STM JOURNALS

Journal of
Aerospace Engineering & Technology

https://journals.stmjournals.com/joaet

ISSN: 2231-038X (Online)
ISSN: 2348-7887 (Print)
Volume 16, Issue 1, 2026
January–April
DOI (Journal): 10.37591/JoAET

Review JoAET

Design and Development of a Mini Drone for Educational Applications

Anup Kumar Sharma[1,*], Rachit Srivastava[2]

Abstract

This paper describes the complete process of designing, building, and testing a small unmanned aerial vehicle (UAV), normally referred to as a drone. The plan combines key concepts from aerodynamics, electronics, control engineering, and embedded programming to produce a functional sample. The drone was developed using lightweight structural materials and affordable components, including brushless DC motors, electronic speed controllers (ESCs), a flight controller, various sensors, and a lithium-polymer (Li-Po) battery. To ensure cost, ease of assembly, and suitability for educational use, lightweight and reasonably priced structural materials were used in the construction of the UAV. The goal was to reduce total weight while preserving enough structural strength to endure flight stresses. Brushless DC motors and ESCs, which provide accurate motor control and effective thrust generation, made up the propulsion system. Because of its high energy density and appropriateness for aerial applications, a lithium-polymer (Li-Po) battery was chosen as the power source. To enable real-time attitude estimation and stabilization, the drone also included a microcontroller-based flight controller and a number of onboard sensors, including accelerometers, gyroscopes, and magnetometers. The development workflow included literature review, mechanical assembly, electronic integration, software setup, and a series of test flights. Performance evaluation focused on parameters such as stability, control response, and power usage. The experimental results showed that the drone was capable of maintaining a steady hover, responding smoothly to directional directives, and functioning with good energy efficiency. This work highlights the value of mini drones as an effective educational tool for learning across multiple STEM domains. It also points toward future improvements such as incorporating GPS-based navigation, computer vision modules, and self-directed flight capabilities to enhance functionality and real-world applicability.

Keywords: Aerodynamics, control engineering, drones, educational tools, electronics, embedded programming, quadrotors, STEM education, UAV

INTRODUCTION

The fast-paced development of drone technology has brought significant changes to various fields, such as defense, security, cultivation, transportation, and ecological studies. Unmanned aerial vehicles (UAVs) are aircraft that operate without an onboard pilot and can fly either independently or through remote control, relying on integrated sensors and control logic. The mini drone developed in this project is based on a quad-rotor configuration, which was selected owing to its simple structure, ease of manufacture, and stable flight behavior [1, 2].

The main aim of the project was to create a small UAV sample capable of performing vital flight actions, including takeoff, stable hovering, forward movement, and safe landing. The drone functions

***Author for Correspondence**
Anup Kumar Sharma
E-mail: anup638829sharma@gmail.com

[1]Student, Department of Electrical Engineering, Bansal Institute of Engineering and Technology Lucknow,India.
[2]Assistant Professor, Department of Electrical Engineering, Bansal Institute of Engineering and Technology Lucknow, India.

Receiving Date: December 04, 2025
Accepted Date: December 11, 2025
Published Date: March 21, 2026

Citation: Anup Kumar Sharma, Rachit Srivastava. Design and Development of a Mini Drone for Educational Applications. Journal of Aerospace Engineering & Technology. 2026; 16(1): 1–7p.

by applying the core aerodynamic concepts of thrust, lift, drag, and weight equilibrium, where its four rotors collectively produce the upward force required for the trip. To ensure stable operation, a flight controller continuously regulates the vehicle speed using real-time data from onboard sensors, such as accelerometers and gyroscopes [3, 4].

By integrating elements of mechanical design, electronic circuitry, embedded programming, and control theory, this study connects classroom concepts with hands-on applications. It offers learners a valuable opportunity to appreciate UAV technology while developing practical engineering and diagnostic skills [5].

MOTIVATION

The motivation for this study arises from the growing use of drones across various industries and educational fields. Today, UAVs play a vital role in tasks such as aerial imaging, package carrying, emergency response, and smart agriculture. In addition, drones serve as an excellent hands-on learning tool for introducing STEM ideology, especially those linked to motion dynamics, control strategies, and embedded system development.

Selecting a mini drone as the focus of this project allowed students to directly engage with the essential technology that powers modern UAVs. This work encouraged creative thinking, improvement, and collaboration, as the team designed and assembled the drone from the ground up. Through the development process, students gained practical insights into how aerodynamic forces, propulsion systems, and control algorithms work together in an actual industrial application.

LITERATURE REVIEW

Austin provided one of the foundational texts on UAV architecture, covering airframe design, propulsion, communication systems, and mission development. The book offers a comprehensive engineering framework for understanding UAV systems from the concept of deployment. Its value lies in establishing the fundamental design constraints and effective requirements that influence both large-scale and small multi-rotor platforms [1]. Beard and McLain presented rigorous mathematical modeling and control principles for small UAVs. The authors introduced nonlinear dynamics, guidance laws, attitude control, and state estimation techniques. Their work is widely used for academic instruction in UAV control and provides the theoretical grounding necessary for quad-rotor stabilization and autonomous flight algorithms [2]. Pounds et al. modeled and controlled a quad-rotor robot and developed a full dynamic model of a quad-rotor using Newton–Euler equations, followed by an analysis of its nonlinear characteristics. The authors proposed control approaches based on the derived model and validated them experimentally. Their contribution is central to understanding multi-rotor dynamics and remains heavily cited in quad-rotor-control research [3]. Bouabdallah, Noth, and Siegwart, PID versus LQ Control for Indoor Quadrotors. This influential comparative study evaluates PID and LQ (linear quadratic) controllers for indoor micro-quadrotors. The authors demonstrated the simplicity and robustness of the PID relative to the performance optimization advantages of LQ control. This study is foundational in showing how classical and optimal control differ in real quad-rotor applications [4].

Hoffmann et al. analyzed quad-rotor flight dynamics, derived linearized models, and designed controllers for basic maneuvers. This research includes real-flight experiments and provides one of the earliest systematic treatments of quad-rotor stabilization and trajectory tracking. Their linearized model has been widely adopted for controller design [5]. The manual describes the hardware architecture, flight modes, safety requirements, and programming interface of the Da-Jiang innovations (DJI) Tello, which is a popular educational drone. It offers practical insights into embedded flight control systems and serves as a reference for beginners learning drone operation and Python-based SDK programming [6]. O'Shea and Hoydis explored deep learning for the physical layer. In his paper, the application of deep learning to communication systems, proposing end-to-end learned physical layers. Although not drone-specific, its relevance lies in its demonstration of how neural networks can optimize wireless broadcasts, which influences future work in drone-to-drone and drone-to-ground communication [7]. Khan, Iqbal, and Zafar [8] designed and developed an educational quadcopter and outlined a low-cost quadcopter designed for instructional use, covering hardware selection, microcontroller programming, and system integration. This work highlights the academic benefits of hands-on drone construction and provides a template for academic and hobbyist learning platforms [9]. Pounds and Mahony presented the mechanical and control design considerations for a four-rotor UAV in the paper, design of a four-rotor aerial robot. It emphasizes structural optimization, rotor configuration, and thrust modeling aspects. This study contributes to early quad-rotor design theory and informs subsequent bio-inspired and robust UAV structural development. Sharma and Singh [10] investigated the integration of drones into engineering education and their potential applications in the classroom. They highlight instructional strategies, curriculum design, and student engagement. This paper shows the growing relevance of drones as tools for STEM learning and conceptual understanding. Valavanis and Vachtsevanos [11] compiled state-of-the-art research on UAV technologies, including aerodynamics, control, navigation, autonomy, and regulation, in the handbook of unmanned aerial vehicles. It serves as an extensive reference for researchers and policymakers and underpins many contemporary developments in UAV algorithms and standards [12]. Mahony, Kumar, and Corke, in multi-rotor aerial vehicles: modeling, estimation, and control, provided a comprehensive overview of multi-rotor research, covering nonlinear modeling, visual servoing, state estimation, and control. Their review is influential in defining the research landscape of multi-rotor UAVs and proposing unified frameworks for controller development. Kim and Shim applied model predictive control (MPC) to quadrotors for precise trajectory tracking. MPC's ability to handle constraints and predict system behavior provides improved performance over classical controllers. This work was pivotal in introducing optimization-based control to UAV flight systems [13]. National Research Council [14] and Autonomy Research for Civil Aviation reported and outlined the future directions for autonomous aviation, addressing safety, regulation, sensing technologies, and certification processes. While broader than small quadrotors, it frames the regulatory and societal contexts in which autonomous UAVs must operate. Park, Kim, and Lee [15] developed a low-cost micro-quadcopter specifically designed for use in STEM education and classroom environments. They detail system integration, sensor selection, and simplified control strategies. This study supports the use of drones as accessible hands-on tools for STEM engagement. Nguyen and Hong [16], in educational quad-rotor development and control, introduced a quad-rotor platform specifically designed for educational laboratory applications. The authors describe the control algorithms, hardware architecture, and experimental validation. Their system emphasizes modularity and safety, making it suitable for deployment in classrooms. Guo et al. presented a lightweight, energy-efficient flight controller aimed at small educational drones. The design simplifies computation while maintaining stable flight, demonstrating how optimized embedded systems can advance the capabilities of low-cost drones [17]. Ebeid, Skriver, and Linnemann [18], in vision-based indoor navigation for educational drones, proposed a low-cost vision-based navigation system that enables drones to operate indoors without GPS. It uses onboard cameras and computer vision algorithms for localization and obstacle detection in the environment. This work is valuable for indoor drone research and educational environments [19]. ISO 21384-3:2019, Unmanned Aircraft Systems—Operational Procedures, specifies operational requirements, safety procedures, and risk-assessment processes for unmanned aircraft system (UAS) operations. It provides a global regulatory framework that guides the safe deployment of drones in commercial and educational contexts.

Gupte, Mohandas, and Conrad [20] surveyed quad-rotor UAVs and reviewed quad-rotor designs, modeling approaches, control techniques, and applications. It offers a broad overview of the state of quad-rotor research at the time and highlights challenges such as stability, payload limits, and autonomy.

OBJECTIVES

The key objectives of the work are discussed below:

1. To design and build a condensed and lightweight drone capable of achieving stable and controlled flight.
2. To bring together and integrate key electronic components—motors, propellers, ESCs, flight controller, sensors, and a Li-Po battery—into a fully functioning UAV.
3. To apply original sleek concepts, such as lift, thrust, drag, and stability, in the design of the drone.

4. To configure, calibrate, and use open-source flight control software for managing flight operations and monitoring system data.
5. Tests of requisite flight maneuvers, including hovering, forward pressure group, and landing, were conducted.
6. To enhance practical skills in electronics, robotics, embedded systems, and mechanization from the beginning to the end of active development.
7. To evaluate the drone's flight performance and identify gear or systems that could be optimized in future iterations.

METHODOLOGY

Research and Planning

This study began with a detailed study of UAV fundamentals, including aerodynamics and various control approaches. Unlike multi-rotor layouts, such as tricopter, quadcopter, and hexacopter structures, the mechanical design and flight behavior of the proposed layout were evaluated. Ultimately, the quadcopter configuration was chosen because it provided an optimal grouping of handy complexity and stable flight performance.

Module Selection

To ensure stable flight performance and longer airtime, the drone was assembled using lightweight and energy-efficient components. The selected hardware and its role are summarized in Table 1.

Hardware Assembly

Each motor was securely installed at the end of each arm of the drone frame. The ESCs were connected to the power distribution board (PDB) through soldered joints and linked to the flight controller. The battery was positioned at the center of the frame to maintain proper weight allocation and ensure a neutral center of gravity. Additionally, the flight controller was mounted with a specific alignment to the drone's pitch, roll, and yaw axes for true sense and control. Figure 1 shows a block diagram of the designed drone arrangement.

Software Setup

Betaflight and Cleanflight were used to set up and program the flight director. The adaptation method involved adjusting the PID limitations to improve the stability and control response of the drone. Several calibration procedures were performed, including the following:

1. Alignment of the accelerometer and gyroscope.
2. Calibration of the ESC throttle endpoints.
3. Mapping of receiver input signals.

Flight stabilization relied on the PID control equation, where the error term *e(t)* represents the difference between the commanded orientation and actual attitude of the drone.

Table 1. Components used in the designed drone system.

Component	Details	Reason
Frame	Carbon fiber 250 mm	Acts as the main structural support
Motors	2204–2300 kV BLDC	Produces the thrust requisite for lift and movement
ESC	20 A ESC	Regulates and controls motor speed
Propellers	5×4.5 inch	Generates lift and directional thrust
Flight controller	F4/F7	Handles stabilization and flight run algorithms
Battery	3S 1500 mAh Li-Po	Stores power for the total system
Transmitter/receiver	6-channel	Enables remote flight operation
Sensors	Gyroscope, accelerometer	Provides compass reading and motion data for stability

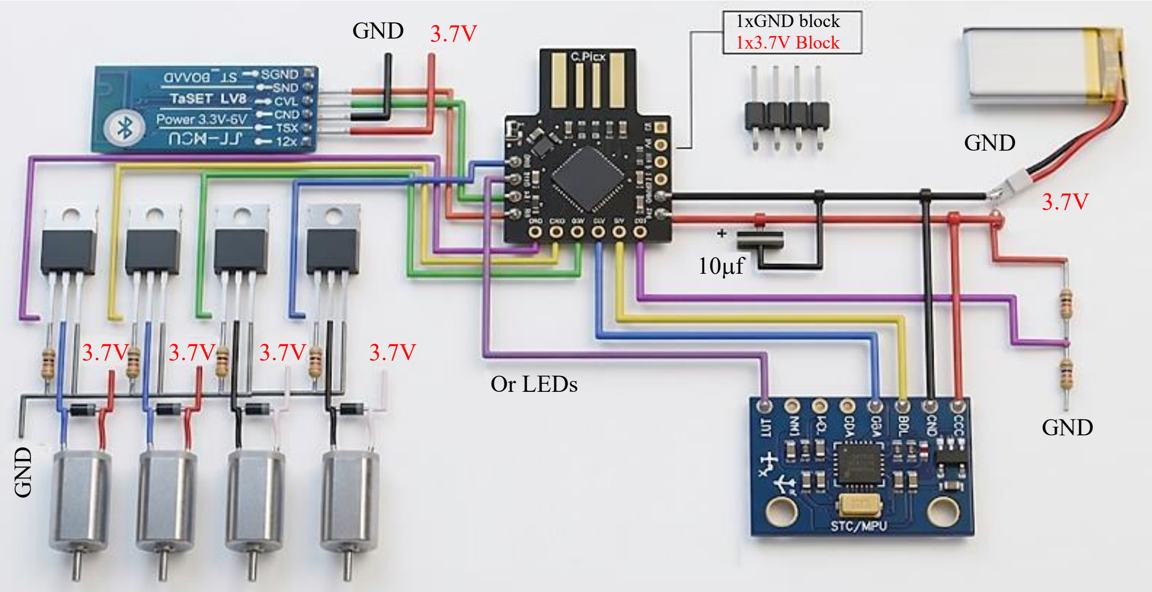

Figure 1. Block diagram of drone arrangement

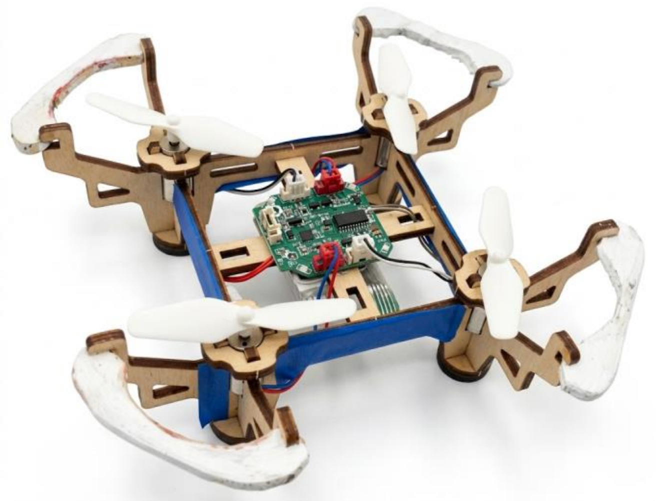

Figure 2. Picture view of developed drone.

Testing and Calibration

Ground-level inspections were first conducted to verify proper motor turning and uniform thrust generation. Low-altitude hover trials were performed to monitor signs of oscillation, volatility, or drifting. Based on these observations, the control gains were adjusted to enhance overall stability. After modification, the drone exhibited steady hovering and smooth, open directional movement. Figure 2 shows a picture view of the developed drones.

RESULTS AND DISCUSSION

The developed prototype confirmed reliable flight performance during both indoor and outdoor evaluations. The major findings are summarized as follows:

1. *Hovering stability:* The drone was able to maintain its elevation with a disparity of only ±5 cm during a 60-second drift test.
2. *Control response:* The wait time between the transmitter input and drone reaction remained under 0.1 s, signifying a highly reactive system.
3. *Flight time:* With a 1500 mAh Li-Po battery, the drone achieved a regular flight time of approximately 9 min.

4. *Power consumption:* Through hovering, each motor drew approximately 2.5 A, indicating good energy efficiency.
5. *Thrust-to-weight ratio:* The ratio was calculated to be approximately 2.1:1 for adequate force for slow maneuvering and stable rise.

PID tuning significantly affects the flight quality. Increasing the proportional gain (*Kp*) improved the drone's openness but also increased the likelihood of oscillation. The derivative gain (*Kd*) helped reduce the vibrations and exceeded the desired value. Through iterative testing, a set of optimized PID values was obtained.

These findings highlight the importance of proper PID calibration and balanced component placement in achieving stable multi-rotor flight. Unimportant feelings were noted at higher throttle levels, likely caused by the minor propeller lack of correspondence.

APPLICATIONS

Mini drones can be utilized in a wide range of fields owing to their small size and versatility.

1. *Education:* They serve as successful hands-on tools for representative concepts in physics, control systems, and fixed electronics.
2. *Surveillance and security:* Ideal for short-distance monitoring, especially in controlled or hard-to-access areas.
3. *Agriculture:* Useful for investigating crop conditions, assessing plant health, and inspecting soil quality at close range.
4. *Taking photographs and videography:* Powerful for capturing aerial images and videos in tight spaces where larger drones cannot operate.
5. *STEM research:* Supports the carrying out of tests, prototyping, and advances in robotics and automation.

CONCLUSION AND FUTURE WORK

This drone productively demonstrated the end-to-end design, construction, and testing of a compact quad-rotor UAV. The prototype delivered stable hovering, smooth maneuvering, and a dependable overall performance. Throughout the development process, the team strengthened their understanding of aerodynamics, forward motion systems, control principles, and embedded encoding.

Future Enhancements

Possible improvements that could further expand the drone's capability include:

1. Slip in a GPS module to enable self-sufficient waypoint navigation
2. Using computer vision algorithms for object naming and tracking
3. Adding altitude-hold and return-to-home functions through barometric sensing
4. Investigate solar-assisted power solutions to extend flight time

This work demonstrates how hands-on drone development can enhance technical skills and instigate creativity among students and researchers, making it a valuable learning skill in modern engineering education.

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