



(A Monthly, Peer Reviewed, Refereed, Scholarly Indexed, Open Access Journal)



Impact Factor: 8.699

Volume 14, Issue 5, May 2025

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www.ijirset.com |A Monthly, Peer Reviewed & Refereed Journal| e-ISSN: 2319-8753| p-ISSN: 2347-6710|

Volume 14, Issue 5, May 2025

|DOI: 10.15680/IJIRSET.2025.1405135|

Design and Aerodynamic Analysis of a Hybrid Modular Drone with Multi-Mode Flight Capabilities

R. Vignesh, J. Jayakumar, J. Rahul, R. Kirubakaran

B.E Student, Department of Mechanical Engineering, Annamalai University, Annamalai Nagar, Tamil Nadu, India

ABSTRACT: This study presents a hybrid modular drone capable of switching between quadcopter and hexacopter modes through a manual structural configuration system. Designed for applications like surveillance and agriculture, the drone features a lightweight frame with arm slots at 60° (hexacopter) and 90° (quadcopter) angles. SolidWorks CFD simulations analyzed drag force and torque, revealing enhanced stability in hexacopter mode for heavier payloads. The APM 2.8 flight controller, paired with PID tuning, ensured robust flight control. Experimental tests validated structural integrity and mode-switching efficiency. This cost-effective, reconfigurable drone offers versatility for multi-domain operations, with potential for advanced payload integration.

KEYWORDS: Hybrid Drone, Modular Drone Design, Multi Mode Flight, Quadcopter, Hexacopter, Modular UAV.

I. INTRODUCTION

Unmanned aerial vehicles (UAVs) have gained significant attention in recent years due to their diverse applications in sectors such as agriculture, surveillance, delivery, and disaster management. Among various UAV types, multi-rotor drones are popular for their vertical takeoff and landing (VTOL) capability, hovering stability, and ease of operation [1]. However, conventional drones are typically limited to fixed configurations, restricting their adaptability for different operational scenarios[2].

To overcome this limitation, the present study proposes a hybrid modular drone design that can be swiftly reconfigured into various flight modes depending on mission requirements. The system allows arms and motors to be detached or added with ease, enabling a seamless transition between quadcopter and hexacopter configurations. This enhances mission flexibility, operational efficiency, and redundancy in case of motor failure [3].

II. DESIGN OVERVIEW

The drone's central frame, designed with square slots at 60° (hexacopter) and 90° (quadcopter), supports manual arm reconfiguration (Fig.1). Arms were 3D-printed using PLA/PETG for prototypes, with carbon fiber [7] planned for production. motors and ESCs (Electronic Speed Controller) were powered by a LiPo (Lithium Polymer) battery.

The control system evolved from Arduino UNO (quadcopter tests) to Arduino Mega 2560 (hexacopter trials) and finally to the APM 2.8 flight controller, configured via Mission Planner. SolidWorks CFD simulations analyzed drag force, torque, and velocity at 10 m/s [2].



Fig. 1: 2D Design





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III. METHODOLOGY

The drone was modelled in SolidWorks, with a circular central frame and detachable arms. Square slots at 60° and 90° ensured precise arm alignment, secured by a locking mechanism to prevent vibration. The slots for quadcopter placed in the upper half of the drone's central body (Fig.2) and the slots for the hexacopter is placed in lower half of the drone's central body (Fig.3), Material selection balanced weight and strength: PLA/PETG for prototyping [7].

Fabrication involved 3D printing the frame and arms, followed by motor and ESC assembly. Challenges included aligning arms during mode-switching and ensuring motor synchronization. The final drone, compact and lightweight, supported both configurations effectively.



Fig 2: square slot at 90° angle for quadcopter

Fig 3: square slot at 60° angle for hexacopter

The motor attachment system was designed to securely mount BLDC (Brushless DC) motors on the modular arms (Fig 4), compatible with both quadcopter and hexacopter modes. Each arm included a 3D-printed mount with a flat base, drilled for four M3 screws to fasten the motor. A raised edge on the mount aligned the motor shaft with the arm's center line, minimizing torque imbalances. Rubber washers between the motor and mount reduced vibrations, enhancing stability during flight [6]. If a motor fails, it can be easily replaced by unscrewing and swapping, unlike traditional drones where motor replacement is more complex due to fixed designs.







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Motor attachment has screwed into the arm

Fig 4: motor attachment method on the drone arms

V. AERODYNAMIC ANALYSIS

Drag force

CFD simulations in SolidWorks quantified drag force and torque.[2],[4] Quadcopter mode recorded an average drag force and torque, Hexacopter mode showed higher drag but better torque distribution, improving payload stability [5].

The drag force values for quadcopter range from (Fig 5) **1.1554** N to **1.1789** N, with an average of **1.1598** N without propeller. This consistent drag profile highlights the drone ability to maintain aerodynamic efficiency with minimal resistance highlights the drone ability to maintain aerodynamic efficiency with minimal resistance.



Fig 5: drag of the drone at 10m/s wind in quadcopter mode without propeller

The drag force values for hexacopter range from (Fig 6) **1.4864** N to **1.5020** N, with an average of **1.4974** N without propeller. The slight increase in drag is expected due to the additional arms and motors but remains within acceptable limits, ensuring the design is aerodynamically optimized for increased payload capacity.





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Fig 6: drag of the drone at 10 m/s wind in hexacopter mode without propeller

Torque:

The torque graph for quadcopter mode (Fig 7) shows values ranging between -0.1918 Nm and 0.0614 Nm. The average torque value stabilizes around 0.0441 Nm, indicating minimal oscillations. This stability confirms efficient thrust generation and balanced rotation for smooth flight dynamics. Torque of the quadcopter is lesser than the hexacopter but less balanced than hexacopter.



Fig 7: torque of the drone in quadcopter mode

In hexacopter mode (Fig 8), torque values increase slightly due to the additional motors. The values range from **0.0540 Nm to 0.0609 Nm**, with an average of **0.0584 Nm**. This higher torque supports the increased lift capability, enabling the drone to handle heavier payloads effectively.



Fig 8: shows torque in hexacopter mode





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Calculation for the drag force and coefficient of the drag for quadcopter:

Drag coefficient (C_d) calculation

Using the drag equation:

$$C_{d} = \frac{2 \times F_{d_tot}}{\rho \times v^{2} \times A} \qquad [14]$$

$$C_{\rm d} = \frac{2 \times 2.58}{1.225 \times 10^2 \times 0.0731} = 0.576 \tag{2}$$

Quadcopter drag coefficient analysis

The calculated drag coefficient (2) $Cd \approx 0.576$ for the quadcopter falls within the expected range for small unmanned aerial vehicles (UAVs) of similar size and configuration. This value accounts for the combined aerodynamic drag contributions from the, arms, and four rotating propellers at a forward flight speed of 10 m/s (36 km/h).

Calculation for the drag force and coefficient of the drag for hexacopter:

Drag of the frame of the c	lrone = 1.50N (obtained through Simulation)
Drag of the propeller	= 0.35N (obtained through Simulation) = $0.35 \times 6 = 2.1$ N for 6 propeller
Total drag (F _{d tot})	= 1.50N + 2.1N = 3.6N
Air density (ρ)	$= 1.225 \text{ kg/m}^3$
Velocity (v)	$= 10 \text{ m/s}^{-1}$
Frontal area (A)	$= 0.095 \text{m}^2$ (obtained through the simulation)

Drag coefficient (C_d) calculation

Using the drag equation:

$$C_{d} = \frac{2 \times F_{d_tot}}{\rho \times v^{2} \times A} \qquad [14]$$

$$C_{d} = \frac{2 \times 3.6}{1.225 \times 10^{2} \times 0.09} = 0.653 \qquad (4)$$

Hexacopter drag coefficient analysis

The hexacopter's drag coefficient (4) Cd = 0.653 reflects its aerodynamic performance at 10 m/s, combining frame drag (1.50 N) and six-propeller contributions (2.10 N). This value 13.37% higher than a comparable quadcopter (Cd = 0.576), results from increased rotor count and larger frontal area, consistent with multirotor trade-offs between redundancy and efficiency.

Flow Visualization of Drone Frame with and without Propellers at 10 m/s

This (Fig 9) displays [2] the airflow pattern around quadcopter drone frame, visualized using streamline contours. The simulation is carried out in a side view at a velocity of 10 m/s. Noticeable vortex formations occur behind the motors and at the arm tips due to flow separation.

(3)





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Fig 9: vortex formation in quadcopter

The (Fig 10) shows the [2] streamline distribution around a **hexacopter drone frame** observed from the side. The simulation, conducted at an airflow velocity of 10 m/s, reveals significant vortex shedding behind the motor housings and arm ends. The central body of the drone disrupts the airflow, creating a distinct wake region characterized by circulating streamlines.



Fig 10: vortex formation in hexacopter

VII. FABRICATION

The hybrid modular drone developed in this study offers practical flexibility by enabling manual transitions between quadcopter and hexacopter configurations. The central frame with square slots at 60° and 90° ensures accurate arm alignment and secure locking (Fig.11), (Fig.12). A replaceable motor attachment system, featuring 3D-printed mounts and vibration-dampening washers, allows quick motor replacements while maintaining flight stability [7]. Overall, the modular design achieves a good balance between adaptability, maintenance ease, and aerodynamic performance.



Fig 11: Prototype of the drone in Quadcopter mode





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Fig 12: Prototype of the drone in Hexacopter mode

VIII. CONCLUSION

This study successfully demonstrated the design and aerodynamic evaluation of a hybrid modular drone capable of operating in both quadcopter and hexacopter modes. The integration of a modular central frame with adjustable arm slots allowed for quick and secure reconfiguration based on mission requirements. The replaceable motor attachment system enhanced the maintainability and operational flexibility of the drone, providing a practical advantage over conventional fixed-motor designs [6].

Aerodynamic analyses through CFD simulations confirmed that both configurations maintained stable flight characteristics within acceptable drag and torque limits [2]. The quadcopter mode proved more efficient for lightweight and surveillance applications, while the hexacopter mode offered improved payload stability and torque distribution, despite a marginal increase in drag [5]. The proposed design demonstrates the potential for multi-domain UAV applications, offering a balance between aerodynamic performance, structural adaptability, and operational convenience.

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