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REVIEW ARTICLE

Current Morphing Wing Technologies and Their Development

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ABSTRACT: Morphing wings are aimed at taking aviation technology a step closer to the complex anatomy and structures of nature, improving aerodynamics, higher flight efficiency, as well as environmental benefits, and more. The promising potential has incentivized research on different types of morphing wings and their implementations on a range of models of aircraft. However, a wide range of technologies at different stages of development in the field is present. The Technology Readiness Level (TRL) scale is introduced to increase clarity within the field. The focus of this paper will be on current advancements of morphing wing technologies and assessing their development on the TRL scale to link experimental data to real-world feasibility. Breaking down advancements into smaller, tangible steps will assist in morphing wing technologies to achieve successful flight implementation.

KEYWORDS: Engineering, Aerospace, Morphing Wings, Technology Readiness Level.

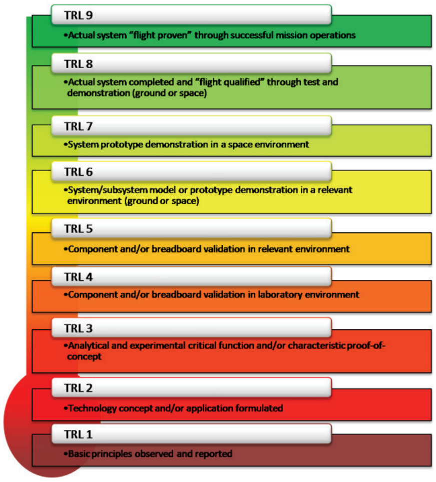
Introduction

Morphing wings are wings that are capable of changing shape during flight. This trait gives the wings high degrees of freedom, allowing for several conjugations. There is considerable potential for morphing wings, the three main benefits being adaptability, flight performance, and efficiency. The freedom allows for transformations in multiple possibilities, providing situational-specific solutions to a variety of challenges. The ability to change and adapt is key to solving problems with multiple subtasks. As current unchangeable aircraft wings are a compromise for performance, morphing wings can be tailored to maximize a desired characteristic to enhance performance.[1] By optimizing the shape for the specific flight condition, morphing wings can lead to a decrease in drag and improved aerodynamics, which reduces fuel costs and lowers emissions for a more sustainable environment.

With advanced vehicle testing systems like wind tunnel tests and computational fluid dynamics (CFD) simulations, researchers can break down their design and test specific parts without having to create a complex flying prototype, reducing the cost and time required for testing.[2] These approaches are restricted in their ability to represent real-world flight, as test conditions are controlled and do not account for variability like turbulence or weather. However, this comes with different analyses and interpretations of results for different researchers, leading to a variety of concepts and ideas without a systematic way to categorize or organize the development of technology within the field.

A potential application of the technology readiness level (TRL) system would be critical in counteracting nonstandard issues in the field. Many organizations use the TRL system to evaluate the development of a technology. The system ranges nine levels, from TRL 1 - 3 being basic concepts and characteristics formulated, TRL 4 - 6 showing prototype readiness in laboratory or relevant environments, and TRL 7-9 demonstrating actual systems in test environments or successful missions. Figure 1 shows the specific rubric for each level NASA uses.[3] This creates a clear benchmark for whether a technology is developed or ready for application.

In current literature, there is plenty of research on individual systems, like Kaygan *et al.*, analyzing the effect of twist morphing wings on aerodynamic performance and control with computational simulations.[4] Alternatively, Review papers tend to include a range of projects developed at different stages, ranging from concepts to functioning prototypes. With varying morphing technologies, successful implementation on flight at a larger scale has been limited, and the state of development is not clear. This paper will explore the current morphing wing technologies and assess them based on the TRL level rubric. The review of the paper is organized by the form of morphing, with section 2 on planform morphing, section 3 on out-of-plane morphing, section 4 on airfoil morphing, and section 5 on bio-inspired morphing. Section 6, discussions on challenges and further advancements will be presented. Finally, section 7 will focus on conclusions.



TRL 9
•Actual system "flight proven" through successful mission operations

TRL 8
•Actual system completed and "flight qualified" through test and demonstration (ground or space)

TRL 7
•System prototype demonstration in a space environment

TRL 6
•System/subsystem model or prototype demonstration in a relevant environment (ground or space)

TRL 5
•Component and/or breadboard validation in relevant environment

TRL 4
•Component and/or breadboard validation in laboratory environment

TRL 3
•Analytical and experimental critical function and/or characteristic proof-of-concept

TRL 2
•Technology concept and/or application formulated

TRL 1
•Basic principles observed and reported

Figure 1: The specific TRL rubric implemented by NASA to assess the readiness of developing technologies. Detailed requirements for each level are specified. [3]

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■ Planform Morphing

Planform morphing is the change in shape of the wings along the horizontal plane of an aircraft. This includes span, chord, and sweep. Across span, chord, and sweep, structural stability and a material durable yet flexible enough for morphing is the bottleneck of development.

Span:

Span morphing refers to the change of wingspan. Wingspan directly influences efficiency and maneuverability of the plane; with a longer wingspan, there is more lift, beneficial for longer and more efficient flights, however is not as agile in movement; with a shorter wingspan, maneuverability for sharp movements makes up for the lack of efficiency. There are two main methods to achieve the extended wing span: 1) adding extra panels or by moving the whole wing outwards, and 2) designing an airfoil that is capable of extending and contracting without additional materials.

Bae *et al.* utilized a moving wing box on the wings of missiles that were able to reach a 50% span extension through additional wing sections.[5] Through aerodynamic investigations and aeroelastic analysis, a reduction in induced drag was achieved; however, at extended states, the structure of the wings was not able to withstand deformation caused by external pressure, leading to aeroelastic instability. Further developments of this technology required are structural testing and the actuation system. With the concept working in analysis, major problems still exist and are identified; this technology demonstrates a TRL level 3.

The Gear driveN Autonomous Twin Spar (GNATSpar) developed by Ajaj *et al.* is a UAV with overlapping wings stowed in the main body during contraction and utilizes a double-sided rack and pinion actuation system with a self-lock mechanism to extend the wing core.[6] The wings were able to extend to 20%. For the wing cover, latex was used, as it withstands the extension and keeps an aerodynamic shape. The self-lock mechanism allows for no extra energy required to overcome the elastic forces of the skin, making the actuation system more efficient. Through wind tunnel testing, the UAV achieved better aerodynamic efficiency. However, it is limited to speeds of 20 meters per second, with wing deformation and flutter occurring past that speed. Further tests should focus on finding rigid skin materials that allow for the wings to extend without changing the airfoil shape. The GNATSpar did not have other flight systems, focusing solely on the morphing wings. This technology would fall on level 4, where the components of the morphing wings were put to test in a laboratory environment.

Vocke *et al.* designed a planar core wing that allowed for 100% extension.[7] The skin of the wing used an elastomeric matrix composite skin, which was able to withstand the extension. During wind tunnel testing, the wing was able to hold up to 130 km/h with a maximum deflection of 0.93%, successfully holding its shape. This research was solely focused on developing a wing to achieve an extension that doubles the length. The testing results might change if the wings were attached to a fuselage or added with an actuation system. Whether the base would be strong enough to hold deformations and flutter will be worth further investigation. The technology development reflects a level 4, as the component was able to achieve successful testing in a laboratory environment.

Chord:

Chord length is the distance of the airfoil from the leading edge to the trailing edge. It is hard to alter the center of the wing, as other systems like the fuel tank and engines are based there. Therefore, developments of chord morphing tend to fall into either leading-edge or trailing-edge morphing, like slats, slots, and flaps, to avoid the other structures on the wings.[8] These are considered control systems, where the result of plane movement is achieved through changing the wing structure. During flight phases like takeoff and landing, where flying speeds are slower, it is harder to generate lift, as lift is directly related to the speed of airflow over the wings.[9] These technologies allow the plane to take off and land more efficiently over shorter distances to meet airport requirements.

Slats and flaps increase the lift of the wing by enabling a smoother flow of wind over the wings. Slats are on the leading edge of the wing, able to extend forward and downward, increasing the wing and camber area. They can increase the angle of attack without airflow separating from the wing, which prevents stalling. The extension creates a gap called a slot, which allows for wind to flow from below to over the wing, acting as a boundary layer and preventing airflow separation. Flaps are on the trailing edge of the wing and extend the camber area, increasing the downward airflow that produces extra lift. Unlike slats, flaps also increase drag as the extension downwards creates a greater surface area from the front. This is useful during landing, as the plane's speed decreases, but lift has to be controlled for a smooth landing.[10]

Both of these systems have been implemented on many plane models, being the fundamental systems for aviation control. The TRL level for this system would be 9, as it has demonstrated successful flight in multiple missions in the real-world scenario.

Sweep:

Sweep refers to the change in angle of the wings relative to the fuselage, where planes are able to sweep their wings back and forth for the desired performance. Typically, sweeping wings are not found on commercial aircraft due to the location of the jet engine, as changing that angle would alter the direction of thrust. Sweep wings are also less effective in slower speed flights, making it more appealing to supersonic aircraft.

When changing the angle of the sweep, airflow over the wings is altered into two different directions, spanwise and chordwise. This is critical for delaying shock wave formations and reducing wave drag at high speeds. Although straight wings can achieve supersonic flight, swept wings are more efficient. By sweeping the wings backwards, the center of gravity and aerodynamic center are changed, which affects its lift and also stability, especially in the longitudinal aspect. Tradeoffs for the sweep wings include reduced lift and undesired stall characteristics where the airflow separates from the wings.

The technology is especially appealing to fighter jets, as swept-back wings during supersonic flight allow for more efficient high speeds, and do not lose the quick, agile maneuverability for lower subsonic dogfights. Examples of this include the F-111 Aardvark, F-14 Tomcat, MiG-23 Flogger, and Panavia Tornado.

Development done under the program Next Generation Morphing Aircraft Structures has driven advancements of morphing wing technologies like Morphing Flight-vehicle Experimental (MFX-1), which has been able to achieve flight and change the geometry of its wings during flight.[11] The actuation system was able to change the wing area by 40 percent, the wing span by 30 percent, and the sweep from 15 to 35 degrees. The UAV achieved speeds up to 120 knots and an altitude up to 600 feet. This demonstrates a TRL level of 8, as the system was able to achieve flight in a real-world scenario. The program is looking to expand the scope of the plane, increasing the size of the plane and reducing morphing durations.

The Oblique wing has been a theoretical design without much advancement in testing, with the main concern being that it is a big change in structure. The design of the planes is fundamentally different from normal wings, where symmetry is abandoned for a more aerodynamic flight, as shown in Figure 2.[12] Especially for planes that fly in both subsonic and supersonic, the desired conditions of a plane are much different during each phase of flight. In theory, the less surface of the rotated wing will reduce drag at high speeds, while maintaining the same center of lift and gravity. This is key as the less difference there is between different states, the smoother transitions and better control. With the center of the oblique wing being the only rotating joint compared to variable sweep, where there are two rotating joints, it is a more straightforward design. This theory was tested out by NASA's AD-1 Oblique Wing, successfully demonstrating the possibility of the concept. However, it was not able to achieve the main goal of reaching supersonic speeds, and flight controls at extreme sweep angles were difficult. Developments have since been paused, as most aviation companies are conservative, especially the commercial industry, as businesses tend to keep the same designs with small improvements to ensure safety and consistency, rather than investing money into a new, developing idea.

Figure 2: NASA's AD AD-1 Oblique Wing that altered the angle of the wings for more aerodynamic flight. The picture shows the plane undergoing test flight, successfully achieving morphing.[12]

Out-of-plane Morphing

Out-of-plane morphing is the change in shape of the wings across the other degrees of freedom. This includes twist, dihedral/gull, spanwise bending, wing folding, and flapping wings. Structural complexity and the conflict with other systems located in the wings are hurdles each technique under out-of-plane morphing has to navigate.

Twist:

Twist morphing is the ability for wings to change their angle of attack while maintaining the same airfoil shape. From the past, this has been viewed as an undesired structural problem, as structural rigidity in the wings was desired. Now, being able to control the flexibility of twist is the goal. Most of the studies on Twist have been focused on roll control, with many comparisons with the current aileron's performance.

Aeroelastic analysis done by Pecora *et al.* was able to show that, through wing twisting, roll rates were 1.6 times greater than ailerons.[13] However, as this is only data analysis, further research on actuator systems and aeromechanical tests is still required for practical implementation. This concept would demonstrate a TRL level of 3, where there is proof of concept, but it still needs further investigation to develop it into a working prototype.

Rodrigue *et al.* were able to design a UAV that utilized shape memory alloy wires at the base of the wing, functioning as an actuation system to change the angle of the wings.[14] Through wind tunnel testing, the wing was able to create lift at low angles of attack, where traditional wings are unable to do so. However, as their paper identifies, this is only focused on a specific section of the wing. This shows a TRL level 4, as a component is tested in a laboratory environment.

Dihedral/gull/spanwise bending:

Dihedral morphing, which is the morphing of the angle of the wings from the horizontal plane, with gull and spanwise being similar changes to the wings. This type of morphing is inspired by birds, as they are able to change the structure of their wings through multiple joints to achieve aerodynamic efficiency. However, this is harder to achieve, as structural complexity is a big challenge due to the high degrees of freedom and multiple joints needed for the desired movement. As shown in Figure 3, there are multiple conjugations of the wings.

Studies done at the University of Florida by Abdulrahim and Lind designed a flying UAV prototype with variable gull wings.[15] The wings are made out of carbon fiber and controlled by a rotary servo that was able to go through angle changes up to 40 degrees relative to the fuselage. The focus of the paper was on flight testing, especially stability. Characteristics like roll, climb, and stall were analyzed, and the gull wings were able to improve controls. Further investigations on flight in the real-world scenario should be done, but the current prototype shows a level 6 on the TRL scale.

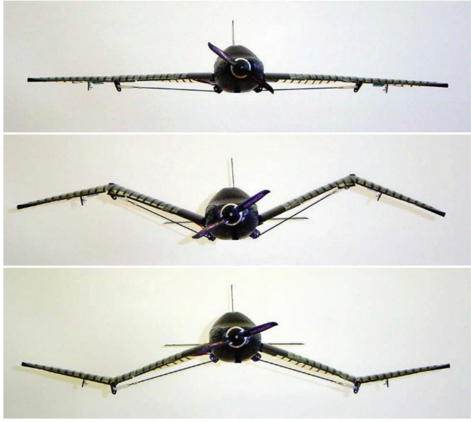

Figure 3: The front angle of the wing going through gull morphing. The plane achieved various configurations and improved flight control.[15]

Wing Folding:

Folding wingtips are an emerging concept that is being introduced into commercial aviation, notably the Boeing 777x, which utilizes this technique. As the name suggests, folding wingtips can fold up when entering space-restricted areas like runways or boarding gates and expand during flight. This is beneficial, as longer wingspans are correlated with higher lift and reduced drag, which can improve the efficiency of flight.[1]

Folding wings have been developed in the military industry for much longer than commercial aviation, with fighter jets like the F/A-18E Hornet utilizing this technique. However, the purpose of the folding wings is not to improve flight performance; rather, it is to allow aircraft carriers to store more jets on deck, where space is very limited. As fighter jets are very complex in design, this technique is mainly used for naval aircraft carrier planes, where space is a constraint.

Hui *et al.* created a bio-inspired UAV that utilizes a folding wing that resembles the wing structure and surface of a pigeon wing.[16] The rectangular wing is connected to the fuselage on one side, and the other has eight bionic feathers attached. The feathers can extend and fold over, reducing drag, increasing lateral stability, and decreasing wing-tip vortex strength. However, the testing is limited to wind tunnel testing, with the focus of the paper on aeroelastic analysis, the UAV is yet to take flight, showing a development of TRL level 3.

■ Airfoil Morphing

Airfoil morphing is the change of the shape of the airfoil or the cross-section of the wing. The two key components of airfoil morphing are the camber and thickness, camber being the curvature of the wing, and thickness being the height of the airfoil. Most developments alter both components together to produce the maximum benefit of aerodynamic efficiency.

NASA and the U.S. Air Force Research Laboratory (AFRL) partnered to develop the Gulfstream GIII Business Jet, which achieved successful flight tests. The plane design utilizes the FlexFoil™ technology developed by FlexSys Inc., where the edge of the wing could reach a change from -9 to 40 degrees, shown in Figure 4. The key to this morphing is that the whole wing is continuous, creating a smooth flow for the wind. The use of a shape memory alloy from composite materials has been an interesting study area due to its lightweight characteristics and simple mechanics, compared to conventional hydraulic pistons. This allows for less drag and better endurance of the plane.[17] Through analysis, the new flap designs have an 8 to 12 % improvement in fuel efficiency. The technology shows a TRL 8, with flight tests being achieved.

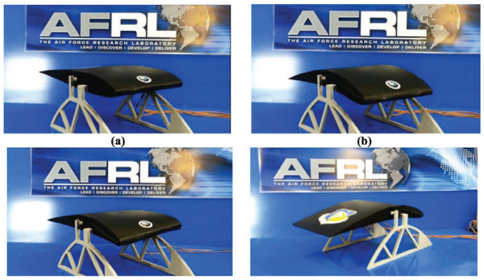

Figure 4: The morphing airfoil design by FlexSys Inc. being researched at the U.S. Air Force Research Laboratory, showing the capabilities of shape memory alloys in airfoil profile change. [17]

■ Bio-inspired

Most morphing concepts are bio-inspired; however, birds often couple many morphing technologies together to achieve the maximal benefit. The section below will discuss some bio-inspired morphing that fits into multiple categories. The technologies included in this section are flapping wings and bird drones.

Flapping wings are an emerging technology utilizing flapping wings inspired by insects, bugs, birds, and other animals of nature. Plane developments have separated thrust and lift into two different systems, with the wings providing lift and the engine producing thrust; however, birds generate both thrust and lift with their wings alone. While current plane systems are more efficient in high-speed flight, the ability of birds to make quick, agile, and precise movements is worth investigating. This technology has been focused on implementation on micro air vehicles (MAVs) or drones, having potential applications for information gathering and surveillance.

The DelFly Nimble is a 29-gram robot that has adopted flapping wings and achieved flight.[18] The robot has two independent wings that can change dihedral angles to maintain stability. The movement of the robot was also able to be controlled by a remote. Despite its lightweight, it is highly agile and is able to function in outdoor scenarios, accommodating light winds. DelFly Nimle has successfully achieved flight, although it still requires work on incorporating other systems to fulfill the ultimate goal of performing real-world tasks. The development is on level 7, where the robot has been demonstrated in an operational environment.

A key reason that separates the maneuverability of birds from that of planes is their ability to utilize different parts of their body.[19] Birds not only change their wings, but also their tail, and twisting also plays a role in their quick, agile cuts. Figure 5 shows the EPFL Raptor-inspired drone designed by Ajanic *et al.*, mimicking the structure of a bird, with artificial feathers at the tips of the wings capable of extension and retraction. The tail also used a similar feather design, having multiple degrees of freedom to tuck, sweep, and change angles. Each degree of freedom was independent, which is useful when paired with the Bayesian learning system; the plane found the most efficient way to fly up to 11%. The team also tested the drone's ability to react to the failure of actuation systems, as they shut off a section on both wings. The drone was able to find an alternative solution and maintain stable flight. The drone was also tested in an open environment, able to fly and able to maneuver effectively. The overall development shows a level 7.

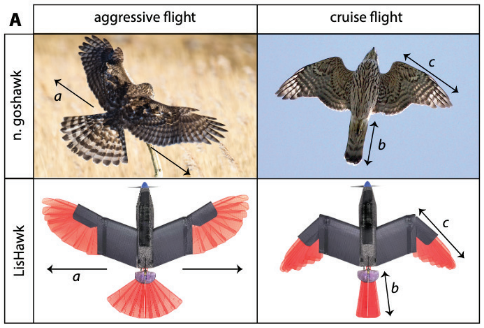

Figure 5: EPFL Raptor-inspired Drone designed after birds, having multiple degrees of freedom and capable of moving to achieve best aerodynamic efficiency.[19]

Discussion

The major challenges faced by morphing technologies will be discussed in this section.

When undergoing morphing, a significant amount of stress and elastic energy is stored in the structures. This requires additional energy to keep the rigid shape, or else structural failure and deformations could arise.[5, 6] One of the main goals of morphing wings is to be more efficient, with maintenance and flight efficiency. As materials are being developed, it is not certain that they are able to support the needs or morphing. In many tests, structural weakness leads to flutter and deformations, as it can not withstand the stress from multiple different sources. This is crucial in testing to couple different methods to actually reflect the state of development. Further research on structurally rigid yet lightweight materials would contribute to the field.

Flexible skins are important in creating the shape of the airfoil. It has to be soft enough to change shape, yet rigid enough to hold the change in an extended position. As naturally elastic energy builds up when going through deformations, many studies have faced the problem of not having a flexible skin that pairs well with the core extension technology.[6] Another issue with flexible skins is the durability, as the materials are subjected to numerous changes, leading to potential safety issues of potential failures. Consistency over an extended period of time creates another potential issue. Current prototypes often focus on the structural development and not necessarily the skin, compromising with what is convenient. Like Vocke *et al.* developing composite skin material, further research in the material science field, where skins complement and do not limit the performance of the plane, would advance the development faster.[7]

Most designs and technologies have focused on smaller UAV flights, and only a few have achieved real-world flight.[11,14-16] The effectiveness of systems when implemented on larger planes is unknown. Not only is the scalability of the plane, when the design is taken out of the lab environment into the air for real flight, but there is a lot of variability in the interaction with the environment. Taking testing of concepts one step further to a real-world environment is a tangible goal for many designs, with the TRL levels 4-6 to reach the levels of 7-9.

Actuation systems are also an underinvestigated area in morphing wings. Current developments focus on achieving transformations and achieving maximum aerodynamic efficiency, which disregards the importance of a reliable control system that controls all these adjustments and movements. With the new technology of artificial intelligence, machine learning, and deep learning, research on implementations to calculate the maximum efficiency of flight would be a breakthrough advancement, like on the EPFL Raptor.[19] Another area of research would be on energy reduction. As explored in the GNATSpar, current actuation systems require much energy.[6] Finding a more efficient way to control could be investigated in detail.

Conclusion

This review paper presented different morphing techniques and assessed the development utilizing the TRL scale to clarify the advancement of each technology within the field. Implementation of a scale indicates progress checkpoints and breaks development into more comprehensive and tangible goals to achieve. For example, a concept tested by computational simulations at a TRL of 3 could set a goal to develop a prototype of the component and test it in the laboratory to reach the next development level. This could aid fields where multiple ongoing research projects are happening at different stages.

As of the current field, planform morphing is the most researched form of morphing, with many published papers. Evident with the multiple TRL level 9 technologies, planform is a straightforward movement and is less complex compared to other morphing forms. With fewer structural constraints, it allows for bigger transformations, creating the biggest aerodynamic effect during flight. Contrastingly, out-of-plane morphing has been less explored, with structural complexity being a major limitation; applications of these technologies would require large amounts of change in existing structures. Airfoil morphing has been studied with different scale concepts or shape memory alloys. However, many components in the wing need to be taken into account for large aircraft.

With plenty of potential for morphing techniques, different insights are frequently presented to the field. Since current systems are tailored for coordination between parts, applying these new concepts is challenging without constructing a completely new prototype, which introduces numerous other problems. This leads to incomplete and partial testing, which is evident by the multiple TRL levels 3-5 that show successful components and concepts, but limited fully working prototypes. This poses the question of whether there is a more efficient way for testing, as a lot of limitations and challenges discussed in the discussion section stem from the fragmentary testing.

To link the gap between laboratory testing and achieving real-world flight, multiple tests should be used in the process of developing a working prototype. Coupling aerodynamic tests with structural, actuation, and control tests will allow for a more rounded assessment of the readiness of the technology, identifying areas that are needed for development. Implementing this would better clarify the state of development and state a clear problem to fix to achieve flight.

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