# Nature's Engineering: A Blueprint for Efficient Aircraft Design

by

*Elvine Philip B. Pineda*

Submitted to the
Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of

*Bachelor of Science*

at the

*Massachusetts Institute of Technology*

June 2011





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## Abstract

The flight of birds inspired engineers like Leonard da Vinci and Wilbur and Orville Wright to design aircraft that mimic the behavior they observed. The success of the Wright brothers' first controllable aircraft ushered in an era of rapid advances in aviation technology leading to the airplanes of today. Despite these advances, airplanes possess many restrictions that prevent them from being as efficient as their nature-engineered counterparts. Researchers have thus returned to the methods of the earlier engineers in aviation and begun observing birds to look for ways to improve aircraft design. Two methods currently being researched to improve aircraft efficiency are morphing wings and perching. Morphing wings allow airplanes to change the shape of their wings to suit the needs of their mission. Perching is a landing maneuver that uses the nonlinear dynamics of stall to create the drag forces necessary to decelerate the aircraft. Experiments on these methods prove them viable for implementation in small scale aircraft such as remote-controlled planes and unmanned aerial vehicles. However, because of the complexities involved in both morphing wings and perching, further developments are necessary to achieve full implementation.

Thesis Supervisor: *James H. Williams Jr.*
Title: *Professor of Mechanical Engineering, Writing and Humanistic Studies*

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# 1 Introduction

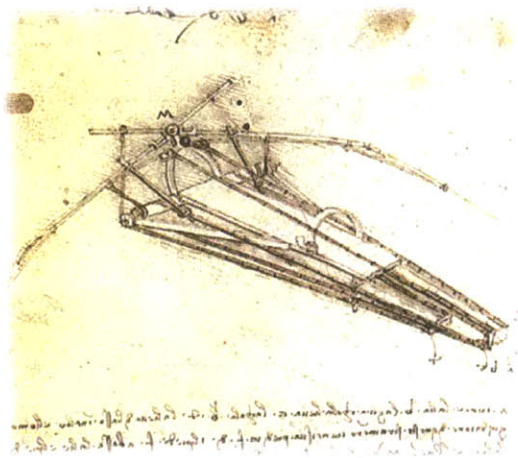

Figure 1 Leonardo da Vinci's flying machine

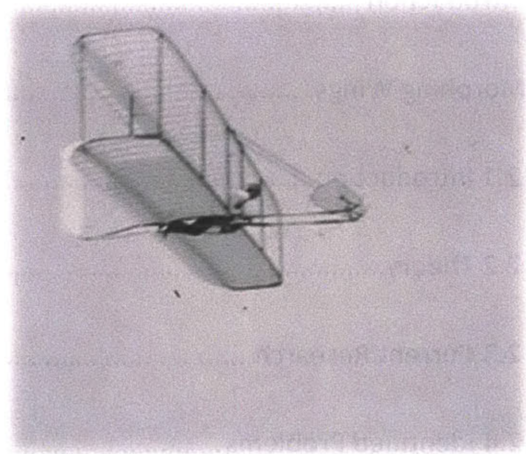

Figure 2 Wilbur Wright piloting his glider in 1902

In the 16th century, Leonardo da Vinci studied birds and wrote his observation in his *Codex on the Flight of Birds*. In this codex were detailed analyses of flight mechanics, air resistance, and the flight of birds. Furthermore, it included proposed designs for his famous flying machines. Although his flight machines, which included a hang glider and a helicopter, failed, they were ideas way beyond his time. Da Vinci, using only observations of nature for inspiration, designed and built machines that were attempted centuries later making him one of the first pioneers in nature-inspired aeronautical engineering.

Moving onwards to the early 20th century, the Wright brothers also began observing the flight of birds and used that as inspiration to develop their first controllable aircraft. This is one of the first documented cases of nature-inspired engineering in aviation achieving success. Since then airplanes have become larger, faster, and more complex. Changes ushered in by technological advances such as jet engines, computers, and lighter materials improved efficiency and controls. The most advanced aircraft of today are capable of carrying over 800 passengers, traveling at 3 times the speed of sound, or maneuvering accurately and precisely at high speeds. Although these were impressive advancements, the basic design of the airplane has not changed much. It contains fixed wings that generate lift for flight and brakes using friction from the ground or reverse thrust.

Studies have shown large inefficiencies in current aircraft design. Take, for example, an airplane landing on a runway. It uses reverse thrust and friction from its brakes to cause it to stop. Moreover, take a look at the ascent and descent of passenger aircraft. It takes the captain some time before he reaches cruising altitude and speed. These aircraft are designed for a particular speed and altitude and are highly efficient at those specifications. However, at any other regime, the aircraft will lose its efficiency. Engineers have tried to alleviate this problem by altering wing design to suit another flight speed or altitude, but each aircraft is still limited to only a small regime.

Researchers are going back to the methods of past engineers and are looking at nature to fix these issues. Their goal is to introduce the next generation of aircraft that uses the observations from birds to produce highly efficient machines capable of flying many different kinds of missions. This paper investigates two methods researchers are trying to develop, morphing wings and perching, to examine their results and feasibility.

# 2 Morphing Wings

## 2.1 Introduction

Most airplanes are restricted in purpose by their wing design. Fighter jets have much more narrow wingspans to accommodate their need for speed and stiffness while making sharp turns. Passenger aircraft like the Boeing 747 are ideal for long flights with their large wingspans. Though airplanes were originally inspired by birds, only very basic theories, such as the air flow over a wing to cause lift, were implemented. There is, however, a great deal more to be learned from birds, and researchers are observing these creatures looking to improve current aircraft design. Take, for example, the situation of a predator bird, such as a hawk, searching for its next meal. It cruises at high altitudes with its wings outstretched scoping the land for vulnerable prey. Once a target has been sighted, the hawk tucks its wings in, dives at a high speed, and precisely maneuvers itself along a trajectory to its target. Within an instant, its prey is clutched securely within its claws and the hawk swoops up avoiding the ground by inches. Moments later, it is gliding again with outstretched wings searching for a safe location to devour its meal.

Figure 3 Boeing 757

Figure 4 Gliding Hawk (Zinkova, M., 2007)

Figure 5 Diving Hawk (Gouldingken, 2008)

Figure 6 F22 Raptor (Bloker, B., 2005)

The hawk demonstrates an innate understanding between the shape of its wings and the resulting aerodynamic properties. It changes its wing orientation to suit the requirements of the situation. Most aircraft today are designed for a single purpose only, usually efficiency at a certain speed. They become highly inefficient with anything else besides that specific speed. Stages of a commercial airline's flight include takeoff, cruising at its prescribed speed, and landing. During takeoff and landing, the aircraft wastes precious fuel accelerating to its most efficient speed and decelerating to a stop. Fighter jets, designed for high speed and quick changes in direction, lose efficiency during low speed maneuvers. These flaws are the motivation for the area of study described in this section, morphing wings. Wings that change shape to suit the requirements of their mission allow for efficiency at all stages of flight. This section details the theory behind changing of wing shape and its effects on aerodynamic ability. Furthermore, current methods of implementing morphing wings and the problems limiting their use are described.

## 2.2 Theory

In *How Swifts Control Their Glide Performance with Morphing Wings*, researchers from various universities in Europe obtained data from actual birds regarding the relation between wing shape and its aerodynamics (Lentink, et al., 2007). Specifically, they were able to decrease sinking rate allowing for greater gliding efficiency or drastically increase turning speed allowing for agile maneuverability. The animals tested were swifts, known for their aerial prowess.

Figure 7 Swift with extended wings (Kuzniar, P., 2006)

To begin, it is necessary to discuss the basic laws that govern flight. This section does not go into detail on the underlying physics but only aims to present the equations necessary to understand the results of the experiment.

As air flows around a wing, it creates a force of lift, $F_L$ and a resistant force drag, $F_D$. Equations 1 and 2 show the relationship between the forces, air, and geometric properties of the wing (Anderson Jr., 2007).

$$F_L = \frac{1}{2} C_L \rho A v^2 \quad [1]$$

$$F_D = \frac{1}{2} C_D \rho A v^2 \quad [2]$$

In these equations, ρ is the density of the air, A is the area of the wing, and v is the velocity of the wing. Although similar, equations 1 and 2 can have greatly differing results due to the natures of the lift and drag coefficients $C_L$ and $C_D$ respectively. These non-dimensional numbers are generally determined experimentally and take into account the complexities involved with laminar and turbulent flow around different geometries. The relationship between the lift and drag coefficients and the angle of attack of a wing are of great importance.

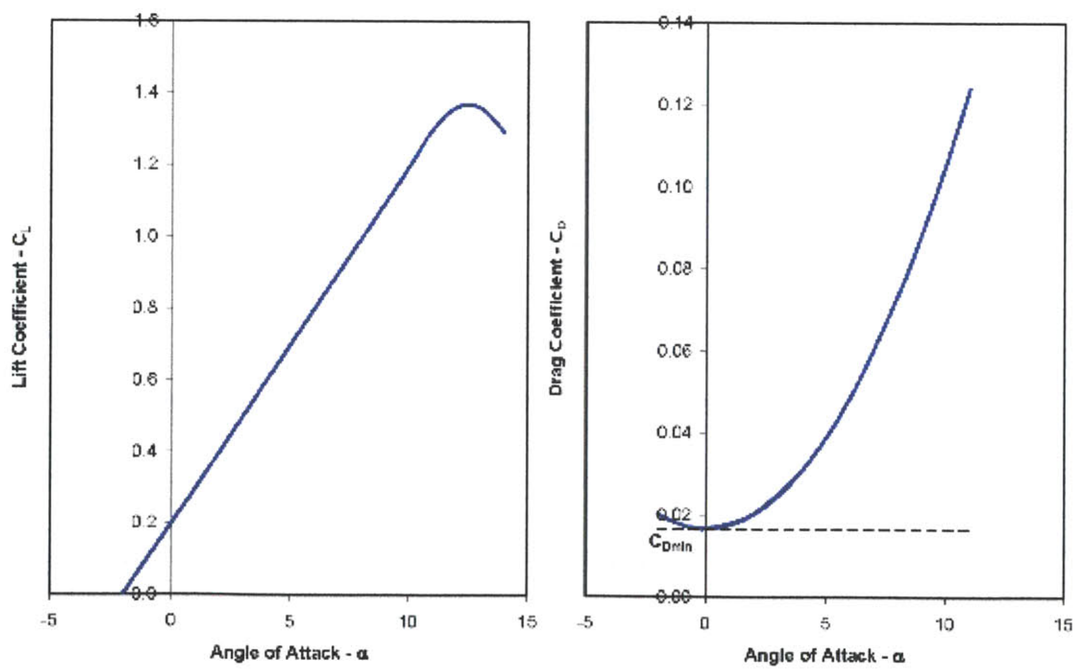


Figure 8 Relationship between drag and lift coefficients and angle of attack (Cavcar)

It is key to note the effect of high angles of attack in Figure 8. At a certain angle, stall point, lift starts to decrease. Furthermore, at high angles of attack, drag has a larger influence on the wing.

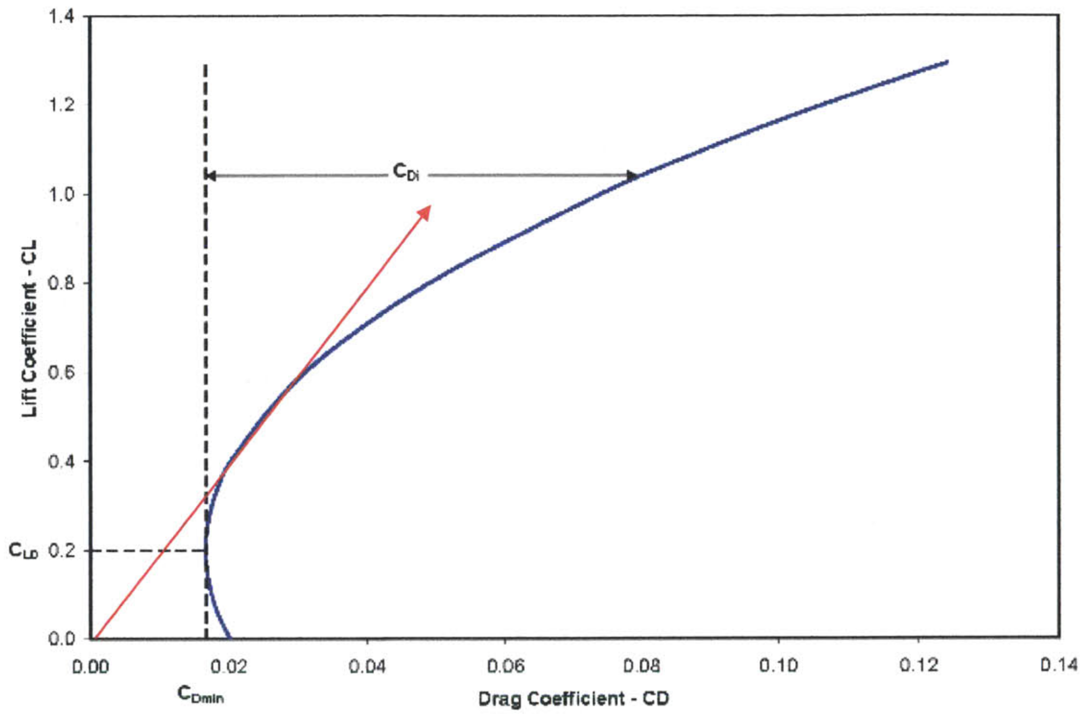


Figure 9 Drag polar - relationship between lift coefficient and drag coefficient (Cavcar)

In Figure 9, the general relationship between the coefficient of drag and lift, the drag polar, is presented. Of importance is the red vector drawn from the origin and its contact with the curve. This point, found by rotating the red vector clockwise until it touches the drag polar, represents the point that provides the most efficient combination of lift and drag (Anderson Jr., 2007). The main conclusion from this graph is that for a given geometry, there is only one angle of attack that maximizes efficiency. Because a typical airplane has a fixed shape, flying at any other angle of attack is inefficient. A bird, on the other hand, has the ability to change its shape and does so to maximize lift and minimize drag. It achieves this by extending its wings or sweeping them in resulting in a change of aerodynamic coefficients as well as the wing area.

Lentink et al. placed the wings of swifts in a wind tunnel and measured their aerodynamic properties with respect to changing angles of attack and sweep, angles of wing extension (Lentink, et al., 2007). The results of the measurements of the drag and lift coefficients are given in Figure 10.

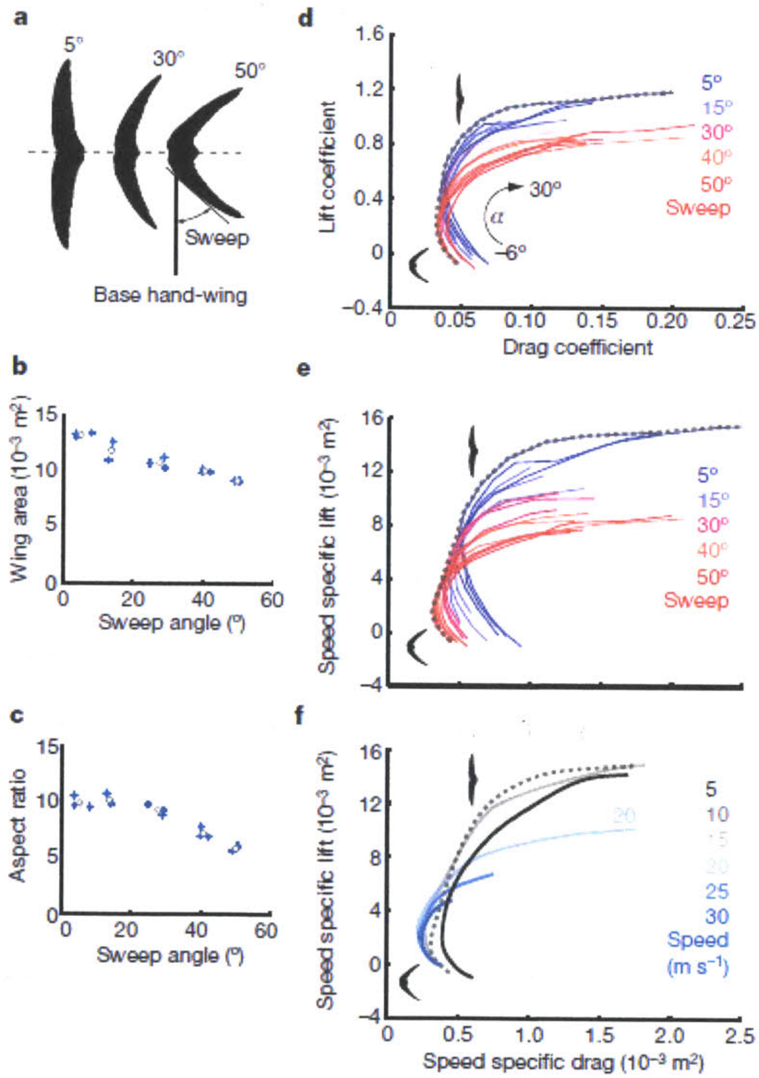


Figure 10 Results of wing experiments (Lentink, et al., 2007)

The first three sets of graphs in Figure 10 show how the changing sweep angle in 10.A alters the wing area and aspect ratio in 10.B and 10.C. In 10.D, the drag polar for each wing configuration is shown. It is important to note that swept wings have a lower lift coefficient at high angles of attack and lower drag coefficient at low angles of attack. Extended wings on the other hand show higher lift coefficients at higher angles of attack but increased drag at low angles of attack. These results show a disparity in aerodynamic performance with differing sweep angles. The dotted line represents the most efficient point of each drag polar. This justifies the implementation of morphing wings. Morphing wings allow aircraft to adjust their profile in order to suit their angle of attack, achieving maximum efficiency at all stages of flight.

Furthermore, graph 10.E shows the results of changing area. When wing size is taken into account, a much larger envelope of maximum efficiency is perceived. In particular, a swept wing can achieve lower coefficients of drag at higher coefficients of lift.

The last graph 10.F represents the maximum efficiency envelopes with respect to changing speed. Notice that at low speeds, the envelope maintains the shape of the original envelope. However, as the speed increases, the envelope shifts left towards lower coefficients of drag and drops off much earlier. This is due to the breaking of wings as the speed increases. Only the swept wings are able to survive the forces at high speeds and thus only their profiles are left in the envelope.

To better illustrate their results, Lentink et al. converted the results from Figure 10 into a different set of characteristics presented in Figure 11.

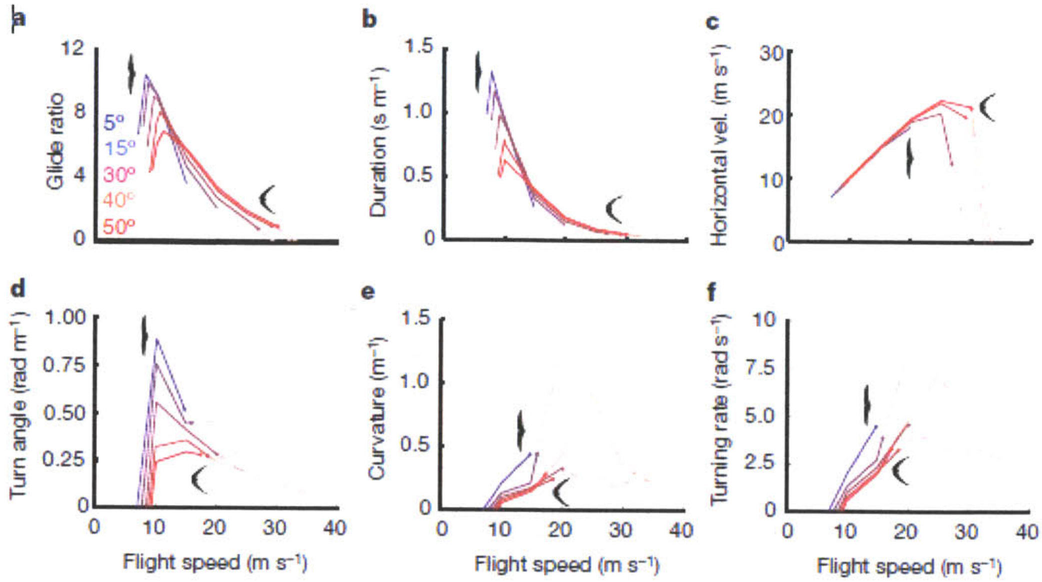


Figure 11 Results of wing experiments (Lentink, et al., 2007)

Figure 11.A represents the glide ratio, a ratio between the forward velocity and sinking velocity of the wing. At low speeds, extended wings have the highest glide ratio. With increasing speed, this glide ratio decreases and at some point, swept wings have a higher glide ratio. The results of glide duration in Figure 11.B are similar. At low speeds, extended wings dominate at high speeds, and swept wings dominate. In Figure 11.C, horizontal velocity represents the only characteristic where swept wings are ideal in all speeds. This is due to its generally lower drag coefficient resulting from a smaller geometric profile. The next three graphs, Figure 11.D, 11.E, and 11.F, represent the abilities of each wing configuration while turning. These results show that extended wings always outperform swept wings regardless of speed. However, notice how the data of each extended wing disappear at lower speeds. This is due to the breaking of the wings during high speed maneuvers. Although swept wings are less efficient at turning, they are much better at handling the aerodynamic stresses of high speed turns.

Based on this analysis, extended wings at a low velocity offer the best performance for a wing. Despite this, swept wings are preferable in certain situations that require high speeds with extreme maneuvering.

The results of Lentink et al. show a clear benefit to having morphing wings. Extended wings provide an advantage at short velocities. But at higher velocities, swept wings exhibit better aerodynamics. Furthermore, swept wings are capable of handling larger stresses and can thus perform better maneuvers at high speed. With these results in mind, the next section deals with the methods scientists are currently developing to apply this knowledge.

## 2.3 Current Research

Research in morphing wings involves the design of mechanisms and materials that deform wings to the proper shape and orientation for efficient flight while being lightweight and strong enough to handle aerodynamic forces. Moreover, the development of a smooth outer shell or skin that conforms to the morphing structure is required. Several researchers have proposed different methods to address these requirements.

In Penn State University, researchers Ramrkahyani et al. have suggested a tendon actuated truss system for a morphing structure (Ramrkahyani, Lesieutre, Frecker, & Bharti, 2004). Individual octahedral cells of the truss pictured in Figure 10 have the ability to deform locally and transmit forces and moments from cell to cell. When combined with the deformations of the adjacent cells, this truss can produce a global transformation that alters its aerodynamic properties.

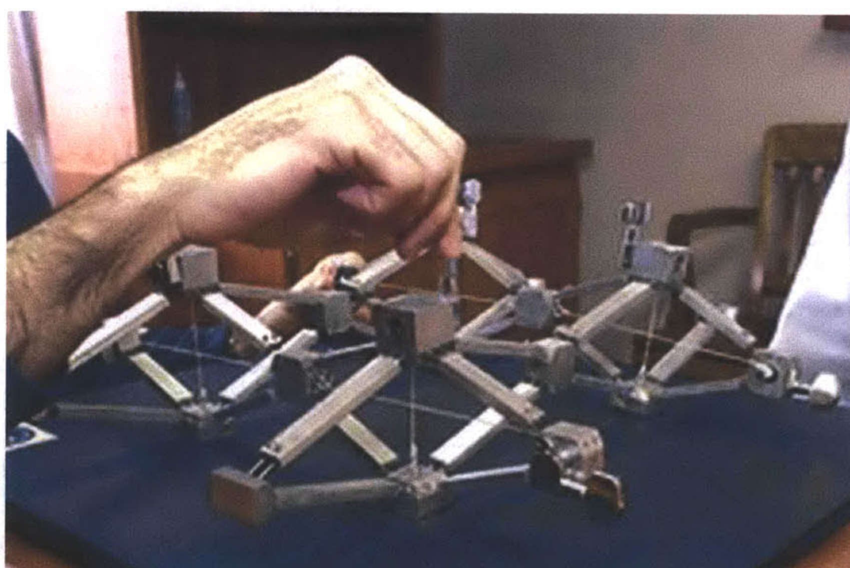

Figure 12 Tendon actuated truss cell (Ramrkahyani, Lesieutre, Frecker, & Bharti, 2004)

Figure 12 is an early prototype of an individual cell. It is octahedral for maximum strength without having to change the length of beams. The joints are compliant allowing for some bending with some torque. Tendons join certain pivots and are arranged in such a way that the cell can be made stable regardless of orientation and location of an applied force. Along with this ability to counter any external force to minimize strain on individual beams, the release or reeling in of these tendons allow for local deformation of the cell.

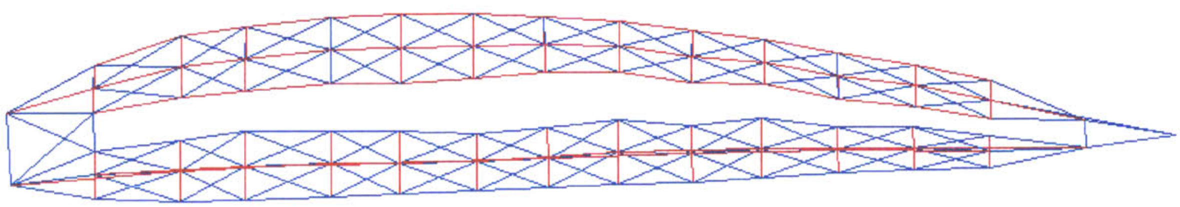

Figure 13 Cross section of proposed wing (Ramrkahyani, Lesieutre, Frecker, & Bharti, 2004)

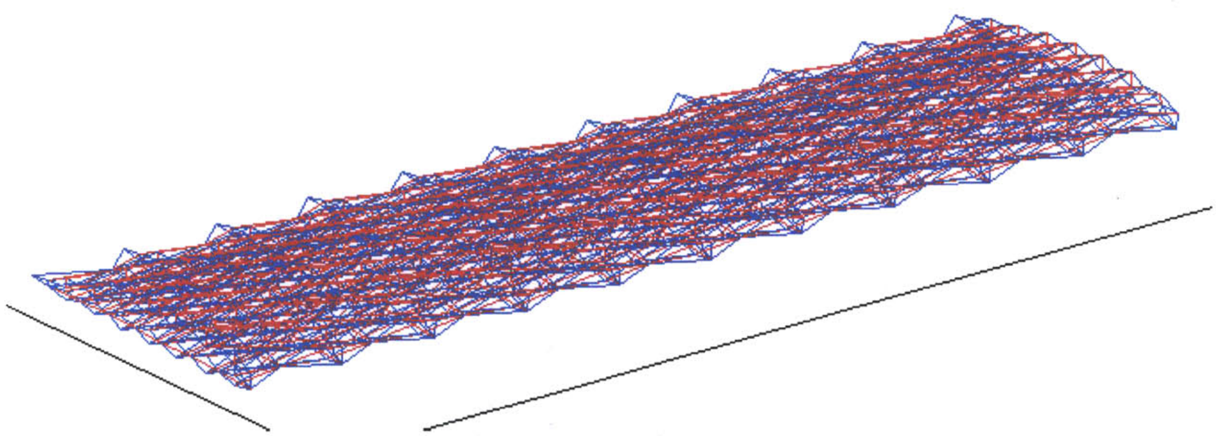

Figure 14 Wing design using tendon actuated cells (Ramrkahyani, Lesieutre, Frecker, & Bharti, 2004)

The individual cells can be combined to form a wing structure pictured in Figures 13 and 14. With the proper control of the individual tendons, the wing can change its sweep angle as well as camber, the curvature of the airfoil. Although, current aircraft already have the capability to change wing camber, it is generally done with discrete control surfaces adding unnecessary drag. With the use of a deformable structure, the surface remains continuous, minimizing drag.

The other fundamental requirement of morphing wings is a deformable outer layer capable of transmitting aerodynamic forces onto the truss. Although not fully developed, proposed designs include the use of Shape Memory Alloys, folded inner skins, multilayer skins, or segmented skins. One promising implementation of a deformable skin involves the use of a honeycomb structure sandwiched between two compliant surfaces (Olympio & Gandhi, 2009).

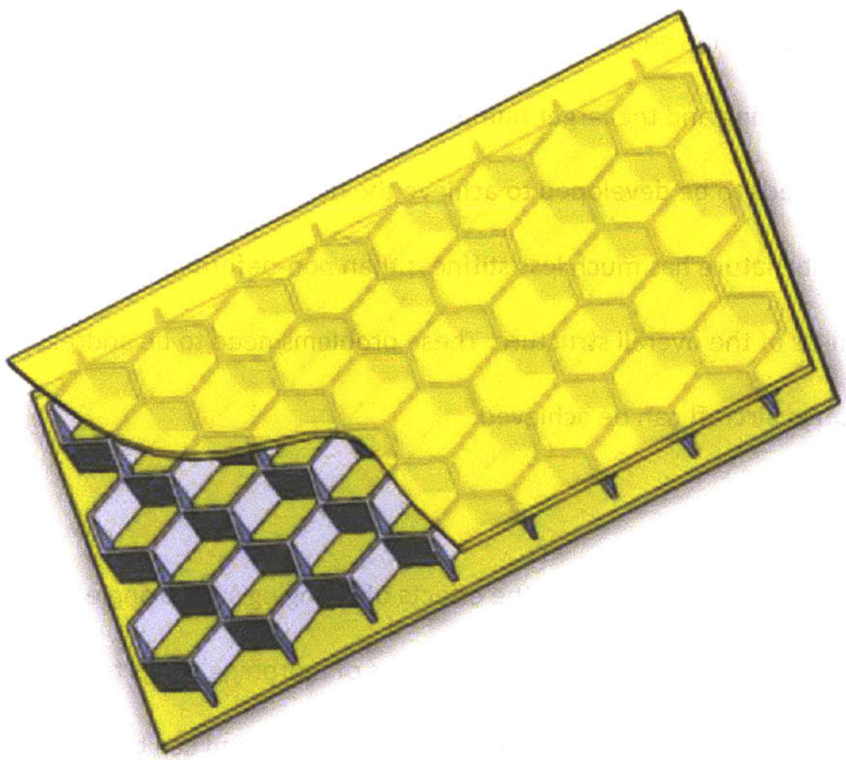

Figure 15 Honeycomb skin (Olympio & Gandhi, 2009)

This structure allows in-plane strain while resisting deflection out-of-plane. The stiffness can also be adjusted by modifying the dimensions of the honeycomb cell. With regards to the requirements for morphing aircraft, this skin, if coupled with high strain materials such as Shape Memory Alloys or Delrin®, allows enough deformation to vary the sweep of a wing while also being able to transfer aerodynamic forces onto the truss it encompasses.

## 2.4 Identified Problems

There are many problems associated with the implementation of morphing wings. Although a compliant truss system is a great option to introduce morphing, it has many weaknesses. Regular trusses have stiff joints to prevent bending of wings. Because of the compliant joints' flexibility, over structural stiffness is compromised. Furthermore, a great degree of complexity is introduced with morphing wings. Because of the large number of cells required to form a wing and the larger number of actuators required to morph it, a complex control system needs to be developed to achieve the desired shape. Moreover, the deformable skin because of its nature has much less stiffness than non-deformable sheets adding to the lessening stiffness of the overall structure. These problems need to be addressed before implementation in aircraft can be achieved.

## 2.5 Conclusion

This section described in detail the effects of changing sweep angle on the aerodynamic performance of wings and current implementations of morphing wings to take advantage of this. Despite problems in stiffness, the designs are promising and can begin to be used in small scale aircrafts such as radio-controlled planes or unmanned aerial vehicles. With further enhancements in materials that increase structural integrity without sacrificing deformability, implementations in larger scale aircraft is possible.

# 3 Perching

## 3.1 Introduction

Figure 16 Owl landing on branch (Hand, A.J.)

Imagine the descent of a Boeing 747 toward an airport. The captain orders passengers to fasten their seatbelts and prepare for landing. The airplane maneuvers itself to align with the runway while decreasing its altitude. Slowly, the airplane makes its descent towards the mile long stretch. On touchdown, the tires screech as the brakes are applied and the passengers are jolted in their seats. Almost a minute later, the aircraft comes to a complete stop.

This method for decelerating, although universally used, is highly inefficient in comparison to nature's way of braking. Take, for example, the descent of an owl towards a tree. The owl soars in the sky with its wings fully outstretched and glides towards its destination. In a split second, its wings tilt upward. The owl comes to a complete stop and gracefully perches on the tree. The owl uses only its aerodynamic properties to cause it to stop. It has innate knowledge of a phenomena called "stall", a regime in aviation that many pilots fear. It occurs when the angle of attack of the wing is so high that the aircraft's lift force begins to decrease and the plane plummets back to Earth. Pilots and scientists avoid this regime because of its unpredictability and potentially fatal consequences.

In recent studies, researchers have begun looking at this phenomena for opportunities to increase the efficiency and the abilities of airplanes. While observing the perching of many different kinds of birds, scientists are attempting to discover the dynamics that occur during this period and are developing ways to control it. Their goals are to create the next generation of aircraft that no longer need runways or brakes to stop, but instead use the aerodynamic capabilities of the plane itself.

## 3.2 Theory

A bird uses the phenomenon of stall to its advantage to create viscous drag and reduce its velocity using its aerodynamic properties. Thus, in order to understand how to control it, a basic understanding of stall needs to be investigated.

Stall occurs when the boundary layer of a fluid over the contour of the wing begins to separate as illustrated in Figure 17 (Anderson Jr., 2007). When the angle of attack of a wing is low, the flow around the wing is laminar and the fluid dynamics can be easily predicted. As the angle of attack increases, the boundary layer begins to separate creating an area of turbulence near the back of the wing. After a critical angle dependent on the geometry of the wing, the separation of the boundary layer increases so significantly that the turbulence generated makes the fluid dynamics unstable and unpredictable. In general, the coefficient of lift begins to drop while the coefficient of drag continues to increase.

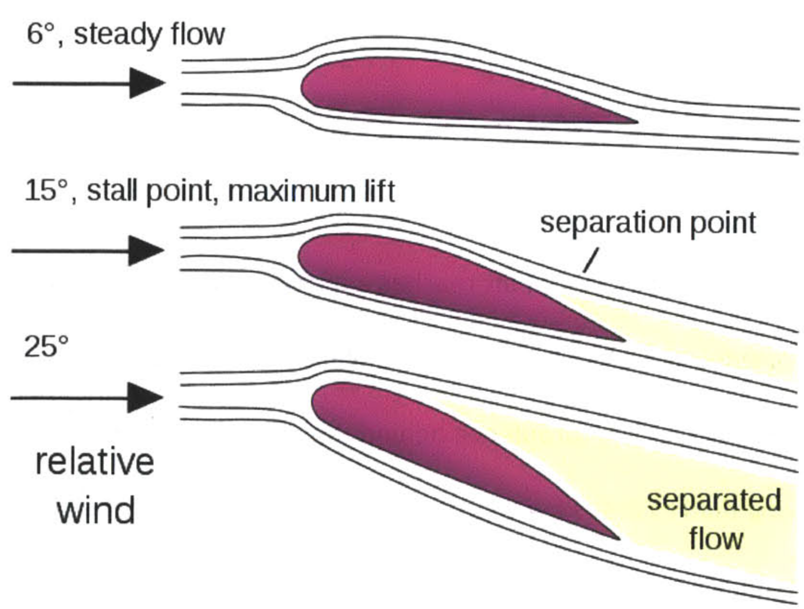


Figure 17 Fluid flow around wing contour

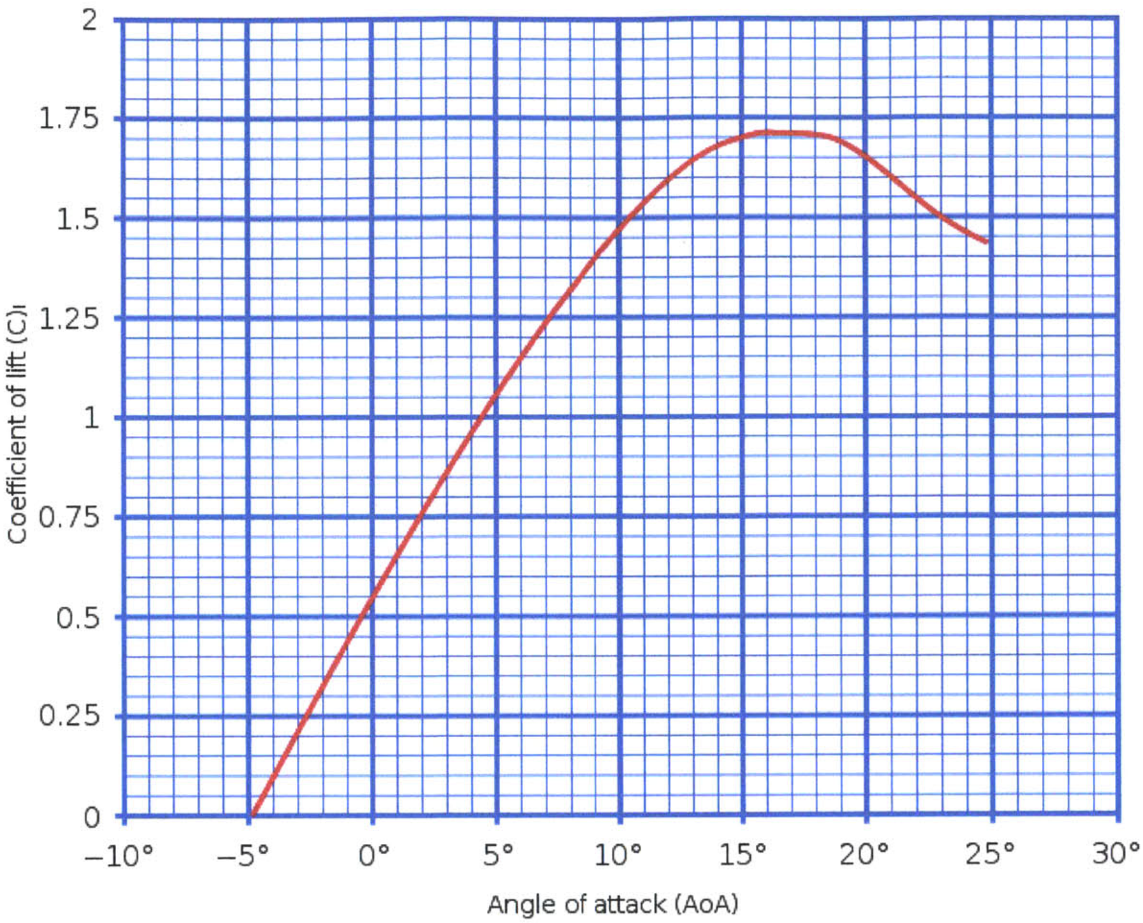


Figure 18 Coefficient of lift versus angle of attack

Figure 18 demonstrates the relationship of the coefficient of lift and the angle of attack. As the angle of attack increases, the lift generated increases linearly. At a certain angle of attack called the stall point, the coefficient of lift reaches a maximum and begins to decrease. This is when a plane is considered stalled. Beyond this critical point, studies have shown the wings to behave similar to flat plates. The turbulence behind the wing prevents laminar flow around its top contour allowing fluid to only flow smoothly below the wing. With the shape of the wing no longer taking effect, the aerodynamics behave similarly to that of a flat plate. As described in the next section, researchers have used this model for predicting wing dynamics during stall.

## 3.3 Current Research

Current research in perching involves the predicting of the dynamics of a stalled aircraft, the control of a stalled aircraft, and landing gear necessary to perch the aircraft. Perching is a relatively new area of study and has seen very few successes. This section summarizes the work of two research groups based at the Massachusetts Institute of Technology and Stanford University that have made successful attempts at perching aircraft.

Because of such non-linearity in the dynamics of stalled aircraft, researchers have resorted to experimental methods to discover the aerodynamics of a stalled aircraft. Researchers at MIT, Cory and Tedrake, launched a radio controlled glider and recorded its behavior with varying angles of attack in order to predict its stall dynamics (Cory & Tedrake, 2008). As expected, the results in Figure 19 show dynamics similar to a flat plate.

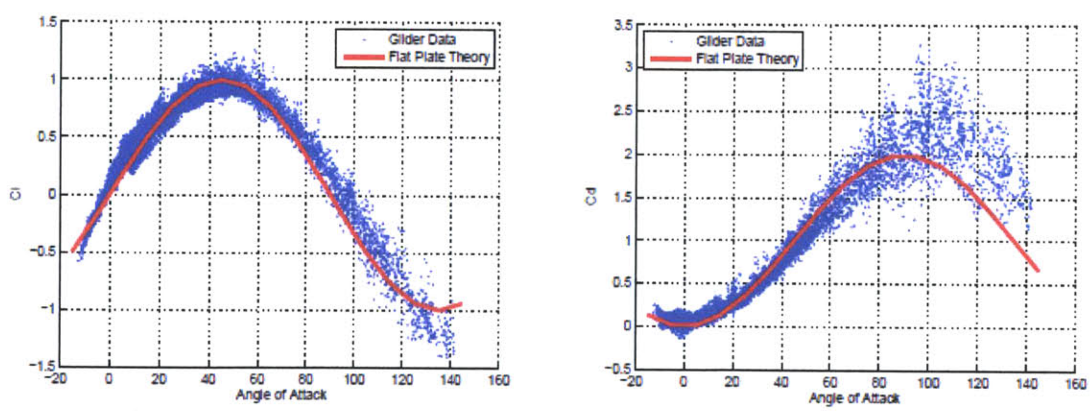


Figure 19 Results of glider experiment (Cory & Tedrake, 2008)

Figure 19 represents the dynamics of the glider as it approaches stall. At low angles of attack, the glider behaves as predicted as shown in Figure 18. At a certain angle of attack, the coefficient of lift reaches its maximum and begins to decrease. At this point, the coefficient of drag continues to increase for a longer period resulting in the viscous forces necessary for perching. The red line represents the dynamics of a flat plate undergoing the same maneuver. This justifies flat plate dynamics as a model to predict the motions of a glider undergoing stall.

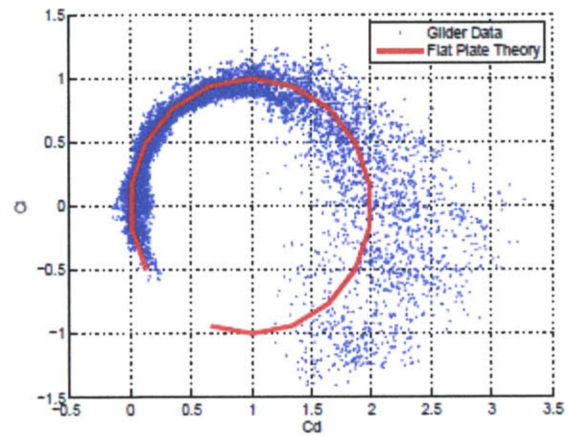


Figure 20 Drag polar of glider experiment (Cory & Tedrake, 2008)

Figure 20 illustrates the drag polar of the glider as it approaches and goes beyond stalling. With its circular path, the lift coefficient is shown to decrease as the drag coefficient increases. Again the data suggest the dynamics of a flat plate.

With a model established, Cory and Tedrake were able to predict the dynamics of the glider and develop a control system to maneuver it. With perching, traditional methods of control are highly inefficient as they seek to counter the dynamics of a system and replace it with a preferred one. Take, as a point of comparison, the Harrier Jet pictured in Figure 21, also a vertical lift and landing aircraft. It uses downward facing thrusters to counter gravity and allow it to levitate in the air and slowly lower itself onto the ground in a stable manner. In contrast, a perching aircraft uses the perceived instability of stall as a method to decelerate and land the aircraft.

Figure 21 Harrier Jet

For their control system, Cory and Tedrake used an infinite-horizon optimal feedback control system. This system sets a cost for each performable action, in the case of the glider, a change in angle of the elevator. Using the predicted dynamics, the algorithm calculates the cost of every path it can take to the desired state and performs the action that requires the least cost. This process is iterated at every change of state in the system so it constantly attempts to find the most efficient path. Instead of replacing the dynamics of the aircraft with its own, the algorithm finds the quickest path to a specific state incorporating the system's dynamics instead of negating them. With a model and a control system at hand, researchers implemented their design on a glider attempting to land on a wire. Images of the result are presented in Figure 22.

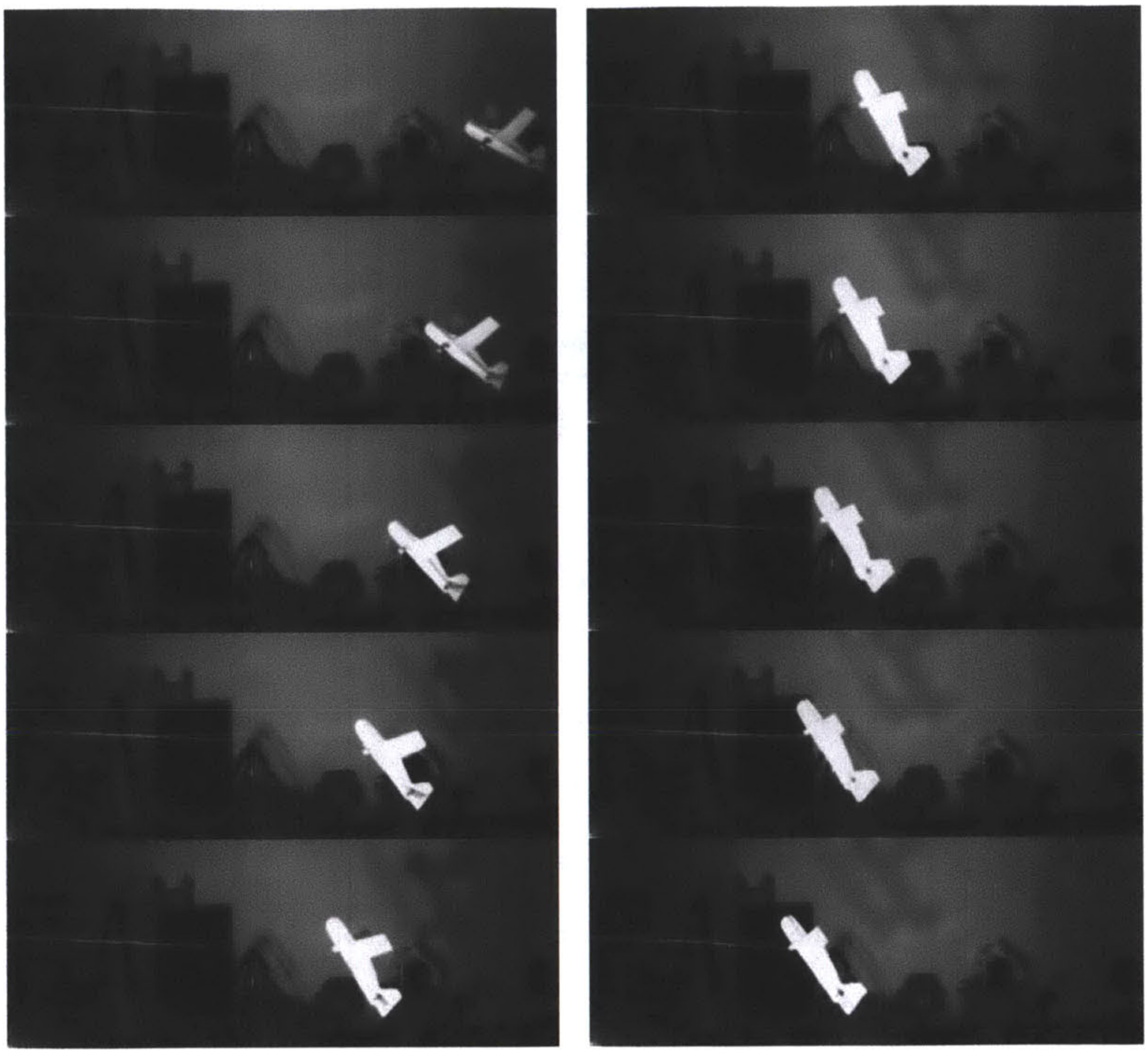

Figure 22 Glider performing perching maneuver (Cory & Tedrake, 2008)

The glider increases its angle of attack and puts the glider in stall. While stalled, the glider slows down and comes to rest on the wire. This experiment was effectively able to use a model to predict the dynamics of the plane and optimized control to find the best solutions to position the glider to land on the perch.

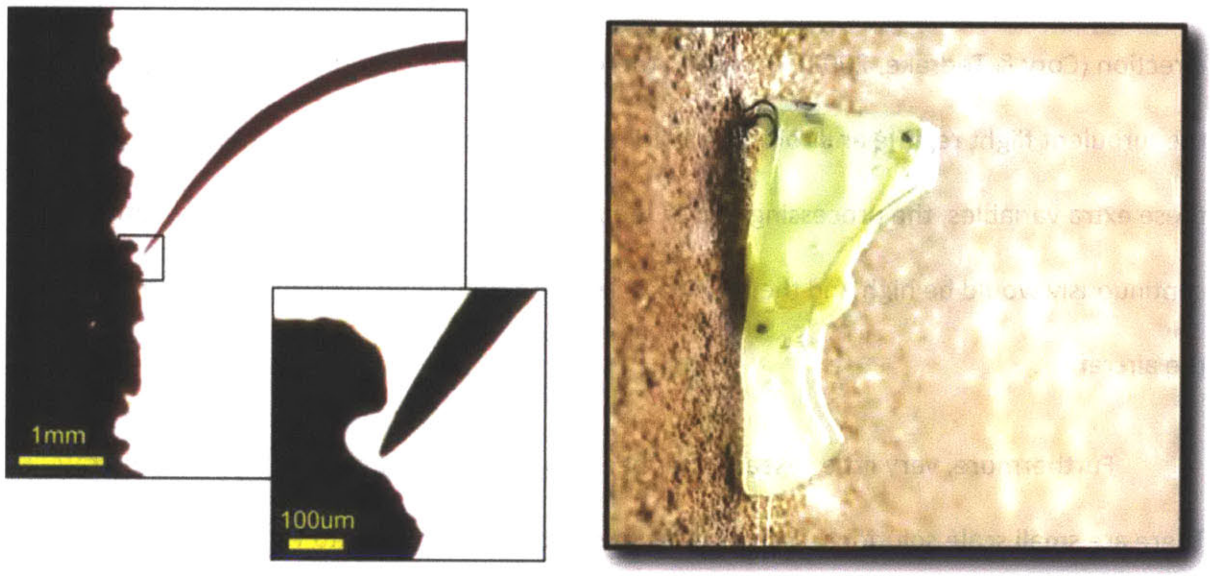


Figure 23 Spine design (Desbiens & Cutkosky, 2009)

To deal with the problem of perching, Stanford engineers, Desbiens and Cutkosky, have developed a mechanism to stick onto walls using microspines (Desbiens & Cutkosky, 2009). These spines have tips on the order of 15 micrometers and penetrate rough surfaces upon impact. They require a specific loading cycle of a force against the wall, a downward force, and a force away from the wall to land. With a controlled flight path that incorporates the viscous forces induced by stall, the glider is able to approach a vertical surface at low velocity and perch using this mechanism. Tests have proven this device to work 80 percent of the time with the 20 percent failure attributed to inaccurate approach.

## 3.4 Identified Problems

Problems in perching include the predictive modeling of the dynamics of an aircraft under stall and computational resources. Although Cory and Tedrake were able to use a model derived from actual data, it was done in a controlled environment with motion only in the pitch direction (Cory & Tedrake, 2008). In reality, there is still a great degree of uncertainty present in the turbulent flight regime and roll and yaw directions need to be taken into account. With these extra variables, the processing power required to compute the most optimal path continuously would be high and the hardware required could effectively increase the mass of the aircraft.

Furthermore, very little research has been done on landing gear for perching aircraft. There are small scale solutions, such as using microspines, to latch onto vertical surfaces. However, this is only applicable to small lightweight aircraft and requires a specific landing area as well as loading cycle (Desbiens & Cutkosky, 2009).

## 3.5 Conclusion

Perching is currently possible using small scale lightweight gliders restricted from turning or rolling. The future of this technology lies in better modeling of stalled aircraft and control algorithms which take advantage of the aerodynamics of aircraft in stall. It is also necessary to develop landing gear and perhaps docking stations to make landing effective and safe. Despite these obstacles, many, including military contractors, have begun looking into this technology as the future of aviation.

# 4 Conclusion

Nature was the inspiration that launched humans into a new era of transportation. After its inception, aviation rarely looked at its originator for further design improvements. With the need for more efficient and versatile aircraft as well as advances in material and computing technology, researchers are once again studying birds for methods to improve current aircraft.

This paper summarizes the work involved with two methods of improving efficiency, morphing wings and perching. Results from studies involving the efficiencies of wings of different orientations illustrate the need for morphing aircraft for efficient flight. It allowed for efficiency at all extremes of flight from low speed long distance flights of commercial airliners to the high speed high maneuverability requirements of fighter aircraft. With perching, the efficiencies of landing are improved upon using the aerodynamics of an aircraft to create the forces necessary to stop the plane instead of relying on friction and sometimes reverse thrust. Not only will this maneuver save costly fuel during landing, it will also minimize space requirements by eliminating the runway.

Despite this research,  the technology to incorporate these ideas is still in its infant stages. Materials needed to cover a morphing wing structure as well as deform with it are necessary. Furthermore, research in predictive dynamics of stalled vehicles as well as landing gear is needed to fully implement a perching aircraft. As of now, only small scale aircraft have the ability to implement these changes.

Nature has been inspiring engineers for centuries, perhaps even millennia, and for good reason. The specimens engineers mimic are more effective and more efficient than their manmade counterparts. With further observations at nature's implementations, human engineering can excel and may begin developing products that can outperform nature itself.

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