Optimization Design of Lightweight 3D-Printed Carbon Fiber Drone Frames: A Computational and Experimental Study

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ABSTRACT

Drones are essential tools in various industries, but optimizing their structural integrity while minimizing weight remains a significant challenge. This study introduces a novel, integrated computational framework for designing lightweight and robust drone frames by combining Computational Fluid Dynamics (CFD), Finite Element Analysis (FEA), and topology optimization. Unlike previous studies that address these aspects separately, the proposed approach unifies aerodynamic and structural performance evaluation to drive the design process. The commercial F450 drone was selected as a benchmark to validate the proposed optimization framework. The study used CFD simulations to assess aerodynamic efficiency and identify dynamic forces, while FEA and topology optimization were used to refine the frame structure, ensuring a lightweight yet robust design. The optimized frame was then fabricated using a novel 3D composite printing with short and Continuous Carbon Fiber (CCF) reinforcements, achieving a 40% reduction in weight without compromising mechanical strength or aerodynamic performance. Real-world flight tests demonstrated that the optimized frame improves energy efficiency, flight stability, and structural durability, leading to extended operational endurance. Compared with its commercial counterpart, the optimized drone achieved a 28% increase in flight time and a 36% improvement in payload capacity.

Keywords-computational fluid dynamics; CFD; topology optimization; drone frame design; 3D composite printing; carbon fiber reinforcement; lightweight structure

I. INTRODUCTION

Unmanned aerial vehicles or drones have become essential tools across diverse sectors such as surveillance, agriculture, logistics, and disaster response [1, 2]. Their ability to access hard-to-reach areas has contributed to advancements in aerodynamics, control systems, and materials. The feasibility of low-cost indoor drones, capable of rapid wide-area scanning for search-and-rescue applications, has been also demonstrated [3]. However, a challenge in drone design lies in balancing flight endurance, structural integrity, and weight reduction. Larger batteries extend flight time but increase weight, leading to higher energy consumption. Conversely, lightweight designs improve efficiency but compromise mechanical strength. Authors in [4] proposed lightweight quadcopter frame designs for ecosystem surveillance by comparing different cellular structures, validating their mechanical performance experimentally, and demonstrating how additive manufacturing enables complex, customizable geometries for improved drone functionality. Authors in [5] presented a lightweight and easily serviceable winching platform for multi-rotor drones, built from standard components and 3D-printed parts, capable of lifting 3-kg payloads with low power consumption. The optimization of 3D-printed drone performance was also investigated in [6]. This trade-off highlights the need for an integrated approach that minimizes structural weight while maintaining sufficient strength and aerodynamic stability. Enhancing this balance is significant for high-performance, long-endurance drone applications.

Advances in simulation-driven design have demonstrated the growing importance of integrating aerodynamics, structural mechanics, and additive manufacturing in lightweight drone development. Authors [7] introduced a comprehensive multi-physics framework that couples FEA with CFD to simultaneously refine the structural stiffness and aerodynamic performance of vehicle body panels. Their approach highlights the potential of co-optimizing load-bearing behavior and flow characteristics, an idea that closely aligns with the integrated design philosophy adopted in the present work. Similarly, authors in [8] developed and validated a CFD-based aerodynamic model for agricultural drones, evaluating propeller lift, airflow behavior, turbulence models, power consumption in hover, and the influence of crosswind on drone performance. Authors in [9] conducted a CFD-based optimization study on various materials for drone blades to enhance aerodynamic performance. Additionally, authors in [10] employed generative-design algorithms combined with additive manufacturing to achieve significant weight reduction in drone frames, emphasizing the value of algorithm-driven topology exploration. Authors in [11] presented the low-cost design and 3D printing of a compact X-shaped quadrotor using PLA, developed in SolidWorks. Authors in [12] demonstrated how topology optimization combined with 3D printing enables the design and validation of ultralight, structurally reliable micro-drones. Authors in [13] investigated the optimization of a DJI F450 quadcopter by applying two complementary methods, namely topology optimization and generative design. Authors in [14] conducted structural analyses on carbon-fiber and ABS-based drone frames, underscoring the necessity of dynamic performance evaluation for ensuring flight stability. The influence of infill patterns on the mechanical behavior of 3D-printed polylactic acid (PLA)–Zn composite drone frame structures was systematically studied in [15]. Authors in [16] also investigated 3D-printed Onyx composites reinforced with continuous glass and carbon fibers, demonstrating exceptionally high gains in stiffness and strength. A multiscale topology optimization framework was developed and applied to the 3D printing of CCF reinforced composite lattice structures in [17]. Together, these studies provide a robust foundation to support the integrated design philosophy adopted in this research and offer potential extensions toward optimization and dynamic reliability assessment for next-generation drone frames.

This study introduces a compact and integrated design framework that unifies CFD, FEA, and topology optimization for multirotor drone frames, enabling simultaneous aerodynamic and structural refinement. In contrast to previous studies that treat these components separately, the proposed approach directly links simulation to fabrication using a novel CCF-reinforced 3D printing. The resulting frame achieves a 40% weight reduction while retaining mechanical strength and aerodynamic stability. These yields improved flight efficiency, longer operational time, and enhanced structural resilience. The use of additive manufacturing further enables material efficiency, rapid prototyping, and scalable customization. As drone applications grow, this study offers a practical and cost-effective pathway for developing next-generation drones and inspires broader application across lightweight structural systems in aerospace, robotics, and beyond. Accordingly, the main objective of this work is to develop and experimentally validate an optimized multirotor drone frame that simultaneously enhances aerodynamic performance, structural efficiency, and payload capacity through an integrated numerical and experimental approach.

II. CFD SIMULATION OF THE F450 DRONE

A. Theoretical Background for CFD

The structural and aerodynamic optimization of a drone frame requires a multi-physics approach, integrating principles from CFD and topology optimization-based FEA. Before any analysis, it is important to establish the theoretical foundation by outlining the governing equations, optimization principles, and mathematical models that contribute to reducing frame weight while maintaining structural integrity and aerodynamic efficiency. The aerodynamic performance of the drone frame was assessed using CFD simulations, which solve the Navier-Stokes equations to evaluate the fluid flow behavior around the frame and propellers.

For low-speed drone flight, air can be considered incompressible flow, and the governing Navier-Stokes equations for fluid flow are given by [18]:

$$\rho\left(\frac{\partial u}{\partial t}+u\cdot\nabla u\right)=-\nabla p+\mu\nabla^2 u+F \quad (1)$$

$$\nabla\cdot u=0 \quad (2)$$

where u is the velocity field, p is the pressure, ρ is the air density, μ is the kinematic viscosity, and F represents external forces (e.g., gravity and propeller-induced forces). The following equations describe how air interacts with the drone frame, leading to drag forces, lift forces, and pressure distribution effects. The aerodynamic forces in the drone are characterized by lift (F_L) and drag (F_D), which can be defined using [19]:

$$F_L=\frac{1}{2}\,C_L\,\rho\,v^2 A \quad (3)$$

$$F_D=\frac{1}{2}\,C_D\,\rho\,v^2 A \quad (4)$$

where C_L and C_D are the lift and drag coefficients, A is the propeller disk of the drone, and v is the free-stream velocity. The optimization process seeks to minimize drag while maintaining sufficient lift, ensuring higher flight efficiency and longer battery life.

Each propeller generates a torque (T) that influences the stability of the drone as in:

$$T = r \times F \tag{5}$$

where r is the distance from the propeller axis. By optimizing the drone frame shape, the study ensures uniform torque distribution, reducing yaw instability, weight, and uneven power consumption.

B. Theoretical Background for Topology Optimization

To achieve a lighter but equally strong frame, FEA and topology optimization were used to refine the structural geometry [20]. The structural behavior of the drone frame is analyzed using Hooke's law for isotropic materials. Topology optimization is governed by the density-based optimization, as defined in (6) and (7), where the material distribution is optimized for minimum compliance:

$$min\, \rho S = \int_1^l \sigma \varepsilon d\Omega \tag{6}$$

subject to:

$$V(\alpha) \le V_{max} \tag{7}$$

where S is the compliance (inverse of stiffness), σ is the normal stress, ε is the normal strain, Ω is the material domain, $V(\alpha)$ is the volume of the structure, and V_{max} is the maximum allowable volume. By solving this optimization problem in Siemens NX, the material is efficiently distributed, resulting in a frame that is lighter than the original commercial design while achieving the preset weight reduction target. Siemens NX uses a density-based topology optimization method, where the material distribution within a design domain is optimized to meet performance objectives (such as minimizing weight or maximizing stiffness) while respecting constraints (such as stress, displacement, or volume). The formulation combines FEA with optimization algorithms to iteratively refine the material structure. This software uses the Solid Isotropic Material with Penalization (SIMP) method as the primary algorithm for topology optimization [21]. This theoretical foundation provides a rigorous mathematical and physics-based framework for optimizing drone frame design. The study successfully integrates CFD for aerodynamic efficiency, minimizing drag while maintaining sufficient lift, and applies aerodynamic forces in FEA and topology optimization to remove excess material and reduce weight. The findings pave the way for next-generation drone structures that are more energy efficient, structurally optimized, and aerodynamically refined.

III. AERODYNAMIC PERFORMANCE OF THE COMMERCIAL F450 DRONE

The aerodynamic performance analysis of the commercial drone frame was performed using CFD simulations in SolidWorks software, which helps understand the interaction of aerodynamic forces with the structure during flight. The numerical simulations were conducted on a quadrotor frame based on the F450 configuration, which features a motor-to-motor diagonal distance of 450 mm. The study focused on three critical parameters: pressure distribution on the propellers, velocity flow characteristics around the frame, and torque variations on each propeller due to aerodynamic forces. The numerical simulations were conducted using a three-dimensional, steady-state formulation under incompressible flow assumptions. The mesh resolution was selected based on the default setting of the software. A uniform velocity inlet and a pressure outlet boundary condition were applied. Pressure and velocity coupling was handled using the SIMPLE algorithm.

The CFD model was configured using a 2.5-million-cell mesh (<5% convergence error), the standard k–ε turbulence model, inlet/outlet boundary conditions of 5 m/s and 0 Pa, and a turbulence intensity of 5%, in accordance with the guidelines of the SolidWorks Flow Simulation Technical Reference [22]. One of the most significant factors influencing drone performance is the distribution of pressure across the propeller blades, as this directly affects thrust generation and lift efficiency, as shown in Figure 1. The simulation results illustrate how air pressure varies across the rotating blades as the drone accelerates from 0 to 10,000 RPM. By analyzing localized high-pressure zones, the study identifies areas where aerodynamic improvements can be made to enhance efficiency while reducing turbulence and power losses.

The interaction between the airflow and the frame significantly influences drag forces and overall flight efficiency, as depicted in Figure 2. After about 1 h of computing, the simulation results reveal how airflow moves around the body of the drone, identifying areas of high resistance in the frame's geometry. High levels of turbulence around the structure contribute to increased aerodynamic drag, forcing the motors to work harder to maintain stable flight. The study examines how the streamlining of structural elements can reduce drag, allowing smoother airflow, improved propulsion efficiency, and extended flight time. The average thrust force of 12 N/motor was computed by integrating pressure and viscous shear stresses over the propeller disk surface inside the rotating region. Similarly, the reaction torque of 3.2 N·mm was obtained using the rotational moment of aerodynamic forces.

The insights obtained from the CFD analysis enable optimizing drone frame design. Identifying high-pressure zones, areas prone to turbulence, and torque inconsistencies allows data-driven modifications to the frame structure to achieve better aerodynamic efficiency. The findings of this simulation not only serve as a benchmark for evaluating the current F450 frame but also guide subsequent topology optimization and composite material integration in the new lightweight design. Ultimately, this aerodynamic analysis ensures that the proposed frame optimization leads to a weight reduction without negatively affecting drone flight performance, stability, or energy efficiency.

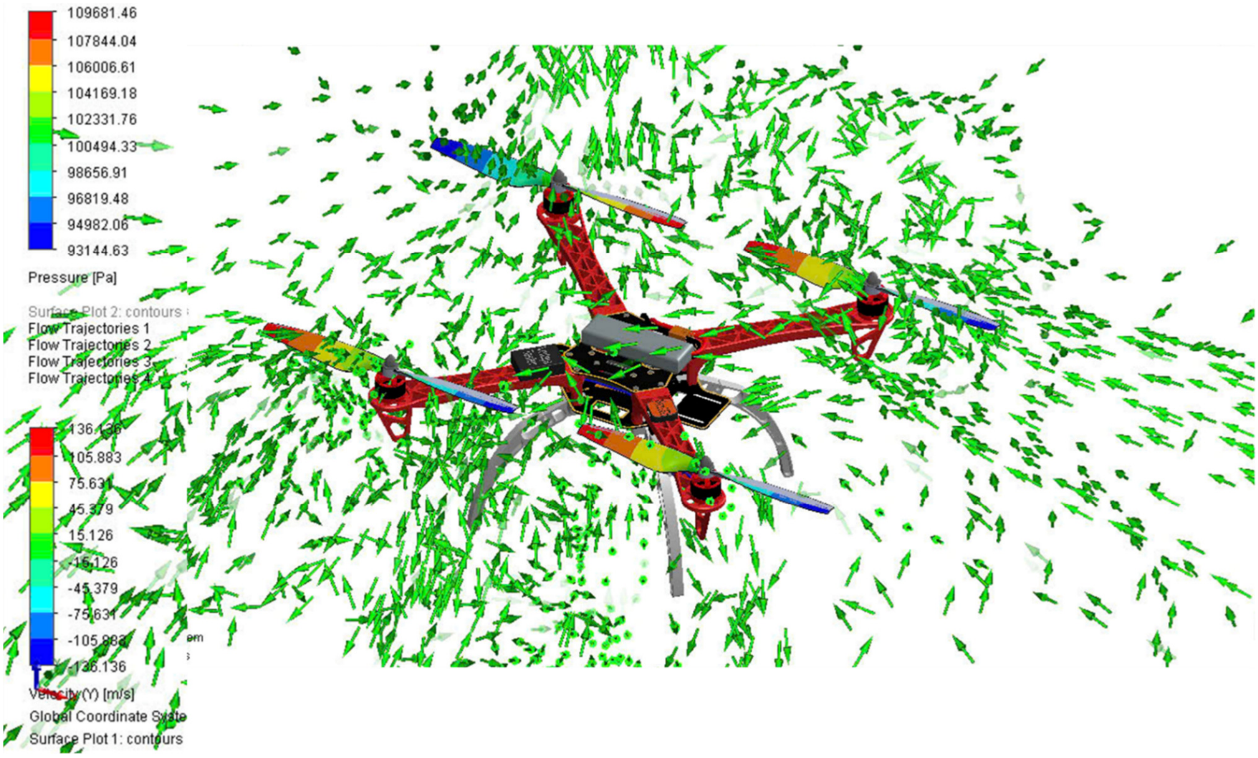

Fig. 1. Airflow surrounding the commercial F450 drone.

IV. OPTIMIZATION AND AERODYNAMIC PERFORMANCE OF THE OPTIMAL DRONE

A. Topology Optimization

The structural optimization of the drone frame was carried out using NX Siemens software with SIMP topology optimization techniques to improve the frame's mechanical efficiency while reducing the overall material usage. The primary goal was to achieve a 40% lighter frame without compromising its ability to withstand aerodynamic forces and mechanical stress during flight, with a penalization factor p of 3. This process required a precise balance between load-bearing capacity, structural stiffness, and weight reduction, ensuring that the frame remains both durable and aerodynamically stable. One of the most significant aspects of drone frame optimization is the strategic removal of excess material while reinforcing high-stress areas. The analysis focused on three main objectives, including maximizing structural efficiency while reducing material usage, maintaining load-bearing capacity at critical points, and ensuring a uniform stress distribution across the frame.

To validate the mechanical performance of the optimized frame, the study applied specific force and torque constraints, simulating real-world operational forces during flight, as illustrated in Figure 2. The simulated force on the original F450 frame is 12 N for the applied force and 3.2 N·mm for the generated torque. The optimal frame was designed to withstand higher force and torque loads, ensuring safer mechanical resilience with 15 N for applied force and 3.5 N · mm for generated torque. The fixed constraints of some surfaces, including 4 holes, are displayed in Figure 2(a). The frame is made up of the reinforced short carbon fiber (PLA-CF) material. The original commercial F450 frame weighed 53.4g. The optimized frame was designed with a target weight corresponding to a 40% reduction from the original frame; therefore, a target weight of 32g was specified in the Siemens NX topology optimization tool. After the optimization reached convergence in 15 min, the final structure was obtained, as shown in Figure 2(b). To improve the quality of the 3D printed frame, the optimal structure was redesigned, as presented in Figure 2(c). The final frame was also tested to check its strength using the FEA module with 33,955 CTETRA elements (10-node tetrahedral element) in NX Siemens. The results indicate that the frame satisfies the strength requirements for flight, as displayed in Figure 2(d).

B. Aerodynamics of the Optimal Drone

The pressure distribution analysis is an important factor in evaluating the aerodynamic performance of the drone. The CFD simulation of the optimal drone was carried out with a similar procedure to that of the commercial one. The results show that the optimal frame maintained a balanced pressure gradient. Furthermore, the velocity distribution remained uniform, ensuring that airflow around the frame, as shown in Figure 3, followed a predictable pattern without excessive turbulence or vortices that could reduce aerodynamic efficiency.

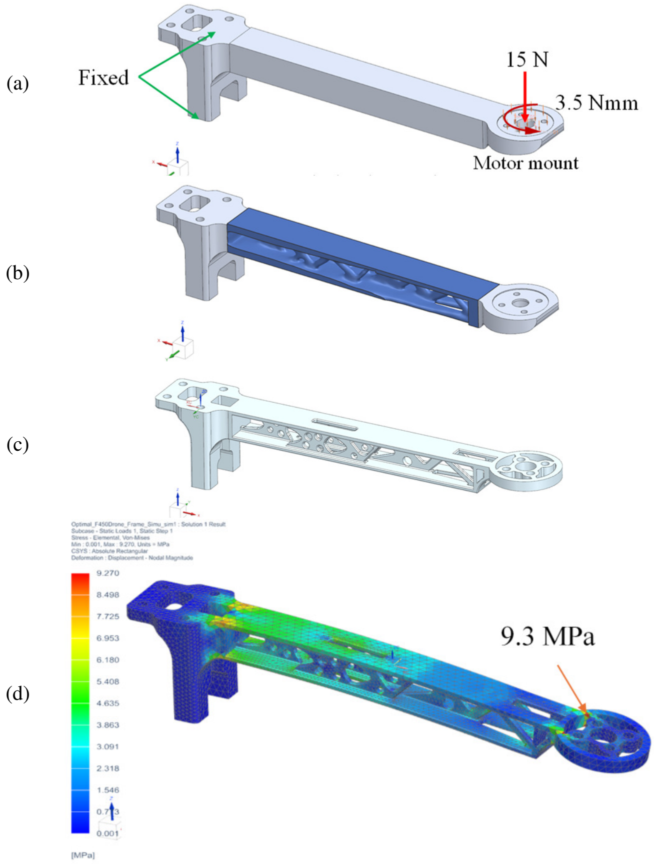

Fig. 2. Topology optimization of F450 drone frame: (a) optimization setting, (b) optimization results, (c) redesigned frame for 3D printing, and (d) strength simulation.

These findings indicate that despite the 40% weight reduction, the drone frame continued to support smooth air movement, allowing stable flight conditions similar to those observed in the original F450 frame. Moreover, the drag force F_D for the optimized frame drops was predicted to be from 0.84 N to 0.63 N, while the corresponding lift force F_L remained essentially the same as that of the commercial drone.

V. FABRICATION AND TESTING

To validate the flight capability of the optimized drone, the corresponding frame was manufactured by 3D composite printing, an advanced additive process that enables the creation of lightweight yet structurally resilient components. The process involved a systematic workflow, beginning with digital preparation, followed by precise material deposition, and ending with post-processing steps to ensure the structural integrity of the printed component. The combination of layer slicing, an advanced printing system, and high-performance composite materials allowed the creation of a drone frame that is both lightweight and structurally optimized, ensuring superior performance in real-world flight conditions.

A novel Aura slicing software from Anisoprint Company was utilized to decompose the 3D model into multiple horizontal layers, each representing a thin cross-section of the final structure [23]. The former can determine the optimal print path, ensuring that material deposition is efficient and structurally continuous carbon reinforced in key load-bearing areas, and adjust printing parameters to maximize both precision and mechanical integrity. To improve the stiffness of the frame, CCF with a diameter of 0.35 mm and PLA-CF were used, as shown in Figure 4. Fiber paths were aligned with the principal stress directions obtained from the FEA results of the optimized topology.

The next stage of the fabrication process involved material selection, where a high-performance composite blend of polymer and carbon fiber was utilized to ensure that the printed frame retained both durability and lightweight characteristics. Table I provides information on the printed materials. The PLA-CF material was made by ESUN (Shenzhen ESUN Industrial Co., Ltd.). Some important printing process parameters after multiple attempts are listed in Table II [24]. The infill ratio was close to 100% with a line internal pattern. Ten layers of carbon fiber–reinforced composite were employed. Key benefits of carbon fiber-reinforced composites in drone applications include superior strength-to-weight ratio, high impact resistance and durability, as well as thermal and environmental stability.

TABLE I. PRINTING MATERIAL PROPERTIES

Material	**Young's modulus (GPa)**	**Poisson ratio**	**Density (g/cm^3)**	**Elongation at break (%)**	**Tensile strength (MPa)**
PLA-CF (ESUN)	6.5	0.35	1.21	5.26	65
CCF - Anisoprint	150	0.26	1.45	-	2200

TABLE II. PRINTING PROCESS PARAMETERS [24]

CCF layer thickness (mm)	**PLA-CF layer thickness (mm)**	**CCF printing speed (mm/s)**	**PLA-CF printing speed (mm/s)**	**CCF temperature (°C)**	**PLA-CF temperature (°C)**
0.36	0.15	20	60	250	200
Building plate temperature (°C)	CCF line width (mm)	PLA-CF line width (mm)	Flowrate (%)	Fan (%)	Wall line of model (-)
50	0.8	0.4	100	100	3

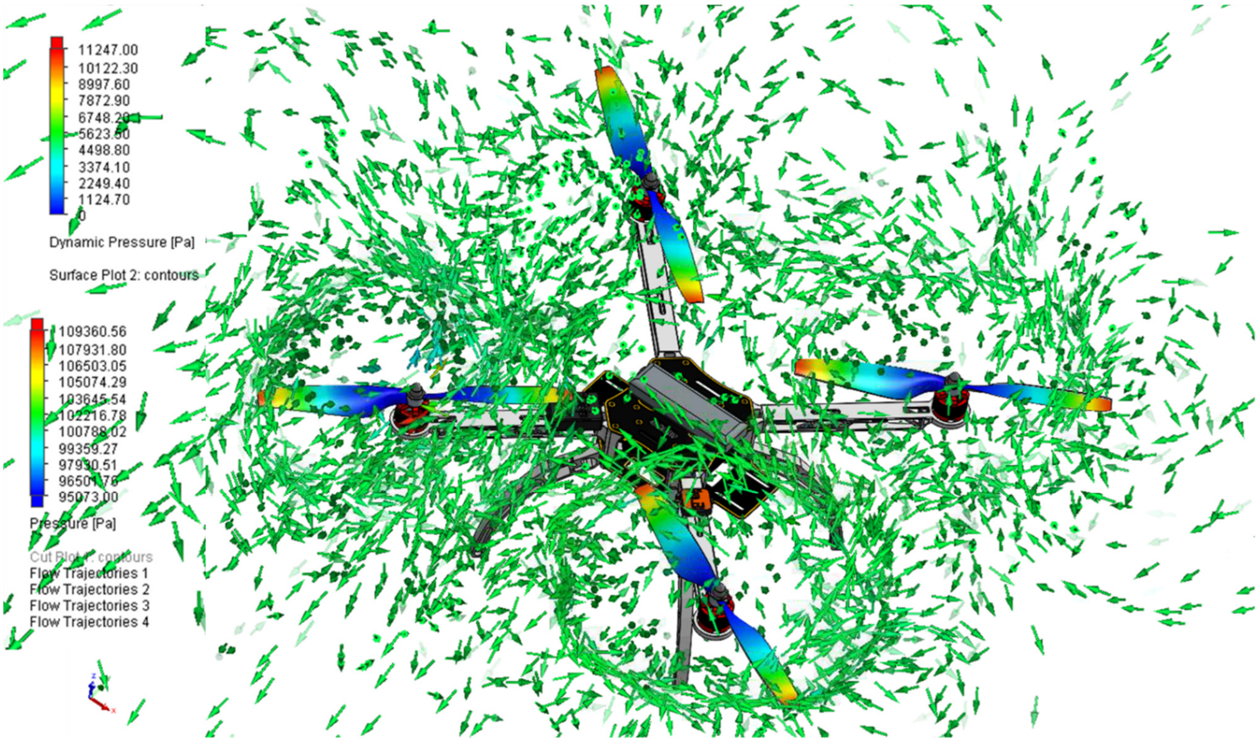

Fig. 3. Airflow surrounding the optimal F450 drone.

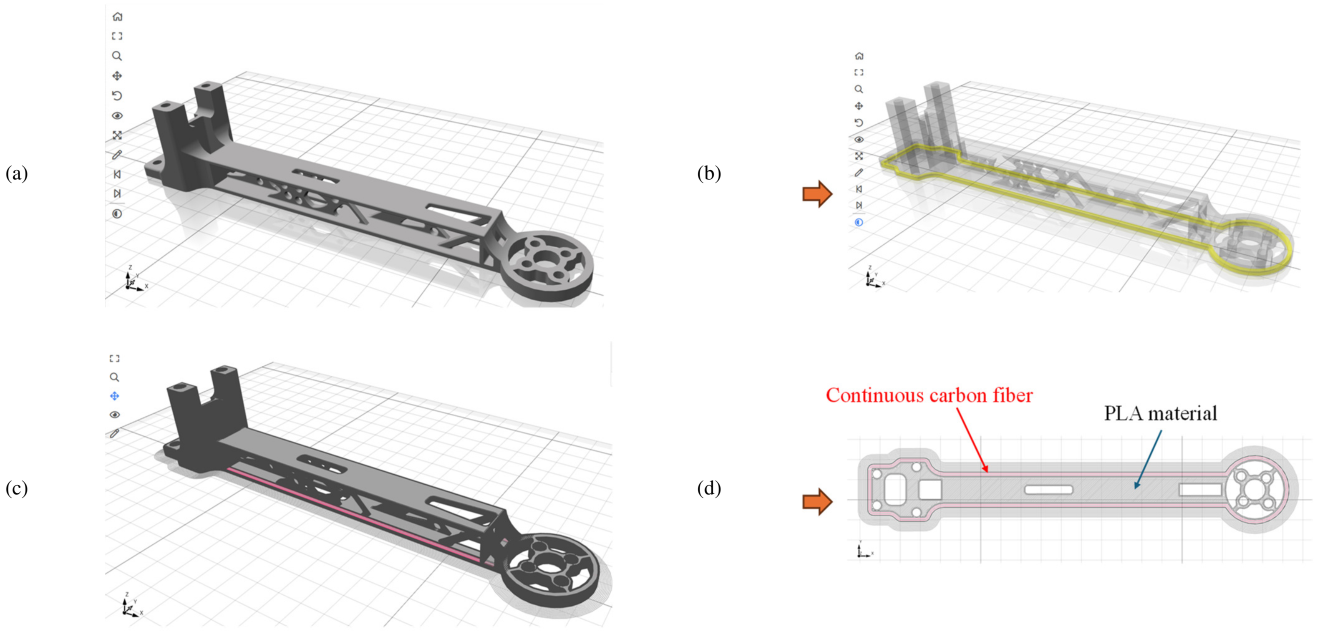

Fig. 4. Frame printing process: (a) optimal frame, (b) CCF setting, printing simulation, and (d) a slicing of the printed frame.

The fabrication process was carried out using the Anisoprint Composer A4, a high-performance 3D printer specifically designed for composite material printing. This printer was selected for its ability to process fiber-reinforced thermoplastics, which offer superior mechanical properties compared to traditional 3D printed materials, as shown in Figure 5. The combination of precise layer deposition, fiber reinforcement, and high-dimensional accuracy makes the Composer A4 printer of Anisoprint company an ideal system for manufacturing lightweight yet structurally robust drone components, ensuring that the optimized frame meets both engineering and aerodynamic requirements. Given the geometric complexity and structural precision required in drone assemblies, dimensional accuracy and printing tolerances are significant factors that influence mechanical fit, rotor alignment, and ultimately, flight performance.

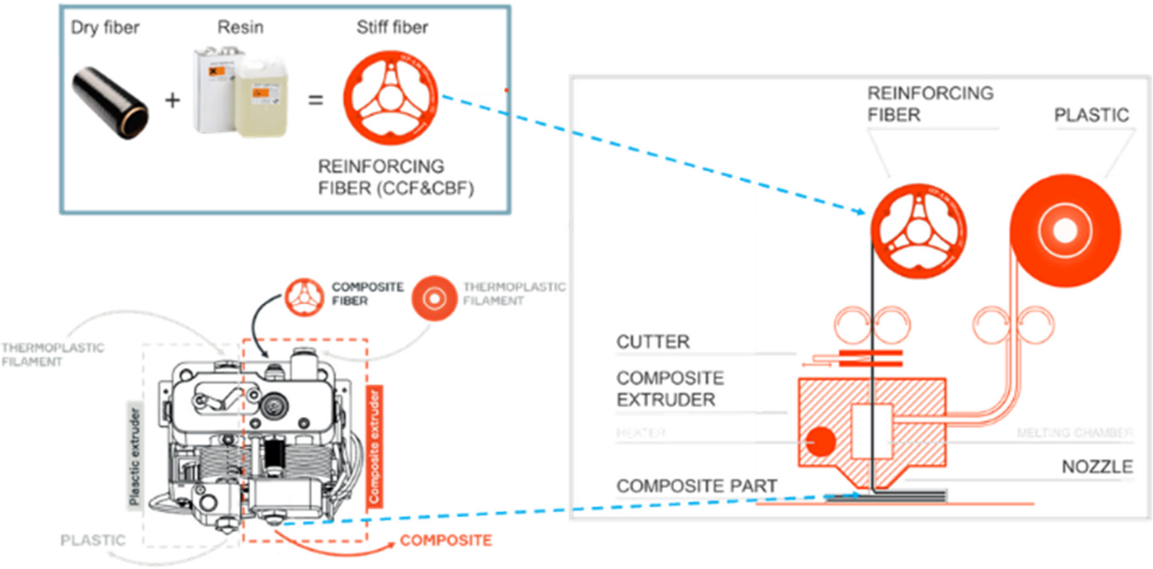

Fig. 5. Printing technology using CCFs of the Anisoprint company.

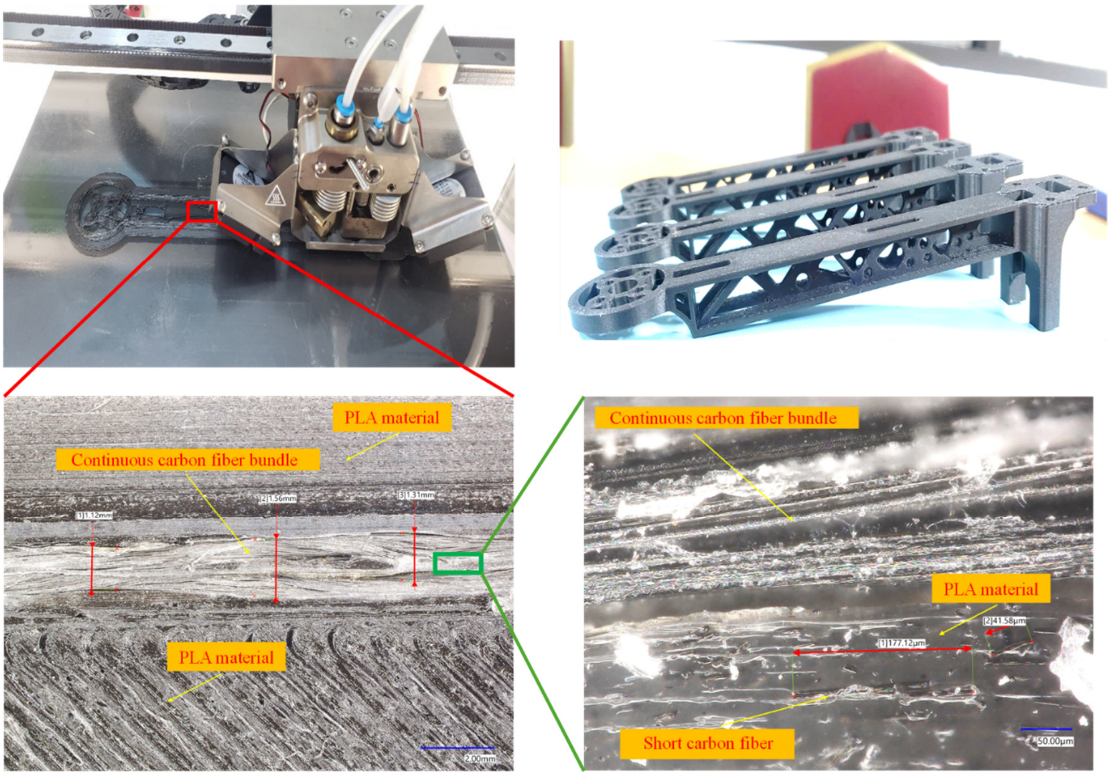

Fig. 6. Printing process and microstructure.

The optimized F450 drone frame was fabricated using the Anisoprint Composer A4, which provides a nominal dimensional accuracy of ±0.05 mm. Furthermore, the layer-by-layer deposition process of the composite filament showed good consistency in print stacking and infill homogeneity, particularly in zones reinforced with CCFs. The surface of the printed frame was also investigated. The VHX-7000N digital microscope of KEYENCE was used. Figure 6 captures the continuous carbon bunch with PLA, demonstrating the strong interface coherence between the fiber reinforcement and the polymer. A zoom-in view of the printed surface is also portrayed in Figure 6. The mono carbon fibers can be pointed out to show the contact among them and the polymer PLA. Both short carbon fibers and CCFs were embedded within the

PLA matrix. The fiber length distribution of the short fibers ranged approximately from 50 to 150 µm.

Once the printing process was completed, the fabricated frame underwent post-processing steps to ensure optimal mechanical performance and precision assembly. These post-processing steps include surface finishing and edge refinement, support removal, structural integrity testing, final assembly, and compatibility checks. The successful fabrication of the optimized drone frame using 3D composite printing in 3 h with support marks a significant advancement in drone engineering, demonstrating the viability of fiber-reinforced additive manufacturing for high-performance aerial platforms.

Following the successful fabrication of the optimized drone frame, the next crucial phase involved assembling the frame on the drone and conducting rigorous flight performance tests to evaluate its structural integrity, aerodynamic efficiency, and overall stability under real-world operating conditions, as presented in Figure 7(a). The main objective of this phase was to verify that the composite 3D-printed frame could be seamlessly integrated into the drone's existing mechanical and electronic systems while maintaining flight dynamics comparable to or superior to the original commercial frame. Some important improvements of the optimal drone with identical electronics are presented in Table III.

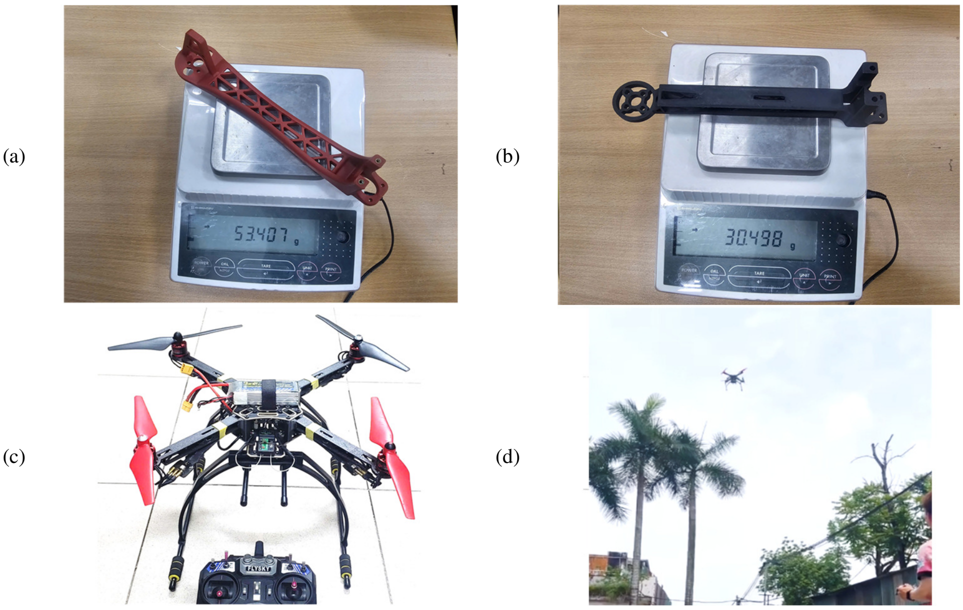

Fig. 7. Assembling and flying testing of F450 drone with the optimal frames: (a) original frame weight; (b) optimal printed frame weight; (c) assembly of F450 with optimal weight; and (d) flying testing.

TABLE III. COMPARISON BETWEEN COMMERCIAL AND OPTIMAL DRONE

Drone	Frame size (mm)	Maximum motor speed (rpm)	Maximum carried load (g)	Battery type	Flying time without load (minutes)
Commercial (53.4g)	450	~13,000	~500	3S-2200mAh Lipo	~5.5
Optimal (30.5g)	450	~13,000	~680	3S-2200mAh Lipo	~7.0
Improvement	-	-	~36%	-	~28%

While the present study demonstrates the effectiveness of integrating topology optimization, CFD/FEA simulations, and composite 3D printing for drone frame design, several limitations remain. First, environmental testing under varying weather and operational conditions was not conducted, confining the assessment of long-term durability and reliability. Additionally, the optimization workflow was manually driven; automating this process could enhance efficiency and repeatability. The structural analysis assumed isotropic material behavior for the composite constituents, which may not fully capture the anisotropic nature of fiber-reinforced materials. The rigor of the study can be enhanced by referring to the work done in [25]. Performance was evaluated under deterministic loading conditions, without considering uncertainties in material properties, loading, or operational environments. Future work will address these limitations by incorporating anisotropic material models and probabilistic reliability assessment methods, such as Monte Carlo simulation [26], to evaluate structural safety and stability under varied operational conditions. In the present study, the numerical framework primarily focused on aerodynamic and structural performance, while thermo-mechanical effects associated with temperature variations and thermal manufacturing processes were not explicitly modeled [27], constituting a limitation of the current work. Due to the early stage of experimental testing, comprehensive validation data remain limited, equally to the numerical and experimental correlation. Future work will address these limitations by incorporating dedicated force measurement systems to enable rigorous quantitative validation [28], while mesh validation will also be conducted. Future research will extend the proposed methodology by incorporating advanced multi-objective and metaheuristic optimization algorithms, such as local search or consensus-based strategies, to enable more flexible and robust lightweight drone frame design [29].

VI. CONCLUSIONS

This study successfully demonstrates a novel, integrated design-to-fabrication framework for developing a lightweight yet structurally robust drone frame by combining topology optimization, Computational Fluid Dynamics (CFD), Finite Element Analysis (FEA) simulations, and composite 3D printing. The findings of the present study are summarized as:

- Numerical simulations and experimental validation demonstrate that the optimized frame achieved a 40% weight reduction compared to the commercial F450 frame while maintaining equivalent aerodynamic efficiency and structural integrity.
- Topology optimization was performed based on simulated aerodynamic loads, including a maximum normal force of 12 N and a torque of 3.2 N·mm, ensuring sufficient mechanical strength under realistic flight conditions.
- The results confirm that the lightweight design does not compromise flight stability, maneuverability, or endurance, making the optimized frame a viable solution for high-performance drone applications.
- Composite 3D printing with fiber-reinforced materials proves to be a cost-effective and structurally advantageous manufacturing approach, offering enhanced design flexibility, material efficiency, and customization potential compared to conventional fabrication techniques.
- Real-world flight tests show that the optimized drone outperforms its commercial counterpart, achieving a longer flight time and a higher payload capacity.

Overall, this research establishes a solid foundation for future advancements in lightweight drone frame engineering, particularly for aerospace, surveillance, and industrial drone applications that demand high endurance and energy efficiency. Future work will focus on integrating multi-objective optimization, machine learning-assisted design, or multi-physics simulations into advanced drone frame development.

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