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Research Article

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Original Paper

Design, Performance Analysis, and Testing of a Camber Morphing Wing for Tactical Unmanned Aerial Vehicles (UAV)

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Abstract: The demand for efficient and sustainable Unmanned Aerial Vehicles (UAVs) has increased significantly in recent years. One of the key reasons for this growth in UAVs is their adaptability and agility across diverse conditions. Flight modes are implemented using control surfaces. Conventional fixed-wing UAVs rely on discrete control surfaces, such as flaps and ailerons, for maneuvering. Although these control surfaces are widely used, they introduce aerodynamic discontinuities, flow separation, and increased drag. The concept of morphing wings is more substantial, but conformal shape change is necessary to avoid these limitations while maintaining flight control authority. One of the most challenging aspects in morphing is its implementation and application to actual aircraft to validate its effectiveness. This study explores the feasibility of using a 3D-printed conformal camber-morphing mechanism in the design and construction of small UAVs. Two different conformal camber morphing mechanisms have been designed, developed, and tested in flight and in the wind tunnel to assess their performance relative to conventional flap-based wings. CFD analysis and wind-tunnel results indicate up to 51.4% and 49.5% improvements in the Coefficient of Lift (C_L), respectively, at the same Drag Coefficient (C_D) of flap-based and morphing wings, highlighting the superior aerodynamic efficiency of the morphing design. The results show that 3D-printed modular morphing can be a practical and effective alternative to conventional flap-based wings, thereby improving UAV aerodynamic efficiency. This research establishes a foundational design flow for integrating morphing technologies into lightweight, low-cost UAV applications, validated through experimental testing and flight tests. The major contribution of this paper is to demonstrate the effectiveness of a camber-morphing wing aircraft through implementation and a rigorous design process, culminating in wind-tunnel and flight testing on a small UAV in its final stage of development.

Keywords: Morphing, Aerodynamic efficiency; L/D; CFD; Wind tunnel; UAV; Compliant mechanism; Articulated (Structure-based) mechanism; Morphing rate; 3D printing; Modular.

Nomenclature and Abbreviation

C_L	Coefficient of lift
C_D	Coefficient of drag
D	Drag force (N)
L	Lift force (N)
L/D	Lift-to-drag ratio (aerodynamic efficiency)
α	Angle of attack (deg)
θ_s	Servo motor deflection angle (deg)
θ_{te}	Trailing-edge deflection angle (deg)
θ_{le}	Leading-edge deflection angle (deg)
LE	Leading edge
TE	Trailing edge
CFD	Computational Fluid Dynamics
UAV	Unmanned Aerial Vehicle
3D printing	3-Dimensional Printing
NACA	National Advisory Committee for Aeronautics
AAW	Aeroelastic Wing
MAW	Mission Adaptive Wing
RSAWC	Rear Spar Articulated Wing Camber

1. Introduction

Nature demonstrates remarkable aerodynamic adaptability among different birds and insects, which continuously modify their wing geometry [1-4]. They alter the wing's shape, span, and area to enhance performance across different flight conditions. The concept of 'Morphing wings' draws inspiration from the biological flexibility and adaptability of these creatures. The term 'morph' comes from the Greek word "meta-morphosis,' which means 'to change shape [5, 6]. In engineering terms, morphing refers to the use of a smart structure or to an approach that employs compliant or rigid-body mechanisms or materials. Traditional aircraft use hinged mechanisms such as flaps, ailerons, and slats. These discrete control surfaces are connected using external hinges and include gaps between the main wing surface and the control surfaces. These hinges, connectors, and gaps introduce surface discontinuities that cause boundary-layer separation, vortex shedding, and increased drag (D) [7].

Although these effects are often overlooked in large conventional commercial aircraft, they are detrimental for small-scale UAVs, where low Reynolds numbers and limited power availability lead to aerodynamic inefficiencies. With the increasing use of small, lightweight UAVs, from environmental monitoring to combat operations, there is a growing need for high endurance. These energy-efficient platforms operate reliably under varying flight conditions. Table 1 compares fixed-wing and morphing-wing aircraft with respect to their flight motion control methodologies, features, and key pros and cons.

Table 1. Comparison between a fixed-wing and a morphing-wing aircraft.

Features	Fixed Wing Aircraft	Morphing Wing Aircraft
Morphing Mechanisms	Control Surfaces: slats, slotted flaps, winglets, retractable landing gear	Leading-Edge (LE) Trailing-Edge (TE) Global (LE+TE)
Features	Discrete, hinged, jointed	Continuous, flexible, elastic, jointless
Cons	- More drag (D) - Flow separation - Airframe noise	- Weight or complexity - Power consumption - Practicality of smart materials - Low-speed flight - Mostly applied to small aircraft
Pros	- Reliability - functionality	- Minimized flow separation - Improved L/D - Increased range - Reduced fuel consumption - Reduced airframe noise - drag (D) minimization - Expanded operational envelope - Multi-functional

The table clearly shows that morphing wings are a promising solution to these challenges. However, various morphing mechanisms have been developed over the years. By allowing continuous geometric changes such as camber, twist, or span variation, morphing wings can optimize aerodynamic performance without mechanical discontinuity. Fig. 1 shows various morphing mechanisms [8].

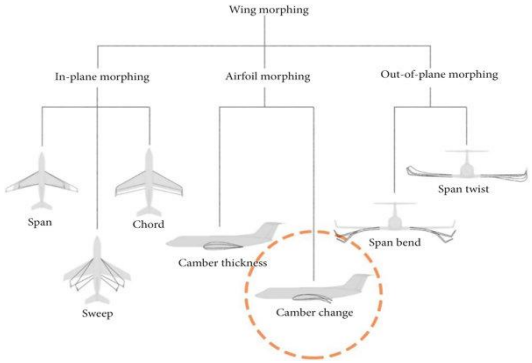


Fig. 1 Different types of wing morphing [9].

Previous research has shown that the morphing mechanism can significantly improve the aerodynamic efficiency, delay stall, and reduce overall energy consumption. These benefits are particularly important for electric and hybrid-electric UAVs, as their endurance largely depends on aerodynamic efficiency because of the limited energy density of onboard batteries or fuel cells [9-16]. Among morphing technologies, the camber morphing mechanism is of particular interest in this research [4]. Previous work has shown that morphing mechanisms can increase aerodynamic efficiency and performance; however, they have been overly complex in design. For example, Barbarino, S. et al. discussed NASA's Active Aeroelastic Wing (AAW) and Mission Adaptive Wing (MAW) programs, in which they demonstrated the morphing wind concept on large-scale aircraft [8]. However, the designs required complex servo-hydraulic systems and heavy actuation architectures, making them unsuitable for lightweight UAVs. Efforts have been made to integrate morphing technology into UAVs and to validate its performance through flight tests, CFD simulations, and wind-tunnel tests. For instance, Bilgen et al. developed and successfully flight-tested a UAV utilizing Macro-Fiber Composite actuators [8]. They used these actuators for solid-state control surfaces and effective roll control without traditional mechanical components. Their proposed morphing technique is shown in Fig. 2.

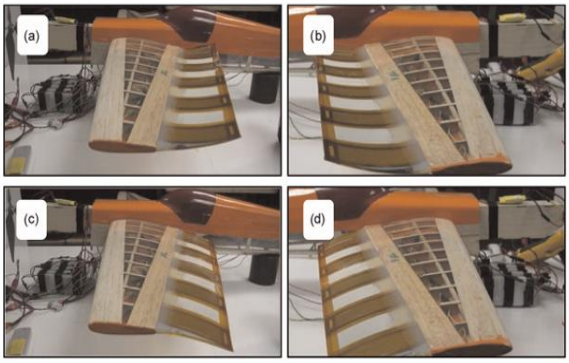
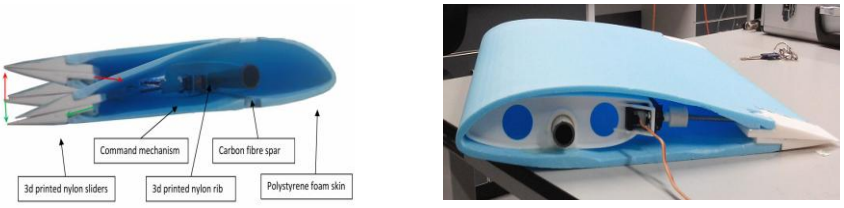


Fig. 2 Left-wing: (a) peak negative actuation and (c) peak positive actuation. Right-wing: (b) peak negative and (d) positive actuation.

The researchers used NACA symmetrical airfoils with a blended leading edge and a thin trailing edge for morphing, as well as tail-stabilizer morphing. Theoretical analysis indicated that the L-curve slope, D-polar, and other metrics were more suitable for morphing UAVs. In contrast, wind-tunnel test data showed that the steady-state roll rate of the morphing UAV was significantly lower than that of the baseline UAV. Chanzy and Keane [17] employed a morphing wing technique featuring flexible skin and a variable camber mechanism. They optimized the technology to enhance aerodynamic performance and validated it through wind tunnel testing. Their proposed model and actual wing are shown in Fig. 3. The researchers used servo actuators coupled to a sliding mechanism to achieve trailing-edge morphing. The researchers used foam-made skin and a nylon-made slide to incorporate a sliding mechanism at the trailing edge. Their proposed design has no hinge on the upper or lower surface of the wing, which reduces D. This results in higher aerodynamic efficiency (L/D) in morphing UAVs than in conventional UAVs, despite L not being significantly increased.



(a) (b)

Fig. 3 (a) 3D model of the morphing and (b) servo actuator with the sliding skin in the test section.

With recent advances in 3D printing technology, designing such morphing mechanisms has become simpler. The use of 3D printing in mechanism design and manufacturing has also gathered interest. Ozbek et al. [18] introduced the Rear Spar Articulated Wing Camber (RSAWC), a cost-effective morphing wing design for UAVs that increases flight endurance by approximately 19% through a fishbone-like rib structure with rear-spar articulation. Their RSAWC wing concept is shown in Fig. 4.



Fig. 4 RSAWC concept wing test.

The researchers introduced the FishBac mechanism, a fishbone-like 3D-printed wing rib, as the basis for morphing wings. Servo motors were also integrated into the wing to enable morphing, and a thermoplastic covering was used as the wing's surface. Kodigaddi et al. [19] developed and tested a 3D-printed trailing-edge morphing airfoil with a flexible zigzag rib. In their design, the leading edge of the baseline wing stays rigid, while the remaining 55% of the wing morphs. The authors used a TPU to fabricate the wings, resulting in a 30% higher L/D ratio than conventional airfoils. Jia et al. also presented a 3D-printed variable-camber morphing wing to improve aerodynamic performance and efficiency. Numerical, structural, and wind-tunnel testing show that the trailing edge can deflect up to 37.90 degrees. The researchers found that the stall angle was delayed by approximately 10 degrees, and the post-stall CL increased by 13%. Most of these works demonstrate the feasibility of incorporating a morphing mechanism into UAV design and fabrication. However, they are often limited to trailing-edge morphing and require a complex actuation process to achieve the morphing motions. The present study aims to bridge this gap by designing, fabricating, and experimentally validating a 3D-printed, modular, dual-actuated camber morphing wing. Two distinct morphing mechanisms have been developed and analyzed in this research. The purpose of introducing two different mechanisms is to demonstrate their potential for UAV design and fabrication, address their limitations, and compare their performance with that of flap-based conventional wings in wind tunnels and CFD tests. By combining modular construction, experimental validation, and aerodynamic performance assessment, this study provides a practical framework for future UAVs that require adaptable flight control and improved efficiency.

In short, many prior works have demonstrated aerodynamic improvements through morphing concepts; most are limited to component-level validation or laboratory-scale prototypes, and none have been implemented on full-scale aircraft. Though prior work has examined the in-flight performance of morphing concepts, it lacks a differential comparison with conventional flap-based wings. In addition, several morphing mechanisms reported in the literature rely on complex actuation systems, smart materials, or structurally intricate architectures. On the other hand, this work employs two distinct mechanisms, specifically designed for manufacturability, modularity, and UAV-level implementation. This research integrates conceptual design, additive manufacturing, multi-level aerodynamic analysis, structural evaluation, and full-scale flight testing in a unified framework. The morphing mechanisms are systematically compared with a conventional flap-based wing under identical operating conditions using both CFD and wind-tunnel experimentation, thereby providing a rigorous, quantitative performance assessment. Ultimately, the optimal morphing design is implemented on a complete UAV platform and validated through flight testing, addressing manufacturability and real-world implementation. Through this comprehensive approach, the study has developed a practical framework for integrating camber morphing into lightweight, low-cost UAV systems.

2. Research Objectives

The objective of this research is to develop, evaluate, and validate a complete camber morphing wing system that enhances the aerodynamic efficiency and flight performance of small unmanned aerial vehicles (UAVs). However, there are significant challenges to adopting morphing technologies in conventional UAVs, including manufacturability, reliability, ease of maintenance, and performance validation. To achieve this, the study pursues three specific goals.

- **Develop both compliant and articulated structure-based morphing mechanisms suitable for UAV integration**:

The first objective of this research is to design and manufacture morphing mechanisms for UAV applications. The design begins with two distinct morphing concepts: a compliant structure-based, continuous-surface mechanism and an articulated-structure mechanism. These mechanisms are developed with an emphasis on manufacturability via additive manufacturing, structural robustness under aerodynamic loading, and the ability to generate smooth, controllable camber deformation without relying on conventional hinged surfaces.

- **Validation of the morphing wing performance through rigorous multi-dimensional analysis:**

After designing the morphing mechanisms, the researchers conduct rigorous analyses to compare the aerodynamic performance of both morphing concepts with that of a traditional flap-based wing. This comparison is conducted using a multilevel analysis framework that integrates kinematic evaluation, computational fluid dynamics (CFD), and low-speed

wind-tunnel testing. Through this approach, the study aims to quantify how morphing affects L generation, D characteristics, stall behavior, and overall aerodynamic efficiency across a broad range of operating conditions.

- **Implement and flight-test the optimal morphing design on a full-scale UAV platform:**

The final objective of the research is to implement the morphing wing concept to validate its use in actual UAV applications. This involves constructing a complete, flight-ready aircraft, including the morphing wing, and conducting controlled-flight tests to evaluate maneuverability, stability, morphing responsiveness, and operational reliability. In short, these goals establish a comprehensive design-to-validation pathway for demonstrating the practicality and performance benefits of camber morphing in UAV applications.

3. Overall Workflow

The research was conducted following a structured, multi-phase decision-tree-based framework specifically to develop and apply morphing-wing concepts to operational UAV systems. Most prior work has demonstrated aerodynamic improvements using morphing airfoils; however, it is often limited to concept development rather than to a framework. In contrast, this study establishes a comprehensive, reproducible workflow for developing morphing wing concepts and integrating them into a full-scale UAV.

The proposed design flow starts with the conceptualization of morphing concepts and progresses to development, performance analysis, and operational demonstration. The decision tree approach ensures that the prototype satisfies predefined mechanical and aerodynamic performance criteria and then incorporates it into a UAV application. The analysis phase of the workflow is especially important, as it includes kinematic analysis, CFD simulation, and wind-tunnel experimentation, which provide the analysis process with sufficient rigor and validated confidence and enable system-level integration within a closed-loop evaluation process. The framework ensures consistency between predicted aerodynamic gains and experimentally verified performance. The major contribution of this research is the creation of a structured framework that extends beyond a single morphing concept.

The overall methodology, illustrated in Fig. 5, outlines the procedural steps followed in this study from concept to flight validation. This work contributes a scalable design flow that bridges the gap between theoretical morphing research and deployable aerial platforms.

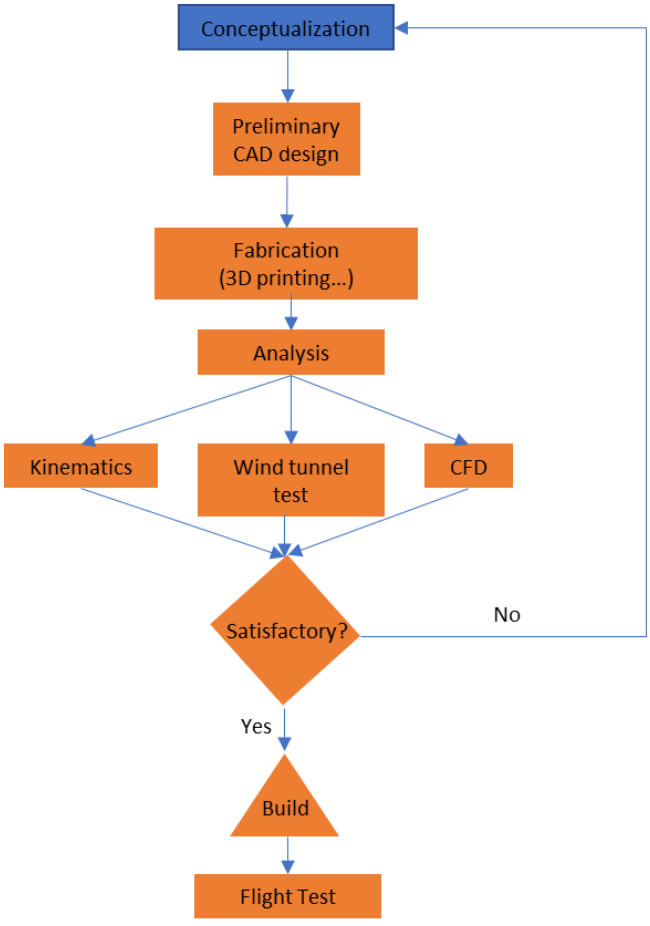


Fig. 5 Flowchart of the research approach

3.1 Conceptualization

The process begins with conceptualization. This step establishes the functional objective of achieving a smooth, continuous camber variation to improve expected aerodynamic performance. Two types of camber morphing mechanisms can be designed- a compliant structure-based camber morphing mechanism and an articulated structure-based camber morphing mechanism. The compliant structure-based camber morphing mechanism has no hinges; instead, it relies on deformation of the wing material. On the other hand, articulated or structure-based camber morphing mechanisms have hinge lines along which the wing morphs. Two distinct camber-morphing mechanisms for both types have been designed in this research.

3.2 Preliminary CAD Design

From this foundation, the workflow transitions into preliminary CAD design. In this step, the conceptual ideas are translated into mechanical architectures that can actually be built. CAD modeling enables articulation of different parts of the design, helps visualize the prototype, and is also used in modern manufacturing techniques such as 3D printing.

3.3 Fabrication

The design is then fabricated using 3D printing. 3D printing is employed in this research rather than other manufacturing processes. The key reason for choosing 3D printing is its ability to enable rapid prototyping and fabrication. 3D printing also ensures a good surface finish and multiple iterations at low cost, with high geometric fidelity.

3.4 Analysis

A comprehensive multi-level analysis framework was employed to evaluate the aerodynamic, structural, and functional performance of the camber morphing mechanism before committing to full-scale aircraft integration. Because morphing systems involve coupled structural deformation, actuation dynamics, and aerodynamic loading, no single analysis method is sufficient. Instead, three complementary analyses—kinematic analysis, computational fluid dynamics (CFD), and wind tunnel testing- were utilized. Each plays a distinct role in validating the morphing concept and in identifying potential issues before flight testing. Table 2 shows the focus and importance of these analysis techniques.

Table 2. Focus and importance of analysis techniques.

Analysis Type	Focus	Importance
Kinematic	Mechanical motion, deformation smoothness	Ensures the mechanism works physically and produces aerodynamic shapes
CFD	Flow behavior, lift/drag, drag polar	Predicts aerodynamic advantages and identifies optimal morphing states
Wind Tunnel	Real force measurements, structural response under load	Validates CFD and reveals physical effects not captured numerically

3.5 Implementation of the aircraft

The analysis steps serve as the rejection criteria, indicating whether the developed morphing mechanism offers an aerodynamic advantage over conventional flap-based wings. Once the analysis shows satisfactory performance, the workflow proceeds to the final implementation. The final step involves designing other UAV components, such as the fuselage and tail, and integrating electronics and propulsion equipment.

3.6 Flight test

The final stage is the flight test, the ultimate validation of whether the morphing mechanism provides real aerodynamic benefits in dynamic conditions. Flight testing confirms UAV stability, control response, power consumption, and

morphing effectiveness in real operating environments, completing the logical progression from concept to airworthy technology. The workflow followed in this research follows a systematic approach, comprising all actions from initial conceptualization to the actual implementation of morphing technologies, with rigorous analysis. The steps have been mentioned briefly in this 'Overall Workflow' section. All the steps are described in detail in Sections 4-8.

4. Conceptualization

At the start of the conceptualization process, the key features are identified. Key design requirements included: (i) maintaining a continuous aerodynamic surface throughout the morphing range, (ii) enabling both leading- and trailing-edge deformation for enhanced L control, (iii) minimizing mechanical complexity and weight to ensure UAV compatibility, and (iv) incorporating modularity to support rapid prototyping and iterative testing. Based on these criteria, two primary morphing strategies are explored: compliant deformation and articulated structural mechanisms.

The compliant structure-based morphing approach relies on flexible internal structures and a bendable outer skin, allowing the wing to deform smoothly as a single continuous surface. This method offers several advantages, including seamless airflow with no hinge gaps, reduced D penalties, and fewer moving parts, thereby improving reliability and reducing mechanical noise. Compliant structure-based mechanisms also distribute deformation more naturally along the airfoil, maintaining smoother camber profiles. However, these mechanisms often exhibit limited ranges of deformation and load-bearing capacity under higher aerodynamic forces, particularly when actuators, such as servo motors, are strained.

In contrast, the articulated or structure-based morphing approach uses discrete mechanical elements—such as linkages, pivots, or rib segments—to actively reshape the wing. However, unlike flap-based mechanisms, the linkages are placed inside the wing. Articulated systems can be designed to amplify servo inputs, enabling substantial aerodynamic changes with lower actuator loading. Their modularity also supports easier maintenance and adjustment of morphing behavior. Nonetheless, the presence of joints and discrete elements can create minor surface discontinuities, potentially increasing D or inducing localized flow disturbances.

By evaluating both concepts against the desired morphing capabilities, manufacturability constraints, and UAV integration requirements, the study includes the design of two morphing concepts of two types. This enabled both mechanisms to be prototyped, tested, and compared within a controlled framework, ensuring that the final morphing solution selected for aircraft integration reflected an optimal balance among aerodynamic smoothness, deformation amplitude, structural reliability, and practical implementation.

5. Design

Camber morphing can be achieved through several structural and mechanical strategies. Two major classes of mechanisms are widely recognized in the literature: (1) compliant structure-based morphing mechanisms, which rely on smooth, continuous deformation, and (2) articulated structure-based morphing mechanisms, which use discrete linkage systems to reshape the airfoil. Both approaches offer unique advantages and constraints regarding structural complexity, manufacturing feasibility, weight, and achievable deformation. In this study, both types of morphing concepts were designed, developed, and evaluated.

5.1 Compliant structure-based morphing mechanism

The designed compliant structure-based morphing mechanism is single-servo actuation-based. Two servo-linkage rods are connected to the leading and trailing edges, thereby generating morphing motion.

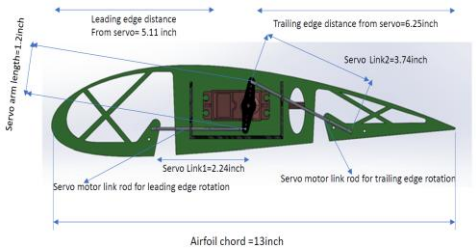


Fig. 6 CAD design of a camber morphing mechanism with detailed dimensions

Figure 6 shows a CAD model of the morphing mechanism, designed in SolidWorks. A single servo motor drives it, and two servo link rods are attached to each side of the servo motor's arm. When the motor rotates clockwise or counter-clockwise, the rod pulls or pushes the flexible structure at both the leading and trailing edges, enabling conformal, smooth

morphing across the entire airfoil surface. The figure also illustrates the detailed dimensions of the morphing mechanisms. Table 3 summarizes them.

Table 3. Detailed dimensions of the morphing mechanism in CAD models

Parts	Dimensions
Airfoil chord length	13 inches
Servo link length 1 (to the leading edge)	2.24 inches
Servo link length 2 (to the trailing edge)	3.74 inches
Servo arm length	1.2 inches
Leading edge distance from the servo	5.11 inches
Trailing edge distance from the servo	6.25 inches

The wing structure was fabricated using carbon fiber for its high strength-to-weight ratio and stiffness. Each wing incorporated three servo motors dedicated to morphing. The leading and trailing edges of the airfoil could dynamically change camber, enabling precise roll control during flight. The completed wings underwent morphing tests to ensure smooth transitions and robust performance under simulated flight loads. A 3D design of the wing and the ribs is shown in Fig. 7.

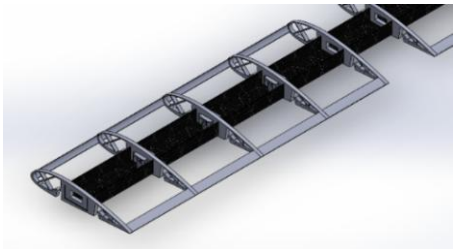
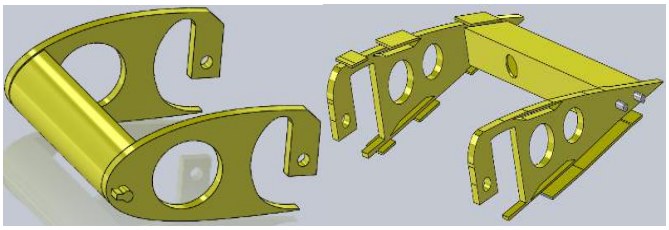


Fig. 7 3D CAD design of the conformal camber morphing wing

5.2 Articulated structure-based morphing mechanism

Unlike compliant mechanisms, articulated structure-based morphing mechanisms deform about hinges. The designed morphing mechanism comprises two servo motors that deform the leading and trailing edges of the wing. The central concept of this modular design is a snap-in/out mechanism that enables easy replacement, design modification, and 3D printing. The entire wing section consists of four parts, with no glue, bolts, nuts, screws, or other joints.



(a) (b)

Fig. 8 (a) The leading edge, and (b) the trailing edge of the morphing wing parts.

Both wing parts are connected by a modular C-channel that also houses the servo motors. The c-channel is connected via a snapping mechanism, making the wing modular and easily repairable.

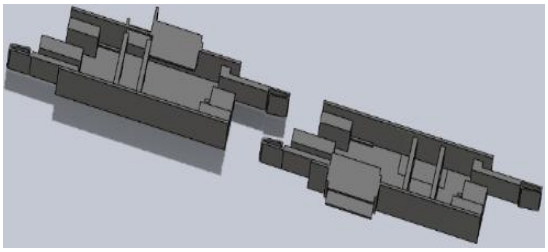


Fig. 9 Modular C-channel with servo housing.

Another important component of the design is the sliding skin mechanism, which enables the wing to morph without wrinkling the skin. The front skin is affixed to the leading edge, whereas the rear skin slides along guiding slots. The wing morphology depends on the central hinge pin, which connects all parts.

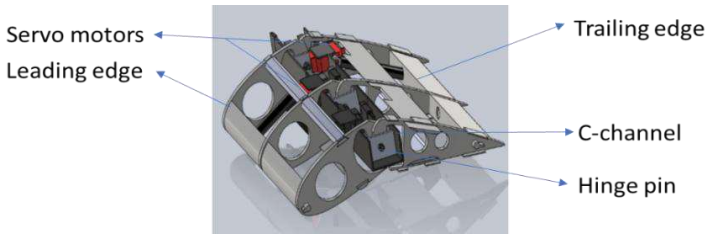


Fig. 10 3D assembly of articulated structure-based morphing mechanism.

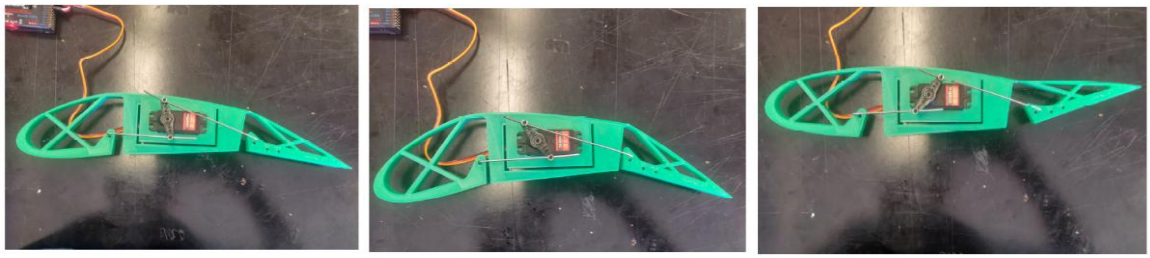
Fig. 10 illustrates a 3D assembled model of a morphing airfoil with the servos that are placed in the C-channel spar, each controlling the leading or trailing edge section of the wing.

6. Fabrication

To evaluate the feasibility and performance of the two camber morphing concepts developed in this study, both designs were physically prototyped.

6.1 Compliant structure-based morphing mechanism

The initial step in the analysis process is to build a prototype of the morphing mechanism. A rib of the morphing airfoil is 3D-printed from PETG. PETG is selected for its high structural rigidity and load-bearing flexibility. The servo motor can rotate clockwise (CW) or counterclockwise (CCW). CW rotation produces negative camber, and CCW produces positive camber as a function of rotation angle.



(a) (b) (c)

Fig. 11 Three different morphing motions: (a) slightly positive, (b) a full positive, and (c) negative morphing motions, respectively.

6.2 Articulated structure-based morphing mechanism

The wing is constructed as an interchangeable 3D-printed module comprising a wing segment based on the NACA 4421 airfoil. The chord length of the wing airfoil is set at 13 inches, allowing servo actuators to be correctly fitted inside the wing. The airfoil is divided into two separate parts. Two leading-edge ribs joined by a stringer form one separated morphing part, and two trailing-edge ribs joined by a stringer form the other morphing part of the modular wing segment. The leading-edge segmented morphable wing part is hinged to the trailing-edge morphable wing part. The rib part is housed in a built-in hinge within the C-channel spar. The thickness of the modular C-channel spar is 2mm. When the wing airfoil morphs positively about the hinge line, it becomes a new under-cambered airfoil with a higher CL. In this design, no screws are used to join the modular parts. C-channel spars are joined together with the help of a self-locking mechanism. PLA is selected for printing morphable wing segment components due to its high strength and low cost. 3D-printed PLA parts require no post-processing to minimize surface roughness, thereby reducing frictional D in flight.

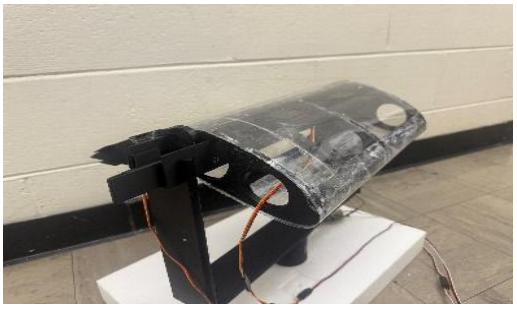
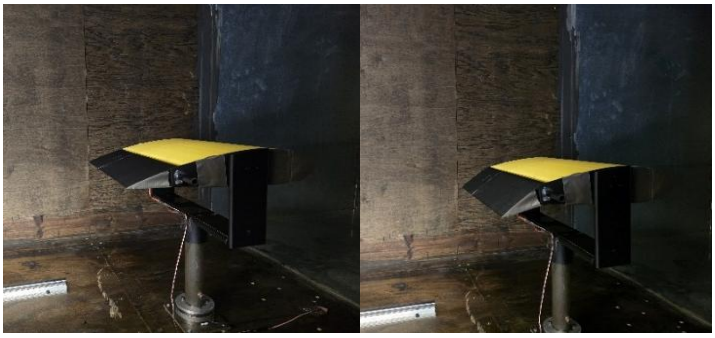


Fig. 12 Fully assembled camber morphing wing section.

A plain flap is also developed from the baseline NACA 4421 airfoil. For direct comparison and keeping the same Reynolds number, the chord and span are made the same as the morphing baseline wing. For the flap-wing configuration, a traditional trailing-edge flap was integrated into the NACA 4421 airfoil and deflected from -30° to 35° using a calibrated servo motor. The flap-wing configuration was rigidly attached to the mounting structure, and flap-angle calibration was verified before each test run. Fig. 13 shows the flap-wing mounted in the test section during experiments.



(a) (b)

Fig. 13 Designed flap-based wing section at (a) initial baseline configuration, (b) flap wing with deployed flap.

7. Experiment and Analysis

To evaluate the feasibility and performance of the two camber morphing concepts developed in this study, both designs were subjected to a comprehensive analysis workflow. Initially, kinematic analysis was conducted for both morphing mechanisms. To assess the comparative advantage of conventional flap-based wings, the articulated-structure-based morphing mechanism was tested against a flap-based morphing wing. This comparative analysis is conducted using Computational Fluid Dynamics (CFD) and wind-tunnel validation. The comprehensive analysis of morphing mechanisms and their subsequent outcomes is presented here.

7.1 Compliant structure-based morphing mechanism

To understand the relationship between the servo actuator and the actual morphing at both the leading and trailing edges, a kinematic analysis is necessary. Kinematic analysis gives us the functional relationship between the command and its actual implementation.

7.1.1 Kinematic analysis of Compliant structure-based morphing mechanism

This section provides kinematic explanations of variable-camber morphing and is expected to supplement aerodynamic and performance evaluations for full-scale UAV design and operations.

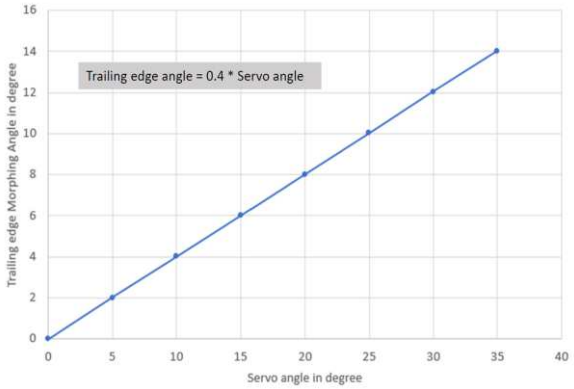


Fig. 14 Electronic components for the camber motion control. [1]

Fig. 14 shows the geometric and physical morphed angles at the airfoil's trailing edge, while the servo motor's angles are controlled. The graph shows a linear, monotonically increasing relationship between them. The maximum angle from the servo is 35 degrees, and the corresponding angle on the trailing edge is 14 degrees. Each 5-degree servo rotation corresponds to 2 degrees at the trailing edge. In an analytical form, the relation is described as follows in Eqn. 01.

$$\theta_{te} = 0.4 \cdot \theta_s \tag{1}$$

where θ_{te} is the angle of the trailing edge, and θ_s is the angle of the servo motor arm.

The graph shows a linear, monotonically increasing relationship between them. Unlike the trailing edge, the maximum angle from the servo is 35 degrees, and the corresponding angle on the leading edge is 12 degrees, which is 2 degrees off compared to the trailing edge. As shown in Eqn. 2, every 5 degrees in the servo is less than 2 degrees (about 1.8~1.9) in the leading edge. 02.

$$\theta_{le} = 0.348 \cdot \theta_s \tag{2}$$

where θ_{le} is the angle of the leading edge in the airfoil, and θ_s is the angle of the servo motor arm.

7.2 Articulated structure-based morphing mechanism

As with compliant structure-based mechanisms, kinematic analysis is also performed for articulated structure-based morphing mechanisms. In addition, a rigorous comparative analysis is conducted to evaluate the performance of the designed mechanism against a conventional flap-based wing prototype [20].

7.2.1. Kinematic analysis of Articulated structure-based morphing mechanism

To establish a performance comparison between the conventional flap mechanism and the morphing wing concept, a sequence of three correlation plots is introduced. These graphs establish the relationships between the servo angle deflection, the corresponding flap deflection, and the change in morphing rate. Initially, the flap-based wing's servo angle is varied to quantify the relationship. Figure 15 illustrates the relationship between the servo deflection angle and the actual flap deflection angle in a conventional system, serving as a baseline reference.

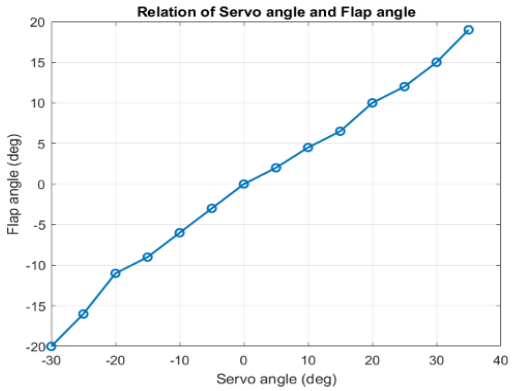


Fig. 15 The relation between servo angle and flap deflection.

The next phase of kinematic analysis is used to show the relationship between the servo angle and the morphing rate. The morphing rate is the rate of change of the morphed airfoil's camber relative to the baseline camber. Figure 16 shows the relationship between the servo angle and the morphing rate.

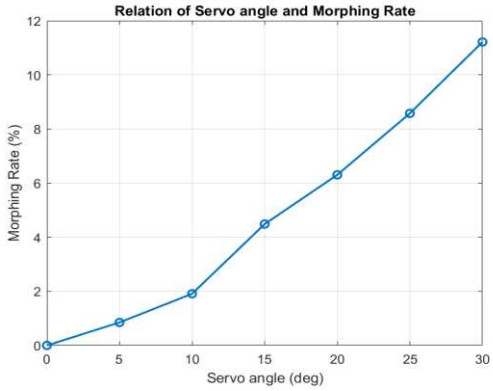


Fig. 16 The relation between servo angle and morphing rate.

Finally, Figure 17 correlates the morphing rate with an equivalent flap deflection angle, providing a standard performance metric for comparing the two systems.

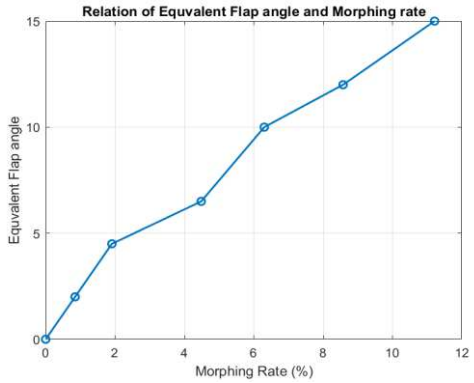


Fig. 17 The relation between equivalent servo angle and morphing rate

This mapping enables a direct comparison of the aerodynamic effects produced by traditional flap deflection versus those induced by smooth camber morphing, under equivalent servo inputs.

7.2.2. CFD analysis of Articulated structure-based morphing mechanism

Computational Fluid Dynamics (CFD) analysis is performed to assess improvements in L generation compared to a flap-based wing. CFD simulation has been done at five different morphing rates for the morphing wing and five different flap deflections for the flap-based wing. All other operational conditions, i.e., wind speed and angle of attack, has kept constant. Before performing the CFD analysis, a mesh convergence study was conducted to reduce mesh-dependent effects in the results.

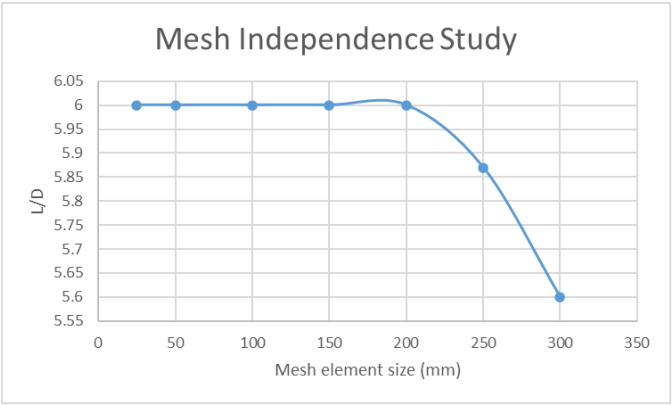


Fig. 18 Mesh Independence Study

Figure 18 shows that the CFD results remain constant across mesh sizes ranging from 25mm to 200mm. A uniform mesh size of 50 mm was chosen for the CFD study to reduce computational costs and ensure accurate results. The viscous SST K-Ω model is used for all analyses, with a velocity inlet boundary condition of 11.5 m/s and a pressure outlet. The comparative CFD result is shown in Figure 19.

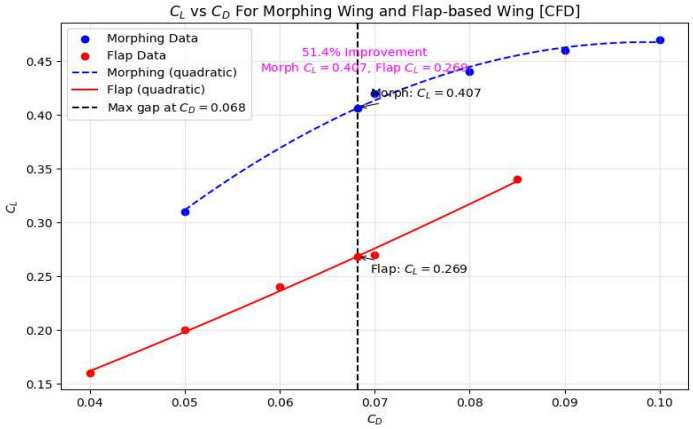


Fig. 19 Comparative drag polar of the morphing wing and flap-based wing from CFD analysis.

The chart shows that the articulated structure-based morphing wing performs better across the entire operational spectrum, with a maximum 51.4% improvement in CL at a fixed CD of 0.073.

7.2.3. CFD Wind tunnel validation of Articulated structure-based morphing mechanism

Similar to the CFD analysis, Wind tunnel tests are also carried out at five different morphing rates for the morphing wing and five different flap deflections for the flap-based wing. For the wind tunnel test, an open-loop, low-subsonic wind tunnel is used at TTU. The wind tunnel can generate a maximum wind speed of 15 m/s, with a test section measuring 1.5 m x 1.5 m. The low-subsonic wind tunnel at TTU features a honeycomb screen to promote laminar flow and ensure uniformity in the test section. The wind tunnel, being relatively long compared to its diameter, also provides a laminar flow in the test section. Force measurements are taken by an ATI Mini85 Load Cell placed on the bottom surface of the tunnel's test section. This is run in parallel with LabVIEW using a data acquisition (DAQ) device, supporting a sampling rate of up to 1000 Hz [21]. The wind tunnel also features a three-directional traverse system, as shown above, for instrument integration to map the flow turbulence within the tunnel. The traverse system can travel 1 meter in the x, y, and z directions.



(a) (b) (c)

Fig. 20 Components of the TTU Subsonic wind tunnel showing (a) the exterior of the wind tunnel, (b) the load cell, (c) the traverse system with induced draft fan.

Figure 21 shows the wind-tunnel experimental setups for the morphing wing and the flap-based wing.



(a) (b)

Fig. 21 Experimental setup for (a) the morphing wing and (b) flap-based wing in the wind tunnel.

The comparative result between the flap-based wing and the morphing wing from wind tunnel tests is shown in Figure 22.

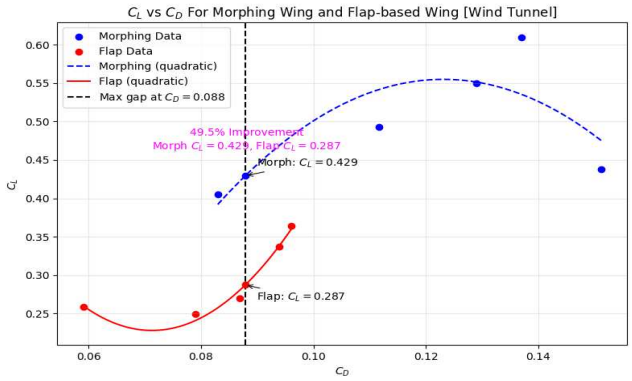


Fig. 22 Comparative drag polar of the morphing wing and flap-based wing from Wind Tunnel analysis.

The chart shows that the articulated structure-based morphing wing performs better across the entire operational spectrum, with a maximum 49.5% improvement in CL at a fixed CD of 0.088.

8. Build & Fly

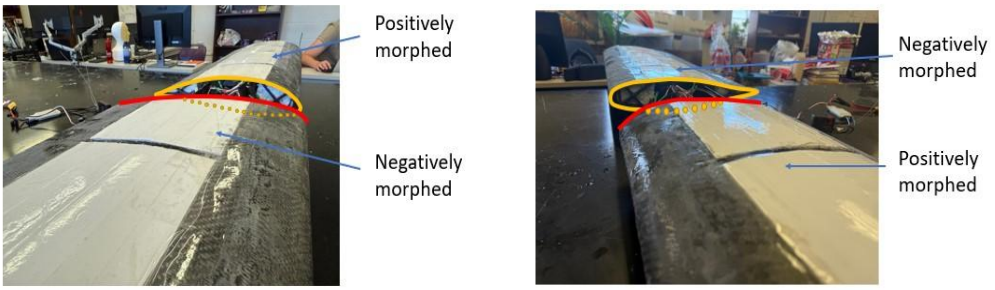
Following successful design validation and performance assessment of the morphing mechanisms, the final stage of this research involved integrating the optimized camber-morphing wing into a fully functional unmanned aerial vehicle and evaluating its performance under real-world flight conditions. To fabricate the morphing airfoil-based UAV, the compliant structure-based morphing technique is chosen. Despite the compliant structure-based mechanism exerting higher loads on the servos during morphing, this method is chosen for its simple design and ease of manufacturing.

8.1 Implementation of the compliant structure-based morphing mechanism in UAV

Building the UAV is a considerable challenge, as it involves designing the rib for the morphing mechanism, assembling the wing with the ribs, and including all the control apparatus. Below are some crucial stages in the building process.

8.1.1. Wing construction

The wing structure was fabricated using carbon fiber for its high strength-to-weight ratio and stiffness. Each wing incorporated three servo motors dedicated to morphing. The leading and trailing edges of the airfoil could dynamically change camber, enabling precise roll control during flight. The completed wings underwent morphing tests to ensure smooth transitions and robust performance under simulated flight loads. The morphing difference between the two sides of the wing during a rightward rolling condition is illustrated in Figs 23 (a) and (b).

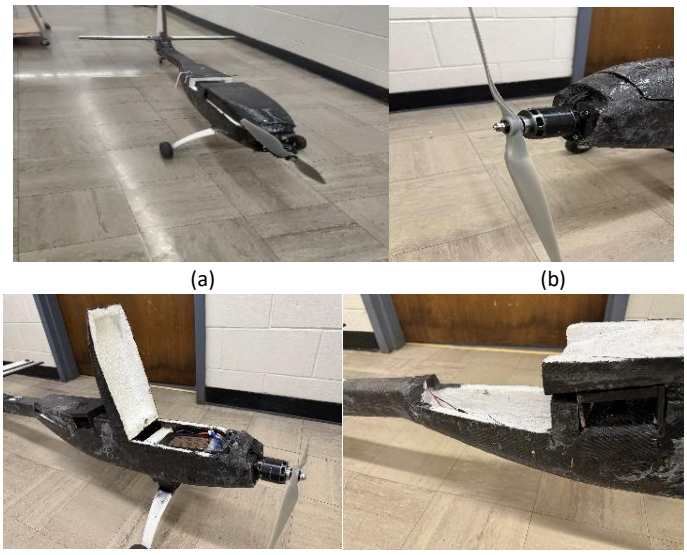


(a) (b)

Fig. 23 Morphing for rightward rolling for (a) the left wing and (b) the right wing, where positive (yellow) and negative morphing (red) are shown accordingly.

8.1.2. Fuselage and Tail design

The fuselage and tail assembly were also modeled in SolidWorks, with a focus on aerodynamics, weight distribution, and structural compatibility with the wings. The fuselage was constructed from lightweight carbon fiber composite and Styrofoam to house the avionics and battery, resulting in a total UAV weight of 8.1 kg. The motor is mounted in front of the UAV's fuselage for propulsion, and a solid wooden block serves as its mounting. The fuselage features two canopies: a front (nose) canopy and a rear canopy. The nose canopy provides the opening for installing the battery, ESC, and other components in their proper locations inside the fuselage. The rear canopy is used during wing assembly on the fuselage and when connecting the tail servo cables to the receiver. It perfectly fixes the wing with the fuselage and tail wiring. The front landing gear is mounted on the bottom surface of the fuselage, and the tail wheel is mounted at the end of the tail boom, integrated with a servo motor to ensure steering during the ground run for takeoff. Fig. 24 shows the UAV's structural components.



(a) (b)

(c) (d)

Fig. 24 (a) The fuselage of the UAV, (b) motor mounting, (c) nose canopy, (d) rear canopy, and (e) wing mounting

A conventional tail provides the UAV with static and directional stability in flight. The horizontal stabilizer is mounted on the tail boom high enough from the main wing's upper surface to avoid the interaction between the wake provided by the main wing and the horizontal control surface to ensure the higher efficiency of the tail. Two independent servo motors actuate the horizontal and the vertical stabilizers. Fig. 25 shows that the horizontal and vertical stabilizers are mounted on the tail boom.



Fig. 25 Horizontal and vertical stabilizers

8.1.3. Assembly and integration

All components, including the wing, fuselage, and tail, were assembled precisely. Servo motors were synchronized with a flight control system to control roll via a morphing mechanism. This eliminated the need for traditional ailerons, providing smoother control inputs. The wing is fastened to the fuselage using four bolts and nuts to support the UAV's overall weight, as well as its vibrational and aerodynamic loads, under all operating conditions, whether in flight or on the ground. Fig. 26 shows the complete assembly of the UAV.



Fig. 26 Completely assembled UAV with a morphing wing

8.2 Flight test

The flight test of the camber-morphing wing-based UAV is conducted at the Hyder-Burke Center of Tennessee Technological University (TTU). The main objective of the flight test was to ensure that the UAV generates enough L to take off using the morphing mechanism and can roll using the morphing wings. The performance from the flight test, as shown in Figs. 27 is primarily focused on the mission-planned flight, using rolling-moment control from the main morphing wings. Conventional control surfaces, such as the rudder and elevator in an airplane, provide additional control moments, including pitch and yaw, to counteract unexpected adverse yaw.



(a) (b)

Fig. 27 The morphing UAV during (a) take-off, (b) performing a left turn, during the flight test.

9. Summary

This study presented the complete workflow for the design, prototyping, analysis, and flight testing of two distinct camber-morphing mechanisms. A comprehensive aerodynamic evaluation framework was employed, combining CFD simulations and low-speed wind-tunnel testing to compare morphing wings with a traditional flap-based wing under

matched conditions. The articulated structure-based morphing mechanism demonstrated a maximum 51.4% improvement in C_L in CFD and 49.5% in wind tunnel testing at equivalent D levels. Although structurally simpler, the compliant structure-based mechanism exhibited smooth, continuous deformation suitable for UAV integration. Based on these findings, the compliant structure-based mechanism was selected for aircraft-level implementation due to its ease of fabrication and integration. Finally, a full-scale UAV incorporating the compliant structure-based morphing wing was built and successfully tested. The aircraft demonstrated stable takeoff, differential morphing roll capability, and reliable in-flight control. Overall, the results confirm that complete camber morphing wings can provide substantial aerodynamic benefits over conventional flap-based systems and can be practically realized using low-cost, modular, 3D-printed structures.

10. Conclusion

This research demonstrates the feasibility and aerodynamic benefits of integrating complete camber-morphing mechanisms into lightweight, small-scale UAVs. By designing and analyzing both compliant structure-based and articulated structure-based morphing concepts, the study provides a broad understanding of how different structural strategies influence deformation quality and aerodynamic performance. The aerodynamic performance improvements of morphing wings confirm their potential to significantly enhance L generation, delay stall, and reduce D penalties compared to traditional flap-based designs. The successful flight test further validates that morphing wings are not only aerodynamically superior but also operationally viable for real-world UAV missions. This study contributes to the morphing-wing field by demonstrating a low-cost, modular, 3D-printed design method that bridges the gap between theoretical morphing concepts and deployable UAV technology. The findings support the adoption of morphing wings as an effective alternative for improving flight efficiency, control smoothness, and mission adaptability in small UAVs.

Author Contributions

Conceptualization: [BW Jo], [MA Islam]; Methodology: [BW Jo], [MA Islam], [A Rahman], [AK Saha]; Formal analysis and investigation: [MA Islam], [A Rahman], [AK Saha]; Writing - original draft preparation: [BW Jo], [MA Islam]; Writing - review and editing: [BW Jo], [MA Islam], [A Rahman]; Funding acquisition: [BW Jo]; Resources: [BW Jo]; Supervision: [BW Jo].

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Financial interests: The authors declare they have no financial interests.

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