Biologically-Inspired Technologies in NASA's Morphing Project

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ABSTRACT

For centuries, biology has provided fertile ground for hypothesis, discovery, and inspiration. Time-tested methods used in nature are being used as a basis for several research studies conducted at the NASA Langley Research Center as a part of Morphing Project, which develops and assesses breakthrough vehicle technologies. These studies range from low drag airfoil design guided by marine and avian morphologies to soaring techniques inspired by birds and the study of small flexible wing vehicles. Biology often suggests unconventional yet effective approaches such as non-planar wings, dynamic soaring, exploiting aeroelastic effects, collaborative control, flapping, and fibrous active materials. These approaches and other novel technologies for future flight vehicles are being studied in NASA's Morphing Project. This paper will discuss recent findings in the aeronautics-based, biologically-inspired research in the project.

Keywords: Biomimetics, biological-inspiration, non-planar airfoils, micro air vehicles, autonomous control, collaborative control, dynamic soaring, nanotechnology, morphing

1. INTRODUCTION

Nature provides many examples of systems with multi-functional components integrated into an efficient and often elegant design. These natural systems are optimized against a set of requirements that may be very different from engineering needs; so direct imitation is not always appropriate. However, much can be learned from studying nature and applying lessons learned to solve common engineering problems. There is a substantial legacy of interesting and successful engineering solutions that were inspired by biology. The widely used reversible adhesive Velcro was developed after noting how plant burrs attach to fur. Numerous advances in novel materials continue to be enabled by studying the exceptional characteristics of membranes, skins, and tissues found in nature. Flight would, undoubtedly, have been considered impossible without the precedent set by the millions of animals that capture flight. Though exact bio-mimicry is often impossible and, at times, technically inappropriate, the field of biomimetics focuses on learning from nature and continues to afford many unique engineering solutions. Biomimetics is an engineering tool that encompasses the abstraction of good design from nature.

Certainly the application of biological learning in aeronautics is far from new. Stephen Dalton notes in his book: "When Wilbur and Orville Wright were studying the principles of flight, they had frequently returned to the bird to check their theories. 'Learning the secret of flight from a bird,' wrote Orville, 'was a good deal like learning the secret of magic from a magician. After you once know the trick and know what to look for, you see things that you did not notice when you did not know exactly what to look for.' By observing the flight of birds, man had eventually found the secret that opened a new era in the history of the world."[1] As was discovered over a century ago, studying nature can lead to a novel approach as well as provide somewhat of a verification for an unconventional technique or methodology. For example, though the development of engineered composite structures was not directly based upon biological inspiration, the ubiquitous and effective use of natural composites suggests that this approach is not unfounded and that there is fertile ground for new developments.

Scaling differences between biological systems and engineered systems require careful consideration. While flying creatures are substantially smaller than the average airplane, the analogies between engineered flight and natural flight suggest that there are still novel insights to be gained from studying nature. These include: tip vortex control via winglets or tip feathers; turbulent drag reduction via riblets or tiny grooves in shark skin; high lift via multi-element

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airfoils or alula; and, separation control via micro vortex generators or a leading edge comb. In reference 2, Anders summarizes several other biomimetic fluidic and aerodynamic approaches.

Recently, there has been increased interest in biology and its application to many technical fields. This is partially due to significant advances in several technical areas including computer and electrical engineering (especially miniaturization and speed), material science (especially non-monolithic and active materials) and bio- and nano-technology. At present, many efforts in biologically-inspired research are underway in universities, industries, and government laboratories. NASA's research in biomimetics includes a variety of topics including human space flight, unmanned space exploration, satellites, and aircraft. This paper will overview NASA's research in biomimetics as it applies to aircraft.

2. BACKGROUND

The research described herein is part of NASA's Morphing Project, which includes fundamental research in smart materials, adaptive structures, micro flow control, optimization and controls.[3,4,5] The project, led from the NASA Langley Research Center (LaRC), is part of the Breakthrough Vehicle Technologies Project, Vehicle Systems Program. The objectives are to develop and assess advanced technologies and integrated component concepts to enable efficient, multi-point adaptability in air and space vehicles. While there is no formal definition for the word "morphing," it is usually considered to mean significant shape change or transfiguration. In the context of NASA's research on future flight vehicles in the Morphing Project *morphing* is defined as: *efficient, multi-point adaptability* and may include very small or large vehicle changes and structural and/or fluidic approaches. In defining "morphing" in this manner, *efficient* denotes mechanically simpler, lighter weight, and/or more energy efficient than conventional systems; *multi-point* denotes accommodating diverse (and sometimes contradictory) mission scenarios; and *adaptability* denotes extensive versatility and resilience to varying conditions or problems. The project strategically incorporates both micro fluidic and small and large-scale structural shape change to address the intertwined functions of flight vehicle aerodynamics, structures and controls. An inter-disciplinary approach provides an opportunity to seek new innovations that may only be possible at the intersection of disciplines. Adding biology to the mix of disciplines further enhances the opportunity for creative technical approaches. The project research is directed towards long-term, high-risk, high-payoff technologies, many of which are considered to be "disruptive" technologies such as biologically-inspired approaches.

The goal of the biologically-inspired research in the Morphing Project is to apply knowledge and lessons learned from the life sciences to enable radical improvements in the integrated aerodynamic, structural, and control characteristics of aircraft. A small, multi-disciplinary team at NASA Langley Research Center was assembled in 2000 to identify potential research breakthroughs offered by learning from (not mimicking) biological systems. Reference 6 summarizes the findings of this effort. From this study, several research efforts in different technical disciplines were initiated in the Morphing Project in 2001. These research efforts include concepts for drag reduction, increased range and endurance, autonomous and collaborative control, enhanced stability and agility, and lightweight material adaptation.

Many of the research topics under study have broad application in aerospace while some are more likely to apply to certain classes of aerospace systems, vehicles, and/or components. The fundamental nature of the current research make it difficult and sometimes impossible to quantitatively predict the benefits that may be realized a priori. The approach being taken is to continually assess the potential benefits and applications of the technologies and seek opportunities for exploiting them. For example, many of the technologies under study have potential application to unmanned air vehicles (or UAVs). UAVs may benefit from biologically-inspired technologies and have a broad range of potential civilian applications (e.g., weather and atmospheric sensing; telecommunications; border patrol; drug interdiction; fisheries patrol; utilities monitoring; coastal surveillance; corporate and civilian security; ground traffic information and control; airborne pollution sensing; remote planetary exploration; search and rescue operations; agriculture; and package delivery). Very small unmanned flight vehicles, micro UAVs (or MAVs), operate on a scale (size and speed) very similar to many natural fliers (birds, bats, and insects) and are more likely to directly benefit from biological inspiration. MAVs may be an inexpensive and expendable platform for short range surveillance and data collection in situations where larger vehicles are not practical. It is important to note that though many of the current research efforts are focused on flight at biological scales, there is significant potential for the insights gained from this research to be applicable to larger, piloted aircraft, systems, and/or components. In addition, development of methods and tools associated with biologically-inspired research are very likely to have application across a broad range of aerospace problems.

The next several sections of this paper will summarize five research areas in NASA's Morphing Project where biology is used as a guide in developing innovative technologies for future air vehicles. As mentioned earlier, the focus of these efforts is to learn from (not mimic) biology and to blend insights gained from the life sciences with our knowledge of traditional aerospace disciplines to seek new solutions. The first two areas discussed, the Hyper-Elliptic Cambered Span study and the Airmass Guidance study, have long-term objectives to improve range and endurance of UAVs for applications such as surveillance, communications, and atmospheric measurement applications. The next two areas discussed, the Autonomous and Collaborative Control study and the Flapping Flight study, are focused on MAVs. With these vehicles, drag and efficiency issues are less dominant, thus the research focus is more on miniaturization, controllability and maneuverability. The Biologically-Inspired Materials study is focused toward lightweight, adaptive material systems for small and large vehicles.

3. REDUCED DRAG WINGS FOR EXTENDED RANGE: THE HYPER-ELLIPTIC CAMBERED SPAN STUDY

The Hyper-Elliptic Cambered Span (HECS) study began as an effort concentrating on biologically-inspired wing configurations that may provide a reduction in induced drag.[2,6] Induced drag accounts for as much as 50 percent of the drag on an aircraft in a cruise configuration. Sometimes called drag-due-to-lift, it can be described as lifting energy lost at the wing tips in the form of large counter-rotating vortices. Natural systems have a continued dependency on efficiency and thus exhibit a variety of unique morphologies believed to reduce induced drag effects. These morphologies are particularly relevant in predatory animals such as sharks, dolphins, and large soaring birds. Many marine animals swim at Reynolds numbers similar to flight vehicles and have features, such as dorsal fins and tails, which exhibit less articulation than a bird's wings. These characteristics potentially make them a good basis from which to design low drag airfoils.

In 1923, Munk used lifting line theory to show that for a planar wing, an elliptic lift distribution produced the minimum induced drag.[7] Since then, all other wing configurations have had their performance gauged against this standard. Observations of avian and marine creatures, however, suggest that a planar wing configuration may not be optimal. Many diurnal birds of prey such as hawks, eagles, and osprey are noted to soar with their tip feathers splayed and progressively canted such as shown in Figure 1. In a study of flying buzzards, Raspet[8] speculated that the splayed tip feathers are used as diffusers to either control the flow beyond the tips or extract energy from the tip vortex. He also noted that during gliding flight, where speeds are much higher, the tip slots are closed, suspecting that in this flight regime reduction of parasitic drag is the goal. Similar tip configurations have been studied for mechanical flight systems. Spillman presents a historical review of a decade worth of work on this topic in reference 9. His presentation of wing tip sail performance verified the previous speculation of Raspet, indicating that the benefits are Reynolds number dependent. At low Reynolds numbers the sails provide improvements in efficiency, but at higher Reynolds numbers skin friction becomes dominant and reduces their benefit.

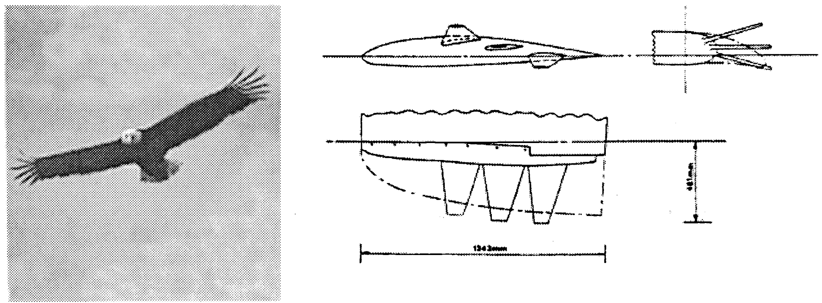

Figure 1: (a) Splayed tip feathers of an eagle in soaring flight, (b) Mechanical implementation of a split tip wing design (from Spillman: 1987).

Other out-of-plane wing configurations have been suggested and tested using theoretical or computational methods. Cone analyzed a variety of wing tip configurations using linear theory, noting that to improve wing efficiency it is necessary to either spread or attenuate the shed vorticity.[10] Many of the tip modifications investigated, however, significantly increase the wing wetted area and it is suspected that at reasonably high Reynolds numbers profile drag will dominate. Kroo and Smith took a novel approach to induced drag reduction by using a genetic algorithm to identify a wing of fixed lift, span, and height with minimum drag. [11] The result is what the authors call a "C-wing" and it yields a predicted efficiency of 1.464, a nearly 50 percent improvement over a planar elliptic wing.

In the late 1980's significant interest developed around planar crescent shaped wings, primarily initiated as a result of a study by van Dam.[12] Considering the wing shape of some of the fastest birds and the caudal fin shape of the faster fish, van Dam used a potential code to evaluate efficiency characteristics of an elliptically-loaded crescent shaped wing. His initial findings indicated an efficiency improvement over a classical elliptic shape of nearly 9 percent. Burkett points out that the observed benefit may be due to wake non-planarities materializing as angle of attack is increased.[13]

The ideas of Cone and Burkett are put to use in the current study in the design of the Hyper-Elliptic Cambered Span (HECS) wing. This wing was configured such that at any angle-of-attack the wake would be hyper-elliptic in shape. Burkett notes that, depending on camber factor, this shape can theoretically lower the induced drag factor by as much as 30 percent. Along with this wing, two other configurations were wind-tunnel tested that leaned more heavily on biologic inspiration. One of these wings was highly swept and took its inspiration from the caudal and dorsal fins of fast swimming sharks. The other directly mimicked a seagull's wing. All three new designs were tested against a planar elliptic wing with a straight trailing edge. The aspect ratio was seven for all wings and the planform area was kept constant so that direct comparisons of wing performance could be made. Lift and drag data were acquired using a drag balance at a Reynolds number of 3.6 million per meter.

Figure 2 shows a plot of the test results from the Basic Aerodynamics Research Tunnel(BART) at NASA LaRC. This plot shows a steep rise and gradual drop in lift-to-drag for each of the wings as the lift coefficient increased. Smooth and repeatable curves are apparent for all configurations except the shark wing. For this particular wing, the data was repeatable but definitely not smooth, suggesting that the flow physics of the wake was changing erratically as angle-of-attack was increased. Figure 2 also shows that the HECS wing and the shark wing outperformed the baseline elliptic wing with improvements in the HECS wing exceeding 15 percent at the higher angles-of-attack.

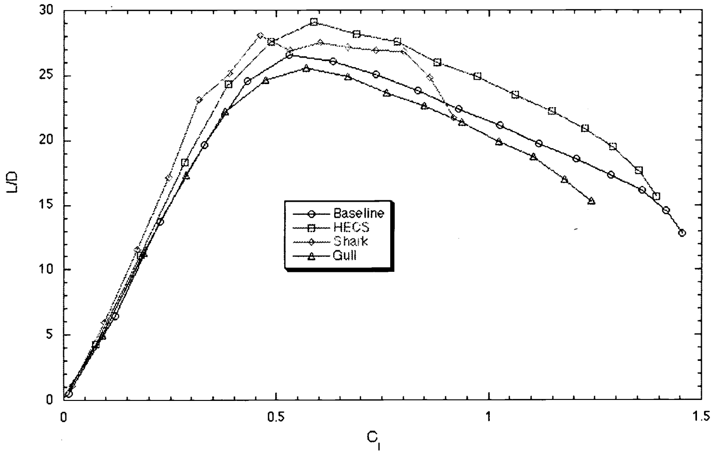

Figure 2: Performance characteristics of four biologically inspired wing configurations tested in Langley's BART tunnel.

While the HECS wing configuration shows promise, there is room for improvement. Along with a significant decrease in induced drag, there is also a decrease in lift. Two approaches are being taken to improve the wing's performance. The first is a physics-based approach aimed at gaining a detailed understanding of the flow phenomena. Both the HECS and baseline semi-span models will be wind-tunnel tested again with more instrumentation including approximately 150 pressure taps. Additionally, various slightly modified versions of the HECS configuration will be tested to gain insight into potential areas for further improvement.

The HECS wing shape lends itself to other aircraft improvements beyond drag reduction. With only minor in-flight wing tip adjustments, yaw, pitch and roll control can be accomplished. This may eliminate the need for a conventional tail and result in further drag savings. Recently, an integrated multidisciplinary team was assembled to examine the other unique aspects of the HECS design. This effort encompasses investigating the feasibility of using such shape changes for aircraft maneuvering. Stability and control analysis of such a vehicle is complex since maneuvers would be accomplished through continuous wing morphing rather than discontinuous adjustments to discrete control surfaces, as is conventionally done. Other issues that will be addressed are the mechanics of an internal structure and the design of an external skin. The challenges here are to determine a feasible internal mechanism that will produce the appropriate shape changes and a skin that will withstand the external aerodynamic loads and still provide flexure. In the advent of successful answers to these and other questions, proof of concept flights, using an existing UAV centerbody, are planned. Initial design work has begun on this configuration shown in Figure 3.

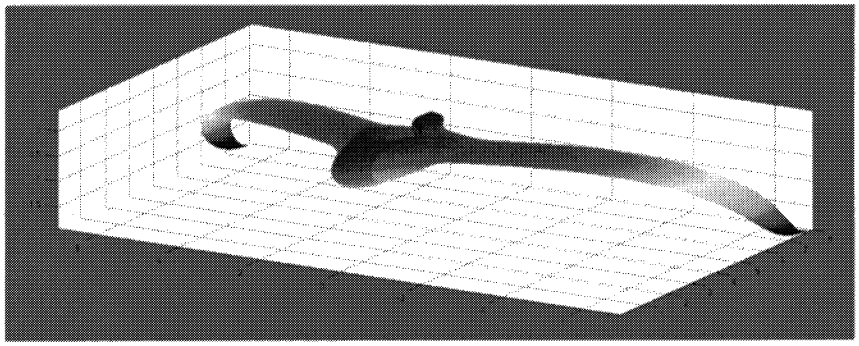

Figure 3: Concept configuration using the HECS wing with a tailless UAV centerbody. Model coloration is for presentation purposes only.

4. DYNAMIC SOARING FOR EXTENDED RANGE: THE AIRMASS GUIDANCE STUDY

A second effort related to improving the range and endurance of UAVs is the Airmass Guidance study. This research effort explores the potential to increase range and endurance by maneuvering a vehicle about a planed flight path, or in the neighborhood of a fixed waypoint, in such a way as to extract energy from the ambient atmospheric velocity field. The most direct approach is to circle in well-defined thermals. These rising columns of air can be strong enough to overcome drag losses and increase a vehicle's altitude. Another approach, called dynamic soaring,[14] involves only a vertical gradient in a horizontal wind field. Gradient conditions commonly occur on the lee side of a hill or very near the surface over flat areas. Nature's use of these effects can be seen in the soaring flight of large birds. The wandering Albatross lives for days at a time over the open ocean, and does much of this just gliding without propulsion from flapping. Ground effects from the ocean's surface give rise to a consistent vertical wind gradient. By flying a spiral path, the Albatross is able to gain energy during a downwind segment at altitude, then return upwind near the ocean's surface where the headwind is less strong.

The first step towards the goal of extending range using dynamic soaring was the development of an aircraft model with appropriate consideration of the effects of winds aloft. In typical powered flight, speeds of the vehicle are much larger than the ambient wind field. Thus, wind field can be described as perturbation effects on a consistent headwind. However, for the case of efficient soaring flight, the vehicle's speed is comparable to the ambient winds, thus wind effects must be considered directly. This involves the introduction of a wind relative coordinate system in addition to inertial coordinates and a body-fixed coordinates. Differential equations involving angle-of-attack, for example, should describe the body relative to an inertial frame, however, look-up tables of aerodynamic performance with respect to angle-of-attack must be body relative to the local wind frame. Dynamic aircraft models incorporating the additional wind-relative frame of reference have been developed and tested in simulated wind fields, as shown in Figure 4(a). In this figure the effect of a steady crosswind and the effect of a crosswind that decreases with altitude are shown on a vehicle with a circular constant velocity flight path. The trajectories show the vehicle being carried downwind, and also show an increase in altitude loss as the vehicle, with fixed inertial speed, fails to maintain optimum speed relative to the airmass.

These simulation models are also in a form suitable for trajectory optimization. Trajectory optimization allows one to find a flight path that is consistent with the vehicle's dynamics and minimizes energy loss. Figure 4(b) shows a typical result for a set of optimal trajectories in a vertical wind field. The starting and end point locations are prescribed in the horizontal plane, and flight path angles are constrained to be periodic at the boundaries. As the strength of the gradient increases, the flight path tends more towards dynamic soaring with more aggressive cycling into and with the wind. These dynamic soaring trajectories, despite a longer flight path, finish with higher altitude and energy than the optimal paths for the lighter wind-gradient cases.

Although these results are encouraging, the optimal solutions may not be achievable in practice because information about the ambient wind field is currently very limited. More work is needed to determine a guidance heuristic that will approximate the optimal solutions given the limited atmospheric information currently available on board the vehicle. These guidance heuristics must then to be evaluated over a range of atmospheric conditions to determine if the sub-optimal solutions provide adequate benefits.

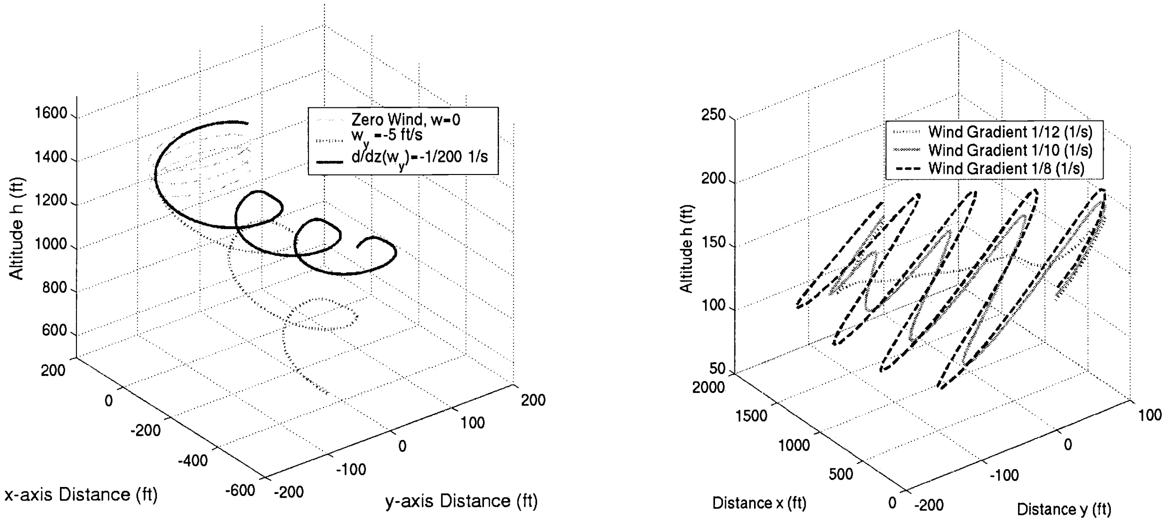

Figure 4: (a) Open-loop trajectory of glider model under various wind conditions, and (b) Optimal glider trajectory for different strength wind gradients.

5. IMPROVED AERIAL OBSERVATION USING MULTIPLE MAVS: AN AUTONOMOUS AND COLLABORATIVE CONTROL STUDY

Many potential uses of UAV's (and MAV's in particular) could benefit from cooperative and collaborative control capabilities so that large numbers of vehicles could be used to cover a large operational area. In a research effort to develop, implement, and test autonomous and collaborative control schemes, the flight dynamics of an adaptive, membrane wing MAV are being investigated. [15,16] The vehicle concept was developed at the University of Florida (see **Figure 5**) and the current research is a cooperative effort between the University of Florida team and NASA. The University of Florida team has continued to refine the vehicle design and develop related systems and components including electric power, vision-based control, and analysis and design methods.[17]. As such, the University of Florida MAV (UF-MAV) has enabled research on several fronts: development of "micro" vehicle technologies and components, innovative aeroelastic concepts, specialized test techniques, and autonomous/collaborative control. The successful development of the vehicle itself could serve as the basis for a low cost, scalable autonomous / collaborative flight control laboratory.

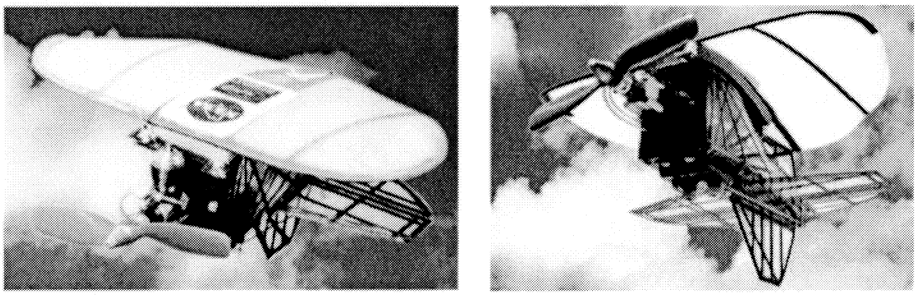

Figure 5: Top and bottom view of 6-inch span, flexible wing University of Florida Micro Aerial Vehicle.

The UF-MAV has the ability to adapt to atmospheric disturbances via a passive adaptive washout mechanism. Wind tunnel experiments were conducted in the NASA Langley BART facility to identify the way in which the deformation of the membrane wing relates to the aerodynamic forces and moments produced by the vehicle. Data collected during these experiments also provided a basis upon which to develop a dynamic simulation of the vehicle in flight and assess the vehicle's stability and control characteristics. This knowledge will support the development of control system architectures for autonomous control of each vehicle and autonomous collaborative control of collections of vehicles.

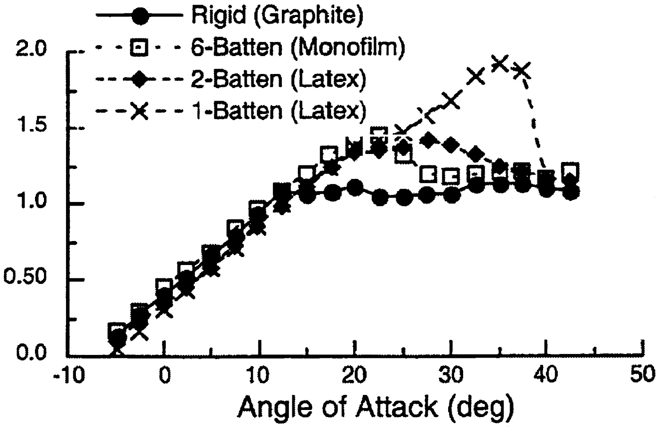

Figure 6: Lift Curves for 6-inch span Micro UAV with various levels of flexibility.

A goal of wind-tunnel testing was to quantify and explain the benefit of using flexible wings already observed in practice. Flight test experiments conducted by University of Florida researchers concluded that flexible wing vehicles had better handling qualities and these vehicles, though not easy to fly, did not require active on-board stability augmentation systems even at the small scale of a 6-in wingspan. This was believed to be partially due to an adaptive washout characteristic that allows the flexible wing to deflect under load. Wind tunnel tests showed that the membrane wing resists stall at high angles of attack[18]. The results for a series of wings with identical geometry and of increasing flexibility is shown in Figure 6. Although all of the wings perform similarly at low angles of attack, the more flexible versions resist stall at much higher angles of attack. This increased range of linear lift-curve behavior may contribute to making the vehicle less susceptible to upset in turbulent wind conditions and improve its inherent stability characteristics.

Stability and control derivatives were obtained from the wind-tunnel data to create an aerodynamic database describing the variations in aerodynamic forces and moments as functions of the control surface positions, throttle setting, angle of attack, sideslip angle, and airspeed. The aerodynamic database and the rigid body aircraft equations of motion were used to produce a six-degree-of-freedom flight simulation of the UF-MAV. The simulation is implemented in Matlab/Simulink™ using a modular structure amenable to future improvements and enhancements.

The simulation model of the UF-MAV was used to perform a number of analyses to assess the stability and control properties of the vehicle. A summary of the modal frequency and damping values for the longitudinal and lateral-direction modes of the vehicle are shown in Tables 1 and 2. These modal parameters are very similar to classical airplanes in form but not in value. The longitudinal modes have the classical phugoid / short period form and the lateral-directional modes have the classical roll / spiral / dutch roll form. Note that the short period mode is stable and lightly damped for all dynamic pressures while the phugoid mode becomes unstable (i.e., negatively damped) at higher speed. The spiral, roll, and dutch roll modes are all stable though the dutch roll mode is very lightly damped. However, the frequencies of the short period and dutch roll modes time constants are roughly ten times faster than a typical piloted aircraft. These results provide a basis upon which feedback control can be developed to greatly improve the flying qualities of the UF-MAV.

Table 1: Longitudinal modes

Dynamic Pressure (psf)	Short Period Mode		Phugoid Mode	
	damping ratio	freq. (rad/sec)	damping ratio	freq. (rad/sec)
1.0	0.13	23.3	0.44	0.85
1.6	0.12	30.2	0.35	0.65
2.0	0.12	32.6	-0.56	0.67

Table 2: Lateral-directional modes.

Dynamic Pressure (psf)	Spiral Mode	Roll Mode	Dutch Roll Mode	
	eigenvalue	eigenvalue	damping ratio	freq. (rad/sec)
1.0	-1.04	-27.7	0.094	21.1
1.6	-1.04	-37.3	0.065	24.2
2.0	-1.02	-42.8	0.050	25.9

A preliminary guidance/control system has been developed to enable investigations of autonomous and collaborative control issues. The controller is composed of two main parts: an inner-loop measurement-based nonlinear dynamic inversion controller for control of angular rates and an outer-loop navigation command follower for control of wind-axis angles. The measurement-based nonlinear dynamic inversion approach uses acceleration measurements in lieu of a complete on-board vehicle model. This approach is less sensitive to vehicle model errors and can adapt to changes in vehicle response characteristics. The method was extended to accommodate application to systems with fewer controls than controlled variables as is the case for the UF-MAV. The guidance loop was designed to allow the simulation model to be integrated into an existing biologically-inspired multiple vehicle collaborative framework. Preliminary results indicate that this is a viable approach for control of MAV's and similar systems. Future efforts will focus on the use of this method as part of a multiple vehicle collaborative control scheme based on swarming.

Future studies will also emphasize efforts to develop additional understanding of the physical properties of the membrane wing concept and use this understanding to improve the design of the vehicle and pursue other aerospace applications. In particular, the membrane wing is being used to apply and assess multidisciplinary design optimization methods for nonlinear aero-structure interaction.

6. ENHANCED AGILITY FOR MAVS: THE FLAPPING FLIGHT STUDY

Although the flexible wing MAV and a number of other designs are quite capable, they do not possess the flight agility and versatility that would enable missions such as rapid flight beneath a forest canopy or within the confines of a building. To satisfy such mission requirements, it is likely that some MAV designs of the future may exploit flapping flight for extreme agility. Many flying insects generate lift through resonant excitation of an aeroelastically tailored structure: muscle tissue is used to excite a structure which exhibits a particular mode shape that is tuned to generate propulsive lift. A number of MAV concepts have been proposed that would operate in a similar fashion.[19,20] A resonance-based flapping MAV design would challenge the current state-of-the-art in flight control for vehicles with highly transient flight-dynamic characteristics.

Current research at NASA LaRC has focused on the development and operation of a biologically-inspired vibrating wing system that provides control over the resonant wingbeat pattern. Key parameters for excitation waveforms that produce various wingbeat patterns are currently under investigation. A comparison of wingtip trajectories produced by the vibratory testbed with those used by the hummingbird during various flight modes is shown in Figure 7. LEDs located at the tips of the wing were used to trace wingbeat patterns as the structures vibrated at flapping frequencies similar to hummingbirds in the same size range (25 Hz). The resulting wingtip trajectories appear as light traces in the testbed photographs presented in Figure 7, and are similar to the hummingbird wingtip patterns that are also shown in the figure. The factors that are approximately matched in Figure 7 include the stroke plane inclination to the body axis of the bird (or testbed), amplitude of the flapping arc, approximate geometry of the wingtip trajectory, and sense of rotation about that trajectory. Note that in forward flight, the wing travels clockwise about the trajectories shown in Figure 7, while in reverse flight the wing travels about the trajectory in a counter clockwise sense. Based on these results, it appears that the biologically inspired design of this apparatus has afforded us the desired control over the wingtip trajectory. Such control is a key element in enabling an ornithoptic MAV to maneuver with birdlike agility.

Future research will use the testbed to generate actuator force, throw and bandwidth requirements, and will produce calibration data for unsteady CFD codes. A hardware-in-the-loop flight dynamic simulation of an agile ornithoptic MAV is envisioned that will enable the development of flight control designs for such a vehicle. Consultation with researchers at the University of Texas in Austin is providing mechanization and actuation insights from insect and avian morphological perspectives.

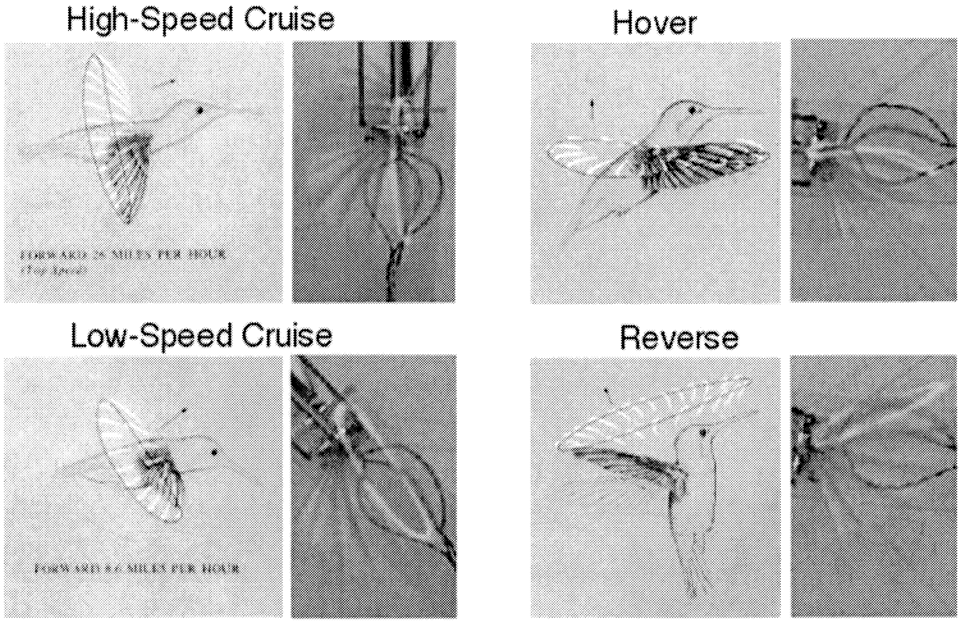

Figure 7 : Wingbeat patterns and wingtip trajectories for hummingbird flight compared with those produced by the biologically-inspired resonant flapping testbed.[21]

In addition to the experimental work in flapping flight, an effort is underway to provide analysis of these motions through Computation Fluid Dynamics (CFD) for 2D and 3D wings with prescribed flapping motion. For a systematic examination of flapping motion, a large set of parameters must be considered. The parameters include: reduced frequency, stroke plane angle, flapping amplitude, wing twist (pitch angle adjustment in 2D) in response to the instantaneous local inflow angle, variable camber of the wing section, and Reynolds number. The output of the CFD analysis includes the typical aerodynamic forces and moments and flight efficiency as measured by propulsion power versus energy input due to the flapping motion and the associated aerodynamic forces.

For this work the Reynolds averaged Navier-Stokes code, OVERFLOW, was used for the unsteady aerodynamic analysis. To accommodate the large motions required for flapping flight, a high precision moving grid algorithm was developed and integrated with the OVERFLOW code. In this moving grid algorithm, a body-fitted hexahedral structured grid is first constructed for the wing at rest. In this grid, the viscous boundary is fully represented. As the wing moves during the calculation, the grid motion algorithm would generate a new grid at every time step, which corresponds to the new wing position in space. The development of this grid motion algorithm represents a significant capability because the moving grid maintains a very high grid quality for the viscous calculation, and the input interface allows the investigator full control of all the flight parameters mentioned earlier in this article.

From the hundreds of cases of two-dimensional calculations, significant insight into the flow physics of the aerodynamics of a flapping wing was gained. For example, the required wing motion is different for take-off/acceleration versus cruise. Variable camber of the wing section was also found to significantly improve the flapping flight efficiency. As expected from the literature, Reynolds number has a profound effect on how a wing would fly effectively.

A limited number of three dimensional flapping wing simulations have been completed. Shown in Figure 8, is the pressure distribution of a "bat" wing on its upper and lower surfaces for a full flapping cycle. Classical good flow behavior is shown in the down stroke. However, flow separation and wing stall are evident in the upstroke half of the cycle.

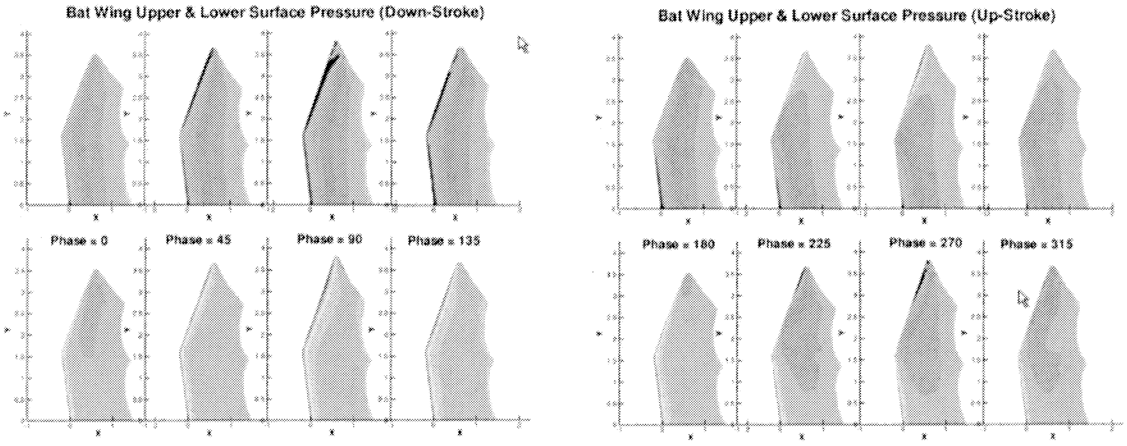

Figure 8: Pressure distribution on the upper and lower surfaces of a "bat" wing for a complete flapping cycle. (Blue indicates suction force on the wing)

This research effort has yielded an enabling technology in CFD analysis to support the development of flapping flight micro vehicles. The CFD tool is now ready for the systematic construction of an aerodynamic database. In addition to aerodynamic analysis per se, the authors envision that this comprehensive CFD analysis method can be linked to two interdisciplinary areas: nonlinear or adaptive control systems and aeroelasticity.

7. REDUCED STRUCTURAL WEIGHT, INCREASED STRUCTURAL ADAPTABILITY: THE BIOLOGICALLY-INSPIRED MATERIALS STUDY

The BIOlogically Inspired SmArt NanoTechnology (BIOSANT) research group is comprised of researchers involved in working at the interface of biomimetics and nanotechnology to develop materials with bioinspired characteristics. One area of research where substantial progress has been made, in response to the needs of the biologically-inspired studies mentioned above, is in the development of an electrically responsive MAV wing. BIOSANT investigators fabricated lightweight, electrostrictive fibers that can be used as a 'tendon' for 'coarse control' and an active wing skin that can be used for finer, dynamic control of the wing. This was accomplished by electrospinning, an approach similar to one being used by biomedical engineers to create scaffolds for tissue engineering.[22] Electrospinning was used to obtain a lightweight adaptive material composed of nanoscale electroactive fibers.

For the MAV application, a charged electrostrictive polymer solution was spun onto the small MAV airframe. The wing skin is a lightweight, fibrous mat with fiber diameters ranging from 200 – 400 nm. The tendon was made by twisting the electrospun fibers into a thicker fiber. Twisting the fiber affords some orientation of the fiber, yielding a material that was responsive to a 3KV sine wave (peak-to-peak) at about 2.8Hz. A weaker response was observed at a higher frequency for the spun MAV wing skin.[23] To improve membrane response to an applied electric field, the electrospinning equipment was modified to induce orientation in the spun fibers. Recently, it was demonstrated that higher degrees of orientation in the spun mats could be induced by replacing the stationary target with a rotating target. Greater orientation was achieved at higher rotation speeds.[24]

The materials development effort was recently expanded to include not just electrostrictive polymers, but piezoelectric polymers as well. The latter class of polymers are being studied because they are capable of both sensing and actuating. The dual functionality will be more desirable in a micro air vehicle wing where simulating the dynamic control of bird flight is being attempted. Figure 9 shows the initial electrospun mats and the second generation electrospun MAV wing.

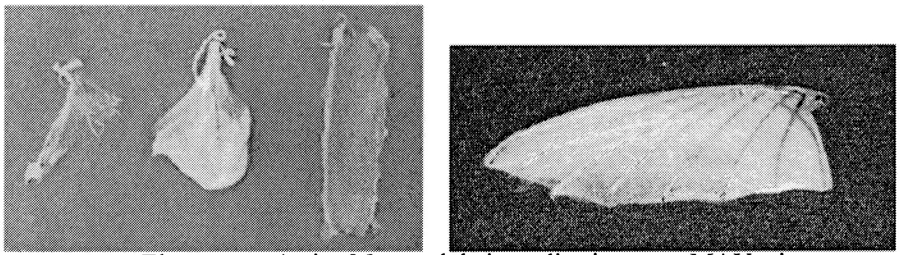

Figure 9: Electrospun Active Mats and their application to an MAV wing

8. FUTURE EFFORTS AND CONCLUDING REMARKS

There are several on-going and interrelated efforts within NASA's Morphing Project that use biology as a guide for research on future aerospace vehicles. From fundamental studies of biology and their application to flight vehicles, the authors hope to gain novel approaches to enabling significant improvements in the capabilities of future flight vehicles. These improvements include: 1) reducing fuel usage and environmental impact and increasing range and endurance via novel planform configurations, dynamic soaring techniques, and lightweight materials; 2) increasing aerial observation capabilities via autonomous and collaborative control; 3) improving stability and stall characteristics via aeroelastic exploitation; and 4) improving maneuverability and agility via flapping and adaptive materials. This research has already yielded many useful and exciting discoveries. Future efforts in the Morphing Project where biology will be used as a guide may incorporate developing lightweight, articulating structural concepts and conducting simple ground and flight experiments. These efforts continue to challenge traditional approaches to aerospace research by offering creative and innovative methodologies that may well unleash truly disruptive technological advancements.

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