section compensates at a slower rate. Since both P and I can overcompensate without friction, the derivative controller provides friction to prevent excessive angular change, keeping the quadcopter stable.

- *The Basic Program Algorithm Implemented for the Microcontroller Involves the Following Steps [15]:*

✓ *Receive Receiver Input:*

Input from the remote-control receiver is processed via an interrupt subroutine.

✓ *Read Gyro Data:*

Angular rate data is continuously read from the gyroscope (L3G4200D). The gyro communicates with the Arduino via the I²C protocol, providing real-time data on the quadcopter's orientation and movement [19].

✓ *Calculate PID Corrections:*

The Arduino processes the gyro data and calculates the necessary adjustments using the PID control algorithm [15].

✓ *Calculate ESC Pulses:*

Based on the PID corrections, the required Pulse Width Modulation (PWM) signals for each Electronic Speed Controller (ESC) are calculated.

✓ *Compensate for Voltage Drop:*

Each pulse is compensated for any potential voltage drop, ensuring consistent motor performance.

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✓ *Send Pulses to ESCs:*

The calculated PWM signals are then sent to the ESCs, which in turn adjust the speed of the motors to achieve the desired orientation and movement.

The Arduino works with a basic structure of variable declaration, void setup(), and void loop() [17]. For enabling interrupts, the Pin Change Interrupt Control Register (PCIR) is used. Setting the Pin Change Interrupt Enable 0 bit within PCIR enables the Pin Change Mask Register 0, allowing changes in states of Pins 0 to 7 to cause an interrupt [17]. Once enabled, a subroutine for the pins is initiated.

For gyro communication, I^2C communication is used, with the Arduino Uno behaving as a slave to the gyro. The gyro's address is 105 in decimal notation [18], as specified for the L3G4200D. Control registers 1 (CTRL-REG1) and 4 (CTRL-REG4) are used for I^2C communication.

- *CTRL-REG1 (20h):*

PD Zen Yen Xen. PD (power mode) is enabled, and Zen, Yen, Xen are set to 1 to enable all three axes of the gyro.

- *CTRL-REG4 (23h):*

BDU BLE FS1 FS0 - ST1 ST0 SIM. The BDU (Block Data Update) bit is set to 1, ensuring that MSB and LSB must be read before the gyro reading is updated [18].

The angular rate value of the gyro is given in 16-bit form by combining two 8-bit registers for X, Y, and Z axes (OUT_X_L, OUT_X_H, etc.).

A snippet of the Arduino code for ESC initialization and motor startup is shown below;

```
#include <Servo.h>
Servo esc1; Servo esc2; Servo esc3; Servo esc4;
int escPin1 = 6; int escPin2 = 9; int escPin3 = 10; int escPin4 = 11;
int minPulseRate = 1000; int maxPulseRate = 2000; int throttleChangeDelay = 50;
void setup() {
  Serial.begin(9600);
  Serial.setTimeout(500);
  initEscs();
}
int a =0;
void loop() {
  if(a==0) {
    delay(2000);
    startUpMotors();
    a = 1;
  }
}
void initEscs() {
  esc1.attach(escPin1); esc2.attach(escPin2); esc3.attach(escPin3);
esc4.attach(escPin4);
  writeTo4Escs(0); // Init motors with 0 value
}
void startUpMotors() {
  writeTo4Escs(1500);
}
void writeTo4Escs(int throttle) {
  esc1.write(throttle); esc2.write(throttle); esc3.write(throttle); esc4.write(throttle);
}
```

Note: The full Arduino code and relevant ATMEGA 328 and L3G4200D datasheets are available for further reference.

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➢ *Experimental Setup and Testing*

The error correction for the PID controller was simulated by setting the PID gain to 1. The resulting data and plots are presented in the Results section. Flight tests were conducted to assess the quadcopter's lift capabilities and image capture functionality.

VI. RESULTS

The error correction simulation, with PID gains set to 1, yielded the following graphical results. The raw data for these plots can be found in Appendix 1.

➢ *PID Component:*

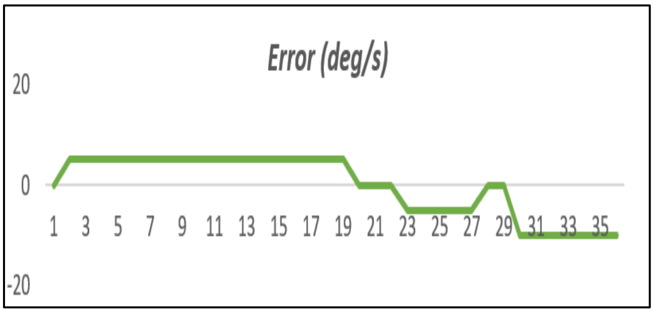

Fig 4 Error Graph for PID Correction

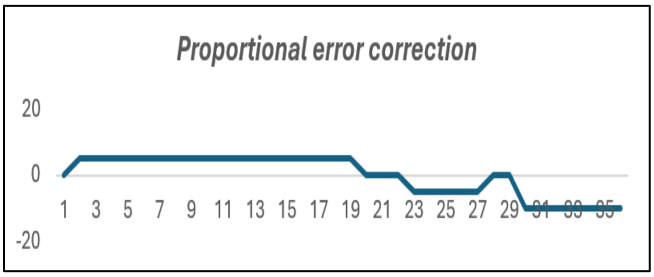

Fig 5 Proportional Controller Correction

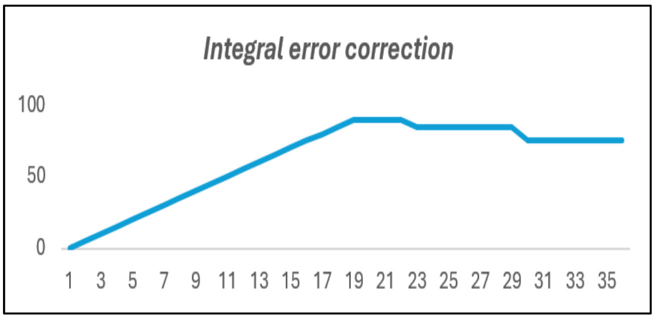

Fig 6 Integral Controller Graph

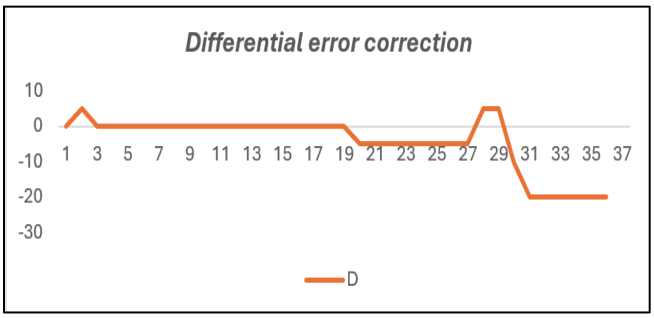

Fig 7 Derivative Controller Graph

In terms of physical implementation, the quadcopter was successfully constructed and demonstrated readiness for flight testing.

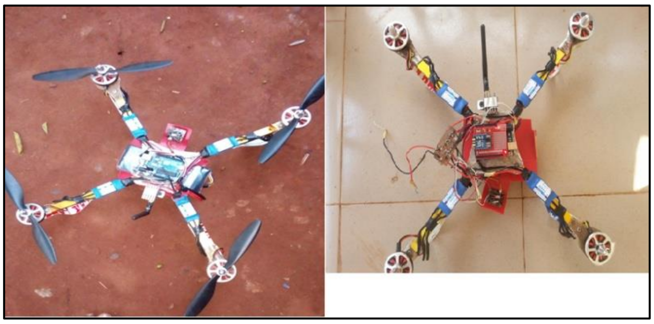
Fig 8: A) Quadcopter Ready for First Flight; B) Quadcopter during Further Development

The project achieved video capturing capabilities with a camera that demonstrated good resolution, providing a viable starting point for building multi-copters with video capturing in the UNN community. The quadcopter was able to lift off the ground to about 1 metre by setting the throttle at 1500 µs.

VII. DISCUSSION

The loop time for the readings recorded (see Appendix 1) is 4 µS, corresponding to the Arduino Uno's refresh rate of 250Hz. Arbitrary numbers were chosen to simulate instability in the PID plots. The first graph (Figure 4) shows the difference between the gyro reading and the receiver input, representing the error that the PID controller works on to stabilize the quadcopter. Even when the pilot intends no movement, air turbulence prompts angular rotation, resulting in a non-zero gyro reading and an offset.

The proportional controller plot (Figure 5) mirrors the error plot when the proportional gain is set to 1. Simulation on a test stand showed that the proportional controller keeps rotations about a centralized position in a frictionless manner, leading to overcompensation.

The integral controller plot (Figure 6) shows an increase when the error is positive and a decrease when it is negative. On a test stand, the I-controller repels rotational movements in a frictionless but slower fashion compared to the P-controller. Its oscillation about a mean position is much slower due to its value slowly increasing or decreasing, also leading to overcompensation.

The derivative controller plot (Figure 7) reacts only to changes in error. When simulated, it stalls the overcompensation of the other controllers by showing resistance to movements, acting as inertia to prevent excessive angular change. However, as throttle speed increases, its effectiveness in slowing down diminishes.

Despite the successes, several challenges were encountered during the project. The camera transmitter exuded significant heat, necessitating the formation and incorporation of a heat sink using corrugated aluminium sheet

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into the design. A major challenge was the faulty gyroscope, which could not be replaced due to cost and project timeline constraints, consequently preventing the full implementation of the PID correction in the physical quadcopter. During flight tests, three propeller blades broke, which were partially repaired with superglue, though one remained chipped. Furthermore, issues with loading the gyro code suggested a faulty Arduino, which was later confirmed and replaced.

The project successfully demonstrated video capturing capabilities and the ability for the quadcopter to lift off. However, the inability to fully implement and test the gyroscope and fine-tune the PID controller limited the demonstration of advanced stability features. This aligns with typical initial prototypes in indigenous development, where resource constraints can impact full realization. The project, despite these hurdles, served as a proof-of-concept for local manufacturing and problem-solving, aligning with the national objective of self-reliance in drone technology. The successful lift-off and image capture capabilities confirm the foundation laid for future iterations.

VIII. CONCLUSION AND RECOMMENDATIONS

This project successfully demonstrated the feasibility of constructing a functional quadcopter for surveillance applications using a combination of locally sourced and imported components. It serves as a foundational proof-of-concept, affirming that with the right skills and resources, indigenous drone development is achievable within the Nigerian context. The project aligns with the current national strategic priority of building local capacity in security technology. Although challenges such as a faulty gyroscope prevented the full implementation of the PID controller in the physical prototype, the project achieved its primary objectives of stable flight and image capture capabilities, laying a robust groundwork.

➢ *Recommendations for Future Work:*

Based on the findings and limitations of this project, the following recommendations are proposed for future iterations:

- *Advanced Control Systems:*

Future work should incorporate a more robust mathematical model for the drone's frame and flight dynamics. Moving beyond empirical analysis to advanced control engineering principles will allow for improved performance and autonomy, such as robust, adaptive or intelligent control laws, which will yield improved performance and autonomy [20]. This involves refining the PID control algorithm and exploring adaptive or intelligent control techniques that can dynamically adjust to environmental conditions and payload changes. Universities can lead research into novel control algorithms tailored for local environmental conditions and resource constraints.

- *Extended Endurance and Advanced Power Systems*

Current battery-powered multi-copters are limited by the low energy density of existing battery technologies, with batteries often constituting a high proportion of the total weight and limiting flight time to barely 4 hours [21]. Future work should explore solutions for extended endurance, such as:

- *Battery Multi-Stage Separation:*

This method involves sequentially disconnecting and discarding used batteries during flight to gradually reduce weight, similar to how aircraft burn fuel. This can significantly improve endurance, with studies showing improvements of over 12.5% to 130.7% depending on the drone's weight [22].

- *Solar-Battery Hybrid Systems:*

The integration of solar cells with batteries offers a promising solution for long-endurance applications. While only a limited number of solar-augmented UAV systems have been developed, this hybrid approach can significantly extend flight duration by continuously recharging batteries during daylight hours [23].

- *Fuel Cells:*

Research into fuel cell technologies for drones can provide higher energy density compared to traditional batteries, enabling much longer flight times for critical missions [24].

Nigerian universities, particularly those with strong engineering and chemistry departments, can research and develop more efficient and locally adaptable power solutions, including advanced battery chemistries and solar integration techniques.

- *Sensor Fusion:*

To significantly improve flight stability and autonomy, upgrade the sensing suite to fuse gyroscope and accelerometer data. An accelerometer offers gravity-referenced orientation, while the gyro captures rapid rotations; combining both via a Kalman or complementary filter delivers drift-free attitude estimates crucial for dynamic environments. Adding magnetometers, barometers and GPS will further enhance situational awareness and enable complex autonomous missions [25]. University research can focus on developing cost-effective sensor fusion modules using readily available components.

- *Achieving Project Milestones:*

Further dedicated effort is required to fully implement and test the gyroscope and fine-tune the PID controller for optimal stability. This includes rigorous testing in various conditions to perfect the remote-control interface for reliable in-flight operation, thereby fully realizing the initially intended functionalities of the prototype. Addressing the challenges related to component reliability and replacement, as experienced with the faulty gyroscope and Arduino in this project, is also crucial for robust development. Universities can establish dedicated drone testing facilities to facilitate rigorous validation and iteration.

- *Enhanced Autonomy and Real-time Processing*

Investigating the integration of Global Positioning System (GPS) for automated control is a vital future direction, moving beyond purely manual control to semi-autonomous or fully autonomous flight for diverse applications. This would enable waypoint navigation, automated mapping, and precise payload delivery. Advancements in Artificial Intelligence (AI) and Machine Learning (ML) are transforming drone autonomy, allowing for intelligent systems capable of complex data analysis and autonomous operation [26]. The global market for AI in drones is projected to reach US$55 billion by 2032, driven by increased automation and efficiency in sectors like military, defence, delivery, and logistics [27]. AI-powered surveillance systems are enhancing public safety and enabling real-time threat detection, facial recognition, and automated alerts [28].

To support increased autonomy and data processing, the adoption of edge computing solutions for drones is highly recommended [29]. Traditional cloud computing introduces high latency, which is problematic for delay-sensitive applications [29]. Edge AI enables real-time decision-making directly on embedded systems onboard the drones, enhancing responsiveness, safety, and computational efficiency in urban logistics and dynamic environments [30]. This approach can significantly reduce path replanning time and improve obstacle-avoidance accuracy [30]. However, it is important to note that utilizing drone-based computing power can significantly drain UAV batteries, reducing flight time. Therefore, a hybrid framework leveraging Edge AI for local decision-making while maintaining synchronization with cloud systems for global updates could be an optimal solution. Nigerian universities therefore can establish research groups focused on developing and optimizing edge AI algorithms for drone applications, leveraging local talent and computational resources.

- *Swarm Intelligence and Cooperative Systems*

The development of drone swarm intelligence and cooperative systems represents a frontier in UAV technology. Swarms of UAVs are envisioned to transform fields from emergency response to military operations, offering scalable, adaptable, and decentralised solutions for dynamic environments [26], [31]. These systems can enhance coverage, scalability, and redundancy for tasks such as surveillance, mapping, environmental monitoring, and tactical missions [26]. Enhanced algorithms enable autonomous agents to make collective decisions, self-organise, and adapt to environmental variables without centralised control, which is particularly critical in mission-critical applications like search and rescue or disaster response [26]. The global swarm robotics market, with UAVs as a dominant platform, is projected to reach US$9.44 billion by 2033, underscoring the immense potential of coordinated aerial systems [32]. Universities can initiate interdisciplinary projects to explore swarm algorithms and their practical applications in local contexts, such as agricultural monitoring or disaster relief.

- *Counter-Drone Technology*

As drone technology advances, so does the need for robust counter-drone measures, especially in security contexts. Future research should consider advancements in counter-UAV efforts, including high-power laser systems capable of precision targeting [33]. The increasing procurement notices related to counter-drone technology by government authorities indicate a growing global focus on mitigating threats posed by unauthorised or hostile drones [33]. Understanding these defensive measures is crucial for a holistic approach to UAV development in national security applications. Nigerian universities can contribute by researching and developing cost-effective, locally deployable counter-drone solutions in collaboration with defence and security agencies.

By pursuing these recommendations, indigenous drone development in Nigeria can move beyond foundational prototypes to advanced, autonomous, and long-endurance systems, significantly contributing to national security, economic development, and technological self-reliance.

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APPENDIX 1:

➢ *PID Error Correction Simulation Data*

The following table presents the data obtained from the PID controller error correction simulation, with the PID gain set to 1.

Time(µS)	Receiver (deg/s)	Gyro(deg/s)	Error (deg/s)	P	I	D
0	0	0	0	0	0	0
4	0	5	5	5	5	5
8	0	5	5	5	10	0
12	0	5	5	5	15	0
16	0	5	5	5	20	0
20	0	5	5	5	25	0
24	0	5	5	5	30	0
28	0	5	5	5	35	0
32	0	5	5	5	40	0
36	0	5	5	5	45	0
40	0	5	5	5	50	0
44	0	5	5	5	55	0
48	0	5	5	5	60	0
52	0	5	5	5	65	0
56	0	5	5	5	70	0
60	0	5	5	5	75	0
64	0	5	5	5	80	0
68	0	5	5	5	85	0
72	0	5	5	5	90	0
76	0	0	0	0	90	-5
80	0	0	0	0	90	-5
84	0	0	0	0	90	-5
88	0	-5	-5	-5	85	-5
92	0	-5	-5	-5	85	-5
96	0	-5	-5	-5	85	-5
100	0	-5	-5	-5	85	-5
104	0	-5	-5	-5	85	-5
108	0	0	0	0	85	5
112	0	0	0	0	85	5
116	0	-10	-10	-10	75	-10
120	0	-10	-10	-10	75	-20
124	0	-10	-10	-10	75	-20
128	0	-10	-10	-10	75	-20
132	0	-10	-10	-10	75	-20
136	0	-10	-10	-10	75	-20
140	0	-10	-10	-10	75	-20

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APPENDIX 2:

➢ *Incurred Cost*

The total cost incurred during the project was approximately N200,000. Some items were imported and purchased in USD, with an exchange rate of N350/USD at the tie of purchase.

COMPONENT USED	COST (USD)	COST(NAIRA)
High Torque Brushless Motors x4	67.96	
FPV Camera	34.88	
Gyroscope, L3G4200D	7.38	
Litium Polymer Battery	74.25	
Propellers x2	2.64	
Electronic Speed ControllerX4	33.06	
Arduino x3	60	
Xbee X2	81.9	
USB capture	30	
Camera Transmitter and Receiver	40	
Diode		150
Capacitor(2200µF)		200
Resistor x5		150
XBEE shield x2	29.9	
Break Away Header longx4	11.8	
Sparkfun XBee Explorer x2	49.9	
Arduino Stackable header Pinx2	3	
USB capture	5.64	
Printing and Binding		10000
TOTAL	N200,000	

Some items are given in USD because they were imported and at the time of purchase the exchange rate was N350/$