3D-Printed Morphing Wings for Controlling Yaw on Flying-Wing Aircraft

Benjamin C. Moulton
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3D-PRINTED MORPHING WINGS FOR CONTROLLING YAW ON FLYING-WING AIRCRAFT

by

Benjamin C. Moulton

A thesis submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE in

Aerospace Engineering

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UTAH STATE UNIVERSITY
Logan, Utah
2021
ABSTRACT

3D-Printed Morphing Wings for Controlling Yaw on Flying-Wing Aircraft

by

Benjamin C. Moulton, Master of Science
Utah State University, 2021

Major Professor: Douglas F. Hunsaker, Ph.D.
Department: Mechanical and Aerospace Engineering

In recent years, various groups have attempted to improve aircraft efficiency using wings with morphing trailing-edge technology. Most of these solutions are difficult to manufacture or have limited morphing capability. The present thesis outlines a research effort to develop an easy to manufacture, fully 3D-printed morphing wing. This approach is advantageous due to the low cost, minimal man-hours required for manufacturing, and speed at which design iterations can be explored. Several prototypes were designed and tested and lessons learned from these iterations have been documented. Additionally, printer settings have been tested and catalogued to assist others attempting to reproduce these results. Performance was considered in terms of total deflection. Two concepts are presented as potential 3D-printed morphing-wing mechanisms. The Airfoil Recambering Compliant System (ARCS) is presented as a solution for a wing using continuous trailing-edge technology. The Kinetic Internal Nexus Compliant System (KINCS) is presented as a solution for a wing using discontinuous trailing-edge technology. The final KINCS design used for a prototype flying-wing aircraft is presented.
PUBLIC ABSTRACT

3D-Printed Morphing Wings for Controlling Yaw on Flying-Wing Aircraft
Benjamin C. Moulton

The flaps on an airplane wing are used to control the aircraft during flight. These flaps traditionally have at most three articulation or hinge points. Recent studies have shown improved flap efficiency using a conformal flap, which deforms following a curved shape. Much of aircraft improvement comes through increasing its efficiency during flight. This efficiency is generally improved by decreasing the drag force on the aircraft. A potential solution to decrease drag is to remove additional lifting surfaces, such as the horizontal and vertical stabilizer ubiquitous on general aviation aircraft. These additional lifting surfaces are used to trim and control the aircraft during flight. A flying-wing aircraft, which has no additional lifting surfaces, is trimmed and controlled using multiple flaps along the main wing. 3D-printing the mechanisms used to control these flaps has significant advantages. 3D-printing is fast, cheap, easy to repeat, easy to replicate, and produces durable parts. Two morphing mechanisms manufactured using 3D-printing are presented as viable solutions to demonstrate yaw control on a flying-wing aircraft. The Airfoil Recambering Compliant System (ARCS) is presented as a solution for a wing using a single flap with multiple actuators. The Kinetic Internal Nexus Compliant System (KINCS) is presented as a solution for a wing using multiple flaps, each with a single actuator. The final KINCS design used for a prototype flying-wing aircraft is presented.
To Andrea
ACKNOWLEDGMENTS

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Benjamin C. Moulton
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NOTATION

c \quad \text{airfoil chord length}

c_f \quad \text{flap chord length}

d_k \quad \text{chord-wise distance between kinks}

l \quad \text{camber line length from leading edge}

l_{hp} \quad \text{camber line length from leading edge to hinge point}

l_{loc} \quad \text{local camber line length from leading edge}

l_p \quad \text{local percentage along the camber line, hinge point to trailing edge}

l_{te} \quad \text{camber line length from leading edge to trailing edge}

m \quad \text{camber line slope}

n_k \quad \text{number of kinks between the hinge point and the trailing edge}

r_a \quad \text{arc radius}

t \quad \text{Bézier step value}

t_{loc} \quad \text{local airfoil thickness}

\theta \quad \text{arc point angle}

x_a, y_a \quad \text{arc coordinates}

x_b, y_b \quad \text{kink mid-line coordinates}

x_c, y_c \quad \text{arc center coordinates}

x_{cl}, y_{cl} \quad \text{camber line coordinates}

x_{cn}, y_{cn} \quad \text{kink cubic-Bézier node coordinates}

x_l, y_l \quad \text{airfoil lower surface coordinates}

x_{loc}, y_{loc} \quad \text{local camber line coordinates}

x_n, y_n \quad \text{kink node coordinates}

x_p, y_p \quad \text{parallel curve coordinates}

x_u, y_u \quad \text{airfoil upper surface coordinates}
### ACRONYMS

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<td>ABS</td>
<td>Acrylonitrile Butadiene Styrene</td>
</tr>
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<td>ARCS</td>
<td>Airfoil Recambering Compliant System</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer Aided Design</td>
</tr>
<tr>
<td>EPP</td>
<td>Expanded Polypropylene</td>
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<tr>
<td>FAA</td>
<td>Federal Aviation Administration</td>
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<td>FDM</td>
<td>Fused Deposition Modeling</td>
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<td>FishBAC</td>
<td>Fish Bone Active Camber</td>
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<td>LRPu</td>
<td>Low-Resilience Polyurethane</td>
</tr>
<tr>
<td>OML</td>
<td>Outer Mold Line</td>
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<tr>
<td>PLA</td>
<td>Polylactic acid</td>
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<tr>
<td>PE</td>
<td>Polyurethane</td>
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<tr>
<td>RC</td>
<td>Radio Controlled</td>
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<tr>
<td>SABRE</td>
<td>Shape Adaptive Blades for Rotorcraft Efficiency</td>
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<tr>
<td>TPU</td>
<td>Thermoplastic polyurethane</td>
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<tr>
<td>VCCTE</td>
<td>Variable-Camber Compliant Trailing-Edge</td>
</tr>
<tr>
<td>VCCW</td>
<td>Variable-Camber Compliant Wing</td>
</tr>
<tr>
<td>XPS</td>
<td>Extruded Polystyrene</td>
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CHAPTER 1
INTRODUCTION

Morphing aircraft have the capability to control aerodynamic forces and moments during flight more efficiently than traditional aircraft. Some designs accomplish this through continuous control-surface deflections such as variable-camber trailing edges or parabolic flaps with sufficient elasticity so that the trailing edge can be continuous. The Wright brothers used wing warping to control their aircraft. This control method was generally omitted from later aircraft designs in order to simplify the manufacturing process. With modern manufacturing methods, recent research has examined how morphing control-surfaces can be developed for use in current aircraft designs [1]. For example, the Air Force Research Laboratory developed the VCCW [2], NASA has developed the VCCTE [3], and a joint effort resulted in the design of the Flexsys aircraft [4]. Some groups have examined the use of piezoelectrics as actuation mechanisms for morphing-wing aircraft [5], as well as piezoceramic composites [6], and some have used corrugated internal compliant-structures to induce wing morphing [5,7]. Morphing wings have also been studied for use on helicopters through the SABRE [8] program using the FishBAC [9] structure.

Although each of these programs has taken a slightly different approach, they have each impacted the direction of the current research. For example, the FishBAC concept consists of a 3D printed bio-inspired airfoil geometry, where a servo is positioned to deflect the trailing edge via a pulley. The skin of this wing design consists of a pre-tensioned elastomeric sheet adhered to the 3D printed wing surface. For the ARCS design we also approached the challenge by employing 3D printing techniques with elastomeric structures.
1.1 FDM Motivation

One difficulty in developing such a complex mechanism lies in the need for rapid prototyping of the morphing control-surface in order to evaluate the performance of various designs. Additive manufacturing is frequently used where rapid prototyping is required. FDM is a sub-branch of additive manufacturing which consists of layering melted plastic in discretized sections to form a three dimensional object. Since the introduction of FDM as a manufacturing method, studies have examined partial and entire traditional aircraft created using FDM [10–12]. Recent studies have used FDM to develop flexible and/or morphing wings [13–18]. Such designs have been successful in demonstrating viable solutions to morphing flight using FDM. There are several advantages to using FDM for this process, as outlined here.

First, FDM is repeatable. The machine will repeat the manufacturing process exactly as detailed in the model G-code file. The removal of human error from the process allows for the model to be reprinted with minimal variation. Minor details in a model can be modified and manufactured with confidence that the resulting product will have been made in the same manner as the baseline model. A CAD model being FDM printed is shown in Fig. 1.1.

Second, compared to manual manufacturing processes, FDM is highly replicable. Given the slicer print settings for a model, a separate FDM 3D printer may achieve the same
results as the original printer. As the process is repeatable, the results can be verified with confidence by an alternate individual. Replicability removes the manufacturing nuances of the fabricator.

Third, whereas a test system’s destruction would cause significant delays due to manufacturing time, FDM allows for a test system to be reconstructed more quickly than traditional manufacturing and assembly methods. The rapid prototyping allows for small changes inspired by a test to be quickly manufactured and analyzed. With FDM, a small replaceable piece may be designed for a modular system. A model generally prints within hours versus the days and weeks required to fabricate the same prototype using a different manufacturing method. This allows for design changes to be explored quickly.

Fourth, the materials for FDM are generally cost effective. Along with the rapid prototyping, the cost decrease allows for several prototypes and testing platforms to be manufactured. The decreased cost also allows one to test various circumstances and designs knowing that the test bed’s destruction will not cause significant financial difficulty.

Finally, the materials for FDM are relatively durable. Even simple FDM materials such as polylactic acid (PLA) can be used to fabricate a sturdy aircraft structure. For example, an FDM radio-controlled aircraft can be landed without landing gear, a boon for weight management.

The purpose of this research is to develop a 3D printed morphing aircraft utilizing the benefits of FDM. This airframe will be tested to demonstrate proverse yaw and yaw control. While several groups have examined morphing wings, few of these designs have been fully 3D printed. Most rely on aluminum test frames or composite manufacturing and significantly long assembly procedures. A fully 3D printed wing’s assembly requires little to no assembly prior to use. This significantly decreases the time and complexity of fabrication.

The present thesis proposes an overview of the design process of this 3D-printed morphing wing mechanism. A description of the internal geometry, which can be applied an arbitrary airfoil, will be provided, printer settings and materials will be explained, and the
resulting characteristics and performance of several designs will be considered. Lessons learned will be catalogued and the final design will be described in detail. The purpose of this thesis is to add a solution for low-cost manufacturing of 3D-printed designs to the body of work on morphing aircraft, and to provide a discussion of the advantages and disadvantages of various designs.

1.2 Morphing Airfoil

One solution to demonstrate yaw control and yaw authority on a flying wing is to create variable induced and parasitic drag along the wing. This can be done by creating a morphing-airfoil geometry. A morphing airfoil is a two-dimensional airfoil design which is capable of changing its shape due to some input. In the case of a morphing airfoil for a Radio Controlled (RC) aircraft, the input is a digital servo motor. Using the input actuation from this servo motor, the preferable morphing-airfoil must have an efficient flap. The design and manufacturing process must be similarly effective.

1.2.1 Articulated and Conformal Control Surfaces

A parabolic flap deflects with the camber line conforming to a curved parabolic shape, rather than the single-joint articulation of a traditional flap. Studies have geometrically defined and examined the aerodynamic performance of a parabolic flap [19]. The geometries for a deflected articulated flap and deflected parabolic flap on a NACA 2412 airfoil are shown in Fig. 1.2.
The discontinuity in the camber line slope as shown in Fig. 1.3 demonstrates an inefficiency of the articulated flap. This inefficiency stems in part from an adverse pressure gradient created on this articulated flap. This adverse pressure gradient causes the flow to separate earlier along the surface of the wing compared to a parabolic flap. This causes the parabolic flap to produce less drag with changes in lift [19].

Another benefit to the parabolic flap can be shown in the flap effectiveness. The ideal section flap effectiveness can be calculated for articulated and parabolic flaps using thin-airfoil theory [19]. This effectiveness is defined as the change in zero lift angle of attack.
resultant from a change in flap deflection. The effectiveness for a NACA 2412 airfoil with articulated and parabolic flap deflection is shown below in Fig. 1.4.

![Fig. 1.4: Compared ideal section flap effectiveness on a NACA 2412 airfoil.](image)

As seen in Fig. 1.4, a parabolic flap is more efficient in deflecting the freestream flow than a articulated flap of similar flap chord fraction. Due to the decrease in drag and increased flap effectiveness, the parabolic flap was chosen as the airfoil deflection method. In order to achieve a truly parabolic flap, the airfoil geometry must be constructed so the aft portion of the airfoil can continuously morph. This can be done by making the aft portion of the airfoil a compliant mechanism. A compliant mechanism is a structure which is inherently flexible and strong, able to deform and revert with a negligible loss in structural integrity [20].

### 1.3 Morphing Wings

A morphing wing is the three-dimensional equivalent to a morphing airfoil. On a morphing wing, an array of servo actuation points deflect the RC aircraft wing to the varying degrees required. These several actuation points allow production of the same lift magnitude on a wing while varying the yawing moment by changing where the drag forces originate. The principle of creating local induced-drag maxima was chosen as the method to control yaw.
For a morphing aft control-surface, the gradient along the trailing-edge must be sufficiently large to produce the requisite high gradients in lift. These high gradients in lift produce the maxima of the induced drag form needed for the required yaw authority. The variable locations of the induced drag maxima along the wing produce the moments used to control the aircraft yaw. Thus, to produce high gradients in lift, the control surfaces must deflect dissimilarly along the wing. This is shown following in Figs. 1.5 and 1.8. Two control-surface types were examined as potential solutions to create large trailing-edge gradients along the wing.

1.3.1 Discrete and Continuous Control Surfaces

The first is a continuous control-surface in which servo motors control the deflection at multiple locations along the wing to maintain a continuous trailing-edge. An example can be seen in Fig. 1.5. One difficulty in this process, as will be examined later in this paper, comes from the need for a flexible skin that can shear deform between two servos, deflecting the neighboring sections in opposing directions.

With this control-surface type, the layering of the TPU and PLA was examined to optimize the skin stiffness and flexibility. Two of the layering ratios are given following.

Span-wise layers - 1:1 ratio

With the slip joint geometry mentioned above, the layering of TPU to PLA was examined as 1:1. The top view of this layering is shown in Fig. 1.6.
This layering allowed for greater flexibility in the span-wise morphing. However, it was not sufficient for the trailing-edge gradients desired. This difficulty motivated the study of greater flex to stiff ratios.

**Span-wise layers - 5:3 ratio**

The final TPU to PLA layering was determined to be a ratio 5:3. This layering was used on the ARCS concept, and the top view can be seen below in Fig. 1.7.

Notably, the PLA sections are not equal as in the 1:1 ratio drawing in Fig. 1.6. The thicker PLA ribs are located where the wing will actuate, providing the stiffness requisite for deflection. The thinner ribs in between the two thicker PLA ribs provide the structural support between the ribs to prevent buckling. This layering provided the necessary flexibility and stiffness for the wing. For this reason, it was chosen for the ARCS design.
The second control-surface type uses discrete flaps in which distinct sections of the wing are unconnected along the morphing aft portion of the wing. An example can be seen below in Fig. 1.8. Each discrete control-surface may be deflected without influencing neighboring control-surfaces. This significantly increases the production of induced drag. Because the control surfaces are not interdependent, they can produce great discontinuities along the trailing edge. Thus, they create greater gradients in lift, and larger maxima in the induced drag form.

Studies examining the yaw authority compared between these two control-surface types were performed by the USU AeroLab and will be published in the future. The findings of that research demonstrate that the yaw authority is greater for a wing with discrete control-surfaces compared to a wing with a continuous control-surface with the same number of actuators. This is caused by the greater gradients in lift associated with the discrete flaps. For this reason, the discrete control-surfaces were chosen for the final control-surface concept.

1.3.2 Boundary Layer Notes

The morphing mechanisms presented in this document are designed and tested for use with a small RC aircraft. This small RC aircraft is designed to fly at speeds between 32 and 80 ft/s [21]. The flow around this demonstrator aircraft will thus be low-Reynolds-number flow. The surface quality and porosity due to FDM print quality are expected to have a significant effect on the boundary-layer thickness along with low Reynolds number flow.
These thickening effects on the boundary layer are expected to decrease the effectiveness of the conformal flaps.

The targeted eventual application for the yaw-control method, to be demonstrated on this small rough-surfaced aircraft, is a large smooth-surfaced aircraft as shown in Fig. 1.9. The large smooth-surfaced aircraft flies in high-Reynolds-number flow. The decreased thickness of the boundary layer of the flow compared between the smaller to larger aircraft will improve the effectiveness of the conformal flaps on the larger aircraft. Though the difference in boundary layer between demonstration and intended application is significant, it is expected that yaw-control method will be useful regardless of Reynolds number or surface quality.

![Horizon, a small RC aircraft](image1.png) ![B2 Spirit, a large military aircraft](image2.png)

(a) Horizon, a small RC aircraft (b) B2 Spirit, a large military aircraft [22]

Fig. 1.9: Size comparison between two tailless aircraft.

### 1.4 Design Constraints

Morphing mechanism requirements were chosen which would be used to certify the final design. These requirements were chosen based on general aviation design requirements along with constraints derived from the yaw-control method. While these requirements were not the only metrics used to certify designs, they were the chief metrics for certification of the final design. Further requirements and constraints are given in the discussion on testing procedure in Section 5.1.

The first design requirement was determined from the yaw-control method. In order to control yaw using the discrete control-surfaces, it was determined that each discrete control surface on the aircraft must be able to deflect ±20°. This deflection amount was then
established as the primary constraint for each morphing-mechanism design.

The second design requirement was determined from the expected flight time of the aircraft. The aircraft propulsion and power systems were designed for a flight time of 30 minutes [21]. Each control surface was assumed to deflected cyclically from full down, to full up, back to full down deflection with a cycle period of 1 second. This would thus require a fatigue lifetime of 1,800 cycles for a single flight.

The third design requirement was determined from general aviation aircraft loading requirements established by the FAA. These regulations are that the structure for commuter / utility aircraft must withstand a positive load limit of 3.8 / 4.4 and a negative load limit of -1.52 / -1.76 [23]. The load limits for this aircraft were set as 4.0 for the positive load limit, and -1.5 for the negative load limit.

The fourth design requirement was determined from visual comparison between parabolic conformal flaps. The average difference between the morphing airfoil mechanism and a comparable analytic parabolically-deflected airfoil was required to be less than 10% $\frac{c}{l}$.

It should be noted that the design process for this morphing mechanism was unconventional. Rather than determine the optimal design and orientation for a morphing mechanism, this work was developed to pursue a design which closed while meeting the design requirements. As such, the author stresses the meeting of design requirements over design optimality as the focus of the design certification.

1.5 Design Reference Drawings

Drawings of each concept tested for the morphing wing research presented here are shown in Fig. 1.10. These drawings are given as a quick access reference for the reader. Five of these concepts will be presented briefly in the body of this document, with more information on all concepts given in Appendix A.
Fig. 1.10: Drawings of concepts outlined in Appendix A.
CHAPTER 2
MORPHING AIRFOILS

2.1 Manufacturing Technique Decision

Several manufacturing processes were examined and tested before the wing design process began. Initially, such materials as memory foam, compliant pinewood ribs and carbon-fiber spars were used to create morphing wing prototypes. However, the salient difficulty lies in the unrepeatability of the process, as well as the time taken to manufacture. Due to these difficulties, FDM was investigated as a potential solution. Several non-FDM manufactured prototypes were successful in demonstrating morphing characteristics. These included creating the wing out of Expanded PolyStyrene (EPS), memory foam, Ethylene-Vinyl Acetate (EVA), and Expanded PolyEthylene (EPE). The wings were manufactured using laser-cut wooden ribs at the actuation locations. However, the manufacturing time did not justify the success. The weight of the more successful prototypes also dissuaded further study of these concepts. More information on these concepts can be found in Appendix subsections A.1 and A.2.

Three aspects critical to the design and manufacturing process were determined to mitigate the manufacturing problem. Each potential design and its manufacturing process were judged on these three critical aspects. First, the manufacturing process was judged on its feasibility. This required the design to be manufacturable using the services and equipment available at Utah State University. Second, the design was judged on compliance. The wing design must be capable of the deflection needed to demonstrate proverse yaw and yaw control. Third, the manufacturing process was judged on cost. The cost of materials and equipment, as well as the time required for fabrication, and the difficulty of fabrication were used to determine the best process. This manufacturing process was iteratively examined throughout the prototyping process. The process eventually resulted in FDM being the
most rapid and reliable method for creating a wing-morphing geometry. The several FDM geometries tested are as follows:

### 2.2 Trailing-Edge Gap

The trailing-edge gap geometry was designed to examine morphing airfoils manufactured using FDM. This morphing airfoil geometry is shown in Fig. 2.1. Shown in the figure are the compliant rib (above) and outer skin (below). The compliant portion of the rib was created from parallel offsets to a set of Bézier curves.

![Fig. 2.1: Trailing-edge gap geometry in a NACA 2409 airfoil, with $c_f/c = 0.5$.](image)

The compliant rib is connected to the inside of the upper and lower surfaces of the outer skin. The rib is allowed to slide along both surfaces, thus creating a morphing aft portion of the airfoil, with the trailing-edge disconnected. Similar morphing mechanisms has been studied before [24]. The rib remained fixed span-wise as well as connected to each surface. This was done by 3D-printing runners span-wise on the peaks and valleys of the compliant portion of the rib. These would slide longitudinally in troughs inside the outer skin during actuation. The section was actuated in one of two ways. One used a servo with a control rod connected to the trailing edge of the compliant rib. The second used a servo with wires connected through the compliant rib upper and lower peaks, similar to other group’s designs [7].

Using the wire actuation concept made the actuation mechanism fully internal, a significant benefit. While initial outer skin prints were too thick, the thickness could be decreased to allow for sufficient morphing deflection. The design is also lightweight due to the low
density of PLA within the model. However, this design has significant drawbacks. With FDM as the manufacturing method of choice, printing the holes for the wire was difficult due to the relative thickness of the compliant section of the rib. Similarly, the runners on the rib and the troughs inside the skin were difficult to create using FDM.

This design was not chosen due to the difficulty in ensuring the rib remained fixed span-wise, as well as that of running the wire through holes in the compliant portion of the rib. Also, the assembly time after printing was significant enough to dissuade further study of this concept. This design difficulty motivated the desire for an all-inclusive morphing mechanism. More information on this concept can be found in Appendix subsection A.3.

2.3 Fish Bone

The fish bone geometry was designed to be a single FDM print morphing airfoil, and can be seen in Fig. 2.2. The structure is printed as a single piece, with the aft outer surface gaps printed large enough to allow deflection and prevent the skin being combined during printing.

![Fish bone geometry in a NACA 2409 airfoil, with $c_f/c = 0.45$.](image)

As seen above, significant influence came from the FishBAC design [9]. A flexible pretensioned outer skin was adhered to the outer surface on the aft portion of the airfoil. This skin allowed for the airfoil to morph without buckling or bowing in the skin surface. This design is actuated similarly to the FishBAC design [9]. A servo controls a pulley attached to the trailing edge. This pulley runs through the aft vertical fins of the design. Another actuation method uses a control rod attached to the trailing edge, powered by a servo motor in the leading edge of the airfoil.
This design is able to morph parabolically. This is due to the compliance centered on the camber line of the morphing airfoil. The design is also lightweight, and extremely flexible. Another benefit came from a prototype being printed out of a flexible material such as Thermoplastic Polyurethane (TPU). The flexible material allowed for a transverse gradient along the trailing edge, to be discussed later. However, the flexible pre-tensioned skin caused significant difficulty. Assembling this skin added undesirable time to the assembly process. The actuation method similarly added undesirable time to the assembly process.

This design was not chosen due to the difficulty in assembly of adhering a flexible pre-tensioned skin to the outer aft surface of the wing. The design also had significant assembly difficulty with the actuation method. The skin drawback motivated a design in which the skin is included in the morphing actuation. More information on this concept can be found in Appendix subsection A.4.

2.4 Slip Joint and Semicircles

The slip joint and semicircles geometry was designed to include a morphing skin, and is shown in Fig. 2.3. The black outer lines on the figure indicate the wholly PLA-printed portion of the airfoil. The blue outer lines indicate the portion of the airfoil which is printed span-wise in layers of PLA and TPU. This layering method, as seen in Fig. 1.6, will be discussed in the following morphing-wing section.

Fig. 2.3: Slip joint and semicircles geometry in a NACA 2409 airfoil, with $c_f/c = 0.5$.

This geometry is morphed by sliding a tongue inside a slip joint on the lower surface of the airfoil. Such slip joint mechanisms have been used before in FDM morphing wings [15]. Due to the connection between the upper and lower surface at the trailing edge, sliding the tongue effectively deflects the aft portion of the airfoil. The semicircles on the inside of the
aft portion provide support for the upper and lower surfaces during printing, preventing
the skin buckling due to heat deformation during FDM. These semicircles do not affect
the morphing mechanism in any significant way. It should be noted that the slip joint
tongue geometry was created using a Bézier curve between the airfoil skin and an inner
parallel-offset airfoil.

This design is extremely simple and lightweight, while providing the morphing capa-
bility desired in the final design. This design’s skin is able to deflect without the difficulty
of post-printing assembly. The mechanism is simply actuated via a servo and control rod
connected to the tongue of the morphing portion. With the semicircles in the aft inner of
the wing, the printed skin does not have significant heat-deformed buckling. However, due
to the absence of connections between the upper and lower surfaces prior to the trailing
edge, this design does not morph parabolically. Due to the single connection at the trailing
edge, the design morphs with greater bowing on the upper surface and lesser bowing on
the lower surface than desirable. This is caused by lack of conformity of the camber line to
a parabolic shape during deflection. This also causes the local thickness to change during
deflection, another significant drawback.

Another problem can be seen in the corner of the groove as shown in Fig. 2.3. This
corner trips the flow, transitioning the flow to turbulent earlier along the chord than would
otherwise occur. However, this corner was left on the lower surface as it was preferable to
trip the flow on the lower rather than the upper surface. This is because tripping the flow
on the lower surface is less likely to affect the lift generated by the airfoil.

This design was not chosen due to the inability to fully conform the camber line as
required by a parabolic flap. This failure motivated a modification of this design where the
upper and lower surfaces are connected to create parabolic deflection. Such a design would
also need to maintain the local thickness of the airfoil. More information on this concept
can be found in Appendix subsection A.13.
2.5 Airfoil Recambering Compliant System (ARCS)

The ARCS geometry was designed to conform the camber line as required for a parabolic flap, and can be seen in Fig. 2.4. The black outer lines indicate the portion of the airfoil which is printed using PLA, and the green outer lines indicate that which is printed using TPU. The blue lines indicate the portion of the airfoil which is printed in span-wise layers of PLA and TPU. This layering method, as seen in Fig. 1.7, will be discussed in the following morphing-wing section.

![ARCS geometry in a NACA 0009 airfoil, with \( c_f/c = 0.5 \).](image)

The actuation occurs on the tongue on the lower surface of the airfoil. As the tongue slides within the groove, the upper and lower surfaces deflect parabolically due to the connecting arcs between the upper and lower surfaces. These TPU arcs are more flexible than the composite flexibility of the upper and lower morphing surfaces. This flexibility contributes to the aft portion parabolic deflection while maintaining the local thickness. The arcs radius is configured larger when closer to the trailing edge of the airfoil. Thus, the arcs closer to the hinge point will move further than those closer to the trailing edge. This causes the change in the camber-line angle to be greater near the hinge point and lesser near the trailing edge. It should be noted that the geometry forward of the hinge point has no bearing on the wing morphing mechanism, and simply provides structural support.

2.5.1 Equations

The geometry for these arcs is determined mathematically from the camber line. The arcs are equally spaced along the camber line between the hinge point and a set point near the trailing edge of the airfoil. The local slope of the camber line is used to determine where the normal to this point intersects the upper and lower surfaces of the airfoil. These points
are used to determine the local thickness as shown in

\[ t_{\text{loc}} = \frac{\sqrt{(x_u - x_l)^2 + (y_u - y_l)^2}}{2} \]  

(2.1)

The local camber line length can then be determined from the camber line points as

\[ l_{\text{loc}} = \sum_{x_{cl}=x_{cl}}^{x_{cl}=x_{loc}} \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2} \]  

(2.2)

after which the local arc radius can be found as the product of the local thickness and a ratio based on the local camber line length. This ratio begins as unity at the hinge point and extends to infinity at the set end point near the trailing edge. This forces the arc geometry to begin as a semicircular arc at the hinge point, and increasingly becomes a constraining vertical connection between the upper and lower surfaces of the airfoil. This is done to encourage the actuation to occur closer to the hinge point than the trailing edge. This arc radius is calculated as

\[ r_a = t_{\text{loc}} \frac{l_{\text{te}} - l_{\text{hp}}}{l_{\text{te}} - l_{\text{loc}}} \]  

(2.3)

The center of this arc can be determined from the upper and lower surface points through which it passes and the arc’s radius. The arc center is calculated as

\[ x_1 = x_m - d_y \frac{d_x}{q}, \quad y_1 = y_m + d_x \frac{d_y}{q}, \quad x_2 = x_m + d_y \frac{d_x}{q}, \quad y_2 = y_m - d_x \frac{d_y}{q} \]  

(2.4)

where

\[ x_m = \frac{x_u + x_l}{2}, \quad y_m = \frac{y_u + y_l}{2} \]  

(2.5)

\[ d_x = x_l - x_u, \quad d_y = y_l - y_u \]  

(2.6)
\[ q = \sqrt{d_x^2 + d_y^2}, \quad d = \sqrt{r_a^2 - \left(\frac{q}{2}\right)^2} \] (2.7)

It should be noted there are two solutions to this method, \((x_1, y_1)\) and \((x_2, y_2)\). The correct solution is that in which the \(x\) coordinate is closer to the leading edge of the airfoil than either the upper or lower surface \(x\) coordinates.

Here the user can determine the top and bottom arc angles, where the arc intersects an inner offset of the airfoil surface. The arc geometry can then be found as

\[ x_a = r_a \cos \theta + x_c \] (2.8)

\[ y_a = r_a \sin \theta + y_c \] (2.9)

With the arc radius and center known, the arc thickness can be added to the radius. Using this new radius with new intersection angles for the new arc and inner offset airfoil surface, the new arc geometry can be found as in Eq. eq:aregeomx and Eq. eq:arcgeomy. For further study of the ARCS geometry, the reader can retrieve the code used to create this geometry \(^1\).

The geometric definition of a parabolic flap [19] may be used to examine the parabolic deflection of any geometry. Examples of the ARCS geometry deflected parabolically are shown in Fig. 2.5.

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\(^1\)https://github.com/benjaminmoulton/ARCSgeometry

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Fig. 2.5: ARCS geometry in a NACA 0009 deflected parabolically, with \(c_f/c = 0.5\).
This design is able to deflect with a parabolic shape while maintaining local thickness. For this lightweight design, little to no assembly is required excepting servo insertion. This decrease in assembly time is due to the simplicity of the design. However, this design is difficult to print. This difficulty is inevitable with multi-material and TPU FDM printing. The TPU used in this case, NinjaFlex™2, is extremely elastic. FDM printing with this material will be discussed in a later section. While use of this material is a significant boon to the deflection, it significantly increases print time and complexity.

It should be noted that the ARCS design is fully proficient at creating a parabolic morphing airfoil. Due to study results on a morphing wing discussed in the following section, and the multi-material requirements of this design, it was not chosen for the final morphing design. The multi-material characteristic motivated the design of a mono-material morphing airfoil. More information on this concept can be found in Appendix subsection A.14.

2.6 Kinetic Internal Nexus Compliant System (KINCS)

The KINCS geometry was designed to be FDM printed from a single material, and is shown in Fig. 2.6. Preliminary prototypes were laser cut out of birch wood 3-ply sheets. These morphing airfoils were stacked onto a spar and connected together at the slip joint tip and trailing edge to ensure continuous deflection across the wing. Due to the success of this design in assimilating the geometry to a parabolic flap, it was considered as a separate potential design, and FDM printed.

Fig. 2.6: KINCS geometry in a NACA 0009 airfoil, with $c_f/c = 0.55$.

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*NinjaFlex™ is owned by NinjaTek, a Fenner Drives, inc. brand*
The kinks connecting the upper and lower surface function similarly to the arcs in the ARCS design. The kinks provide elastic connections which constrain deflections to conform the camber line to a parabolic shape, while maintaining local thickness. The kinks provide the requisite compression and tension for the morphing airfoil to deflect parabolically. Actuation is powered by a servo placed in the leading edge of the airfoil. The servo is connected to the tongue via a control rod.

2.6.1 Equations

The geometry is created for each kink as follows. The nodal local camber-line percentage of the morphing portion of the airfoil is found using Eq. (2.2) as

$$l_p = \frac{l_{loc} - l_{hp}}{l_{te} - l_{hp}}$$  \hspace{1cm} (2.10)

The nodes of the kink are initialized as a line which connects the inner upper and lower surfaces of the geometry as

$$x_{ni} \in x_n = x_u - i \frac{x_u - x_l}{n_k}, \quad 0 \leq i \leq n_k$$  \hspace{1cm} (2.11)

$$y_{ni} \in y_n = y_u - i \frac{y_u - y_l}{n_k}, \quad 0 \leq i \leq n_k$$  \hspace{1cm} (2.12)

where $i$ is an integer. The node points are then shifted in the $x$ direction to create the kink nodes

$$x_n = \begin{cases} x_{ni} = x_{ni} - \frac{1}{2}d_kl_p, & 1 \leq i \leq n_k + 1 \\ x_{n+1} = x_{ni} - \frac{1}{2}d_kl_p, & 1 \leq i \leq n_k + 1 \end{cases}$$  \hspace{1cm} (2.13)

These node points are then used to determine the cubic–nodal points required for a cubic Bézier curve. These points are defined as

$$x_{cn} = [x_{ni}, x_{ni}, x_{ni+1}, x_{ni+1}]$$  \hspace{1cm} (2.14)
\[ y_{cn} = \left[ y_{n_i}, \frac{y_{n_i} + 3y_{n_{i+1}}}{4}, \frac{3y_{n_i} + y_{n_{i+1}}}{4}, y_{n_{i+1}} \right] \]  (2.15)

The cubic-nodal points are used to define the kink center Bézier curve as

\[ x_b = (1 - t)^3 x_{cn_0} + 3 (1 - t)^2 t x_{cn_1} + 3 (1 - t) t^2 x_{cn_2} + t^3 x_{cn_3} \quad , \quad 0 \leq t \leq 1 \]  (2.16)

\[ y_b = (1 - t)^3 y_{cn_0} + 3 (1 - t)^2 t y_{cn_1} + 3 (1 - t) t^2 y_{cn_2} + t^3 y_{cn_3} \quad , \quad 0 \leq t \leq 1 \]  (2.17)

All the Bézier curves are appended to form a single line, from which points are generated two parallel curves as

\[ x_{p_i} = \frac{x_{b_i} + x_{b_{i+1}}}{2} - \frac{d \left( x_{b_{i+1}} - x_{b_i} \right)}{\sqrt{\left( x_{b_i} - x_{b_{i+1}} \right)^2 + \left( y_{b_i} - y_{b_{i+1}} \right)^2}} \]  (2.18)

\[ y_{p_i} = \frac{y_{b_i} + y_{b_{i+1}}}{2} + \frac{d \left( y_{b_{i+1}} - y_{b_i} \right)}{\sqrt{\left( x_{b_i} - x_{b_{i+1}} \right)^2 + \left( y_{b_i} - y_{b_{i+1}} \right)^2}} \]  (2.19)

The \( d \) value is used to offset the curve by a predefined half-thickness. Fillets are added where the kink meets the upper and lower surfaces to remove stress concentrations. For further study of the KINCS geometry, the reader can retrieve the code used to create this geometry \(^3\).

The parabolic deflection of this morphing airfoil can be determined using the definition of a parabolic flap [19]. Examples of the KINCS geometry deflected parabolically are shown in Fig. 2.7.

\(^3\)https://github.com/benjaminmoulton/KINCSgeometry
The KINCS geometry is able to conform the camber line to deflect parabolically. The design has the added benefit of being FDM printed from a single material, thus removing the need for difficult and time-costly bi-material 3D printing. This design is simple and incredibly easy to print. Due to the decrease in the number of upper to lower surface-connections required, there is also a decrease in weight for this design. Printing this geometry out of one material frees the second printhead on a dual-extruder printer to print symmetrically to the first head. With the decrease in complexity, and ability to morph the airfoil using a mono-material FDM print, this design was chosen for the final mechanism. More information on this concept can be found in Appendix subsection A.18.

2.7 Airfoil Selection

Several airfoils were considered for use with the morphing mechanisms mentioned previously. The Eppler 335 airfoil was examined due to the airfoil’s reflexed trailing-edge. An airfoil with a reflexed trailing-edge is used on flying wings because it creates a positive pitching moment about the aerodynamic center of the wing [25]. A later prototype examined the same Eppler 335 airfoil with the thickness as 50% that of the original thickness. This thinner prototype demonstrated a thinner airfoil could deflect further with the same actuation distance as a prototype using a thicker airfoil. This is caused by the decrease in the thickness distribution’s ability to dampen out the deflection from the slip joint actuation. As the airfoil surface is closer to the camber line, the same actuation length on the lower surface results in a greater translation of the trailing edge. The study of this airfoil was discontinued due to the ability with a parabolic flap to artificially create a reflexed trailing-edge.
Thinner airfoils such as the NACA 0006 and AS6903 [26] were also examined. These airfoils were used due to the thinness requisite for the deflection on a continuous control-surface as described in the following morphing-wing section. The NACA 0006 airfoil had the added benefit of being a symmetric airfoil, providing a test bed for the proof of concept of a parabolic flap creating lift at zero angle of attack. The study of these airfoils was discontinued in favor of an airfoil which produces lift at lower angles of attack.

The NACA 2412 airfoil was also examined due to the airfoil’s generation of lift at small angles of attack. Due to the morphing wing design change discussed in the following morphing-wing section, and to allow room for servo-mechanisms, the NACA 2412 airfoil was chosen for the final morphing geometry. This airfoil has provided the necessary thickness for the servo-mechanisms, as well as the camber to produce lift at low angles of attack. For this reason, this airfoil is to be used in the final morphing geometry design.
CHAPTER 3
MORPHING AIRFRAME MODELING

Here is outlined the process for developing a morphing airframe CAD model. This process used the aircraft geometric distributions to determine the morphing airfoil shape at each node. The tool MachUpX\textsuperscript{1} was used to determine the distributions of chord, dihedral, and control point location for each spanwise node designated by percent span.

3.1 Morphing Airfoil

The equations governing the development of the ARCS and KINCS development were outlined in Subsections 2.5.1 and 2.6.1. The airfoil was generated using the tool Airfoil-Database\textsuperscript{2}. This airfoil was modified using the morphing airfoil equations and split into distinct parts: the outer surface of the airfoil, the inner compliant-mechanism geometry (ARCS/KINCS), the inner aft surface, the slip-joint tongue, the slip-joint mouth, and the inner forward surface (wing box). This was done to simplify spline creation for geometry curves that met at non-zero angles.

3.1.1 Airfoil .dxf File Creation

These complex geometries were imported into SolidWorks using CAD .dxf files. These files can be used to define spline, compound lines, and points in 2D and 3D space. The morphing airfoil geometry code for both KINCS and ARCS was built to output the morphing shape as a series of splines in a .dxf file. For the non-airframe prototypes this series of splines was imported to define a 2D shape from which a 3D wing section could be created.

\textsuperscript{1}https://github.com/usuaero/MachUpX
\textsuperscript{2}https://github.com/usuaero/AirfoilDatabase
3.2 Morphing Airframe Modeling Files Creation

Using the chord distribution from MachUpX, a morphing airfoil was generated at each of the wing node locations. The airframe was split into sections for ease in modeling discrete control surfaces, as shown in Fig. 3.1. These sections included a bay section with a control surface, a fan section for the ducted fan propulsion system, five wing sections with a control surface each, and a wingtip section. The distributions values were then linearly interpolated for the root and tip of each of these sections. The new interpolated chord value was then used to determine the morphing airfoil shape for the root and tip of each section. This 2D shape was shifted to account for the dihedral of the wing. This final shape was exported as a .dxf file.

![Fig. 3.1: Sections of airframe CAD model.](image)

The distributions morphing airfoils were then used to generated splines which traversed the span of the wing, split into the predetermined sections. These splines were exported as a .dxf file for each section of the airframe. The location of the root and tip of each section was then used to generate lines on a plane to indicate the planar faces of each section root and tip. The lines generated to create these planes were then exported as a .dxf file. The final step in generating the modeling files was to create a hub shape for each control surface. This shape was used to thicken the tongue of the slip-joint to strengthen the servo control rod connection point to the tongue. These hubs were then exported as a .dxf file.
The wetted area of the airframe was only modified in the fan section. This was done to provide a smooth surface to cover the embedded ducted fan systems. A series of spanwise 3D splines were generated and stretched to create a smooth bump on the upper surface of the section. These guide curves were then exported as a .dxf file. Shapes for the fan inlet and exit were also generated and exported as .dxf files.

### 3.3 Morphing Airframe CAD Modeling

The plane-lines were then imported into a base CAD file. These lines were imported on a plane normal to the nose of the aircraft. The lines were then used to generate planes which would intersect the aircraft at the root and tip of each section. These lines and planes are shown in Fig. 3.2. The hub shapes were also added to this base file. Each section of the airframe was then modeled from the base file. As the airframe was symmetric, only the right side of the airframe was modeled. Apart from the base CAD file, a base fairing was created for placement over the servo bays on each morphing section.

![Plane and plane-lines in base CAD model.](image)

(a) isometric view

(b) aft view

Fig. 3.2: Plane and plane-lines in base CAD model.
3.3.1 Morphing Section

Using the base CAD file, the morphing airfoil for the root and tip of each morphing section was imported on the intersection planes. Using the 3D guide curves generated from the distributions file, the morphing airfoil shape was lofted between the root and tip. Holes were then cut using a similar method to remove material from the wing box and aft morphing sections of the airfoil. A servo bay was then cut out of the lower surface of the section. The strengthened hub for the actuation control-rod connection was then added to the tongue. Planar end caps were then added to the root and tip of each section for section adhesion purposes, and pegs and holes were added and cut from these caps for alignment during adhesion. A portion of the tip of each control surface was finally removed to avoid control-surface binding during flight.

![Fig. 3.3: CAD modeling of morphing section.](image)
Four additional components were then created for each morphing section, outside the morphing part CAD file, shown assembled in Fig. 3.4. The first was a servo mount part positioned inside the servo bay, used to screw a retainer over the servo into the wing section. The second component was a support piece to be FDM printed as support material for the servo mount part. The third component was a fairing based on the base fairing part cut to conform to the surface of the wing section. The fourth and final component was a support kink to be FDM printed as support material in the control surface to improve surface quality. These four parts were positioned within the wing section in a CAD assembly and exported as .stl files to be FDM printed.

Fig. 3.4: Additional components in a morphing section.

3.3.2 Bay Section

The control-surface bay section had some additional modeling steps. Material was removed from the upper surface of the bay section to allow for placement of electronics, sensors, and ballast. This section was then split chordwise in order to fit on the 3D printer bed. A cover was then modeled to be placed over the bay to protect the electronics as well as hold a GPS sensor and pitot probe. Screw anchors were also modeled to attach the bay cover to the bay section. The CAD model for each of these components is shown in Fig.
3.3.3 Non-Morphing section

Using the base CAD file, the non-morphing sections were modeled using an airfoil at each root and tip, with guide curves to conform the shape to the distributions file geometry. In the case of the wingtip section, the model was then split into two parts to remove the need for support material when printing.

3.3.4 Fan Section

The non-control surface fan section also had some additional modeling steps. After lofting the bump on the upper surface of the section, material was removed from this bump to allow for the ducted fan placement, inlet, and exit. A cover was created for inserting and protecting the ducted fan, along with screw anchor inserts. A portion of the tip of this wing section was removed to prevent binding of the control surface outboard of this section. This section was finally split chordwise in order to fit on the 3D printer bed. The CAD model for each of these components is shown in Fig. 3.6.
3.3.5 Slicer

Excluding the bay, each section fit completely on the 3D-printer bed. The wing morphing sections and wingtips were each printed with their mirrored counterpart (right and left). The morphing sections were printed with 100% infill, and the non-morphing sections with 3% infill. Support material was used with the bay and fan sections. The screw anchors, servo mounts, and fairing mounts were printed with 50% infill. More information on the print settings can be found in Chapter 4.
CHAPTER 4
PRINTING CHARACTERIZATION

Having chosen FDM as the manufacturing method, an FDM printer with the desired characteristics was required for manufacturing. The desirable characteristics are given following. The slicer print settings and materials are tabulated below.

4.1 FDM Printer Selection

Following the decision to manufacture the wing using FDM, an FDM printer was selected. Potential FDM printers were examined based on the stipulations of a large build volume (greater than 300 x 300 x 300 mm$^3$), dual extrusion capability, price less than $2,500, and having direct-drive extruders. These requirements were deemed necessary characteristics to print the morphing wing mechanism. The printers examined are shown below in Table 4.1.

<table>
<thead>
<tr>
<th>Printer</th>
<th>Dual Extruder</th>
<th>Volume mm x mm x mm</th>
<th>Direct-Drive</th>
<th>Low-Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prusa i3 MK3</td>
<td>-</td>
<td>250 x 210 x 210</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Ultimaker S5</td>
<td>✓</td>
<td>330 x 240 x 300</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Creality3D CR-X</td>
<td>-</td>
<td>300 x 300 x 400</td>
<td>-</td>
<td>✓</td>
</tr>
<tr>
<td>Vivedino T-Rex 3.0</td>
<td>✓</td>
<td>400 x 400 x 700</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>BCN3D Epsilon</td>
<td>✓</td>
<td>420 x 300 x 400</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Raise3D Pro2 Plus</td>
<td>✓</td>
<td>280 x 305 x 605</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The Vivedino T-Rex 3.0 was chosen for this application. The dual extrusion capability allows the user to print dual-material prints, such as with PLA and TPU, as well as
print symmetrical objects simultaneously. The larger build volume was desired due to the expected airframe size. With an expected span of 10 ft, the root chord was designed to be 33 in. With a minimum build plate size of 300 x 300 mm, the large root section can be split in two chord-wise and placed diagonally on the print bed. Direct-Drive extruders are preferable when printing with materials such as the TPU NinjaFlex™. Whereas Bowden extruders push the filament through an extended tube into the hot end, direct-drive extruders push the filament directly into the hot end, preventing most filament tangling and tensioning problems.

4.2 Materials

Conventional FDM materials were used for the manufacturing of the morphing mechanism. The materials were chosen based on their mechanical and thermodynamic properties as well as their relative complexity to use. While several materials were considered, only those used to create prototypes are here discussed.

4.2.1 Mechanical Properties

Originally all FDM printing was done using PLA. PLA is an inexpensive simple filament used in FDM. PLA was preferred to ABS as PLA printing fumes are less toxic than ABS fumes. Also, PLA provided sufficient structural strength, as demonstrated by a previous FDM printed RC aircraft shown in Fig. 4.1.

Fig. 4.1: Flight test of an FDM printed non-morphing RC aircraft.
PushPlastic™ PLA was used for the rigid sections of the ARCS geometry and the entire KINCS geometry. The PLA is used to add strength and flexibility to the printed structure. Notably, the PLA must be printed in thin sections to provide the flexibility. Using a skin thickness of two walls of 0.4 mm thickness were generally sufficient for the morphing upper and lower surfaces.

To provide the flexibility and stretchability required in the ARCS continuous-trailing-edge concept, TPU was examined as a potential secondary material. The TPU was incorporated with the PLA in later printing as a bi-material part. This was done in former prototypes using Flexfill™ printed in the aft portion of the wing. However, this flexible material did not provide the stretching required for the trailing edge gradient during a differential deflection. The TPU NinjaFlex™ was employed to provide this differential gradient. This extremely elastic TPU is difficult to print due to its flexible nature. However, it provides measurable elasticity for the trailing edge differential deflection. The rigid portion of the wing design was printed out of PLA. Later, PLA with TPU composite printing was incorporated in the skin on the morphing section to provide stiffness to the skin. The mechanical properties for the materials used and discussed are shown below in Table 4.2.

Table 4.2: Mechanical properties of materials used for FDM.

<table>
<thead>
<tr>
<th>Material</th>
<th>PLA [27]</th>
<th>NinjaFlex™ [28]</th>
<th>Flexfill™ [29]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, g/cm³</td>
<td>1.24</td>
<td>1.19</td>
<td>1.22</td>
</tr>
<tr>
<td>Tensile Strength, yield, MPa</td>
<td>110.32</td>
<td>4.0</td>
<td>53.7</td>
</tr>
<tr>
<td>Elongation, break, %</td>
<td>160.0</td>
<td>660.0</td>
<td>318.0</td>
</tr>
<tr>
<td>Young’s Modulus, MPa</td>
<td>3,309.48</td>
<td>12.0</td>
<td>444.0</td>
</tr>
<tr>
<td>Hardness</td>
<td>-</td>
<td>85 shore A</td>
<td>98 SHore A</td>
</tr>
<tr>
<td>Glass Transition, °C</td>
<td>-</td>
<td>-35</td>
<td>-</td>
</tr>
<tr>
<td>Melting Point, °C</td>
<td>205</td>
<td>216</td>
<td>215</td>
</tr>
</tbody>
</table>

1FlexFill™ is owned by Fillamentum, inc.
4.2.2 Thermodynamic Properties

The filament colors were chosen based on their heating properties in outdoor conditions. Darker colors retained heat above the glass transition temperature, causing structural failure. Prototypes were colored to easily distinguish between the TPU and PLA. Eventually, models were printed out of all white materials as this color retains heat the least in higher outdoor temperatures and strong sunlight. However, PLA can also fail when kept in such conditions as a hot car, which was avoided. A test was performed to determine the heating characteristics of the 6 different potential materials. This was done by placing prototypes manufactured of each material in a hot environment for a period of time. The temperatures were recorded over time till they reached relative stability. The results from this study are shown in Fig. 4.2.

![Fig. 4.2: Glass transition temperature test using various materials.](image)

The mono-material KINCS concept was designed due to the change in morphing design from continuous to discrete flaps. The removal of TPU from the print significantly decreased the time and complexity of the FDM printing process. The second extruder could then be used for symmetrical printing.
4.2.3 Manufacturing Orientation Properties

Peculiar to FDM is the effect of print orientation and infill geometry on the strength of the part. An FDM part is significantly stronger in directions not affected by the layering of the material during printing. Where most FDM printers print up, a force from the side would be the most successful at causing structural failure in a part. Thus, the print orientation / direction has a significant effect on the structural strength of the part.

The printer and print settings also affect the strength of an FDM printed part. From this work, the author has noticed the printer design to have a significant effect on the surface quality of the part. Print settings such as infill can also especially affect the strength of a printed part.

It should be noted that with rare exception, the author always printed the morphing mechanisms with the span oriented along the printer z axis, or up. While this decreased the strength of the parts in the z direction, this print orientation eliminated the need for support material. The support material was noticed to cause significantly poorer surface quality, causing increased post-processing manufacturing time. Increased manufacturing speed was determined to be the preferable option.

4.3 Methods

The following print settings and techniques resulted in the best print quality. It should be noted that the nozzles used to print the ARCS and KINCS geometries are 0.4 mm in diameter. Table 4.3 gives the settings used in the slicer Cura to recreate the ARCS and KINCS geometries. It should be noted that E stands for extruder, with E1 being the left extruder, and E2 being the right extruder. Unless otherwise stated using this nomenclature, the settings are shared between extruders.
Table 4.3: Print settings for the ARCS and KINCS geometries.

<table>
<thead>
<tr>
<th>Setting</th>
<th>ARCS Value</th>
<th>KINCS Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer Height, mm</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Line Width, mm</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Wall Thickness, mm</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Z Seam Alignment</td>
<td>Random</td>
<td>Random</td>
</tr>
<tr>
<td>Infill Density</td>
<td>3.0%</td>
<td>100.0%</td>
</tr>
<tr>
<td>Build Plate Temperature, °C</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>E1 Material</td>
<td>PLA</td>
<td>PLA</td>
</tr>
<tr>
<td>E1 Print Temperature, °C</td>
<td>210</td>
<td>225</td>
</tr>
<tr>
<td>E1 Flow Rate</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>E1 Enable Retraction</td>
<td>True</td>
<td>True</td>
</tr>
<tr>
<td>E1 Retraction Distance, mm</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>E1 Retraction Speed, mm/s</td>
<td>30.0</td>
<td>60.0</td>
</tr>
<tr>
<td>E1 Nozzle Switch Retraction Distance, mm</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>E1 Print Speed, mm/s</td>
<td>30.0</td>
<td>60.0</td>
</tr>
<tr>
<td>E2 Material</td>
<td>TPU</td>
<td>PLA</td>
</tr>
<tr>
<td>E2 Print Temperature, °C</td>
<td>235</td>
<td>225</td>
</tr>
<tr>
<td>E2 Flow Rate</td>
<td>120%</td>
<td>100%</td>
</tr>
<tr>
<td>E2 Enable Retraction</td>
<td>True</td>
<td>True</td>
</tr>
<tr>
<td>E2 Retraction Distance, mm</td>
<td>0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>E2 Retraction Speed, mm/s</td>
<td>10.0</td>
<td>60.0</td>
</tr>
<tr>
<td>E2 Nozzle Switch Retraction Distance, mm</td>
<td>7.0</td>
<td>10.0</td>
</tr>
<tr>
<td>E2 Print Speed, mm/s</td>
<td>20.0</td>
<td>60.0</td>
</tr>
<tr>
<td>Z Hop When Retracted</td>
<td>True</td>
<td>True</td>
</tr>
<tr>
<td>Z Hop Height, mm</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Build Plate Adhesion Type</td>
<td>Brim</td>
<td>Brim</td>
</tr>
<tr>
<td>Build Plate Adhesion Extruder</td>
<td>Extruder 1</td>
<td>Extruder 1</td>
</tr>
<tr>
<td>Brim Width, mm</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>
Due to the difficulty of printing TPU’s, some lessons learned are given here. First, the NinjaFlex™ must be slowly inserted into the nozzle to prevent bunching up. Second, the flexible material extruder must have a print speed less than or equal to 30 mm/s. Third, the user should allow as little retraction as possible. Fourth, the user should print with a separate nozzle for TPU. Fifth, the user should replace the TPU nozzle frequently to prevent clogging, and print at 235°C. The author recommends using a nozzle solely for printing the TPU and replacing the nozzle when printing with other materials. The author recommends nozzle replacement over cold pulls, but for cold pulls the author recommends using taulman3D Nylon 645 filament.
CHAPTER 5
LESSONS FROM PROTOTYPING

Various examples are given of the successes and failures of the FDM manufacturing-method with each geometry. Significant testing results of the morphing airfoil and wing concepts as mentioned above are given below.

5.1 Morphing Prototype Testing Procedure

The testing of each concept followed a general stepped-testing process. As each design successfully passed each test, it was raised to the next test type. The general outline for this layered approach is given here to classify the important testing milestones for each concept.

5.1.1 Airfoil Test

The first test was a kinematic (non-powered) deflection test. The concept was FDM printed as a morphing airfoil with a minor spanwise length (1 - 6 inches). The concept was manually deflected to determine the maximum positive and negative deflections to which the prototype could be actuated. The threshold value for this testing was \( \leq \pm 25^\circ \), which was the maximum amount to be expected from the control law.

After the design was iterated to successfully deflect to the requisite amounts, the design was tested to examine the parabolic deflection of the airfoil shape. Code was written to plot an airfoil deflected parabolically at various angles using equations for the parabolic profile [19]. The parabolically-deflected airfoil was printed out on a piece of paper. The prototype was then deflected on top of this printout in order to visually examine the parabolicity of the concept, as shown in Fig. 5.1. The design was iterated till it matched the parabolic shape as closely as possible.
5.1.2 Wing Test

The second test was also a kinematic test of the design. In this case, the concept geometry was FDM printed with a larger spanwise length (6 - 12 inches). This level of testing was used to examine how sweep, taper, and various other wing characteristics would affect the wing deflection. The goal of this testing was to ensure these structural changes would not impede the conformal deflection of the compliant flap.

5.1.3 Static Test

The third test was a static deflection test, as shown in Fig. 5.2. The bay for a servo mechanism was CAD modeled into the wing before FDM printing. One purpose of this test was to determine how the actuators should be positioned in the wing. This testing was used to determine how the actuator should be connected to the compliant surface, how the actuator should be oriented and where it should be placed\(^1\) in the wing, as well as how the actuator should be affixed to the wing.

\(^1\)As the aircraft was a belly-lander and the servo mechanisms were to be accessed from the underside of the aircraft.
Once the actuator system was determined, the mechanized wing was tested to ensure it could deflect to the desired amounts. If the concept consistently failed these tests, it was returned to airfoil testing to improve the flap compliant-mechanism. In the case of those concepts which were designed for a continuous control-surface, this testing was also used to determine and increase the gradient of the trailing-edge when neighboring actuators were deflected oppositely.

5.1.4 Dynamic Test

The fourth test was a deflection test of the wing under dynamic conditions. Servo actuators were installed in the wing and controlled to actuate the flaps continuously through the range of expected flap deflection angles. This wing was held outside the window of a car driving in the range of the expected flight envelope (20 - 55 mph), as shown in Fig. 5.3. The purpose of this test was to study the wing compliant-mechanism under dynamic loading conditions similar to what would occur during a flight test.
Fig. 5.3: Dynamic test using prototype P14I19.

This test was used to resolve various structural problems. These problems included fluttering at the trailing edge due to minor gusts, bowing of control rods, surface deformation during flight, and servo performance when deflecting the wing with a force applied.

5.2 Morphing Airfoil Lessons Learned

Distinct lessons learned throughout this project as related to the morphing airfoil development are given in Tables 5.1 and 5.2. Images of these models are shown in Fig. 5.4. Not all lessons learned were deemed pertinent to the present section. For further information on the motivation, testing, and results for each prototype, the reader is directed to Appendix A.

5.2.1 Prototype Designation

Regarding the prototype nomenclature, "P" indicates a Prototype conceptual change, "I" a new Iteration of the Prototype, "M" a Modification of an Iteration, and "S" a Section. The first three divisions indicate the significance of a design change. A full concept change led to a new Prototype designation. Continued Iterations on this design further improved the morphing-wing model characteristics. If the Iteration was further studied with minor changes, the design was termed a Modification. Some few designs were split into Sections and designated as such. However, most Iterations were neither split into Sections nor
underwent Modification. Thus, the "S" and "M" designations were dropped from the model name.

The reader should note that the trailing-edge gap geometry was given the Prototype designation P3. The remaining morphing-airfoil concept designations are as follows: the fish bone concept was given P4; the slip joint and semicircles concept was given P13; the ARCS concept was given P14; the KINCS concept was given P18.
Table 5.1: Significant prototyping lessons learned.

<table>
<thead>
<tr>
<th>Prototype</th>
<th>Notable Success</th>
<th>Propelling Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>P3I1</td>
<td>3D printing works best span-wise</td>
<td>Skin must be thin for actuation; need structure in leading edge to prevent deformation</td>
</tr>
<tr>
<td>P4I1</td>
<td>Thin PLA can uniformly deflect sufficient</td>
<td>Spine too thick (must be $\leq 0.8$ mm)</td>
</tr>
<tr>
<td>P4I9</td>
<td>Flexible material prints well as an airfoil skin</td>
<td>TPU does not stretch to allow a trailing edge gradient</td>
</tr>
<tr>
<td>P13I4</td>
<td>Support for flexible material allows for tall prints</td>
<td>Surfaces must be constrained to maintain airfoil-thickness distribution</td>
</tr>
<tr>
<td>P13I7</td>
<td>Adhesion between TPU and PLA is better in the X or Y direction than in the Z direction in the 3D-printer frame</td>
<td>It would be easier to print the ribs with the structure to avoid manufacturing complexity</td>
</tr>
<tr>
<td>P14I1M1</td>
<td>ARCS allow for the thickness of the airfoil to remain constant during deflection</td>
<td>Need the morphing aft portion printed mostly of flexible material to allow for trailing edge gradient in differential deflection</td>
</tr>
<tr>
<td>P14I4</td>
<td>Flex ratio can be increased without significant detriment to stiffness</td>
<td>Need to examine a mechanized concept</td>
</tr>
<tr>
<td>P14I8</td>
<td>Tongue control hole must be stiff</td>
<td>Need to test trailing edge gradient</td>
</tr>
</tbody>
</table>
Table 5.2: Significant prototyping lessons learned (continued).

<table>
<thead>
<tr>
<th>Prototype</th>
<th>Notable Success</th>
<th>Propelling Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>P14I9M5</td>
<td>Good ratio of TPU to PLA is 5:3, with 7:1 between ribs; sufficient stiffness for</td>
<td>Need a thinner airfoil to improve deflection range</td>
</tr>
<tr>
<td></td>
<td>deflection with PLA smaller ribs 1/8 in. wide and the actuation ribs 1 in. wide</td>
<td></td>
</tr>
<tr>
<td>P14I14</td>
<td>Thinner airfoil leads to better deflection</td>
<td>Need 5 smaller ribs in between actuation ribs</td>
</tr>
<tr>
<td>P14I17</td>
<td>An avian-inspired airfoil deflects parabolically</td>
<td>Must examine a 3-servo mechanized concept</td>
</tr>
<tr>
<td>P14I19</td>
<td>No trailing-edge flutter during a dynamic test; Successful ARCS parabolic</td>
<td>Improve surface quality of print</td>
</tr>
<tr>
<td></td>
<td>deflection</td>
<td></td>
</tr>
<tr>
<td>P17I08M01</td>
<td>KINCS design can conform to parabolic deflection</td>
<td>Difficult laser-cut rib assembly</td>
</tr>
<tr>
<td>P18I03M04</td>
<td>KINCS can be 3D printed</td>
<td>2 kinks provides too much aft stiffness</td>
</tr>
<tr>
<td>P18I08M05</td>
<td>Single kink works best for parabolic deflection of KINCS mechanism</td>
<td>Deflection is not sufficiently parabolic as determined from visual comparison</td>
</tr>
<tr>
<td>P18I10M00</td>
<td>Successful KINCS parabolic deflection</td>
<td>–</td>
</tr>
</tbody>
</table>
Fig. 5.4: Prototypes as described in Tables 5.1 and 5.2.
Figure 5.5 shows the resultant parabolic deflection on the ARCS and KINCS concepts. While both concepts demonstrate parabolic deflection, the KINCS concept was chosen for use with discrete flaps due to it being manufacturable from a single material.

Fig. 5.5: KINCS and ARCS geometry deflected parabolically, with $c_f/c = 0.5$.

### 5.3 Morphing Wing Lessons Learned

The KINCS and ARCS designs both had similar difficulties with taper and sweep geometric characteristics. In a tapered section, as the tongue moves forward within the slip joint (deflecting the flap downward), the taper causes the tongue to slide transversely. With taper, the tongue tip will slide toward the section tip, and the tongue root will slide toward the section root. In a swept section, as the tongue moves forward within the slip joint, the sweep causes the tongue to slide transversely, but in the opposite direction of the taper (assuming traditional taper and sweep). With sweep, the tongue tip will slide toward the section root, and the tongue root will slide toward the section tip.

Taper has been noted to have a greater effect on this transverse sliding than sweep. This was found on the morphing-wing discrete-flap segments of the Horizon aircraft [21]. The Horizon aircraft has significant taper with a root chord of 2.75 ft and a tip chord of 0.917 ft, and sweep which is linearly changing from $0^\circ$ at the root and $45^\circ$ at the tip [21]. Due to these opposing effects, the sliding problems were nearly negligible on the Horizon
aircraft.

5.3.1 Differential Deflection

This research as described in Table 5.1 and shown in Fig. 5.4 began as a study to manufacture a continuous trailing-edge morphing wing. Examples of this type of deflection is shown in Fig. 5.6.

![Differential deflection on the ARCS geometry.](image)

(a) P14I17 - two actuators  (b) P14I19 - three actuators

Fig. 5.6: Differential deflection on the ARCS geometry.

Significant problems impeded further study of this design, as shown in the buckling of the flexible skin surface seen above. It was at this point in the design process that the decision was made to construct the wing using discrete flaps, eliminating the need for a flexible skin. Further study is recommended into the use of the ARCS mechanism for 3D printed morphing-wing aircraft.

5.3.2 Discrete Deflection

With the determination to use discrete flaps, the KINCS mechanism was chosen for the final design. As it is a mono-material design, it was much simpler and faster to print. This control-surface type can be seen on a model of Horizon in Fig. 5.7.
Fig. 5.7: Discrete deflection on Horizon wing-segment (P18I17S04 - P18I17S07).
The final design for the morphing-wing tailless aircraft was chosen between the ARCS and KINCS designs, as well as the discrete and continuous control-surfaces. Four studies were performed to determine whether the final design met the design constraints. The results for these studies are presented with notes on testing procedure for each study.

6.1 Design

The KINCS mechanism used with discrete control-surfaces was chosen for the final design. A flying-wing design has been outlined using the KINCS morphing geometry [21]. The final KINCS morphing airfoil is shown in Fig. 6.1. Some geometric changes were made for the final flying-wing design. These changes include an I beam for wing structural rigidity located near the hinge point, and custom infill geometry in the leading-edge portion to allow for cables through the wing. In blue on the figure is the optimal placement for the servo mechanism, a Hitec™HS-5245MG digital servo.

![Fig. 6.1: Final KINCS geometry in a NACA 2412 airfoil, with $c_f/c = 0.66$.](image)

The servo was attached to the tongue of the conformal flap with an adjustable pushrod connector. A portion of the flap tongue was thickened to increase the strength of the attachment point. The discrete control-surfaces were cosine clustered span-wise to improve
Horizon’s yaw control. The CAD model can be seen in Fig. 6.2. The reader can retrieve the CAD models used to manufacture this aircraft\textsuperscript{1}.

Fig. 6.2: Cosine clustered discrete flaps on Horizon aircraft CAD model.

The servo locations can be seen on the lower figure in Fig. 6.2. The servos were placed spatially in the middle of each discrete section. The Sections on Horizon are designated numerically as described above, with 00 for the root section, and 07 for the tip section. It should be noted that Sections 01 and 07 are non-morphing Sections. Section 01 is non-morphing due to the placement of the ducted fans to propel Horizon. Section 07 is the non-morphing wing tip section.

6.1.1 Deflection Study

The deflections for the outboard morphing sections are given in Fig. 6.3. The multiple data points for each Section indicate the various tests performed.

\textsuperscript{1}https://www.thingiverse.com/thing:4672874
The morphing sections were noted to bind when deflecting near each other. This was mitigated by removing a slice from the tip portion of each Section of 1/4 in. at the trailing edge linearly up to no removal at the hinge point. This change resulted in the high deflections shown above. This demonstrates the KINCS mechanism capability of deflecting ±20°. Further study is recommended into the use of the KINCS mechanism for 3D printed morphing-wing aircraft.

6.1.2 Fatigue Study

A fatigue test was performed on two sections of the Horizon aircraft. This was done to ensure the compliant mechanism and servo attachment to the wing and tongue would not fail during a flight test. For each test the section was set to actuate at a specific frequency over the range of maximum expected deflections. The setup and results for these tests are shown below in Table 6.1.
Table 6.1: Fatigue test setup and results for each section.

<table>
<thead>
<tr>
<th>Designation</th>
<th>P18I21S05</th>
<th>P18I21S06</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deflection range (°)</td>
<td>±25</td>
<td>±25</td>
</tr>
<tr>
<td>Servo</td>
<td>Hitech™HS-5245MG</td>
<td>Hitech™HS-5065MG</td>
</tr>
<tr>
<td>Cycles completed</td>
<td>15,586</td>
<td>24,227</td>
</tr>
<tr>
<td>Final time (h)</td>
<td>4.329</td>
<td>9.529</td>
</tr>
<tr>
<td>Cycle period (s)</td>
<td>1.0</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Due to the number of cycles completed for each section no further fatigue study was performed. The test on P18I21S05 was terminated upon reaching a number of cycles that the aircraft was unlikely experience (after eight 30 minute flight tests). The test on P18I21S06 ended due to a burnt-out servo, indicating the servo would fail (after thirteen 30 minute flight tests) before the compliant flap or servo attachments would fail. In both tests the servo mount screws loosened due to the vibrations of the servo motor. However, this was not determined worth concern since the actuators would not be expected to actuate as high as the tested frequencies. A photo of the fatigue test setup of P18I21S05 is shown in Fig. 6.4.

![Fatigue test setup](image_url)
6.1.3 Failure Load Study

The section of Horizon which had failed during previous load testing was loaded to failure to determine the maximum positive load limit of the aircraft. The section was loaded in the middle of the span. A 1.75 inch diameter ring was used to localize the transfer of the load from a shelf onto the wing section, with the wing pinned at either end. The wing was loaded to failure, and the calculated results are shown in Table 6.2.

Table 6.2: Load test to failure results on P18I22S0.

<p>| | |</p>
<table>
<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure Weight, lbf</td>
<td>152.790</td>
</tr>
<tr>
<td>Failure Moment, ft-lbf</td>
<td>49.338</td>
</tr>
<tr>
<td>1-g Weight, lbf</td>
<td>31.329</td>
</tr>
<tr>
<td>Max Positive Load Limit</td>
<td>4.877</td>
</tr>
</tbody>
</table>

The 1-g weight value was determined from the weight that would be placed in the middle of the section to create an equivalent moment on the aircraft accounting for the outboard sections. This moment was set to be the same as calculated fully loaded with an elliptic lift distribution. A photo taken during the load test is shown in Fig. 6.5. As the spar-structure of the section was symmetrical up and down, the positive load limit results were determined to be equivalent for the negative load limit results.
6.1.4 Parabolicity Study

The OML of the ARCS and KINCS mechanisms was used to determine the parabolicity of each concept. For this procedure, the mechanisms were deflected to a set amount and photographed. The photos were then digitized using a plot digitizer to analyze the OML for each mechanism when deflected. Code was written to create the parabolic profile for the airfoil using equations for the parabolic flap [19]. The OML data points for the analytical parabolic flap and the approximated parabolic flap were interpolated as a function of surface length. Data points were initialized linearly along the surface length. The distance difference between the data points for the analytic and approximated flaps were averaged and normalized. This process is shown below in Fig. 6.6
Fig. 6.6: FDM part deflection digitized from photo compared to analytic deflection.

The results for the average difference are shown in Fig. 6.7a, and for the difference standard deviation are shown in Fig. 6.7b. Results are shown for the difference around the whole airfoil, as well as the difference values of solely the flap. This was done to remove the effect of differences in the leading edge of the airfoil.

Fig. 6.7: Parabolicity study results for KINCS and ARCS mechanisms.
Morphing aircraft have the potential to control aerodynamic forces more efficiently than traditional aircraft. Recent studies of morphing flight have demonstrated the viability and preferability of morphing flight. Several of these recent studies have examined FDM manufactured wings. FDM has several advantageous characteristics. These include decreases in cost and time for the manufacturing process. A fully 3D printable wing which requires little to no post-processing can be used with significant improvement in iterative design.

A morphing wing is designed based on the aerodynamic benefit of conformal flaps. These flaps are more efficient than traditional flaps, and can be employed using compliant mechanisms. A wing with compliant-mechanism control-surfaces may control yaw by creating a differential drag profile. This drag profile can be created by using a single continuous trailing edge control surface or several discrete control-surfaces.

Various concepts were studied throughout this research as potential morphing-wing design. The ARCS design can be used as a fully 3D printable design. This design actuates with significant deflection, sufficient to control in-flight forces as a continuous control-surface. The KINCS design can also be used as a fully 3D printable design, and is recommended for use with discrete control-surfaces. This mechanism is capable of producing the necessary deflection for a yaw-controllable flying-wing aircraft.

A method was developed for CAD modeling a morphing airframe. This process consisted in creating morphing airfoils for the root and tip of each morphing section, and lofting the geometry between these surfaces using guide curves constrained to the airframe geometry. The optimal FDM print settings for each section were determined. The methods which produced the best 3D print quality have been condensed and catalogued.
The testing procedure for each design began with optimizing the conformal deflection of the camber line to a parabolic profile. The design was then tested for structural and actuation purposes. As a final step the design was tested under dynamic loading. The principal lessons and educative failures for the continuous and discrete control-surfaces have been catalogued.

The KINCS mechanism is presented as the final design for use in a morphing flying-wing RC aircraft. The KINCS design with the discrete control-surfaces passed all studies determined necessary to certify the morphing-mechanism design. The KINCS morphing airfoil design was able to deflection ±20° using a servo motor. The KINCS / discrete control-surface design was fatigued above the cycle limit expected during eight 30 minute flight tests. The discrete control-surface design was loaded to failure resulting in a maximum positive and negative load limit of 4.877. The KINCS morphing airfoil design was found to deflect parabolically with an average OML difference less than 0.1\(\frac{x}{c}\).

It should be noted that the KINCS morphing airfoil used with discrete control-surfaces is not the optimal design for an FDM manufactured morphing-wing. The final design presented from this work is simply the design which closed, meeting all the testing procedures and design requirements. The author recommends the KINCS and ARCS designs for further use in morphing RC aircraft. The author also recommends further research into the optimal design for a morphing-wing compliant-mechanism.

The author recommends further work into analytically determining the KINCS and ARCS characteristics which optimally deflect the wing as a conformal flap. Further work could also examine a design concept in which a spar hole can be easily placed. The author also recommends further work in designing a morphing mechanism which does not disrupt the flow around the airfoil. Finally, the author proposes further work should examine development of morphing wing mechanisms based on the work presented here for general aviation aircraft.
REFERENCES


APPENDICES
APPENDIX A
Prototype Iterations

Here are given the Iterations for each Prototype. For brevity, a general drawing is provided for each conceptual Prototype. As not all lessons learned could be placed in Tables 5.1 and 5.2, motivation and testing results are given for each Iteration and Modification. These lessons are given here as a reference and source of information on how the ARCS and KINCS concepts were created. Significant insight can also be gained through the lessons learned from the other concepts. For more information on the iterations, the reader is directed to published videos of each Iteration\(^1\).

Regarding the prototype nomenclature, "P" indicates a Prototype\(^2\) conceptual change, "I" a new Iteration of the Prototype, "M" a Modification of an Iteration, and "S" a Section. Where the prototype has no modifications or sections, the "M" and "S" designations are removed. The testing performed on each prototype is given with each designation. For these tests, "K" indicates a kinetic test, "S" indicates a static test, and "D" indicates a dynamic test. Kinematic tests were performed to physically study the model actuation. Static and dynamic tests were performed to study mechanically actuated via a servo mechanism in a static environment, as well as dynamic flow, respectively.

A.1 Concept 1

The first concept tested is shown below in Fig. A.1. Shown in pink is XPS, a stiff foam; shown in blue is PE, a flexible foam; shown in brown are the laser-cut plywood compliant ribs. The wing is actuated via a control horn at the trailing edge of the compliant rib.

\(^1\)https://www.youtube.com/channel/UCwEjw-M8jqbE-vwEh19uJRA/videos. Videos are searchable by prototype designation (i.e., P111).

\(^2\)The author uses Prototype to indicate a general concept (i.e., P13), and prototype to indicate a specific iteration (i.e., P14I7M1).
P1I1 - K

The purpose of this Iteration was proof of concept for this Prototype. During actuation the control rods bowed due their insufficient thickness. A bowing in the trailing edge between control points was noticed due to the flexibility of the foam.

P1I1M1 - K

A control rod was threaded through the trailing edge to prevent bowing. This solution did fix the bowing in the trailing edge. However, slight fluttering was noticed at the trailing edge due to the low density of the foam.

P1I2 - SD

This prototype was actuated with powered servos. It was dynamically tested to examine the fluttering at the trailing edge under flight conditions. The fluttering was significant enough to discourage use of lightweight PE foam in the final concept. It was also noticed during this test that the control rod attachment to the control horns was too high.

This first dynamic test was performed in a ‘poor man’s’ wind tunnel - holding the prototype outside the window of a car. This test demonstrated the viability of the platform as a wind tunnel test for RC aircraft. The test was performed over the range of 25 - 55 mph (36.7 - 80.7 fps), which was the expected flight-speed range of the morphing RC aircraft.

Fig. A.1: Drawing of concept 1.
P1I2M1 - SD

The previous prototype was modified to connect the control rods to the control horns at a lower position. This prototype was also dynamically tested, the result being the wing had a greater deflection range due to the connection point change. However, the fluttering was still an impediment to overcome.

P1I3 - SD

This wing was tested to examine how sweep would affect the deflection of the mechanism. No significant effect was noticed. The control rods were noticed to bow at greater deflections, due to their relatively small diameter, and long length.

P1I3M1 - SD

A different control rod was used on this mechanism. Rather than a control rod with a z bend at either end, one with tang-and-clevis attachment points. While they did bow less, the fluttering at the trailing edge was still a significant detriment.

P1I4 - SD

The trailing edge of this prototype was replaced with LRPu (memory foam). Due to the foam’s higher density, the fluttering at the trailing edge was much smaller. A control rod threaded through the trailing edge also aided in preventing the trailing edge flutter. However, the foam’s higher density also caused the prototype to weigh more than desired for an RC aircraft.

P1I4M1 - SD

The control rods were replaced for this prototype with thicker (2 mm) control rods made of carbon fiber (rather than steel). The stiffer control rods improved the deflection achieved.
The trailing edge foam on this prototype was replaced with EPP foam. This lower density foam, was unfortunately stiffer, resulting in too little deflection. Due to the difficulty in finding a compliant lightweight material for the trailing edge, research into a morphing wing manufactured using this concept was discontinued.

A.2 Concept 2

The second concept tested is shown below in Fig. A.2. Shown in pink is XPS, a stiff foam; shown in blue is PE, a flexible foam; shown in brown are the laser-cut plywood compliant ribs. Note, the PE foam in this concept is a skin rather than a solid section. The wing is actuated via a control horn at the trailing edge of the compliant rib.

![Fig. A.2: Drawing of concept 2.](image)

The purpose of this Iteration was proof of concept for this Prototype. This prototype was difficult to deflect due to the initial stiffness of the trailing-edge material. Buckling was noticed on this surface, though the material could deflect to the desired amount.

A soft foam core was added to the trailing edge between the upper and lower surface skins to aid in buckling prevention. no significant difference was noticed.
P2I3 - S

Stringers were added to decrease the surface buckling. These stringers were carbon-fiber control-rods which were hot glued to the underside of each surface. Though they did aid in surface buckling, they did not eradicate the problem.

P2I4 - S

The skin for this prototype was made from LRPu, with a PE core. This resulted in greater continuous deflection with less buckling. However an open trailing edge prompted the 'sewing' of the trailing edge with a control rod.

P2I4M1 - SD

The trailing edge on this prototype was sewn, resulting in improved deflection, but greater buckling.

P2I4M2 - SD

The foam inner core was removed to see if it would decrease buckling. No significant change was noticed.

P2I5 - SD

The trailing-edge upper and lower surface material was replaced with EPP. The material had significant difficulty deflecting greater than $\pm 2^\circ$.

P2I6 - SD

The trailing-edge material was changed once again to LRPu. More stringers (and thicker) were added to the underside of the upper and lower surfaces. However, no significant change was noticed in the buckling. Due to the undesired buckling, and manufacturing difficulty, research into a morphing wing manufactured using this concept was discontinued.
A.3 Concept 3

The third concept tested is shown below in Fig. A.3. Shown in blue is the wing outer-surface manufactured from PLA using FDM; shown in red is the wing compliant rib also manufactured from PLA using FDM. The wing is actuated via a control horn at the trailing edge of the compliant rib.

![Fig. A.3: Drawing of concept 3.](image)

P3I1 - K

This prototype was printed as a proof of concept. Part of manufacturing this prototype was to test the manufacturing benefits of FDM. The test was used to demonstrate rapid prototyping available through FDM. It was noted on this prototype that the skin was too thick to allow for sufficient compliance.

P3I2 - K

The leading edge portion of this prototype was walled off to test the deflection when the wing did not have the leading edge aiding with compliance. The deflection remained sufficient, while the skin was still too thick.

P3I3 - K

The leading edge of this prototype was walled off chordwise, but not spanwise. This was done to test a simple printed wall along the leading edge without the extra material for the root and tip of the prototype. The mechanism compliance was the same as that of P3I2. It was decided that a thinner skin would improve deflection.
P3I4 - K

The skin thickness was decreased to 1.0 mm for the morphing trailing-edge. A thin groove was printed in the wing chordwise to situate the Bézier rib. The skin was sufficiently thin for deflection. However, the groove was not deep enough to hold the rib.

P3I5 - K

This prototype was manufactured to examine how taper would affect the morphing deflection. The wing section was tapered with a ratio of 0.67. The taper was not noted to have much effect on the wing deflection.

P3I6 - K

The bridging (3D-printing over a gap) of the printer used for these prototypes was tested. This was done to examine how a morphing section would interact with a connected non-morphing section. The bridging distance on this print was too great for the printer resulting in a malformed surface. The non-morphing tip of the section was used to show that the interaction between a morphing root and non-morphing tip would be similar to a morphing root and tip deflected in opposing directions.

P3I7 - K

Runner walls on the inside surface were added to the right and left of each rib to position and constrain the rib spanwise. The resultant deflection was more capable due to the rib being held in place. However, the rib had no attachment to the upper and lower surfaces. If actuation were to occur at the trailing edge of the rib, the non-deflected surface (i.e. the upper surface if the flap is deflected down) would not hold to the rib.

P3I8 - K

A servo hole on the upper surface was added to this prototype. The compliant rib was printed with holes chordwise to allow for a servo to pull a wire connected to the trailing edge, which would be constrained through the compliant bending of the rib. The servo hole
was printed to small to fit the servo. The wired rib concept worked, though it was difficult to assemble.

**P3I9 - K**

For this prototype the servo hole was embedded in the wing. Ledges were added to the servo runners to constrain the surfaces to the compliant rib’s movement. Feet were added to the compliant rib peaks and troughs to hold onto the runner ledges. Due to the thickness of the airfoil, the servo arm was too large though it fit in the servo hole. The rib feet and runner ledges were extremely difficult to print with sufficient quality.

**P3I10 - K**

The purpose of this prototype was to examine the print quality of the leading edge when switching the airfoil to an Eppler 335. The print quality was sufficient to print the leading edge closed. Due to the manufacturing difficulty of the rib feet and runner ledges, research into a morphing wing manufactured using this concept was discontinued.

**A.4 Concept 4**

The fourth concept tested is shown below in Fig. **A.4**. This concept uses a structure similar to that used in the FishBAC concept [9]. Shown in blue is the wing manufactured from PLA using FDM. The wing is actuated via a control horn at the trailing edge of the wing. An elastomeric pretensioned skin would be applied over the trailing edge surface structure.

![Fig. A.4: Drawing of concept 4.](image-url)
P4I1 - K

This prototype was printed as a proof of concept. The wing was able to deflect near the desired amounts $\sim \pm 15^\circ$. The thickness of the compliant spine was too great to allow for greater deflection.

P4I2 - K

The spine thickness of this prototype was decreased. This allowed for greater deflection, on the order of $\sim \pm 30^\circ$. This range was what was desired for the final concept.

P4I3 - K

The fish-bone concept was tested on an Eppler 335 airfoil. No significant difference was noticed in the deflection of the airfoil compared to P4I2.

P4I4 - K

Scales were added to the fish bone vertical pieces. These horizontal ledges followed the airfoil outer skin. They were added to cover the spanwise holes created by the fish bone geometry. The 3D printer was able to print this scales to nearly close the holes without closing the hole.

P4I5 - K

The fish-bone geometry was modified so the fish-bone spine followed the airfoil camber-line. This caused a slight improvement in the deflection, mostly due to the confirmation of the camber line being conformed to the deflection shape.

P4I6 - K

A one-fifth scale version of the Manta (airframe prior to Horizon) airframe was printed using the fish-bone geometry. This prototype demonstrated the effects taper and sweep had on a small scale version. Taper severely impeded deflection.
The scale creation was modified so the scales could be placed forward and aft of each spine vertical part. No significant improvement was seen in the deflection.

A three-fourths scale version of the Manta airframe was printed. The bay section of the Manta airframe deformed during printing, showing the need for infill. The control surfaces were glued together, and had significant problems deflecting due to stiffness. This prompted the use of flexible filament (TPU).

A section of the three-fourths scale Manta was printed using Flexfill TPU. The deflection was optimal. The leading edge and bridging had difficulty printing without deformation or failure. The skin was not stiff enough to take aerodynamic loading.

The same Manta section was printed with the scales connected between fish-bone spines. This model was not able to deflect at all, and exhibited similar problems to those with concept 2. Due to complexity of using a post-fabricated pretensioned skin, research into a morphing wing manufactured using this concept was discontinued.

The fifth concept tested is shown below in Fig. A.5. The inner material of the fish-bone concept is removed to allow for differential deflection between actuators. Shown in blue is the wing manufactured from PLA using FDM. The wing is actuated via a control horn at the trailing edge of the wing. An elastomeric pretensioned skin would be applied over the trailing edge surface structure.
Fig. A.5: Drawing of concept 5.

P5I1 - K

This prototype was printed as a proof of concept. Though it was able to create a gradient trailing edge between two ribs, it would also require a pretensioned skin like concept 4. The scales for this prototype were glued on to each rib/stringer. The print quality was poor.

P5I2 - K

An intermediary rib that was unconnected to the leading edge was added to this prototype. The glueing surface was insufficient for this, and so printing the scales on the ribs was proposed. The print quality for this prototype was also poor.

P5I3 - K

The stringers were lengthened chordwise to create the scales. This worked really well. The print quality was much better than the previous prototypes. The bridging at the tip of the wing section was not so good.

P5I4 - K

A wall was added to support the bridge printing of the tip rib. Though this improved the print quality of the face, the wall hindered the differential deflection at the trailing edge.
This prototype was tapered. This was done to examine the print quality of this concept when it is tapered. The print quality was not good enough for use in a final concept.

A one-fifth scale version of the Manta airframe was printed using this concept. Most of the scales melded during printing and had to be disconnected with a razor.

A section of a three-fourths scale version of the Manta airframe was printed using this concept. The printer had difficulties as there were larger gaps, taller towers, and longer bridging. The print failed part way through. Due to the difficulty in printing this concept with sufficient surface and structural quality, research into a morphing wing manufactured using this concept was discontinued.

The sixth concept tested is shown below in Fig. A.6. A different method is used to support a skin between two ribs, this concept being with sine-wave-like undulating spires. Shown in blue is the wing manufactured from PLA using FDM. The wing is actuated via a control horn at the trailing edge of the wing. An elastomeric pretensioned skin would be applied over the trailing edge surface structure.

Fig. A.6: Drawing of concept 6.
P6I1 - K

This prototype was printed as a proof of concept. The undulating connections did not print well at this scale, and were extremely flimsy. Due to the insufficient structural support, research into a morphing wing manufactured using this concept was discontinued.

A.7 Concept 7

The seventh concept tested is shown below in Fig. A.7. A different method is used to support a skin between two ribs, this concept being with an extruded set of Bézier curves. Shown in blue is the wing manufactured from PLA using FDM. The wing is actuated via a control horn at the trailing edge of the wing. An elastomeric pretensioned skin would be applied over the trailing edge surface structure.

![Fig. A.7: Drawing of concept 7.](image)

P7I1 - K

This prototype was printed as a proof of concept. The deflection of this concept was not especially better than previous concepts. It also would be harder to adhere a skin surface to, compared to previous concepts.

P7I2 - K

This prototype was tapered to study how the deflection would be affected by taper in the wing. Due to the difficulty of applying a pretensioned elastomer skin, research into a morphing wing manufactured using this concept was discontinued.
A.8 Concept 8

The eighth concept tested is shown below in Fig. A.8. This structure uses the fish-bone concept printed from two materials. Shown in white is the wing leading edge made out of PLA using FDM; shown in black is the wing compliant trailing edge made out of TPU using FDM. The wing is actuated via a control horn at the trailing edge of the compliant rib. Due to the difficulty of applying a pretensioned elastomer skin, research into a morphing wing manufactured using this concept was not started.

Fig. A.8: Drawing of concept 8.

A.9 Concept 9

The ninth concept tested is shown below in Fig. A.9. The scales of the fish-bone concept are shifted to act as a pretensioned surface. The part would be printed in two pieces that would be curved initially, upper and lower, which would be adhered together. Shown in blue is the wing manufactured from PLA using FDM. The wing is actuated via a control horn at the trailing edge of the wing. Due to the difficulty of adhesion between the upper and lower surfaces, research into a morphing wing manufactured using this concept was not started.
A.10 Concept 10

The tenth concept tested is shown below in Fig. A.10. This structure uses the fish-bone concept printed from two materials. Shown in white is the wing leading edge and compliant trailing edge parts made out of PLA using FDM; shown in black is the wing compliant trailing edge parts made out of TPU using FDM. The wing is actuated via a control horn at the trailing edge of the compliant rib. Due to the difficulty of applying a pretensioned elastomer skin, research into a morphing wing manufactured using this concept was not started.

A.11 Concept 11

The eleventh concept tested is shown below in Fig. A.11. The wing surface is made from a chain-linked material. The wing is actuated via a control horn at the trailing edge of the compliant rib. Due to the difficulty of creating this concept, research into a morphing wing manufactured using this concept was not started.
A.12 Concept 12

The twelfth concept tested is shown below in Fig. A.11. The wing is made up of a stiff leading edge section, and discretized trailing edge sections. The wing is actuated via a rod-actuation mechanism through the hinge point. Due to the difficulty of actuating this concept, research into a morphing wing manufactured using this concept was not started.

A.13 Concept 13

The thirteenth concept tested is shown below in Fig. A.13. Shown in white is the wing outer-surface made out of PLA using FDM. The wing is actuated via a control horn connected to the slip-joint tongue of the compliant trailing edge.
This prototype was printed as a proof of concept. The concept showed promising deflection, though there was disproportionate bowing of the upper and lower surfaces during deflection.

The trailing edge was printed using a TPU. The print quality was not good. The flexible material needed a support structure as it prints.

These prototypes were printed for use as demonstrators at a variety of student showcases and presentations.

Semicircular supports were added to the inside of the upper and lower compliant surfaces. They successfully supported the structure during printing, though the print quality was poor.

A support piece was connected to the upper and lower surfaces of the compliant section to conform the deflection to the camber line. The connections did not allow parabolic...
deflection, but simply made the trailing edge rigid.

**P13I6 - K**

The trailing edge was printed in spanwise layers of PLA and TPU. The deflection was much better than previous prototypes. However, the layer adhesion between the TPU and PLA was poor.

**P13I7 - K**

The ratio of PLA to TPU was decreased to improve the flexibility of the compliant surface. However, this did not significantly improve the deflection of the wing. Due to difficulty of spanwise layer adhesion and nonconformity of the camber line to a parabolic profile when deflected, research into a morphing wing manufactured using this concept was discontinued.

**A.14 Concept 14**

The fourteenth concept tested is shown below in Fig. A.14. Shown in white is the wing outer-surface made out of PLA using FDM; shown in black is the wing compliant arcs made out of TPU using FDM. The wing is actuated via a control horn connected to the slip-joint tongue of the compliant trailing edge.

![Fig. A.14: Drawing of concept 14.](image-url)
P14I1 - K

This prototype was printed as a proof of concept. This first concept had deflection problems due to the floppy ALL TPU trailing edge. It acted as a four bar linkage instead of a compliant system.

P14I1M1 - K

The arcs were printed out of TPU for this prototype. This prototype was successful in deflecting parabolically! Layering of PLA and TPU could allow a deflection gradient at the trailing edge between actuators.

P14I2 - K

The trailing edge was printed in layers of PLA and TPU. This improved the deflection gradient, but stiffened the compliant mechanism.

P14I3 - K

The arcs and outer surface were printed using PLA, with only the hinges printed using TPU. There was not a significant improvement in the mechanism.

P14I3M1 - K

The whole shape was printed from PLA. the deflection was nonexistent. The flexible material is required.

P14I4 - K

The ratio of PLA to TPU was 2:1. This prototype had much better flexibility while allowing some deflection gradient at the trailing edge.

P14I5 - K

This section was tapered to examine its’ effect on the wing compliance. The taper did not seem to have a significant effect.
**P14I7 - K**

The wing was printed with a spanwise length of 7 inches, where the first and seventh inches were a PLA compliant rib with TPU arcs, while the remaining 5 inches was a PLA leading edge with TPU arcs and a 2:1 ratio of TPU to PLA for the surface of the trailing edge. This system resulted in fantastic deflection.

**P14I7M1 - K**

The same wing was printed, with the 5 inches of material being all TPU at the trailing edge. This was done to bracket the deflection gradient at the trailing edge, and work between these two (2:1, 1:0) to determine the optimal ratio for stiffness and gradient deflection.

**P14I7M2 - S**

The P14I7 concept was printed with servo bays for each compliant rib. The actuation was less than expected due to the servos fighting each other.

**P14I8 - S**

This was a 2 inch spanwise concept. It was created to examine the servo’s ability to deflect the compliant structure without fighting a servo in the opposing direction. The deflection was good, though the connection to the flexible tongue was too soft for the servo to perfectly control the deflection.

**P14I8M1 - S**

The tongue was printed using PLA to improve the stiffness of the connection from the servo. The deflection was much better controlled with this method.

**P14I9 - S**

The all flex trailing edge model P14I7M2 was printed with servo bays. The servos were able to deflect with sufficient deflection gradient between actuation ribs. However, there was significant buckling in the skin surface.
P14I9M1 - S

A single $\frac{1}{8}$ inch PLA rib was added in the middle of the compliant trailing edge surface. This improved the buckling, but did not remove it.

P14I9M2 - S

Two $\frac{1}{8}$ inch PLA ribs were added spaced along the compliant trailing edge surface. This improved the buckling, but did not remove it.

P14I9M3 - S

Three $\frac{1}{8}$ inch PLA ribs were added spaced along the compliant trailing edge surface. This improved the buckling, but did not remove it.

P14I9M4 - S

Four $\frac{1}{8}$ inch PLA ribs were added spaced along the compliant trailing edge surface. This improved the buckling, but did not remove it.

P14I9M5 - S

Five $\frac{1}{8}$ inch PLA ribs were added spaced along the compliant trailing edge surface. This prototype had no buckling on the trailing edge surface. There were adhesion problems between the PLA and TPU in the printer z direction.

P14I10 - S

The actuation ribs were decreased in size from 1 inch to $\frac{1}{2}$ inch. This resulted in a greater deflection gradient between actuators.

P14I11 - S

Fillets were added to the arcs to stiffen the surface. This was done as a possible preventative to buckling, to avoid the problems of layer adhesion issues. No noticeable difference was seen.
In another attempt to decrease the buckling between actuators, the second and fourth arcs were removed. This did not improve the buckling.

The flap chord fraction was increased to 0.6. This was done to test the gradient deflection with a larger flap. The deflection increased between actuators.

A half as thick airfoil was used for this test. This resulted in better deflection as the compliant surface did not have to stretch as far spanwise when deflected.

An avian-inspired airfoil was tested to examine deflection of an airfoil with minimal trailing edge thickness. Though the deflection was better, the difficulty of inserting a servo into the wing remained.

The fourth and fifth arcs were removed to improve the buckling. No noticeable improvement was seen.

This prototype was a mechanized concept using the avian airfoil. As before, the span was segmented with two 1 inch control ribs having a PLA outer surface and a 5 inch morphing section between these control ribs. This morphing section had five $\frac{1}{8}$ inch PLA ribs with TPU elsewhere. This concept had a deflection gradient of $\sim \pm 25^\circ$. 
Whereas the arcs on previous prototypes were modeled concave to the hinge point, the arcs were printed convex. There was no significant difference in the deflection for this prototype, compared to a representative model.

This concept was tested using a NACA 0006 airfoil. This was done to examine a thinner airfoil’s deflection. This concept had three actuation points: The wing was segmented with three 1 inch control ribs and two 5 inch morphing sections. The servos were oriented so the outer two would actuate up while the middle one actuated down. The servos fought each other, but were able to create a differential gradient of $\sim \pm 25^\circ$. They also were able to actuation and hold the compliant mechanism shape when dynamically loaded.

This concept employed a 50% thick Eppler 335 airfoil. It also had sufficient deflection of about $\sim \pm 20^\circ$. However, there was pulling on the middle servo from the two opposing servos.

The avian airfoil was tested with the 13 inch span design. This design had lesser deflection than P14I20 or P14I19. This was due to there being less material to stretch at the trailing edge. The middle servo broke out during this test.

The avian airfoil was tested using a rib-morphing-rib-morphing-rib design. The control ribs were $\frac{1}{2}$ inch instead of 1 inch. This improved the deflection at the trailing edge. However, the actuators deformed the control ribs during deflection. Problems were still noticed with the middle servo fighting the other two servos.
The ARCS concept was tested on a one half scale version of the Horizon airframe. The bay control surface was unable to deflect greater than $\pm 4^\circ$ due to the taper in the section. There were also deflection problems in the outboard wing sections. For improving the controllability of Horizon, after this prototype the control surfaces were cosine clustered. It should be noted that the control surface design from this prototype forward was made of discrete control-surfaces rather than a single continuous control-surface. For more information on this change, see Subsection 1.3.1.

The arcs in the bay section were straightened spanwise in this one half scale version of the Horizon airframe bay section. It did not improve the deflection capabilities in the bay.

The actuation hub connection in the bay was moved outboard to allow for the bay to be printed in two pieces. However, the taper in the bay still prevented deflection.

The full scale outboard-most and inboard-most morphing sections were printed. This was done to examine the effect of taper on the other sections of Horizon, printed at full scale. There were still deflection problems, with the outboard section incapable of deflecting to the amounts required.

A symmetric airfoil, NACA 0012, was tested for the half-scale Horizon bay-section. This did not improve the buckling and non-deflection problems noticed earlier. Due to change from continuous to discrete control-surfaces, research into a morphing wing manufactured using this concept was discontinued.
A.15 Concept 15

The fifteenth concept tested is shown below in Fig. A.15. Shown in white is the wing outer-surface made out of PLA using FDM; shown in black is the wing outer surface made out of TPU using FDM. The wing is actuated via an actuation-rod connected to each PLA section. The rod would twist to control the wing, while the TPU sections would interpolate the gradient between the neighboring PLA sections.

![Fig. A.15: Drawing of concept 15.](image)

This prototype was printed as proof of concept. However, the print failed in several locations trying to adhere the PLA and TPU. Due to difficulty in manufacturing this concept, research into a morphing wing manufactured using this concept was discontinued.

A.16 Concept 16

The sixteenth concept tested is shown below in Fig. A.16. Shown in white is the wing outer-surface made out of PLA using FDM; shown in black is the wing compliant surface and arcs made out of TPU using FDM. The wing is actuated via a control horn connected to the slip-joint tongue on the upper and lower surfaces of the compliant trailing edge.
This prototype was printed as proof of concept. It was difficult to insert the actuators and connect them to the compliant trailing edge. Due to difficulty in controlling the actuation of this concept, research into a morphing wing manufactured using this concept was discontinued.

A.17 Concept 17

The seventeenth concept tested is shown below in Fig. A.17. The design was made up of discretized laser-cut compliant ribs slid onto a spar. A flexible filament connects the tongue and trailing edge of each compliant rib. The wing is actuated via a control horn connected to the slip-joint tongue of the compliant trailing edge.
P17I1 - K

This prototype was printed as a proof of concept. This concept was laser cut from birch-wood plywood sheets $\frac{1}{8}$ inches thick. The tongue was disjointed along the span of the section. The deflection was minimal, but it could be increased by changing the thickness.

P17I1M1 - K

Tape was added around the tongue for the tongue to translate as a solid entity. This way the tongue could be actuated from one side, affecting the other.

P17I2 - K

This prototype was laser cut from balsa sheets. The material was too soft, and broke too easily. Further testing would require a stronger material.

P17I3 - P17I3M5 - K

This test was used to study the ARCS mechanism placed inside the wing (varying arc thickness, 2.0 to 1.5 mm). The arcs provided too much structural support. The second through fifth arcs were removed to study the effect. No noticeable improvement was found.

P17I3M6 - P17I3M10 - K

Smaller arc thicknesses were tested, from 1.4 to 1.0 mm in thickness. The parabolicity of the deflection was improved, but not significantly.

P17I4 - P17I4M1 - K

As the arc removal was tricky to perform without breaking neighbor arcs, Only the first arc was laser cut on this prototype. The deflection was similar to that of P17I3M10.

P17I5 - P17I5M5 - K

This prototype was the first to use what would become the KINCS concept. Each prototype had a two-degree kink (two peaks) with varying thickness (2.0 to 1.0 mm), and
forward and backward directions. The resulting deflection was more parabolic than P17I4.

**P17I6 - P17I6M3 - K**

This Iteration was used to test three-degree kinks of varying thickness (1.5 to 1.0 mm), forward and backward. The parabolic deflection compared to a parabolic printout was closer than the two degree kinks used in P17I5. Forwardness and backwardness of the kinks seemed to have little effect on the parabolic deflection profile.

**P17I7 - P17I7M5 - K**

This Iteration was used to test four-degree two-count kinks. These prototypes were compliant enough to deflect the camber line following a parabolic profile!

**P17I8 - P17I8M6 - K**

This Iteration was used to test four-degree three-count kinks. The extra kink provided too much stiffness. Due to the time required to laser cut each rib, research into a morphing wing manufactured using this concept was discontinued.

**A.18 Concept 18**

The eighteenth concept tested is shown below in Fig. A.18. The design is FDM printed using PLA. The wing is actuated via a control horn connected to the slip-joint tongue of the compliant trailing edge.

Fig. A.18: Drawing of concept 18.
This prototype was printed as a proof of concept. This design was used to test an FDM concept using the geometry created while researching Prototype 17. The prototype was able to deflect parabolically!

The geometry creation of the KINCS mechanism was changed to use sets of n-count four-degree Bézier curves rather than a single n-degree Bézier curve. The kinks were printed thinner to improve the deflection. However, the kinks were too thin for the 3D printer to properly print them.

Different kink thicknesses were tested with the further aft kink printed thicker to force the compliance to occur nearer the hinge point. The thinner kinks worked best, with removing the second kink working best of all.

This Iteration was used to test different kink thicknesses with the second of two kinks removed. The prototype P18I4M0, which had a thickness of 0.45 mm and only the first of two kinks, had the most parabolic deflection.

This Iteration was used to mechanize and dynamically test the KINCS concept. During the test the wing underwent dynamic loading with no fluttering at the trailing edge or straining of the servos.

The bay section of a half-scale Horizon was FDM printed using the KINCS concept. The wall near the trailing edge was straightened through the span of the section to attempt
to resolve the deflection problems due to taper. The problem was not resolved.

**P18I7 - K**

Both the kinks and the trailing-edge wall were straightened for this test. The problem was not resolved.

**P18I8M0 - P18I8M5 - K**

This Iteration was created to test the optimal thickness of the kinks for FDM print quality. The kink that was the thinnest while printed without errors had a thickness of 0.47 mm.

**P18I9M0 - P18I9M4 - K**

This Iteration was created to test the kinks shifting toward the leading edge and trailing edge. The kink that was deflected the most parabolically was that which had no forward value, and a value of 1.0 for that towards the trailing edge.

**P18I10M0 - P18I10M4 - K**

This Iteration was created to test the kinks attachment point shifting. No significant improvement was seen.

**P18I11M0 - P18I11M2 - K**

This Iteration was created to test the kinks degree being increased and decreased. No significant improvement was seen.

**P18I12 - K**

This prototype was printed to test the modeling procedure for the ducted fan. The results showed a need to change the fan placement and guide curve values.
P18I13 - K

Due to the deflection problems of the tapered bay section of Horizon, the taper was removed from the bay and transferred to the fan section. This prototype was used to test the employ of a Hitech™HS-5065MG servo to deflect the full-scale bay-section. This servo was not powerful enough to deflect the bay, thus a 5245 servo would be required.

P18I14

This Iteration was only modeled. It was used to test the modeling procedure for the Horizon aircraft. For more information on this procedure, see Chapter 3.

P18I15 - S

The Servo00 section (S02) of the full-scale Horizon airframe was tested for deflection capability. It was noticed that the cubic interpolation used between distribution nodes resulted in a severely tapered section at the root of this section. This tapered piece was demonstrated to prevent deflection, and when removed the problem was resolved.

P18I16 - S

The Servo03 section (S04) of the full-scale Horizon airframe was tested for deflection using the Hitech™HS-5065MG servo. Like the bay, it could not be powered by the 5065, but it could by the 5245.

P18I17 - S

This Iteration was used to demonstrate the deflections on one half of the Horizon airframe. Neighboring sections would bind, requiring the removal of a slice of the morphing compliant surface from the tip of each Section.

P18I18 - K

This Iteration was used to test tolerance fixes for the ducted-fan cover in the fan section (S01). The tolerance changes were sufficient for the fan cover to fit properly in the section.
**P18I19 - K**

Due to the flimsiness of the bay section with only one kink, additional kinks were added to the section. This resulted in improved surface quality and continuity during deflection.

**P18I20 - S**

The first full-scale full-span print of the Horizon airframe. The triangle slices were removed from the tip of each section. The servo mounts were glued inside the servo bays in each morphing section. Structural problems prompted rearranging of the servo bays and the addition of an I beam in the fan section.

**P18I21 - S**

This Iteration was created with the servo mounts to be FDM printed inside each servo bay. Support kinks were printed with each morphing section to improve finished surface quality. Sections of this prototype were fatigue tested (see Subsection 6.1.2).

**P18I22 - SD**

This Iteration was created to implement the structural changes required in P18I20. This prototype was the first flight test of the Horizon aircraft.