The Morphing Wing: Birds Know Best

A morphing wing is more competitive compared to the conventional fixed-wing design as it allows an airplane to perform more tasks effectively. An airplane with a morphing wing can change the geometric shape of its wing during flight and optimize its performance based on mission requirements. Despite the ability to improve airplanes' energy efficiency, there are still many issues with the wing-morphing technology that need to be resolved before it can be fully implemented. Nevertheless, a morphing wing will certainly play an essential role in the future of aviation because of the exceptional benefits it has for airplanes.

"Should airplanes look more like birds?"

For thousand of years, humans have been observing birds from the ground with wonder and jealousy. This curiosity to understand how birds are able to fly in the air has motivated humans' desire to fly, and ultimately the development of airplanes [1]. Since birds are the source of inspiration for airplane development, airplanes should, supposedly, look more like birds in order to become more energy efficient. However, airplanes today look quite different from birds in many aspects as shown in Figure 1. In fact, through experiments and comparison between airplanes and birds, researchers have found that airplanes can achieve better efficiency if they can "behave" more like birds in flight, and morphing technology makes it possible [1]. The following sections will introduce the concept of morphing and its biological inspiration, the history of wing-morphing technology, its benefits to airplanes, different wing-morphing approaches, as well as some of the limitations.

Figure 1. Differences in appearance between a bird and an airplane.
http://www.fastcompany.com/1704545/should-airplanes-look-birds

What is Morphing?

Most airplanes today have the conventional fixed-wing design that only allows airplanes to do one thing very well, but perform poorly in many other tasks [2]. For instance, an unmanned airplane often needs to switch between loiter and attack role in a mission. However, the two tasks contradict each other in terms of their design requirements, and the only way to optimize the airplane's efficiency is by changing the wing shape in flight through morphing technology [2-3].

Morphing airplanes are multi-role aircrafts that can change their external shapes significantly in order to fulfill different mission requirements in flight [2]. The word morphing derives from the word metamorphose, meaning a transformation or a change in the form or nature of something [4]. By this definition, morphing technology can range from small-scale morphing such as retractable landing gear, flaps and slates, to large-scale morphing such as wing-twisting and folding wings. This paper will focus on the most common form of morphing, which is the wing-morphing technology. It allows an airplane to change the geometric shape of its wings in flight. Researchers have been trying to break through the boundary of the conventional fixed-wing configuration and design a wing that can twist, fold, sweep, or transform during flight. In order to do so, researchers have been getting help from the greatest teacher of all time – nature.

Birds Know Best

Birds are the best example of morphing at work. Through observations, researchers have long recognized that birds change their wing structures in flight to perform specific maneuvers [5]. For example, Figure 2 shows that a peregrine falcon changes its wing shape to transition from efficient cruise to aggressive maneuvering when it dives for its prey. The change in the shape of the wings allows the bird to reduce drag, thus increasing its energy efficiency to capture its prey – which translates to fuel efficiency in aircrafts [5]. Through the wing-morphing technology, airplanes are able to behave more similarly to birds, which improve their performances in different flight conditions.

Figure 2. A peregrine falcon transitions from loiter mode (with larger wing area) to attack mode (with smaller wing area) as it dives for its prey.
http://files.dnr.state.mn.us/publications/volunteer/young_naturalists/bird_flight/bird_flight.pdf

History of The Morphing Wing

The idea of a morphing wing is far from new. In 1903, the Wright brothers emulated the flight of birds and developed the idea of wing warping, which used pulleys and cables to warp the wings to make turns and provide roll control – an essential ability to stabilize an airplane and return it to its original position after getting disturbed by external force such as wind. The technique was then abandoned as soon as metals substituted fabric and became the primary material for airplanes, as metals did not have the flexibility to be warped like fabric wings. What replaced the wing-warping technology to provide roll control was the creation of flap-like structures called the “ailerons” on the trailing edge of the wings as shown in Figure 3.

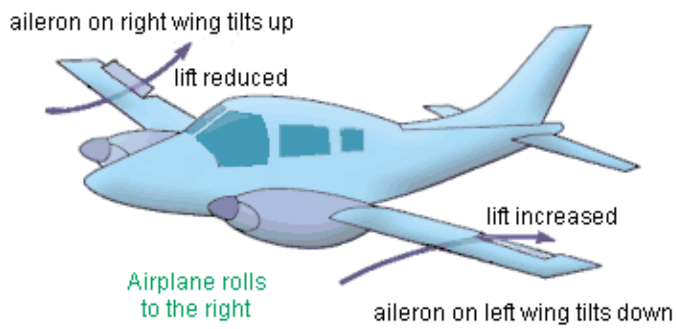

Figure 3. Roll motion of an airplane with the use of ailerons.
http://virtualskies.arc.nasa.gov/aeronautics/5.html

Nevertheless, the wing warping idea surfaced again in the Active Aeroelastic Wing (AAW) as new technology allowed wing twisting to be done in a controlled manner [7]. AAW exploits structural flexibility and uses the power of the air to twist the wing into a desired shape, whereas the conventional wing deploys aileron to change the shape of the wing. Figure 4 shows the differences between AAW and the conventional aileron. This new technology was able to replace the conventional aileron configuration in stabilizing an airplane. NASA's Dryden Flight Research Center tested the AAW technology on F/A-18 Hornet, and was able to prove that the roll maneuverability could be improved by twisting the wings. [7] Furthermore, studies also showed that AAW could expand the design space for a lightweight fighter aircraft, and generate roll moment without the aid of a horizontal tail [8].

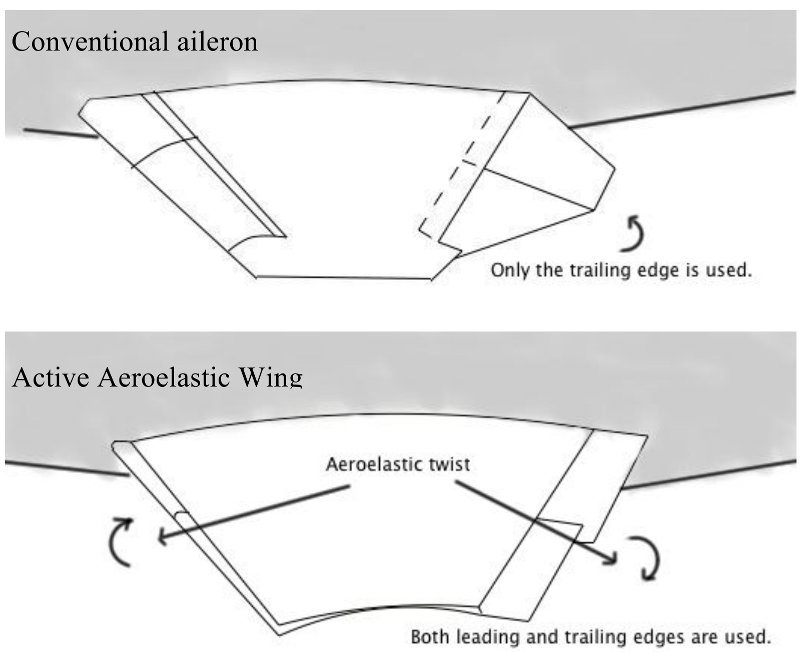

Figure 4. Difference between a conventional aileron and an AAW after receiving a right roll command. (Line drawing by the author, based on http://dc166.4shared.com/doc/qoAtSJb5/preview.html and [8])

The folding-wing concept is another popular morphing technology. The concept started in 1915, when Frederick Handley Page invented the World War I Handley Page O/400 Bomber. The wing-folding mechanism allowed the bomber to fit into a standard canvas Bessoneau hangar despite its large wings [9]. Later in 1920, when there was a growing need in the U.S. Navy for airplanes to occupy less space in aircraft carriers, Grumman's engineers invented a foldable wing called the STO-wing. The STO-wing was applied to the Wildcat, and it was able to increase the plane carrying capacities of the early World War II carriers by more than 50 percent as shown in Figure 5 [9].

Figure 5. The Grumman F4F Wildcats on the left side of the picture demonstrated the use of wing-folding mechanism to save space on an aircraft carrier.
http://upload.wikimedia.org/wikipedia/commons/c/ca/F4F_Wasp_1942.jpg

The next example of a morphing wing is the variable sweep wing concept, in which a wing can be swept back and forth during flight. When an airplane flies at a speed close to the speed of sound, the wings will begin to shake and a shock wave will be formed behind the wings, which creates drag on the body of the aircraft. In order to minimize drag at high speed, wings can be simply swept back to generate the illusion of longer wings [10]. However, since swept wings are only good in high speed, it will be less efficient for an airplane with swept wings to fly in low speed. In order to balance the tradeoff between high and low speed flights, the variable sweep wing concept could be applied. In fact, the variable sweep wing concept was claimed to be the most successful wing-morphing technology by Weisshaar, as far as objectives are concerned. [2] The Bell X-5 was the first jet-powered aircraft that started using variable sweep wing design as shown in Figure 6. The sweep could vary from 20 degrees to 60 degrees [11]. Although the variable sweep wing concept used a pivot mechanism that added extra weight as well as complexity, it was able to outweigh the penalties and improve airplanes' efficiencies in both low and high speeds [2][11].

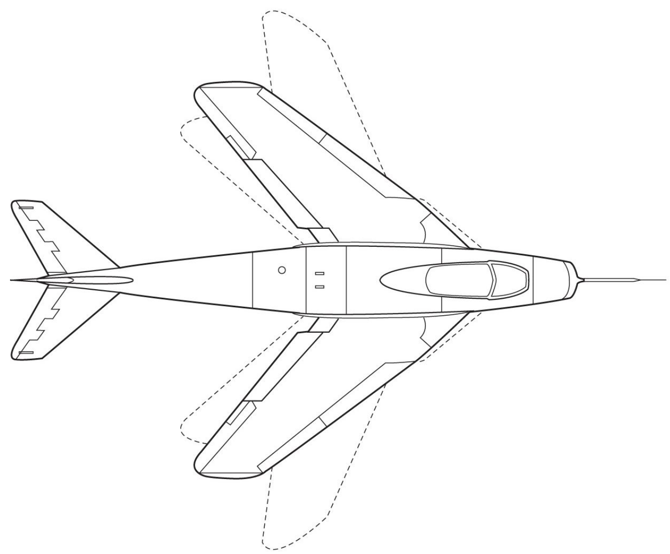

Figure 6. An engineering drawing of the Bell X-5 showing the variable sweep wing concept.
http://www.456fis.org/X-5/Bell_X-5_afg-041110-046[1].jpg

The inventions cited above represent only a small fraction of the enormous morphing technologies and concepts. Some proved to be useful while some did not, as morphing solutions always led to penalties in terms of cost, complexity, or weight [2]. In order for morphing technology to be effective, there needs to be one or more contradictions in the aircraft design requirements. Example of a contradiction is shown above in the variable sweep wing concept, in which a fixed swept wing could allow an airplane to fly efficiently in high speed but not in low speed. If an airplane is designed to fly in low speed only, then adding morphing devices such as the variable sweep wing will only add unnecessary weight and downgrades the aerodynamic performance.

Why Morph?

As discussed above, since morphing always comes with some penalties, the overall improvement on airplanes is usually slight. Nevertheless, the slight improvement is still very important for aviation. For instance, as the fuel cost is getting higher each day, fuel-saving methods have become a major concern for many airlines and companies. According to the NASA Dryden studies, "even a 1% reduction in airfoil drag would save the US fleet of wide-body transport aircraft $140 million per year, at a fuel cost of $0.70 per gallon." [12] In other words, the main benefit of morphing wings is to reduce drag, improve energy efficiency, and ultimately reduce fuel cost.

Realizing that morphing wings have the potential to revolutionize aircraft design, many researchers have been interested to explore different possibilities in the morphing technology. There are three main approaches in the morphing technology that have been widely studied: material approach, structural approach, and multidisciplinary approach.

Modern Wing-Morphing Concepts: Material, Structural, and Multidisciplinary Approaches

Material Approach

The material approach involves the use of smart actuators and smart materials, such as Shape Memory Alloy (SMA) as shown in Figure 7 [13]. Smart materials are able to change their external shapes significantly after receiving certain stimuli such as temperature, pressure, magnetic field, etc. Therefore, using smart materials to build wings could allow an airplane to change its wing shape in flight. Although smart materials can provide lightweight actuation, the scalability is still uncertain, which means that the final shape of the wing may not be the desired wing shape [14]. As a result, the outcome may be disastrous and the airplane may lose its stability in flight.

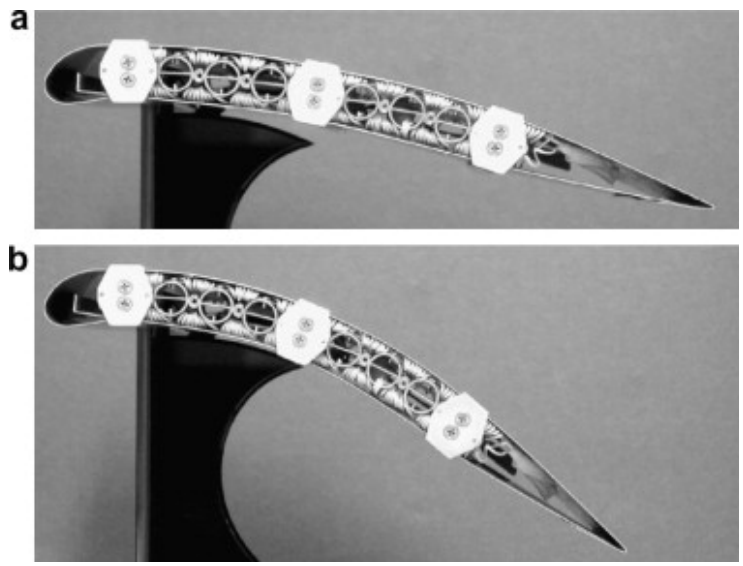

Figure 7. Morphing wing with the use of SMA material. (a) Un-morphed. (b) Morphed.
http://origin-ars.els-cdn.com/content/image/1-s2.0-S0261306909004968-gr4.jpg

Structural Approach

In comparison, the structural approach uses a compliant mechanism, which is "a single-piece flexible structure that delivers the desired motion by undergoing elastic deformation as opposed to the rigid body motion in a conventional mechanism." [14] Figure 8 is an example of a compliant mechanism in an adaptive wing, which has the ability to change its shape smoothly without using any rigid wing devices such as hinged flaps and ailerons. The actuator applies a force to the system and causes the compliant mechanism to deform due to structural flexibility. The deformed compliant mechanism then causes deformation of the wing boundary, which, in turn, changes the shape of the wing [15]. The main challenge in this mechanism is that the design needs to be flexible to transmit motion, yet stiff enough to withstand the wing loads [14].

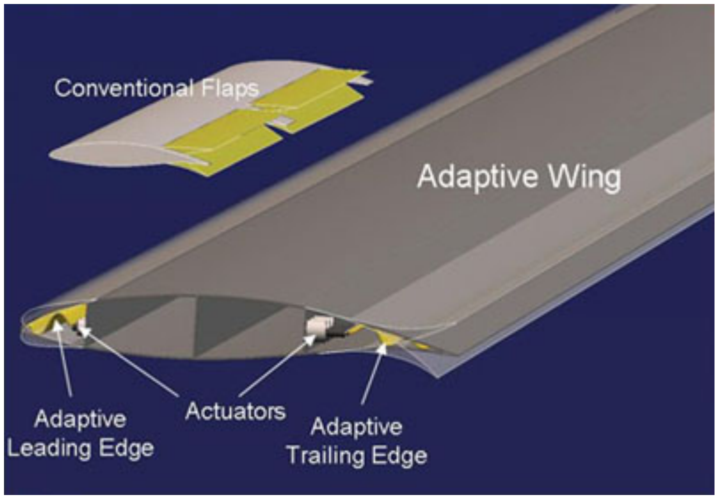

Figure 8. An adaptive wing with embedded compliant systems.
http://www.flxsys.com/Applications/Shape%20Morphing/Adaptive%20Compliant%20Wing/

Multidisciplinary Approach

The multidisciplinary approach is a passive morphing technique that minimizes the energy required for actuation to improve energy efficiency. In fact, this is very similar to the flying mechanism of a bird as shown in Figure 9. It can be broken down into three processes according to Fausz [16]: sensing, computation, and actuation.

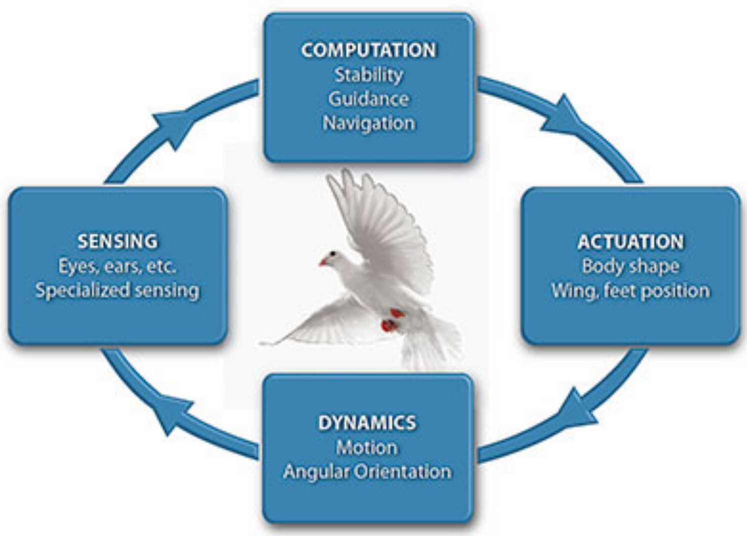

Figure 9. Illustration of the interdependence of different subsystems in a morphing flight.
https://www.apologeticspress.org/apPubPage.aspx?pub=1&issue=621

i) Sensing
A bird needs to detect and sense the atmospheric condition around it, as well as its position so that it can perform the correct action in a given environment. Similarly, in order for a morphing airplane to react correctly to the surrounding environment, sensor equipment is required to collect data such as air pressure, altitude, air speed, and its position relative to other objects [16].

ii) Computation
After collecting enough data, the sensor inputs will be integrated and processed in the brain of the bird, or alternatively, the flight computer for a morphing airplane. As the airplane morphs and changes its shape, flight stability is very crucial and it has to be maintained throughout the flight. Therefore, the control system needs to process the sensors' inputs, compute the correct responses using finite element software, and generate commands that trigger actuation with the minimum energy [16].

iii) Actuation
Morphing flight does not only require specialized structures, but also requires specialized actuators to move and position those structures [16]. The actuator components receive commands from the control system and change the wing shape accordingly to optimize an airplane's performance.

Limitations

Most of the wing-morphing concepts introduced above are still in the development stages. More issues need to be addressed and resolved as the morphing scale gets bigger. Safety is the biggest concern because many undesired things could happen when an airplane morphs during flight [1]. For example, the flexible material may not be strong enough to withstand the wing load and could result in disasters. Furthermore, morphing duration may also be another major concern. The aircraft performance can be affected in several different ways when the wing is morphing in the air; therefore, the time to morph must be as short as possible in order to minimize risk.

Conclusion

Wing-morphing technology is undeniably the future of aircraft design. It allows airplanes to operate efficiently under different flight conditions by changing the wing shape in flight, just like birds who change their wing positions to perform different tasks. The ultimate goal of morphing technology is to optimize airplanes' fuel efficiency and maneuverability. However, the goal can only be achieved if the limitations such as additional weight, cost and complexity can be minimized. More importantly, researchers need to prove that the morphing technology is able to change the wing shape safely and effectively without causing any risk. If those issues can be resolved, then, the future where "giant birds" can be seen roaming around and morphing their wings seamlessly in the air will not be too far away.

References

[1] S. Barbarino, O. Bilgen, R. M. Ajaj, M.I. Friswell, and D.J. Inman. (2011, June). A Review of Morphing Aircraft. *Journal of Intelligent Material Systems and Structures* [Online]. *22*, pp. 823-877. Available: http://michael.friswell.com/PDF_Files/J194.pdf

[2] T. Weisshaar. (2006, Oct. 1). Morphing Aircraft Technology – New Shapes for Aircraft Design. Aeronautics and Astronautics Department Purdue University West. Lafayette, Indiana. [Online]. Available: http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA479821

[3] E.A. Leylek and M.F. Costello. Benefits of Autonomous Morphing Aircraft in Loiter and Attack Missions. presented at AIAA Atmospheric Flight Mechanics Conference [Online]. Available: http://arc.aiaa.org/doi/abs/10.2514/6.2010-7507

[4] T.A. Weisshaar. (2013, April). Morphing Aircraft Systems: Historical Perspectives and Future Challenges. *Journal of Aircraft* [Online]. *50(2)*, pp. 337-353. Available: http://arc.aiaa.org/doi/abs/10.2514/1.C031456?journalCode=ja

[5] J. Fausz. (2010). *Morphing Flight: Beyond Irreducible Complexity [Online].* Available: https://www.apologeticspress.org/apPubPage.aspx?pub=1&issue=621

[6] W. Cole. (2002, May). *Technology That Enables Wing 'Warping' Rolled Out at Dryden* [Online]. Available: http://www.boeing.com/news/frontiers/archive/2002/may/i_pw.html

[7] NASA Dryden Flight Research Center. *Back to the Future: Active Aeroelastic Wing Flight Research* [Online]. Available: http://www.nasa.gov/centers/dryden/news/FactSheets/FS-061-DFRC.html

[8] P. M. Flick, M.H. Love, and P.S. Zink. (1999, October) The Impact of Active Aeroelastic Wing Technology on Conceptual Aircraft Design. *Strutural Aspects of flexible Aircraft Control.* Available: http://www.dtic.mil/dtic/tr/fulltext/u2/p010484.pdf

[9] An American Society of Mechanical Engineers. (2006, May). *Wing-Folding Mechanism of the Grumman Wildcat* [Online]. Available: http://files.asme.org/asmeorg/Communities/History/Landmarks/10382.pdf

[10] S. Simpson. (2008, May 05). *Swept-Wing Design and Function* [Online]. Available: http://www.helium.com/items/1025172-swept-wing-design-and-function

[11] *X-5* [Online]. Available: http://www1.nasa.gov/centers/dryden/news/FactSheets/FS-081-DFRC.html

[12] A. Bolonkin and G. Gilyard. (1999, October). Estimated Benefits of Variable-Geometry Wing Camber Control for Transport Aircraft. *Technical Memorandum, NASA Dryden Flight Research Center* [Online]. Available: http://www.nasa.gov/centers/dryden/pdf/88647main_H-2368.pdf

[13] A.R. Rodriguez. Morphing Aircraft Technology Survey. presented at 45th AIAA Aerospace Sciences Meeting and Exhibit [Online]. Available: http://arc.aiaa.org/doi/abs/10.2514/6.2007-1258

[14] K. Lu and S. Kota. (2003, June). Design of Compliant Mechanisms for Morphing Structural Shapes. *Journal of Intelligent Material Systems and Structures* [Online]. *14*, pp. 379-391. Available: http://www.seas.gwu.edu/~kjlu/papers/jimss03-KJLU.pdf

[15] K. Lu. (2004). Synthesis of Shape Morphing Compliant Mechanisms [Online]. Available: http://www-personal.umich.edu/~btrease/share/KJLU-Dissertation.pdf

[16] J. Fausz. (2010). *Morphing Flight: Beyond Irreducible Complexity* [Online]. Available: https://www.apologeticspress.org/apPubPage.aspx?pub=1&issue=621