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Application of electrolaminates for the development of biomimetic morphing unmanned aerial vehicles

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Abstract

Morphing aircraft offer the promise of performance that can be optimized for a range of flight profiles. But such capability places challenging demands on the morphing system that cannot easily be met with conventional actuators or smart materials. Electrolaminates use electrostatic forces controlled by the application of a voltage (typically high-voltage but extremely low-current) to controllably bond or unbond layers of a laminated composite structure together. Such on-demand bonding can be used to effectively change the stiffness of the structure or control elongation or twist of the structure. This technology has multiple benefits compared to other smart material or conventional actuator-driven approaches; it is thin and light, has very low energy requirements, and offers rapid response capabilities controlled by simple electronics. These capabilities can enable bio-inspired morphing with large numbers of degrees of freedom and high spatial resolution. We designed, fabricated, and tested a fully functional morphing-wing unmanned aerial vehicle (UAV) with telescoping wings and a splaying, bird-like tail enabled by electrolaminates. Key features of the current UAV configuration include: a variable wingspan of 1.2–2.4 m with a corresponding change in the wing area of nearly a factor of four; no vertical tail; and a horizontal tail area variable by a factor of three. The ability to asymmetrically control the tail area allows for independent pitch and body circulation control. The tail area is changed by a separate electrolaminate clamping mechanism. The variable-area tail uses 'feathers' that can be overlapped or splayed as needed. The practical shape-changing is enabled by electrolaminate materials that can rapidly lock the orientation of the feathers. The electrolaminate clutches support more than 5 nm of torque and are sufficient to resist expected flight loads. We also designed, fabricated, and tested other morphing-wing designs enabled by electrolaminate technology to create a wing with smoothly sliding skin that is capable of changing chord and camber with a single linear actuator. Our results suggest that electrolaminates can practically enable bio-inspired, small (Group 1 and 2) morphing UAVs.

Keywords

Biomimetic, electrolaminates, telescopic wings, morphing unmanned aerial vehicles, electrostatic clutch

Introduction

Motivation

Morphing aircraft—aircraft that change shape or state depending on the flight or threat conditions as birds and bats do—can approach optimal configurations for each specific segment of the flight or mission envelope. This capability contrasts with conventional designs in which the aircraft is optimal for only one specific flight condition and off-design conditions are compromised. Cruise conditions for commercial aircraft are by far the most common. Morphing aircraft designs would have particular benefit for military aircraft because any given mission may involve varying periods of time when the aircraft has to cruise, loiter, and dash or maneuver at high speed.

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The challenge in morphing is to ensure the costs—in terms of weight, complexity, and reliability—do not outweigh the benefits.

Biological systems can achieve large shape changes with a large number of degrees of freedom; this is partly a consequence of the integrated lift and thrust design of flapping wings. Large-scale aircraft are capable of shape changes with one or two degrees of freedom by controlling wing sweep or with modest changes in chord and camber. However, these approaches require substantial additional mass and complexity in the form of actuators, transmissions, and structure that maintains the strength and alignment of the wing elements. Such characteristics are challenging to include in small-scale UAVs even for a limited number of degrees of freedom, let alone mimicking the wide range of morphing capabilities of biological creatures.

Existing approaches to implement bio-inspired morphing structures often use "smart materials" such as piezoelectrics[1] or shape-memory alloys.[2] With few exceptions, these smart material approaches rely on the energy transduction properties of the actuation technology. That is, the change in stiffness or shape depends on the conversion of the applied work into electrical energy or vice versa. This limitation results in much smaller changes in stiffness or shape. Typically, the changes in stiffness are less than a factor of two. Ref. 3 detailed the limitations of conventional approaches to variable stiffness materials. Ref. 4 provided a comprehensive review of such methods based on smart materials and other approaches.

Some researchers have achieved large changes in stiffness of composite structures using heat-induced melting or softening of components within (e.g., Refs. 5 and 6 used a low-temperature melting metal embedded in an elastomeric matrix to create materials that could dramatically change stiffness when the metal component melts. The mechanism by which shape memory polymers work is similar to this approach, but at a molecular level.[7] Such methods are relatively slow, limited in the range of operating temperature material properties, and require large amounts of energy due to the need to heat a significant amount of material.

Novelty of electrolaminates

In contrast to the approaches highlighted above, we describe designs with electrolaminates, a new approach to layered composite materials and structures that use electrostatic clamping to control the sliding between layers of a laminated structure.[8] Controlling sliding allows for large changes in both stiffness and shape. In addition, the clamping action itself does not perform significant work and so the composite materials are not subject to the limitations of many smart material approaches. Table 1 summarizes the benefits of electrolaminates that are relevant to UAVs.

Electrolaminates do not self-actuate. They can only create shape changes if external forces operate on them. Normally, these changes would be effected based on manual control or algorithms that optimize performance parameters such as speed or range over a given flight profile. Under some circumstances, these forces can be imposed by the airflow during flying, such as automatic response to sudden gusts or the ability to use the energy of turbulence to effect actuation by carefully timing the clamping and release. But generally, a means of actuation must be included. While electrolaminates do not eliminate the need for additional actuation, a single actuator can be used to produce variations of shape control. The electrolaminates can unclamp only where shape change is desired, for example. Further, electrolaminates do not require complex transmissions or motion constraints since they can be part of the wing structure itself. A wide variety of actuators may be utilized including pneumatic or hydraulic actuators. An actuator that is particularly attractive for use on UAVs is a twisted-string actuator. These use a rotary input, such as from a small motor high-speed motor. In a manner similar to a tourniquet, the high-speed rotary motion shortens the string pair, and the motion is converted into low-speed, high-force linear motion.[9] Very little additional mass beyond that of the motor is needed.

While electrostatic clamping has found wide utility in materials-handling in the semiconductor industry, it (or any type of controllable clamping for that matter) has rarely been used at the interface to control stiffness, shape, or damping. Ref. 10 used electrostatic clamping between layers of a composite material for stiffness and damping modulation of civil engineering structures, and Diller et al.[11] used it to create a variable stiffness element that acted as a linear clutch for prosthetic and orthotic devices for the lower leg. In this application, as in UAVs, the fast action and light weight of the electrostatic mechanism was key. Aukes et al.[12] used electrolaminate rotary elements as clutches in the joints of fingers of an underactuated robotic hand. The clutches allowed a single cable drive to actuate any number of the three finger joints. The clutches also allowed the hand to lock into a desired shape. The ability to use only a few actuators to achieve a desired shape of a multi-degree-of-freedom structure is particularly important for UAVs as well.

Research on rotary electrostatic clutches [e.g., Refs. 13 and 14] is instructive for analysis and modeling of clamping forces because these clutch designs are similar to those using electrolaminates. However, the ability of the layers to conform to one another with the electrostatic clutches developed in this study has already allowed us to greatly

Table 1. Benefits of electrolaminates for UAVs.

Electrolaminate feature	UAV benefit
Low mass and power consumption	Provides longer range, more maneuverable
Wide range control of stiffness (at least two orders of magnitude)	Small forces needed for shape change, aeroelastic control
Simple structure with flat layers	Allows for both planform and profile control (as well as twist)
Robust – electrolaminate failure is not catastrophic (can snap back into place if unclamped)	Offers crash survivability and energy absorption for aeroelastic control
Temperature insensitivity	Allows operation over a very wide range of temperatures for aerospace applications
Fast response	Controls aeroelastic response and gust resilience

exceed the rotary clutch clamping forces reported in the literature.

Overview of paper

This paper discusses a new approach to enable bio-inspired morphing in UAVs based on electrolaminates—materials that can vary in stiffness and shape over a wide range.

First, we describe the basics of electrostatic clamping and electrolaminates. Next, we present a more detailed implementation of the use of electrolaminates for rotary clutches to control the positioning elements of a morphing tail that is inspired by the way birds control splaying of their tail feathers. Then, we describe how electrolaminates can be more fully exploited in UAVs with morphing wings and provide a discussion of areas for future research.

Background on electrolaminates

Electrolaminates are comprised of rigid elements (e.g., thin carbon fiber or polymer sheets, metals, or other structural materials) and compliant elements (e.g., elastomers, foams, or extensible truss-like structures). The connectivity between elements is controlled with electrostatic clamping. Electrostatic clamping is fast, energy efficient, and requires almost no added mass (generally only thin insulators and electrode coatings are needed). Although clamping does require electrical energy, no energy is needed for external mechanical work and therefore the energy cost is minimal. If an electrolaminate slips under a high load condition (i.e., during a crash) it can easily be reset by simply turning it off and removing the load. In fact, the slippage absorbs energy in the form of frictional heating. Thus, we believe a morphing UAV that utilizes electrolaminates for shape control will have inherent robustness.

When the electrolaminate is in the clamped condition, its stiffness approaches that of the rigid elements it is made of (not unlike conventional composites). In the completely unclamped condition, its stiffness is dominated by the compliant material element. Since both of these materials may be used in a given application, the range of stiffness can be large. Figure 1 shows how electrolaminates work.

The range of achievable stiffnesses with two configurations (linear and bending) may be understood using simple models assuming linear elasticity.

For the linear case, we consider EA to be a metric of linear rigidity, where E is the effective linear modulus of elasticity and A is the effective cross-sectional area. For laminates, in the unclamped (voltage off) state the effective value of EA is roughly

$$EA \approx E_{\text{elastic}} \left(A_{\text{rigid}} + A_{\text{elastic}} \right) \tag{1}$$

where the subscripts denote that the parameter is for the rigid or elastic materials.

In the clamped state, it is

$$EA \approx E_{\text{rigid}} \left(A_{\text{rigid}} + A_{\text{elastic}} \right) \tag{2}$$

Since the modulus of elasticity of the rigid material can be orders of magnitude greater than that of the elastic layer, we see that the effective stiffness of the linear electrolaminate can also vary by the same ratio between the stiffness of the rigid and elastic layers.

Similarly, for the bending electrolaminate, we use the flexural rigidity, EI, as the relevant metric, where I is the area moment of inertia of the beam about its bending axis. In the unclamped (voltage off) state, the flexural rigidity is roughly

$$EI \approx 2E_{\text{flex}} \frac{bh^3}{12} \tag{3}$$

where the subscript "flex" denotes the property of the flexible layer and b and h are the width and thickness of the flexible layer, respectively.

In the clamped state, it is

$$EI \approx 2E_{\text{flex}} \left[\frac{bh^3}{12} + \frac{bhd^2}{4} \right] \tag{4}$$

where the width and thickness of both the flexible and spacer layers are the same and d denotes the thickness of the

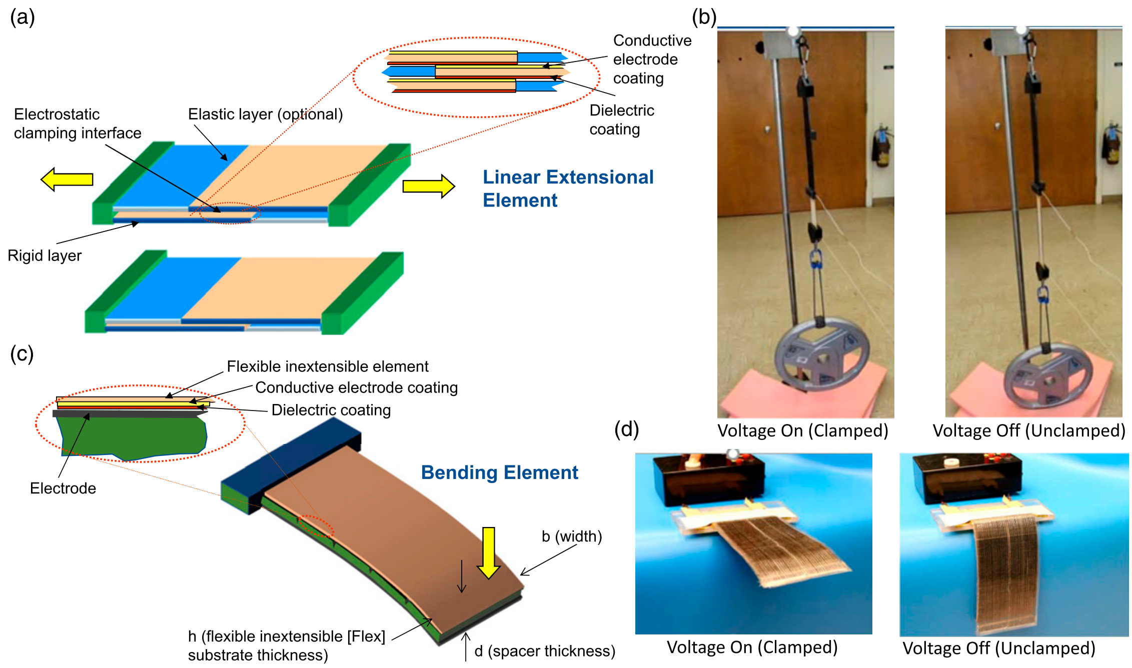

Figure 1. Basic operation of the electrolaminates; (a) linear extensional structure; (b) linear electrolaminate capable of supporting 22 kg in clamped state; (c) bending electrolaminate structure; (d) example of bending electrolaminate supporting its own weight in clamped mode.

spacer layer. Since d can be much larger than h, we see that the change in the effective rigidity modulus can again be very large.

While the above analysis used simplified models of bending, the ability to achieve very large changes in stiffness has been validated. Figure 2 shows an example of a linear extensional electrolaminate undergoing testing in a tensile test apparatus. The test element had the basic layered construction shown in Figure 2(b). One layer consisted of an aluminum plate that served as both the electrode and the rigid backing material. The other layer consisted of a thin polyurethane coating on a metal plate. The polyurethane was attached to the metal plate with a conductive tape (3M Corp. 9712 electrically conductive adhesive transfer tape). The tape served as the other electrode. A voltage of 750V was applied across the electrodes. Figure 2(a) shows the measured resulting force versus displacement. The difference in the slope of the clamped (voltage on) and unclamped (voltage off) states indicates that an effective change in stiffness of more than 100 can be achieved by applying a voltage.

Electrolaminates are also capable of resiliently absorbing a large amount of energy. Figure 2(c) shows the ability of the material to slip and reclamp repeatedly, even if the clamping force is exceeded. In this test, the voltage of 750V was maintained throughout the test. The energy that can be absorbed during the extension of the electrolaminate is roughly the area under the curve of Figure 2(c). In the clamped state, the load that can be supported is dictated by the clamping pressure and the area of overlapping electrodes (as will be discussed in more detail later in this section). With sufficient overlap area, the clamping force can approach the breaking strength of the more rigid materials. Yet, the extensibility of the electrolaminate can be determined by the more elastic layer. Therefore, we can have materials that are both strong and capable of large extensions without failing. This ability translates to large energy absorption (such as might occur during a crash). Unlike passive materials that might rely on sliding of layers, the clamping force can be removed by removing the voltage. This feature allows the electrolaminate to snap back to its original length once the load is removed. Thus, electrolaminates can absorb a large amount of energy without failure.

Most of the published work describing electrostatic clamping refers to electrostatic chuck technology for wafer-handling in the semiconductor industry (e.g., Ref. 15). Electrolaminate technology, on the other hand, covers a broader range of materials and conditions. In particular, the ability of at least one clamping surface to be able to conform

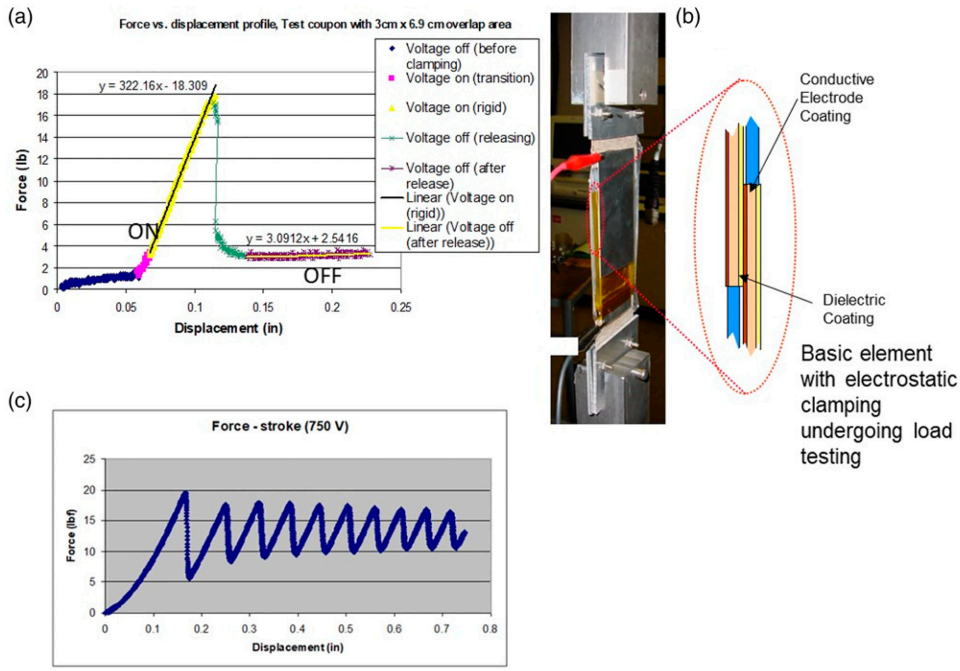

Figure 2. Performance of a linear electrolaminate; change in tensile modulus in clamped and unclamped states as measured with hydraulic tensile test apparatus (top left); structure of test article (right); stick slip performance of the linear electrolaminate as measured with the tensile test apparatus (bottom left).

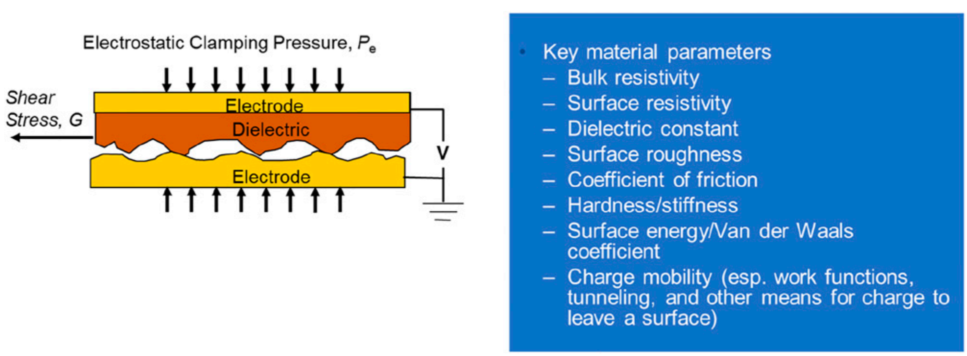

Figure 3. Schematic of an electrostatic clamping interface with roughness greatly exaggerated (left) and properties affecting clamping performance (right).

to the other surface when voltage is applied across the interface is important and distinct from most prior electrostatic clamping work.

Electrolaminate performance depends upon the electrostatic forces acting across the sliding interface. Clamping is a function of both the mechanical and electrical properties of the interface materials. Figure 3 illustrates this point.

Generally speaking, there are two types of electrostatic clamping, Faraday and Johnsen-Rahbek.[16] Faraday clamping utilizes a highly resistive dielectric layer. Clamping forces occur across both the dielectric and the air gap. Due to charge migration issues, Faraday clamping requires bipolar and time-varying applied voltage. Typically, AC voltages are used for this type of clamping.

In Johnsen-Rahbek clamping, the dielectric is weakly conductive.[17] The small amount of charge leakage prevents the charge migration issues and allows DC voltages to be applied to maintain clamping. The electric field that causes the clamping occurs across the air gap caused by the surface roughness and some of the high points of the dielectric. Since the surface roughness can be minimal, Johnsen-Rahbek clamping allows for high clamping forces at lower voltages compared to Faraday clamping. Johnsen-Rahbek effects typically occur for dielectric resistivities of

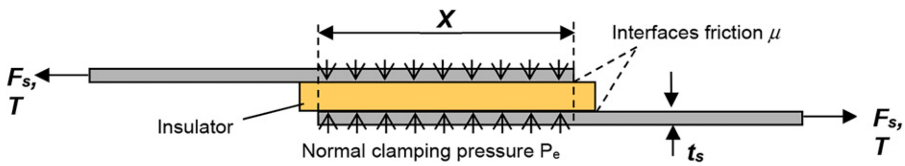

Figure 4. Basic clamping element of a linear electrolaminate. The grey elements are generally flexible but inextensible. Parallel elastic elements are not shown.

10^7 to 10^{11} Ω-m.[18] We used Johnsen-Rahbek clamping for the investigations described in this paper.

The ability of the electrolaminate to maintain the high-stiffness clamped state without slippage of the layers depends on both the physics of the electrostatic clamping and the area of clamping. Figure 4 shows two clamped elements of a linear electrolaminate (but it may also be considered to be any interfacial portion of an electrolaminate such as a bending electrolaminate). The materials are clamped with a normal electrostatic pressure P_e when a voltage is applied. If the clamping surface has a coefficient of friction μ, and the clamp area is $A = X\ W$ where W is the width into the drawing, then the shear or in-plane force F_s that can be supported is

$$F_s = P_e A \mu = P_e X W \mu \tag{5}$$

The force F_s is a measure of how much load the electrolaminate can support before slippage occurs. From equation (5), the tension stress T in the inextensible elements can be written as

$$T = \frac{F}{(W\, t_s)} = \frac{P_e \mu X}{t_s} = \frac{G X}{t_s} \tag{6}$$

where t_s is the element thickness and $G = P_e \mu$ is a nominally scale-invariant number representing the supported shear stress across the clamping interface. By making thinner rigid (flexible but inextensible) elements, the stress supported by the electrolaminate layer theoretically increases indefinitely as t_s is decreased. In practice, the layer would yield when the yield stress of the rigid elements is reached; hence, we note the theoretical strength and theoretical strength-to-weight ratio of an electrolaminate can be equal to the values for the scale material itself. By stacking the basic element shown in Figure 4 in parallel, a strong electrolaminate can be achieved.

In practice, typical values for shear stress are up to 100 kPa. Therefore, an electrolaminate with an area of overlap of 100 cm^2 could hold 1000 N. The thickness of electrolaminate can be on the order of 0.1 mm or less.

Electrically, an electrolaminate looks like a leaky capacitor. The amount of leakage depends on the bulk conductivity of the dielectric as well as surface roughness and interfacial effects. Even theoretical analyses typically rely on empirical correction factors.[19] The amount of power required to hold the electrolaminate in the clamped state is typically 0.1 mW for each square centimeter of clamping area. More power is required to initially charge the capacitor. The peak power depends on how fast clamping is desired. Minimum achievable clamp and unclamp response times are on the order of 10 ms.

Examples of application to UAVs

We sought to demonstrate how the unique capabilities of electrolaminates can be utilized to achieve new levels of morphing for small UAVs.

The simplest and most beneficial morphing concept is to change the wing area. With all other parameters (such as fuselage dimensions, wing aspect ratio, total weight, etc.) being constant to the first order, Lift/Drag (*L/D*) can be minimized at any velocity if V^2S (where V is velocity and S is wing area) is kept a constant (e.g., if velocity is doubled, the wing area will have to be reduced by a factor of four to achieve optimal flight performance). Such a large area change can be achieved with a telescoping wing. This approach is practicable and achievable using standard or custom 3D-printed components.

Independent control of pitch together with circulation control over the body itself is provided by a deflectable, variable-area tail, wherein overlapping 'feathers' are splayed as needed. In such a design, a standard tail geometry is replaced by a trailing edge flap that converts the fuselage into a lifting body.[20–22]

We designed, fabricated, and tested a UAV with morphing wings and a tail enabled by electrolaminate technology. Key features of the final optimized UAV design (shown in Figure 5) included: variable wingspan of 1.2–2.4 m with a corresponding change in wing area of nearly a factor of four; no vertical tail; a horizontal tail area variable by a factor of three; stability in all three axes; all actuation mechanisms (battery, engine etc.) housed in the fuselage; and all of the structure except for the tail section 3D-printed on a Raise 3D Pro2 printer using PLA filament material. The design is flight capable; however, for a flying prototype the 3D-printed plastic structure will need to be replaced with high-strength carbon composite parts that can also be 3D-printed on a high-end printer. The Young's modulus of

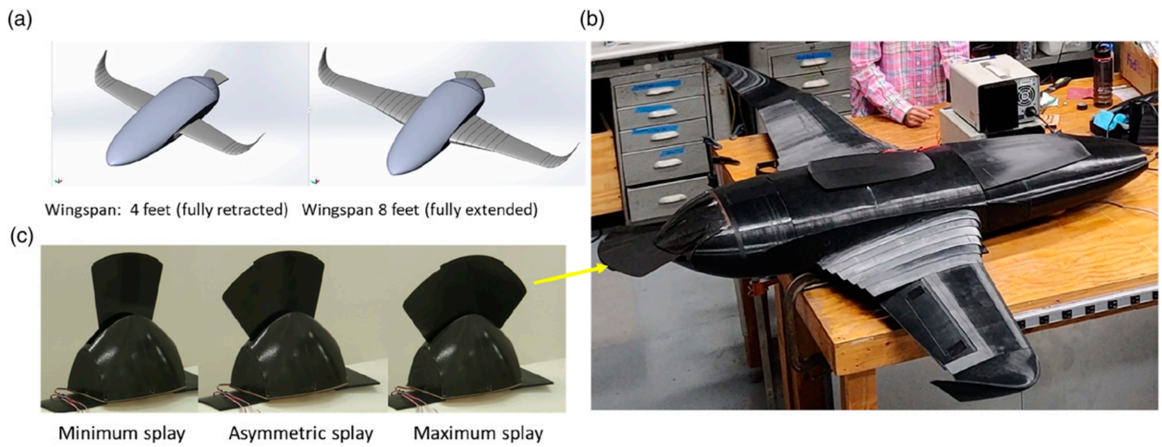

Figure 5. Bio-inspired UAV concept; (a) telescoping wing action; (b) functional prototype using 3D-printed shell materials; (c) splaying tail displaying different configurations.

carbon composite laminates is 10–20 times higher than PLA and can be expected to provide reduction in structural weight by a factor of three–four.

Details of the aerodynamic design, flight performance, wind tunnel tests, etc. are described in Refs. 23 and 24. This unique bird-inspired design has reduced drag because the deflected flap effectively controls the location of the rear stagnation point, and hence the curvature streamlines over the body itself. The ability of the tail to have asymmetric lift can eliminate the need for a vertical tail. It is the splaying tail where we focused our primary efforts on implementing the use of electrolaminates.

Deep dive - electrolaminate clutch

We developed and tested a tail-splaying system for the UAV (Figure 5) that highlighted some of the benefits of electrolaminates. The rotation of the two movable feathers allowed for a change in the area of roughly a factor of three. The carbon-fiber composite tail feathers were arranged around a central pivot, and the middle feather was fixed. The other two feathers could independently rotate outwards. The movable feathers were controlled independently using conventional model aircraft servos. To allow for asymmetric tail splaying, one servo drove each of two movable feathers. Figure 6 shows the tail assembly with the shell removed and indicates the location of the servos.

The splaying mechanism highlighted the abilities of electrolaminate rotary clutches. One clutch was on each of the movable feathers. The clutches could lock the splaying position in place and disengage the servos. This approach protected the servos and drive train components in the event of a crash or other extreme event. It also saved energy by not requiring a stall current to be maintained on a backdrivable servo. Such clutches also have the potential to allow for multiplexing of actuation for control with large numbers of degrees-of-freedom.

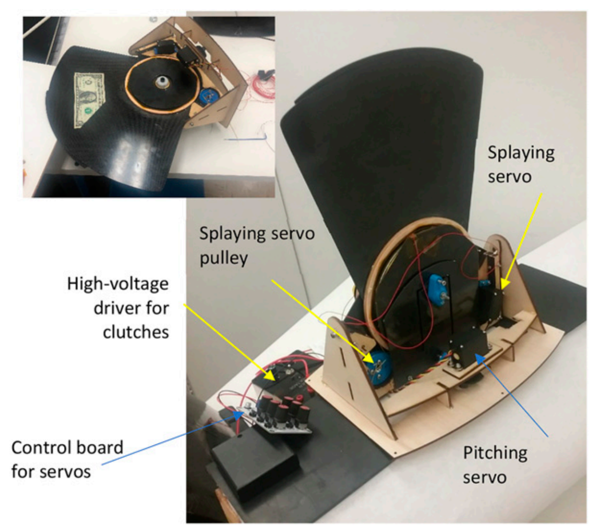

Figure 6. Internal tail feather assembly with manual control electronics (US dollar bill in inset shows scale).

Figure 7 shows the location and design of the clutches. We used a commercially available thermoplastic polymer film as the dielectric. The electrode was a commercially available carbon-loaded polyimide.

We verified the actuation functioned under flight load and wind tunnel test conditions by demonstrating the individual tail feathers could operate with a 1 kg mass attached to the distal end. We also demonstrated the three feathers could pitch with a 6 kg mass acting on all three feathers. These results show the actuation would work in all anticipated test conditions of the wind tunnel. The actuation system was designed with a “weak link” in which overloading caused slippage of the driving pulley. The

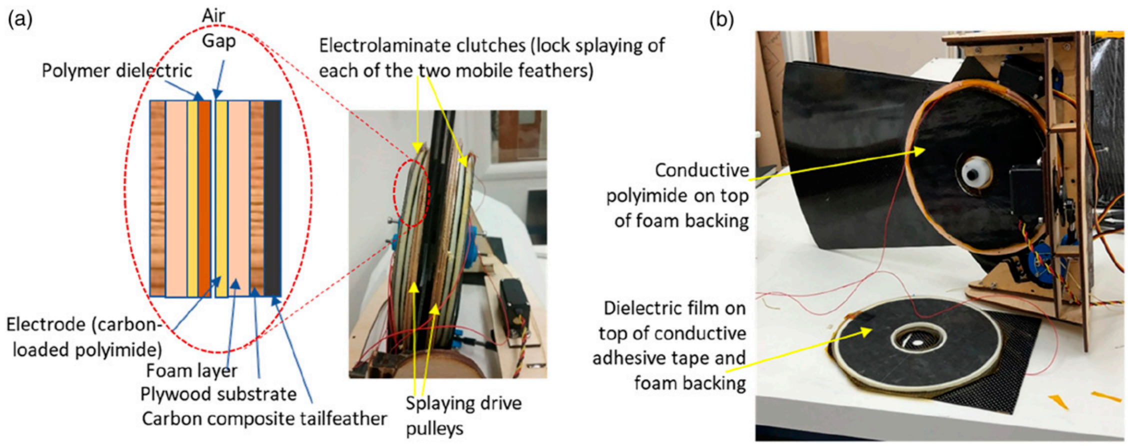

Figure 7. Structure and location of the electrostatic clutches, (a) schematic and photo showing the details of construction of the clutch; (b) clutch shown partially disassembled in tail section. Clamping connects the movable feathers to the central fixed feather.

electrolaminate clutches also prevent damage to the servos when locked.

The electrostatic clutches produced roughly 5 Nm of locking torque as measured by hanging weights on the tail feathers oriented in a horizontal position. This value is more than enough to resist anticipated flight loads.

The clutches operated at roughly 800V with a steady-state current draw of 10 µA for a continuous power draw of less than 10 mW—far below that required to maintain a stall condition of a servomotor.

The mass of the clutches was 93 g each. Much of that mass was as a result of placing the clutching elements on their own rigid backing for easy evaluation and swapping. A more optimized design could directly integrate the clutches with the tail feathers themselves. The mass of the active clutching materials was less than 10 g—the true added mass of the electrostatic clutching feature.

Future uses of electrolaminates

While the rotary electrolaminate clutches show promise, they do not fully exploit all the capabilities of elecrolaminates in realizing morphing UAVs. In particular, they do not morph the shape of the wings. To that end, we also performed preliminary investigations of how electrolaminates can be more fully exploited for wing morphing.

Figure 8 shows the planform and representative wing cross-section of a notional UAV. By selectively locking the top or bottom elements, or both, changes in chord and camber can be achieved. By allowing one of the elements to remain unlocked, the stiffness of the wing section can be dramatically reduced. Such an approach might be useful for mitigating gust response in a method similar to that of birds. Control of camber either explicitly through the solid surface, or implicitly through laminar separation bubble shaping, can significantly alter the balance of *L*/*D* upon command.[25]

Note this approach to morphing does not require a stretchable skin. When in the clamped state, the skin of the electrolaminate-enabled morphing section is largely rigid and thin. Further, the wing can be made stiff in torsion loading using a "torque box" to resist torsional loads when the electrolaminates are clamped.

A second exploration was focused on the telescoping wing of the UAV of Figure 5. The wing sections use thin skin sections that telescope using a single linear actuator. The actuator was attached to a single sliding mechanism that maintained alignment during morphing. Although not implemented in the proof-of-concept research shown in Figure 5, electrolaminates can enable stronger and lighter wings based on telescoping sections. The sliding skin sections do not have to be individually rigid or tightfitting since they may include a slit that allows them to elastically adjust their circumference yet achieve rigidity when clamped.

Electrolaminates can lock the individual sections; this allows a solution that is at once simple, light, and rigid. Further, additional electrostatic clamping can allow for greater shape control by selecting which sections will slide when the single linear actuator pulls on the structure. Figure 9 shows a notional design in which these features could be incorporated into the wings of a UAV similar to the one shown in Figure 5.

Summary and directions for future research

Electrolaminates offer new capabilities for realizing bio-inspired morphing in UAVs. We showed the potential for electrolaminates with benchtop functional models. In

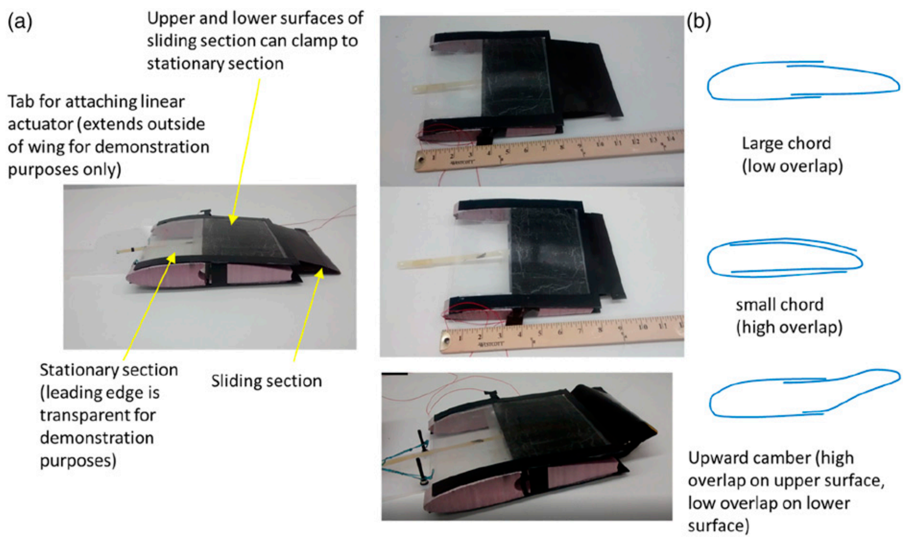

Figure 8. Demonstration of the use of linear electrolaminates as airfoil skins to achieve changes in chord and camber; (a) construction of the demonstration device; (b) operation of the device to show chord and camber changes.

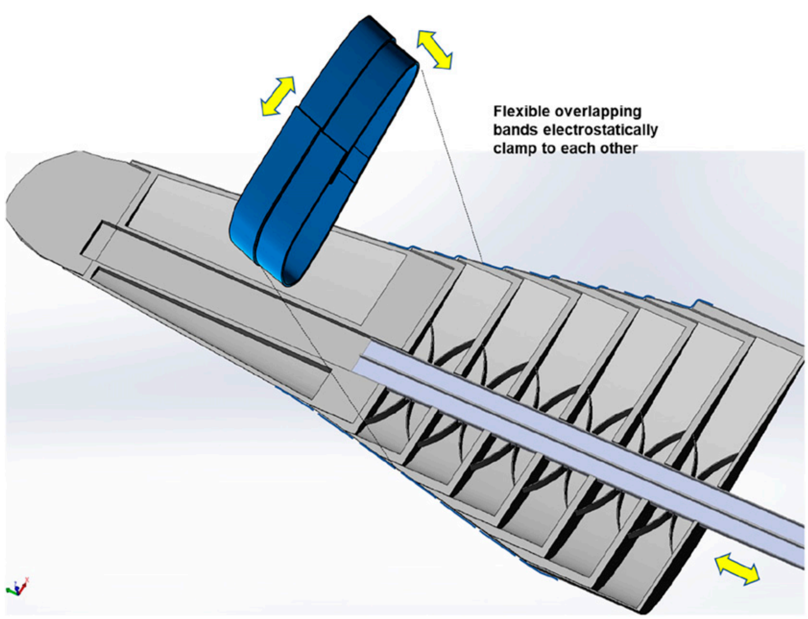

Figure 9. Conceptual design of how electrolaminates can enable a robust yet lightweight sliding section wing capable of large-scale morphing. The wing sections are surrounded by overlapping bands of electrolaminates. These bands can clamp to each other to provide greater wing stiffness as well as allow selection of which sections slide in response to the single linear actuator used for telescoping.

particular, electrolaminates in the form of thin and light rotary electrostatic clutches were shown to operate on a fully functional proof-of-concept model of a unique bird-inspired morphing UAV to enable robust operation of tailfeather splaying. We also showed designs aimed at exploiting the capabilities for strong and capable wing morphing. In particular, wing morphing that does not require either an elastic covering or precisely interlocking pieces is desirable.

Future work will focus on practical implementations of the technology including the selection of materials that can operate robustly over a very wide range of environmental conditions. In particular, it will be important that the materials be unaffected by extremes of temperature. At present, the thermoplastic polymer materials used for the dielectrics do show temperature sensitivity that can degrade performance. Ceramic materials may be a better option and allow operation in extreme environments. Further, such materials may have improved wear, allowing a longer UAV lifetime.

We focused on binary performance and considered that the electrolaminate is either locked in the high-stiffness clamped state or unlocked in the low-stiffness state. However, the electrostatic forces can be applied while sliding occurs and may serve to provide a controllable damping force used for vibration control and intelligent energy absorption. More generally, models and resulting algorithms that will allow optimization of shape control or distributed elasticity to best achieve the desired structural properties and eventually optimize the flight characteristics for a given mission will need to be developed in order to best exploit electrolaminate technology.

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Declaration of conflicting interests

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