Aerogami: Composite Origami Structures as Active Aerodynamic Control

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Abstract

This study explores the use of origami composite structures as active aerodynamic control surfaces. Towards this goal, two origami concepts were designed leveraging a combination of analytical and finite element modeling, and computational fluid dynamics simulations. Wind tunnel tests were performed at different dynamic pressures in conjunction with two different active control laws to test the capability of obtaining desired drag values. The experiments revealed excellent structural rigidity and folding characteristics under aerodynamic loading. Future work will focus on developing advanced origami designs that allow for more deterministic folding as well as improved weight, stiffness, and fatigue characteristics in the use of materials. Upon completion of these improvements, it is anticipated that full-scale testing on a vehicle could be meaningfully conducted.

Keywords: Aerogami, A. Smart materials, A. Polymer-matrix composites (PMCs), C. Computational modeling

1. Introduction

Composite materials continue to be an important and active area of research in materials science and engineering. This continued research is due in large part to the significant benefits over traditional metal/alloy structures, including weight savings, superior tailorability, and superior specific strength compared to other materials [1][2]. However, despite the several benefits, the problem of readily and efficiently constructing more complex shapes with composite materials remains [11]. Recent works at the University of Washington have explored the feasibility and possible advantages of combining the ancient art of origami and composite materials [12][13]. The resulting systems feature configurations of many smaller pieces of composite material that are easily constructed in bulk which fit together in
intricate shapes using a variety of flexible joints, allowing streamlined construction of highly complex geometries with composite materials.

Likewise, many researchers have explored the possibility and paved the way to model and control the actuation and kinematics of complicated structures, ranging from morphing wings [14, 15], to harvesting power from vibration using piezoelectric materials [16].

Motivated by the advanced folding capabilities of origami composites and the solid fundamentals of control theory of the aforementioned complex structures, the purpose of this project is to explore the feasibility of utilizing origami composite structures as aerodynamic control surfaces. Specifically, origami technology could enable the development of large drag surfaces that can be stowed in a much smaller area than traditional airbrakes [17]. Additionally, this project seeks to address current challenges with actuation through design of origami shapes that can be controlled via a single linear actuator. Active feedback control systems [18] were implemented into the design, allowing the aerodynamic surface to automatically adjust shape given varying airflow conditions in order track a desired drag force.

Wind tunnel testing was performed on two original origami designs in the University of Washington 3 ft x 3 ft wind tunnel with the following goals: (i) to measure drag forces at different actuation percentages and dynamic pressures, (ii) to test control laws and their ability to track a given drag value, and (iii) to observe structural integrity and flutter characteristics of the test assembly. These tests were run at varying actuation percentages (10-90%) at dynamic pressures ranging from 479 to 1915 Pa (corresponding to 10-40 psf).

2. Theoretical framework

Two different geometries of origami structures were designed: “Worm”, a simple four-panel design as shown in Fig. 1 and “Dino”, a more complex configuration incorporating two Worms connected by a central fan inspired by the frilled lizard (Fig. 2). These designs were evaluated according to different criteria, including manufacturability, controllability, structural rigidity, and the magnitude of generated aerodynamic forces. A notable advantage of the foregoing origami surfaces compared to traditional control surfaces is that, notwithstanding the complex folding behavior, they require only a linear actuation system. The following sections briefly describe the folding kinematics and drag forces.

2.1. Folding Kinematics

The displacement of the actuator $x(\alpha)$ as a function of the angle of attack of the front plate, $\alpha$, of Worm and Dino can be derived from the geometry in Fig. 3. The inverse of this function $x^{-1}(\alpha) = \alpha(x)$ can then be computed analytically, giving the following simple equation for the angle of attack as a function of actuation displacement:
\[
\alpha(x) = \arccos \left[ \frac{l_{BP}^2 - l_{FP}^2 - (l_{FP} + l_{BP} - x)^2}{2l_{FP}(x - l_{FP} - l_{BP})} \right] = \arccos \left[ \frac{\psi^2 - 1 - (1 + \psi - x/l_{FP})^2}{2(x/l_{FP} - 1 - \psi)} \right]
\]  
(1)

where the dimensionless geometrical parameter \( \psi = l_{BP}/l_{FP} \) was introduced. As can be noted from Fig. 4 which shows the angle of attack as a function of the linear displacement \( x \), the foregoing relationship is highly nonlinear. Proper design of the ratio between the lengths of the frontal and back panel can be used to obtain the desired evolution of the angle of attack during folding.

2.2. “Worm” drag analysis

The drag force, \( D \) generated by the origami surface can be generally expressed as:

\[
D(\alpha) = C_D(\alpha)qS
\]  
(2)

where \( q = 1/2\rho v^2 \) represents the kinetic energy of the fluid, \( \rho \) is the fluid density, \( v \) is the flow velocity, \( S \) is the surface area of the origami, and \( C_D \) is a drag coefficient which can be found in aerodynamics handbooks \[^{19}\] or calculated by Computational Fluid Dynamics (CFD). By simple trigonometric arguments, the frontal projection of the surface area \( S \) of “worm” can be written directly as a function of the linear displacement:

\[
S^{\text{worm}}(x) = l_{FP} \cdot \sin(\alpha(x)) \cdot \omega
\]  
(3)

where, as shown in Fig. 3 \( \omega \) is the plate width and \( \alpha(x) \) is used from Eq. (1). Finally, combining Eqs. (1), (2), and (3), it is possible to express the drag force in “worm” as a function of the displacement of the linear actuator, \( x \), by the following simple expression:

\[
D_W(x) = C_D[\alpha(x)]q \cdot S^{\text{worm}}(x)
\]  
(4)

2.3. “Dino” drag analysis

The folding kinematics for the Dino composite origami is the same as that of two orthogonal Worms with the addition of a fan in-between. Thus, the main addition to the drag \( D_D(x) \) is related to the unfolding of the fan which can be simply approximated as a triangular area between the frontal projections of the two worm plates, as graphically shown in Fig. 6.

With reference to the schematic in Fig. 5 where the edges of the fan are given by two vectors \( \mathbf{w}_1 \) and \( \mathbf{w}_2 \), one can write the following equations:

\[
\mathbf{w}_1 = \begin{bmatrix} l_{FP}\cos(\alpha), 0, l_{FP}\sin(\alpha) \end{bmatrix}^T
\]  
(5)

\[
\mathbf{w}_2 = \begin{bmatrix} l_{FP}\cos(\alpha), -l_{FP}\sin(\alpha), 0 \end{bmatrix}^T
\]  
(6)
The angle $\theta$ between these vectors is the angle at which the fan is deployed. Noting that $w_1 \cdot w_2 = (l_{FP})^2 \cos(\theta)$, this angle can be determined from the scalar product between the $w_1$ and $w_2$. This gives the following equation:

$$\theta = \cos^{-1}(\cos^2(\alpha)) \quad (7)$$

Leveraging the foregoing expression, the surface area as a function of the linear displacement, $x$, can be calculated as follows:

$$S_{\text{dino}}(x) = 2l_{FP} \sin (\alpha(x)) \cdot \omega + \frac{l_{FP}^2 \sin^2 (\alpha(x))}{2} \quad (8)$$

where $\omega$ is the width of the front plate (Fig. 6 compare the surface areas of “worm” and “Dino” and show references schematic for the frontal areas and $h = l_{FP} \cdot \sin \alpha(x)$).

Then, combining Eqs. (1), (2), and (8), it is possible to express the drag force in “Dino” as a function of the displacement of the linear actuator, $x$, by the following simple expression:

$$D_D(x) = C_D [\alpha(x)] q \cdot S_{\text{dino}}(x) \quad (9)$$

3. Design of the origami control surfaces

The design of the origami surfaces and of the control laws for their deployment was based on a combination of Computational Fluid Dynamics (CFD) and Finite Element (FE) simulations devoted to the initial estimation of the aerodynamic loads, structural deflections, and stresses. A description of the models and the main steps adopted for the design are provided next.

3.1. Computational Fluid Dynamics (CFD) simulations

The proposed origami surfaces must provide desired values of drag force while guaranteeing structural integrity. To obtain a proper understanding of the aerodynamic forces and to optimize the design of the proposed concepts, CFD analyses were conducted. Fig. 7 shows the velocity streamlines of the “Worm” and “Dino” in the 90° configuration for a freestream velocity of 26.8 m/s (60 mph) calculated by ANSYS Fluent [20], using the k-ω SST turbulence model [21]. This model was chosen for its accuracy in simulating separated flow, an aspect that is critically important for the design of the origami control surfaces. In the simulation, the density of air was assumed to be 1.225 kg/m³ (sea level density) and the temperature was assumed to be 20°C. The Reynolds number was estimated to be 900,000 assuming a chord length of 0.5 m and a dynamic viscosity of 1.821 \times 10^{-5} m²/s (at 20°C). It is important to note that the full testing assembly was not run in CFD because the force sensor is designed to only measure drag on the origami panels. The drag outputted by CFD was 9.64 N for Worm and 26.8 N for Dino. The projected areas were 0.0148 m² for Worm and 0.0434 m² for Dino. Therefore, the Dino produced over two and a half times more drag with a little less than three times
the surface area. A simulation was then run for Worm at 53.6 m/s (120 mph). This was the highest wind speed tested in the wind tunnel and the CFD results showed that Worm would produce 43.9 N of drag. This is in very good agreement with initial analytical calculations in which the front panel of worm was approximated as an inclined flat airfoil. For $\alpha = 90^\circ$, $C_D \approx 1.2$ \cite{19} and Eq. 9 gives a drag force of 45 N. This value was then used for structural analysis.

3.2. Finite Element Modeling

During the actuation of the origami, the greatest load case on the primary aerodynamic surface, the front panel, occurs when it is perpendicular to the free stream flow. From CFD analysis at a speed of 53.6 m/s (120 mph) this load is 43.9 N, evenly distributed along the surface. For a first course calculation, the folding joints of the primary aerodynamic surface were modeled as simple supports, the plate was modeled as a wide beam, and the material was assumed to be isotropic with $E = 140$ GPa, $\nu = 0.3$, $L = 130$ mm, and $w = 3.07 \times 10^3$ N/m.

The design criteria for a deflection value of 5 times the thickness of the entire plate was set. This criterion was used to solve for the minimum number of plies necessary for the plate such that aeroelastic effects would have minimal influence on aerodynamic force analysis. Each individual ply thickness was known to be 0.168 mm nominally. The modulus of elasticity value was conservatively selected for quasi-isotropic analysis. The results of the analysis indicated that 6 plies of carbon were necessary to meet the design coupled with one sheet of fiberglass. The total deflection with 6 plies of carbon and one ply of fiberglass was calculated to be 4.94 times the thickness of the plate (4.98 mm).

Preliminary samples taken from Worm prototypes indicated that the observed deflection was less than that predicted by the model. This suggested that the model used was conservative and did not accurately portray the stiffening effects of the added urethane and fiberglass or the boundary conditions of the problem. This inaccuracy motivated the development of a more accurate FE model.

Fig. 8 shows the maximum deflection of the Worm when actuated at 90° as simulated in the FE software FEMAP \cite{22}. 20000 elements were used to simulate the composite material, using a laminate property with a properly assigned layup and meshed using linear quadrilateral elements.

The material model for the composite plates was orthotropic, with Young’s moduli $E_1 = 181$ GPa and $E_2 = 10.3$ GPa, a shear modulus of $G_{12} = 7.17$ GPa, a Poisson’s ratio of $\nu_{12} = 0.28$ \cite{23}. The mass density was set equal to 1.6$g/cm^3$. The analysis predicted the maximum deflection to be 0.341 mm occurring on the plate perpendicular to the flow. Comparing the deflections with modal analysis, also performed in FEMAP, only the first mode shape was found to be important. Higher fidelity orthotropic models coupled with aeroelastic effects will be investigated in the future. Additionally, more CFD analysis will be performed on the deformed shape of the aerodynamic surface to determine the sensitivity of aerodynamic loads to aeroelastic effects.
3.3. Controller Selection

Using the results found from analytical derivations, computations, and the testing of control hardware, a Simulink model was developed to assist in control design. With this model in place, two control laws were designed taking into account the noise levels expected in the load sensor (less than ±0.1 N) and the modeled behavior of the Arduino and the linear servo.

Based on simulation results, “bang-bang” [18, 24] and proportional [18] control laws were chosen for software implementation. The motivation for this choice is threefold. First, the servo system adopted in this work was selected to favor robustness, simplicity, and cost-effectiveness over speed. Accordingly, a controller with low rise time was desired to mitigate the slow actuator movement. Second, the servo could only receive commands that set an extension length, making it difficult to control the velocity of the actuation. Third, the existence of only one sensor meant that PID control laws would require a large amount of sensor processing to numerically approximate the velocity and integral of the state potentially adding additional delay and inaccuracies.

Lastly, it is worth mentioning that the inertial terms that often lead to underdamped behavior in proportional and bang-bang controllers [18] were found to be negligible in the Worm and Dino due to the low weight of the composite structure. Through simulations, the bang-bang and proportional controllers displayed adequate behavior for the available hardware.

4. Manufacturing

The fabrication of the composite origami consisted of several steps, which followed the manufacturing procedure recently proposed by the authors in [12] and [13] using Vacuum Bag Only (VBO). First, pre-impregnated plain weave T700 carbon fiber plies from Toray [25] were taken out of -11°C storage, let thaw in a vacuum bag, and placed in a CNC fabric cutter by Autometrix [26]. Then, the desired panels were precisely cut out and curing of the thermoset resin followed. Two metal plates were cleaned using scrapers and acetone before a thin layers of release agent was applied to the plates. Three plies of carbon panels were combined into a [0°/90°/0°] layup for increased strength. These panels were placed between the two metal plates and cured in the hot press following the manufacturer specifications. Teflon sheets were used in between the carbon panels and the metal plates as needed to ensure easy separation after curing. The composite panels were then cut with a water diamond saw and sanded down to their precise dimensions.

Once the composite panels were prepared, the next stage was to prepare a sandwich structure where two sides of CFRP facets are joined together using a single layer of dry fiberglass in between impregnated with a very flexible urethane epoxy provided by Sharkthane [27] with A shore number of 30. To do so, a small amount of glue was temporarily used to correctly lay down the “Dino” and
“Worm” configurations on a large metal or garolite plate, as shown in Fig. 9-a, b. Bagging Tape was then placed around the panels and a sheet of dry fiberglass was placed on top of the panels (Fig. 9-c). The urethane system was mixed and evenly distributed before placing a set of panels over the fiberglass (Fig. 9-d). A Teflon sheet was placed over the panels and the bridge piece was placed near the edge of the Bagging Tape (Fig. 9-e). The vacuum bag was placed over the Teflon and pushed down into the Bagging Tape to create an airtight seal (Fig. 9-f). The vacuum pump hose was attached to the bridge piece (Fig. 9-g), and the vacuum was turned on and left on overnight. The panels were then taken out of the vacuum bag assembly and trimmed to the right dimensions.

5. Testing

5.1. Experimental setup

The composite surfaces described in the previous sections were tested to verify their performance in terms of aerodynamics, controllability, and mechanical behavior. All the tests were performed in the $3 \times 3 \times 8$ ft wind tunnel at the University of Washington which is a open-loop facility capable of 135mph (60m/s) flows with a 9 : 1 contraction ratio.

For the testing, a new origami test stand shown in Fig. 11 and Fig. 10 was designed to minimize possible airflow perturbations seen by the origami control surface during actuation. In the fully-closed (flat) position, the origami was designed to sit 1.5 ft above the wind tunnel floor, exactly in the center of the wind tunnel. This minimized boundary layer effects from the wind tunnel walls. As can be noted from Fig. 11 and Fig. 10, the test stand was fixed to the floor through 4 bolts, and the bottom plate supporting the entire test assembly was connected to floor by a center strut with a low drag airfoil cross-section.

During the tests, the origami structure sat on 3D printed PLA components which were bolted to an aluminum plate. All forward facing 3D printed components were designed with contoured leading edges to improve airflow quality over the origami test article. The front origami panel was bonded in place with methyl-methacrylate adhesive to the front fairing.

At the rear of the aluminum plate, an Actuonix L16-R linear actuator pushed the rear plate of the origami thus actuating the entire control surface. The rear plate of the origami was wider than the other origami plates and slid along two 3D printed rails which were bolted to the aluminum plate. Behind the actuator sat an enclosed Arduino control unit used to give the actuator commands. To protect the control electronics from the flow, a 3D printed conical wind shield was placed over the actuator and in front of the Arduino control box (Fig. 10 arrow 2).

The aluminum plate was bolted to a linear rail upon which it slides. The linear rail was then bolted to a lower aluminum plate bolted to the supporting strut. At the rear of the test article a force sensor
was placed and bolted to both plates. As the upper plate rested on a rail, its motion was unconstrained along the flow direction, thus loading the force sensor in shear, which consequently measured the drag generated solely by the origami.

Wind tunnel q-calibration was conducted before any data was taken by sweeping the dynamic pressure from 0 to 1915 Pa (corresponding to a wind speed of 180 mph) so that the dynamic pressure value read by the wind tunnel Pitot-static probe matched the true dynamic pressure value. Next the assembly’s structural integrity was tested by slowly increasing the dynamic pressure from 0 up to 1915 Pa.

An important aspect of the experimental campaign was the development of the actuation and data acquisition systems. These were designed so that the apparatus would be able to independently read and log forces generated by the origami, to independently execute the controls algorithm, and to fold/unfold the origami shapes via a single linear actuator. An Adafruit data-logging shield \[30\] was used to implement data logging capabilities in an Arduino Uno, which served as the main controller. A 20 kg Phigits shear load cell (CZL635) \[31\] was used to measure the drag generated by the origami. The 20 kg model was chosen to place expected drag readings in the middle of the sensor’s range, improving accuracy. A Spark-Fun load cell amplifier (HX711) \[32\] was used to convert analog to digital readings for the load cell. An Actuonix RC linear servo (L-16R) \[28\] was used as the control actuator. This model was chosen for its built-in RC controller, allowing it to be directly controlled by the Arduino unit.

5.2. Worm Wind Tunnel Testing

To characterize the folding behavior and aerodynamics of “worm”, a series of actuation sweeps were conducted at 478.8, 1436.44, and 1771.6 Pa. The sweeps actuated the origami from 10 to 90% actuation in 10% increments, recording the forces generated by the Worm at each increment. Next the bang-bang control law was tested multiple times at dynamic pressures of 718.2, 1436.4, and 1915.2 Pa targeting drags of 9.81, 19.6, and 35.3 N (corresponding to load cell readings of 1, 2, and 3.6 kg) respectively. The proportional control law was also run at the same dynamic pressures with the same drag targets.

5.3. Dino Wind Tunnel Testing

The wind tunnel testing process for the Dino proceeded in the same way as that of the Worm, albeit with different operating dynamic pressures and drag targets. Because the Dino has a larger surface area than the Worm, the tested dynamic pressures were reduced in an attempt to mitigate the larger stresses developed in the testing apparatus. Additionally, the modified testing apparatus for the Dino imposed a maximum extension length for the actuator. Therefore, the actuation sweeps were performed from 10
to 70% actuation in 10% increments at dynamic pressures of 440.5, 785.2, and 991.1 Pa (corresponding to wind speeds of 60, 80, and 90 mph respectively). To test the Bang-Bang and Proportional control responses, controlled deployments were performed at dynamic pressures of 440.7, 783.4, and 991.5 Pa targeting drag forces of 14.7, 24.5, and 29.4 N (corresponding to load cell readings of 1.5, 2.5, and 3 kg respectively). The design of the Dino testing configuration was the same as the Worm, with the exception of the 3D printed parts conforming to its specific geometry. The full Dino testing apparatus can be seen installed inside the 3ft x 3ft wind tunnel in Fig. 11.

6. Results

6.1. Preliminary mechanical investigation

Before performing the experimental campaign, preliminary tests on worm prototypes were conducted to verify the structural integrity of the system and identify possible design criticalities. After the first Worm prototype was manufactured, it was concluded that the joint spacing was too large, leading to structural instability. This raised concerns of destructive flutter occurring during the wind tunnel test. In response, a Worm and Dino with smaller joints of 3 mm were manufactured and flutter was not observed during wind tunnel testing. However, wind tunnel results exhibited that the spacing could have been even smaller. At low actuation percentages for the Worm, actuator extension caused the soft joints to buckle and additional actuator displacement was required before the origami would begin folding as desired (this phenomenon can be observed in Fig. 12 as the flat lines from 10 to 20 psf). Therefore, the limiting factor for joint spacing should only be the joint’s radius of curvature.

6.2. Aerodynamic testing

In order to quantify the forces experienced by the test apparatus at various levels of actuation, a number of actuation sweeps were performed in the wind tunnel. Fig. 12 shows drag forces and coefficients determined experimentally in the wind tunnel at dynamic pressures of 478.8, 1436.4, and 1771.6 Pa over actuation percentages ranging from 10-90% for the Worm test assembly, and dynamic pressures of 440.5, 785.2, and Pa over actuation percentages ranging from 10-70% for the Dino. For calculations of drag coefficients ($C_D$), Eq. 9 was used. The area of the front plate ($0.0143 m^2$) was taken as the reference area for the Worm, and an area of 0.0434 m$^2$ was used for the Dino. Error bars associated with the load cell uncertainty of ±0.1 N were too small to be visible in plots and were therefore neglected.

It is clear to see in Fig. 12 that as actuation approaches 100% and the front plate of the Worm becomes perpendicular to the free-stream flow, the Worm $C_D$ calculated for $q = 1436.4$ and 1771.6 Pa approach that of a flat plate ($C_D \approx 1.2$). This result provides confidence in the validity of the results
at these dynamic pressures. It is also clear that the Worm $C_D$ at low actuation percentages represents a stark departure from the overall trend. The cause of this was due to the flexible joints being too large, impeding the initial actuation as described earlier.

For the Dino, it can be seen that both the drag force and $C_D$ trends transition from concave up to concave down at some intermediate actuation percentage. This phenomenon is likely caused by the folding procedure of the Dino. Early on in the folding process, the inner fan transitions from being stowed to fully extended. This accounts for the transition between the initially steeper increase in drag while the fan is being deployed, to a shallower increase once it has already been deployed. This is supported by the surface area trend modeled by Eq. 8, where it can be seen that the rate of change of surface area decreases at higher angles of attack, resulting in lower increases in drag generation. It is also interesting to note that the Dino $C_D$ for the highest dynamic pressure of 991.1 Pa is actually lower than that for 440.5 Pa. There are two possible explanations for this result. First, as the drag coefficient is proportional to $(D/q)$, it is likely the case that drag is increasing at a diminishing rate in proportion to $q$. This phenomenon is observed in the wind tunnel results for many different rigid bodies. Second, it is also likely that strong wind perturbations were generated off the bow of the test apparatus that had more deleterious effects at increased wind speeds. Additionally, the Dino produced 21.8 N of drag at 70% actuation and 440.5 Pa dynamic pressure, which represented a 20.6% difference from the 26.8 N value predicted by CFD. The reduced experimental value is likely due to friction in the test apparatus rails and interference from the bow of the apparatus. Because the CFD results were intended mainly for determining the drag to be input into FEA simulations, further comparison between CFD and wind tunnel values is neglected.

6.3. Control Response Testing

After sweeps had been performed, the bang-bang and proportional control laws were tested at dynamic pressures of $q = 718.2, 1436.4, \text{ and } 1915.2 \text{ Pa targeting drags of } 9.81, 19.6, \text{ and } 35.3 \text{ N for the Worm.}$ The controller responses can be seen in Fig. 13, where the red dashed lines represent the target drag for each run. The bang-bang and proportional control laws were tested on the Dino at dynamic pressures of $q = 440.7, 783.4, \text{ and } 991.5 \text{ Pa targeting drag forces of } 14.7, 24.5, \text{ and } 29.4 \text{ N, respectively.}$ The results can be seen in Fig. 14. It is worth noting that the target drags were varied case-by-case in order to place each targeted drag value towards the mid-range of actuation length at each run to avoid over-extending the actuator.

From Fig. 13 and Fig. 14, it can be seen that the bang-bang control law resulted in large oscillations of drag force, which often did not reach a steady-state value over the timescale of the test. Oddly, this behavior was most pronounced for the Worm, at the middle dynamic pressure, $q = 1436.4 \text{ Pa.}$
It should be noted that the bang-bang oscillations were not originally predicted by simulation, and after close inspection of the controller command data it was hypothesized that a combination of signal, actuation, and sensor delay may exist in the control loop. After introducing a delay of 0.8 seconds into the simulation model, the oscillatory behavior was recreated. This provides strong evidence to the existence of this delay in the physical system. Hence, the lack of convergence at 1436 Pa is believed to be caused by aerodynamic loading slowing the actuation speed of the servo to a response rate that corresponds to the predicted 0.8 second delay. It was also observed in subsequent tests that there was little agreement between separate runs at the same conditions, suggesting that the bang-bang control response is susceptible to small changes in flow conditions. For these reasons, the bang-bang control law is considered ill suited for this application and is not recommended in future work.

The proportional control response behaved as predicted by simulation. As seen in Fig. 13 and Fig. 14, the proportional controller produced little to no overshoot, indicating an over-damped control response which converged in all experiments. Near critically damped behavior was originally desired in the control response, but low actuation speeds limited the rise time and required the response to remain in an over-damped regime. It can also be seen that proportional control effectively rejected the signal delay that caused the "bang-bang" to oscillate. Finally, it is interesting to note the proportional controller also exhibited effective rejection of large amounts of load measurement fluctuations caused by vibration. Because of these disturbance rejection properties, a proportional controller should be adequate for future tests.

7. Conclusion

Two origami aerodynamic control surfaces, Worm and Dino, successfully demonstrated the feasibility of constructing deployable drag surfaces with composite origami. "Worm" successfully functioned as a minimum viable product concept and paved the way for the more complex "Dino", which more effectively leveraged the use of origami in the drag surface design. After completing the manufacturing of the Worm prototype and performing wind tunnel testing, a thickness of six plies was found to provide sufficient stiffness. Higher fidelity finite element models informed with CFD results of the Worm and Dino geometries were created, which yielded reasonable deflections similar to those observed during preliminary tests.

Additionally, it was found that initial designs for the joints left far too much space between panels, leading to a decrease in overall structural rigidity. Subsequent Worm and Dino models were constructed with smaller joints of 3 mm to alleviate this problem, and wind tunnel testing exhibited that flutter
in the joints was not an issue. It was determined that future origami designs could likely incorporate even tighter joint spacing.

The testing apparatus passed structural integrity tests in the wind tunnel up to wind speeds of 120 mph, exhibiting only minimal vibrations and deflections. Additionally, the Worm and Dino geometries were found to fold correctly past initial actuation percentages with only a single actuator, even at high wind speeds. These results provide confidence in the feasibility of applying origami composites as aerodynamic control surfaces in real-world applications.

Wind tunnel controller tests exhibited that proportional control converged accurately towards reference drag values, while the bang-bang control exhibited large oscillations and often did not converge towards a solution in given time. The lack of a steady-state response for the bang-bang control law was hypothesized to be due to a combination of signal, sensor, and actuator delay, which was supported by simulations. It was determined that the proportional controller’s disturbance rejection characteristics were adequate for use in experiments moving forward. Regardless, the use of a linear actuator with faster response times to cut down on actuator delay is strongly recommended in future designs. Upon incorporation of this improvement, the Aerogami frameworks developed in this paper could represent first prototypes for an improvement on control surface designs for aeronautical or terrestrial vehicle applications.

Acknowledgments

The authors would like to express their deep gratitude to the William E. Boeing Department of Aeronautics and Astronautics at the University of Washington (UW-AA) for providing its facilities and resources for the wind tunnel testing. We would also like to thank Prof. James C. Hermanson at the UW-AA for his advice and the insightful discussions on the project.
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Figure 1: Worm retracted/extended

Figure 2: Dino deployment stages

Figure 3: Geometry used in derivation of $X(\alpha)$
Figure 4: Plot of the angle of attack as a function of the linear displacement for increasing values of $\psi$.

Figure 5: The edges of the fan on Dino represented geometrically as vectors $\mathbf{w}_1$ and $\mathbf{w}_2$. 

Figure 5: The edges of the fan on Dino represented geometrically as vectors $\mathbf{w}_1$ and $\mathbf{w}_2$. 

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Figure 6: Area difference between the Worm and Dino as a function of the Actuator Displacement.

Figure 7: Left: Frontal view of the velocity streamlines for Worm at full actuation and a freestream velocity of 26.8 m/s. Right: Velocity streamlines for Dino at full actuation with a freestream velocity of 26.8 m/s.
Figure 8: FEMAP finite element model showing the exaggerated (50x) deflections of Worm under maximum load. Maximum deflection was 0.341mm in the flow-wise direction.

Figure 9: Step by step manufacturing of the Worm panel using VBO approach. (a) A working surface is cleaned and release agent is applied. (b) The first layer of the facets is laid down. (c) The dry fiberglass sheet is deposited. (d) The urethane epoxy is manually spread over the fiberglass. (e) The top layer of facets is laid down. (f) The teflon or peelply is laid on top of the specimen and the vacuum bag is pushed down. (g) The specimen is let curing overnight.
Figure 10: The worm (left) and the Dino (right) assembly in the 3' x 3' wind tunnel.

Figure 11: CAD drawing and rendering of the Dino assembly as reference. 1) Dino origami sits on a rail allowing for motion along flow direction, 2) wind shield cover protects linear actuator, Arduino, and load sensor, 3) assembly bolted to wind tunnel floor. On the bottom right a detailed view of the L16R Miniature Linear Servo system.
Figure 12: Measured drag and drag coefficients at different dynamic pressures and actuation percentages for the Worm and Dino.

Figure 13: Bang-bang and proportional control law responses for the Worm at dynamic pressures of 718.2, 1436.4, and 1915.2 Pa targeting drag values of 9.81, 19.62, and 35.32 N, respectively. Targets are shown by dashed lines.
Figure 14: Bang-bang and proportional control law responses for the Dino at dynamic pressures of 440.7, 783.4, and 991.5 Pa targeting drag values of 14.72, 24.53, and 29.43 N, respectively. Targets are shown by dashed lines.