Design, Build, and Fly a Lightweight, Rigid, Modular 3D-Printed UAV

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This paper presents the design, fabrication, and flight testing of a modular 3D-printed fixed-wing aircraft. The aircraft incorporates several design innovations to address the challenges of additive manufacturing, including a segmented wing divided into multiple parts, a novel female–male–female jointing mechanism to overcome limitations in printer bed size, and a longitudinally adjustable wing–fuselage connector to achieve proper center of gravity balancing. Lightweight Polylactic Acid (PLA), combined with honeycomb internal structures, was employed to reduce weight while maintaining structural integrity. Optimized printing parameters ensured high-quality results in narrow, thin geometries. The fuselage design further incorporated cutouts to minimize mass without compromising rigidity. Aerodynamic simulations confirmed sufficient lift-to-drag performance, and structural analysis demonstrated low deformation and stress levels well below material yield strengths. The prototype was successfully tested, validating stability, control effectiveness, and the durability of the modular joints. The results highlight how modular design and additive manufacturing can be combined to produce lightweight, transportable, and cost-effective UAVs with reliable flight performance, offering a framework for broader applications of 3D printing in aerospace systems.

Nomenclature

AOA	=	angle of attack
C_D	=	coefficient of drag
C_L	=	coefficient of lift
c	=	chord
D	=	drag force
L	=	lift force

I. Introduction

Unmanned aerial vehicles (UAVs) have experienced rapid advancements in recent years, driven by the need for lightweight structures, increased efficiency, and flexible manufacturing methods. Additive manufacturing (3D printing) has emerged as a promising technology for aerospace applications, offering advantages such as geometric complexity, reduced tooling costs, and rapid prototyping and small-batch production [1]. Fixed-wing UAVs particularly benefit from weight reduction and streamlined aerodynamics, which enable extended flight times and improved performance [2, 3]. Traditional manufacturing methods impose limitations on internal geometries, modularity, and transportability. In contrast, 3D printing—particularly fused deposition modeling (FDM)—enables the efficient realization of internal lattices, honeycomb infill, and modular structures [4, 5]. Another important design approach is modularity, which improves manufacturability, maintenance, and transportability. Modular UAV designs with 3D-printed components are feasible and cost-effective, while enabling easier repairs and reconfigurations [6].

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However, challenges remain in balancing aerodynamic efficiency, structural strength, and manufacturability. Surface finish, layer adhesion, infill density, and joint design significantly influence both aerodynamic performance and structural reliability [7]. Material selection, such as using PLA or lightweight PLA, and proper tuning of print orientation and print speed are also critical for success.

The study highlights aerodynamic analysis using CFD, structural validation using finite element methods, and flight-test results, thereby demonstrating the feasibility of low-cost, modular, and transportable UAVs manufactured using additive manufacturing.

II. Problem Statement

Typical RC airplanes are traditionally made of Styrofoam, balsa wood, or composites. These materials are lightweight and relatively inexpensive. But they have disadvantages: Styrofoam has poor durability and low strength; balsa wood is difficult to process; and composites are more expensive. In addition, composite materials require specialized manufacturing processes, which are difficult for DIY projects. The use of additive manufacturing technologies, such as 3D printing, can be the solution. 3D printing enables rapid prototyping, lightweight structures, and smooth surface finishes. However, key challenges include limited printer size, ensuring structural rigidity, potential weaknesses in the joints, etc. Maintaining a balance between ease of manufacturing and good aerodynamic performance is a significant challenge. Furthermore, the transportability of a large aircraft is also a key challenge, so the modularity of different components is important.

The focus of this study is to design, manufacture, build, and flight test a 3D printed aircraft. The main focus is to use 3D printing throughout the manufacturing process. The target is to achieve good aerodynamic performance while ensuring structural rigidity, modularity, and transportability.

III. Literature Survey

Additive manufacturing technologies have been widely adopted across various manufacturing applications, and the aviation industry is also not far behind. Gibson et al. provide an overview of additive manufacturing processes, including 3D printing, highlighting issues such as anisotropy, surface finish, and interlayer bonding that directly affect structural performance in flight hardware [8]. On the other hand, Alami et al. examined the possibility of these processes in aerospace and automotive industries, emphasizing weight reduction, sustainability, and resource efficiency as key benefits [9]. These findings underscore the importance of using alternative additive manufacturing processes in the aviation industry, especially for UAVs.

However, some key factors need to be considered when using 3D printing. Material selection is a major factor in this regard. Vakharia *et al.* demonstrated multi-material additive manufacturing using high-temperature PEI systems, showing that print orientation and bonding critically influence strength-to-weight efficiency [10]. Similarly, Iftekar *et al.* reviewed advances and limitations in polymer-based additive manufacturing. Their research shows that PLA and lightweight PLA are promising materials that balance manufacturability, surface quality, and mechanical properties [11]. Poljaček *et al.* confirmed in their study that properly printed PLA can provide sufficient stiffness and rigidity for a lightweight UAV [12]. Graba and Grycz assessed the mechanical properties of different PLA filaments for UAV projects. Their work shows how filament type and printing conditions influence stiffness and the potential for weight savings [13].

In short, these studies show that 3D printing with PLA and Lightweight PLA can be the solution in making rigid, modular, and transportable UAVs.

IV. Aircraft Design Methodology

The idea of using 3D printing technology to construct RC airplanes offers precise control over geometry, weight distribution, material properties, and more. This also enables rapid prototyping, the use of complex geometries, such as honeycomb structures, to increase the airplane's strength while reducing its weight, and cost-effective manufacturing processes. The highlight of our approach is the modular design for the aircraft wings. Each wing is divided into four smaller sections for easier manufacturability and transport, as shown in Figures 2 (a)-(b). This innovative approach solves two major problems: manufacturing large RC airplanes with conventional small 3D printers and transporting them for flights.

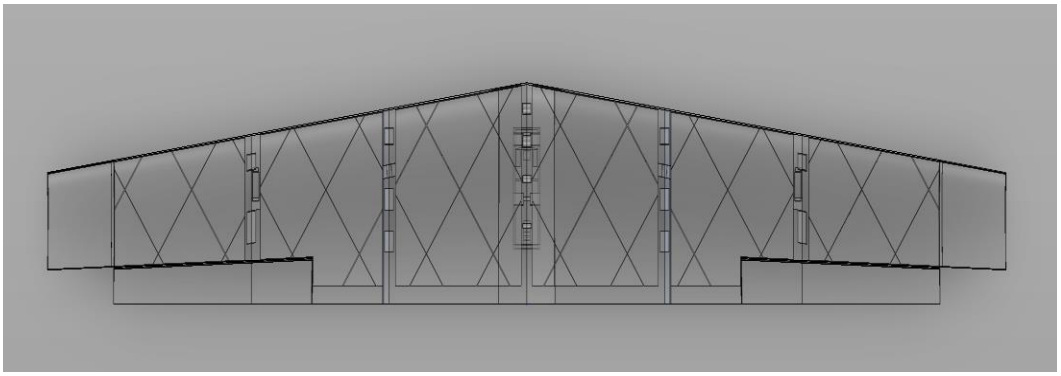
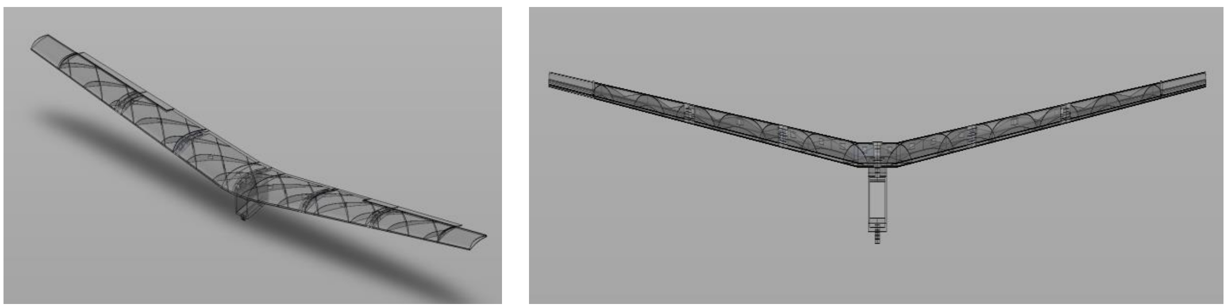


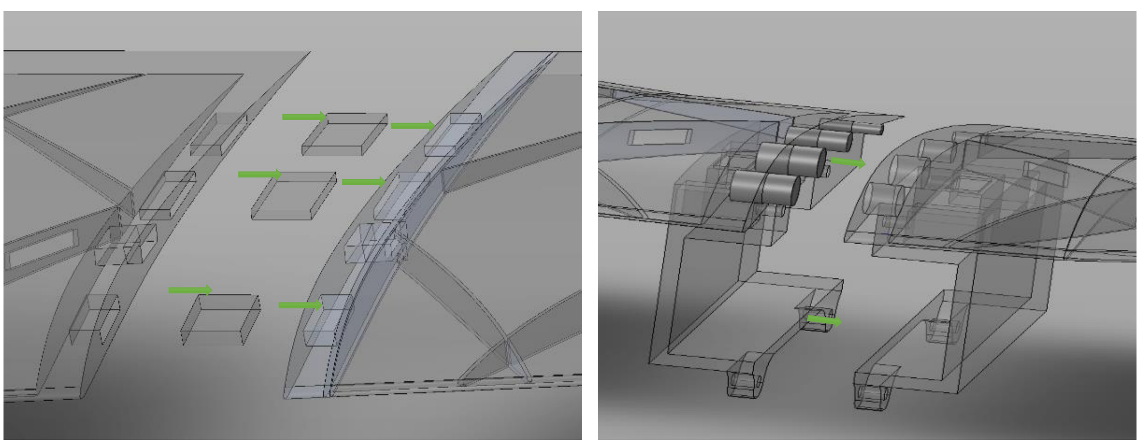
Figure 1. Top view of the wing showing the honeycomb structure inside



(a) (b)

Figure 2. (a) Full wing design, (b) Front view of the wing.

Small slots are used instead of screws to connect the parts, providing a rigid connection and simplifying the assembly. Instead of using typical male-female joints, a rather different female-male-female joint is used, allowing the printer's full size to be used, as shown in Figures 3 (a)-(b).



(a) (b)

Figure 3. (a) A female-male-female joint connects the wing sections, (b) Wing connection mechanism with the fuselage.

To facilitate easier transport, two wings are connected to the fuselage via a hub. Another significance of this connection mechanism is that it allows longitudinal movement of the entire wing relative to the fuselage, thereby balancing the aircraft's center of gravity, as shown in Figure 4.

Reducing the aircraft's weight, especially in the rear fuselage, is crucial to ensure it glides. However, it is also important to resist lateral and vertical movement due to aerodynamic forces. The rear part of the fuselage also needs to be rigid enough to hold the vertical and horizontal stabilizers and control surfaces. An innovative design approach is taken to address all of these issues while minimizing the weight. Slots are cut into all fuselage surfaces to minimize weight while maintaining sufficient rigidity to resist bending and lateral movement.

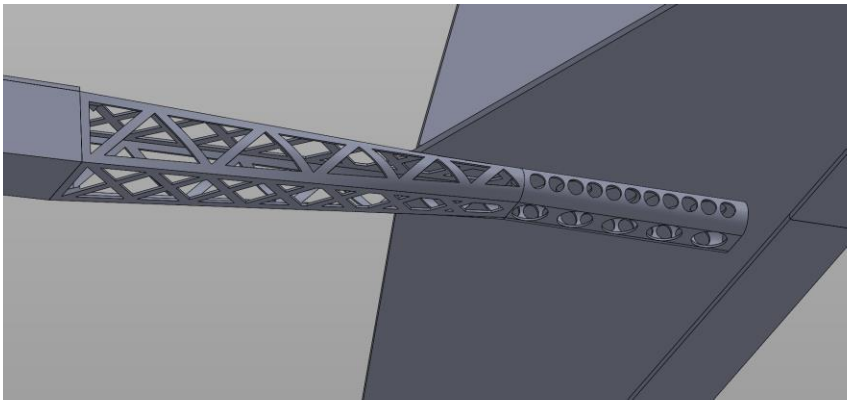


Figure 4. Rear fuselage with the tail support

The CAD drawing of the assembled aircraft is shown in Figure 5. Below.

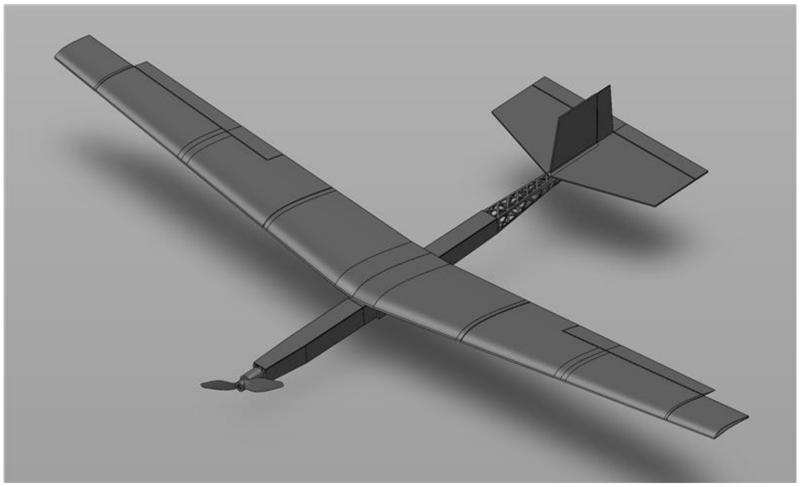


Figure 5. CAD drawing of the 3D printed aircraft

The modular system also allows for easy maintenance, as individual components can be replaced if damaged. This approach will also reduce the cost. The initial design is created in SolidWorks and printed on the BambuLab X1 Carbon printer.

The primary design parameters of the aircraft are shown in Table 1 below.

TABLE 1. Structural design specification

Parameter Name	Value
Wing segments	8
Span of each segment	241.67 mm and 114 mm for the wingtips
Total wingspan	1714 mm
Length of the airplane	1000 mm
Span of horizontal stabilizer	500 mm
Width of horizontal stabilizer	92.7 mm
Elevator width	32 mm
Vertical stabilizer height	173.5 mm
Rudder width	32 mm
Airfoil type	NACA 2032C
Root Chord	8 in
Tip Chord	6 in
Dihedral angle	50

In addition to the propulsion components, other electronics are used for flying the aircraft. This equipment plays a crucial role and is selected to keep a focus on minimizing weight. Four 9g servos operate the control surfaces, a transmitter-controller operates the airplane, and an ESC transmits the signal to the motor. The specifications of the electronic components are given in Table 2 below.

TABLE 2. Electronics specification

Name of the Equipment	Description of the equipment	Quantity
ESC	40A RC Brushless Motor Electric Speed Controller ESC 3A	1
Servo Motor	9g Servo motor	4
Transmitter- Controller	Flysky FS-i6 6CH 2.4GHz Radio System RC Transmitter Controller	1
ESC	40A RC Brushless Motor Electric Speed Controller	1

V. CFD Analysis

An ANSYS Fluent simulation is performed to analyze the aircraft's aerodynamic performance. For simplicity, only the wing is simulated. The L generated by the wing is found to be 37.5N, while the D is 2.64N at a 20 m/s wind speed. The overall aerodynamic efficiency of the wing is 14.2, as shown in Figures 6 and 7.

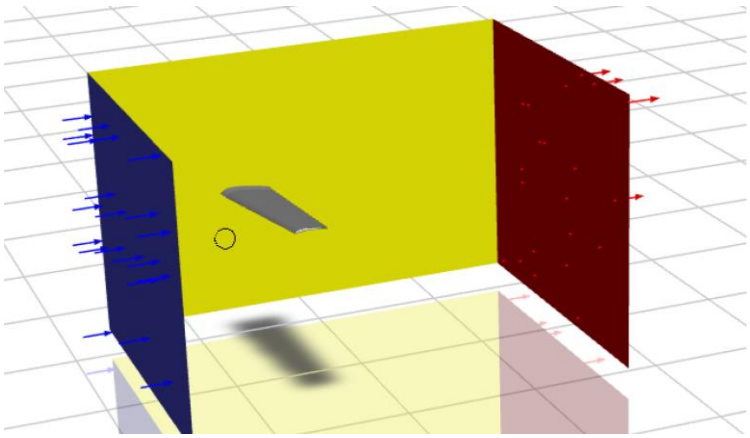


Figure 6. Aerodynamic analysis of the wing of an aircraft using ANSYS-Fluent

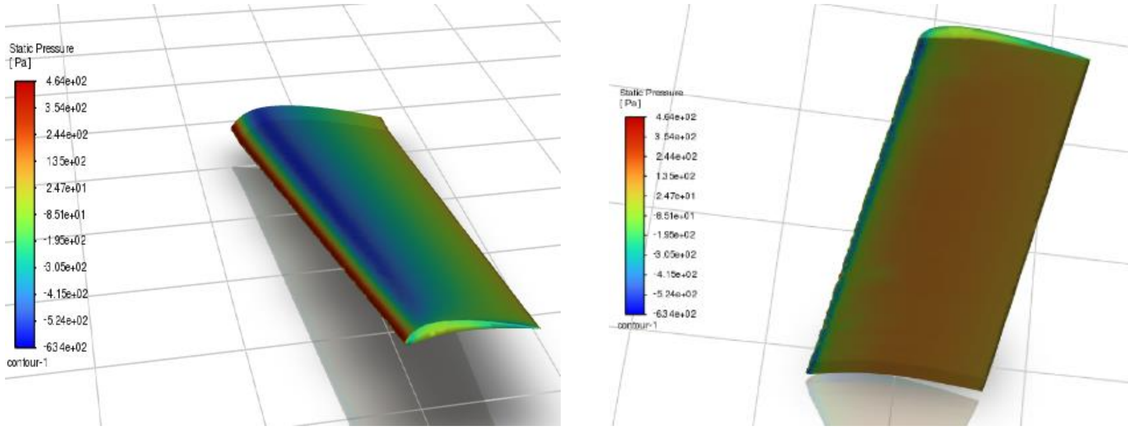


Figure 7. Static pressure of the top and bottom wings in ANSYS Fluent.

A separate structural analysis of the UAV shows that the center of gravity is located 350mm from the nose of the fuselage, while the total weight is 1300 ± 20 g. Static structural analysis of the wing was conducted in ANSYS WorkBench, as shown in Figure 8.

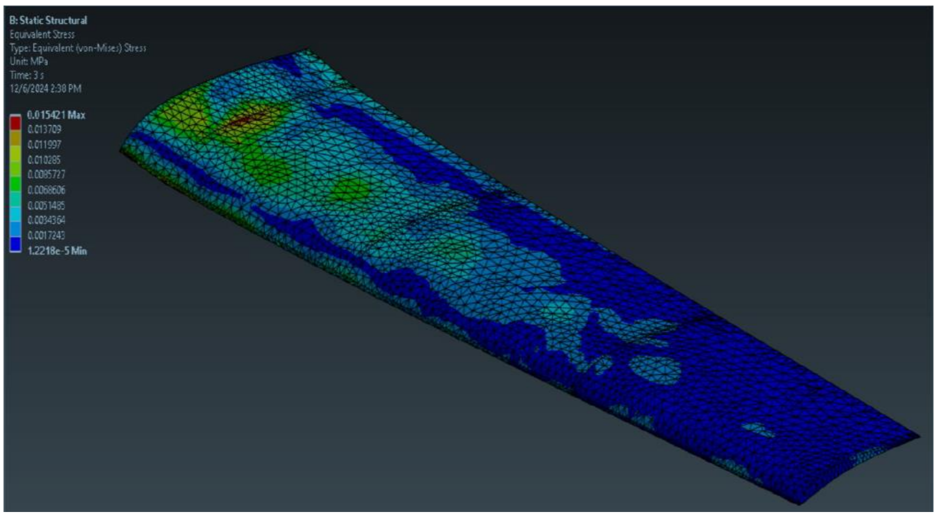


Figure 8. Structural analysis of the wing in ANSYS

The results showed a very low deformation and stress with a high factor of safety.

1. **Deformation**: Maximum deformation was 0.0876 at the far end of the wing
2. **Full wing Stress**: Equivalent stress maxed at 0.015 MPa, which was well below the tensile yield strength of 27.44 MPa.
3. **Joint Stress**: The equivalent stress at the joint was even lower, with a max of 0.008 MPa.

The CFD analysis shows that at 30 m/s, the plane's joints are safe, with stresses far below the yield strength. This study validated that the thickness and internal structure are sufficient.

VI. 3D Printing

The Bambu Lab X1C 3D printer is used for printing aircraft parts. One challenge with this printer is its printing volume. The maximum length the printer can print is 250 mm. However, our modular design concept allowed us to overcome this challenge.

Moreover, to meet the rigidity requirement, we switched from standard PLA to lightweight PLA. However, we encountered difficulties printing narrow sections with lightweight PLA. The printing speed and temperature were modified to ensure the printing quality. The printing settings used during printing are shown in Table 3 below.

TABLE 3. 3D printing considerations

Parameter	General PLA	Lightweight PLA
Initial layer speed		
Initial layer speed	50 mm/s	25 mm/s
Initial layer infill speed	105 mm/s	50 mm/s
Outer layer speed		
Outer wall speed	200 mm/s	100 mm/s
Inner wall speed	300 mm/s	150 mm/s
Small parameter	50%	20%
Sparse infill speed	270 mm/s	135 mm/s
Internal solid infill	250 mm/s	125 mm/s
Top surface	200 mm/s	100 mm/s
Overhang speed	0 mm/s	0 mm/s
	50 mm/s	25 mm/s
	30 mm/s	15 mm/s
	10 mm/s	5 mm/s
Temperature		
Nozzle temperature	190-220 ^{0}C	240-250 ^{0}C
Bed temperature	30-60 ^{0}C	30-60 ^{0}C

VII. Flight Test

The assembled aircraft, as shown in Figure 9, underwent multiple flight tests (Figure 10) to evaluate its aerodynamic performance, stability, and control effectiveness. The tests were conducted under calm weather conditions to minimize external disturbances and ensure reliable data collection. The aircraft demonstrated smooth takeoff, stable cruise, and responsive maneuverability, with effective operation of the ailerons, elevator, and rudder. The foldable propeller reduced drag during glide phases, while the modular wing design maintained structural integrity throughout flight maneuvers. The center-of-gravity adjustment feature proved crucial in achieving longitudinal stability, confirming the practicality of the adjustable wing–fuselage connector. Overall, the flight tests validated computational and structural predictions, showing that the modular 3D-printed aircraft could achieve reliable performance while maintaining lightweight construction and ease of transportability.

Figure 9. Fully assembled 3D printed aircraft

(a) (b)

Figure 10. (a) Flight test at steady state flight, (b) flight test at ascending condition.

VIII. Summary

The development of the competition aircraft centered on innovative design strategies tailored to the opportunities and constraints of 3D printing. A modular wing structure was created, divided into eight segments connected via a novel female–male–female joint system, enabling a larger span despite the limited printer bed size. Internal honeycomb infill patterns were employed to maximize stiffness while minimizing weight, and a longitudinally adjustable wing–fuselage connector was integrated to allow fine-tuning of the center of gravity. The fuselage incorporated strategic cutouts to reduce mass without compromising rigidity, while lightweight PLA was selected to improve the strength-to-weight ratio further. Printing parameters, including speed, temperature, and orientation, were optimized to address challenges in adhesion and print quality for narrow geometries. Together, these design and manufacturing choices demonstrated how 3D printing can overcome traditional limitations in UAV fabrication, providing a lightweight, transportable, and structurally reliable aircraft.

IX. Conclusion

The study highlights the feasibility of using additive manufacturing to design and fly lightweight, structurally sound, and cost-effective modular UAVs. The innovations in modular design, joint mechanisms, and material optimization proved essential in balancing aerodynamic efficiency with manufacturability. Flight testing confirmed that a low-cost 3D-printed platform can achieve reliable stability and maneuverability while remaining easy to transport and repair. These findings suggest that modular 3D-printed UAVs are not only suitable for competition environments but also hold promise for broader applications in rapid prototyping, low-cost research platforms, and future scalable UAV systems.

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References

1. Jo, B.W., and C.S. Song, *Thermoplastics and photopolymer desktop 3D printing system selection criteria based on technical specifications and performances for instructional applications.* Technologies, 2021. **9**(4): p. 91.
2. Islam, M.A., et al. *Design, Implementation, and Test Flight of a Lightweight Camber Morphing Wing Aircraft* in *AIAA AVIATION FORUM AND ASCEND 2025*. 2025.
3. Islam, M.A., et al. *Design and Implementation of a Variable Camber Mechanism for a Small Fixed-Wing UAV (Unmanned Aerial Vehicle)*. in *2024 IEEE International Conference on Robotics and Biomimetics (ROBIO)*. 2024. IEEE.

4. Somnic, J. and B.W. Jo, *Status and challenges in homogenization methods for lattice materials.* Materials, 2022. **15**(2): p. 605.
5. Somnic, J. and B.W. Jo, *Homogenization methods of lattice materials.* Encyclopedia, 2022. **2**(2): p. 1091-1102.
6. Technologies, N. *Ultra-Light Weight and Strong 3D Printing*. 2021 [cited 2025 Dec. 10].
7. Mitroudas, T., et al. *Towards 3D printed modular unmanned aerial vehicle development: The landing safety paradigm*. In 2022, the *IEEE International Conference on Imaging Systems and Techniques (IST)*. 2022. IEEE.
8. Ian Gibson, I.G., *Additive manufacturing technologies: 3D printing, rapid prototyping, and direct digital manufacturing*. 2015, Springer.
9. Alami, A.H., et al., *Additive manufacturing in the aerospace and automotive industries: Recent trends and role in achieving sustainable development goals.* Ain Shams Engineering Journal, 2023. **14**(11): p. 102516.
10. Vakharia, V.S., et al., *Multi-material additive manufacturing of high temperature polyetherimide (PEI)–based polymer systems for lightweight aerospace applications.* Polymers, 2023. **15**(3): p. 561.
11. Iftekar, S.F., et al., *Advancements and limitations in 3D printing materials and technologies: a critical review*. Polymers, 2023. **15**(11): p. 2519.
12. Mahović Poljaček, S., et al., *Mechanical properties of 3D-printed PLA structures observed in framework of different rotational symmetry orders in infill patterns.* Symmetry, 2025. **17**(3): p. 466.
13. Graba, M. and A. Grycz, *Assessment of the mechanical properties of selected PLA filaments used in the UAV project.* Materials, 2023. **16**(3): p. 1194.