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A SUMMARY OF CUTTING-EDGE RESEARCH ON MORPHING AIRPLANE BASED ON INTELLIGENT MATERIALS AND STRUCTURES

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Abstract. This article reviews current innovations in the use of intelligent materials and structures for morphing airplane covering specific applications of actuators, sensors, and controllers. Morphing refers to a gradual transformation of an object's appearance or form. In the past, electrical actuators were used to do morphing; now, advanced materials like SMA and piezoelectric materials are used. A typical aircraft's flying envelope is designed to be optimized for just one or two flight conditions, not for all of them. A bird's wings, on the other hand, can be repositioned to fly optimally in any situation. Aerodynamic performance can be improved by making modifications to the aircraft wing, and it is possible to find the best configurations for any flight scenario. A wide range of flight conditions can be improved using morphing technology. It is assumed that extra weight of the morphing components is considered acceptable in order to justify the strengths of a morphing aircraft. Modern mechanical and hydraulic technologies are not thought to be the best options for morphing aircraft. The benefits of "smart" materials and constructions include their high energy density, controllability, variable stiffness, and capacity to withstand significant strain. These characteristics equip researchers and designers with novel design ideas for morphing aircraft.

Keywords: Bird’s wings, Morphing Airplane, Piezoelectric, Smart structures

1. INTRODUCTION

Morphing in aviation refers to the process where the external shape of a vehicle is altered by deforming its skin or structure. This allows the aircraft to adjust to different flight conditions and enhance its performance, such as reducing air resistance and increasing fuel efficiency. The technology can be used on various parts of the aircraft, such as the wings, flaps, and control surfaces, and allows them to change shape during flight. Morphing is not only used in aviation, but has also been applied to other types of vehicles, such as cars and spacecraft, for similar benefits.

The use of this technology slowed down after that time because traditional control structures were simple enough. Recently, with the optimization of conventional control surfaces reaching its limits and advancements in numerical analysis, the idea of using morphing has reemerged as a way to improve efficiency in the field of aviation research. Morphing technologies can be categorized based on the type of deformation they produce on the wing. Different types of morphing exist, each creating a unique type of change in the wing's shape. The type of deformation produced on the wing can vary, and the wing can undergo planar deformation, out-of-plane transformation, or change in aerodynamic surface profile, depending on the type of morphing technology used. Titanium was used to manufacture the complete wing structure, including the wing box, wing pivots, and wing skins.

One of the properties of piezoelectric material is that, application of electric current causes a change in the dimension of the material and vice versa. A sensor can be made with this characteristic. By installing piezoelectric sensors within the structure or on its exterior, internal structural degradation can be identified using ultrasound and sound. In order to regulate the motion of a multi-stable structure, piezoelectric sensors have been employed to track the load and deformation bifurcations. The velocity of a morphing structure can also be measured using this kind of sensor. Abdullah EJ, Bil C, and Watkins S[1] worked together to evaluate the effectiveness of using shape memory alloy actuators to improve the functionality of UAV-specific adaptive airfoil control systems. Airoldi A, Crespi M, Quaranta G[2] worked on creating a morphing airfoil that integrates a composite chiral structure in its design.

Depending on the variable dimension, a wing's degree of morphing can be categorized as large, medium, or small. The large group includes deployable wings, variable-span wings, variable-sweep wings, and folding wings. Medium range includes variable-chord wings, variable-camber wings, flexible winglets, and twisting wings. The tiny category includes bulging wings and variable-airfoil wings. There are few advantages of the aircraft with morphing technology over the fixed-geometry aircraft which includes the design of a multi-mission aircraft with superior performance in multiple flight conditions. Adding foldable and variable-sweep wings to a fighter can significantly enhance the flight envelope and lower the aircraft's fuel consumption while still providing good performance at all speeds.

Ajaj RM, Friswell MI, Flores EIS, et al.[3] conducted a cognitive investigation into span morphing as part of their design study. Shorter takeoff distances are possible for airplane with variable chord or variable camber wings. Low-speed aircraft can perform better aerodynamically with twisting wings, flexible winglets, and variable-span wings. Span-wise morphing offers fuel efficiency benefits. To satisfy its varied requirements, different morphing stages need for different kinds of materials and structures. Prabhakar et al.[4] showcased a variable-span, variable-sweep morphing UAV through their design and dynamic analysis. Similarly, Santos [5] developed and experimented with a variable-span wing, demonstrating enhanced aerodynamics compared to a standard fixed wing, particularly at higher speeds. Variable sweep, predominantly employed in military fighter aircraft to attain increased supersonic cruising velocities, has been implemented in aircraft designs like the MIG-23 and F-14. By modifying the wing's twist, twist morphing reduces both "wash-in" and "wash-out" and changes the lift distribution along the wing's span. One kind of morphing wing design that can significantly change the wing area is the folding wing. An aircraft with foldable wings was tested in a wind tunnel by Lockheed Martin [6] in 2007. Furthermore, the feasibility of using light weight materials to bend the outer segments of aircraft wings and their control surfaces in order to obtain ideal angles during flight was confirmed by NASA's Span wise Adaptive Wing (SAW) project [7].In the investigation of aerodynamic properties, the leading edge, trailing edge, thickness, and other associated features have been the main focus of either two-dimensional morphing airfoils or three-dimensional airfoils [8]. However, little research has been done on the aerodynamic characteristics unique to larger folding designs, including Z-shaped folding wings. A dynamic meshing technique to study the aerodynamic traits of NACA 0012 airfoils and three-dimensional wings equipped with morphing trailing edges has been performed [9]. A semi-passive morphing airfoil concept [10] that relies on bending-torsion coupling, achieved through adaptive shear center positioning and torsional stiffness.

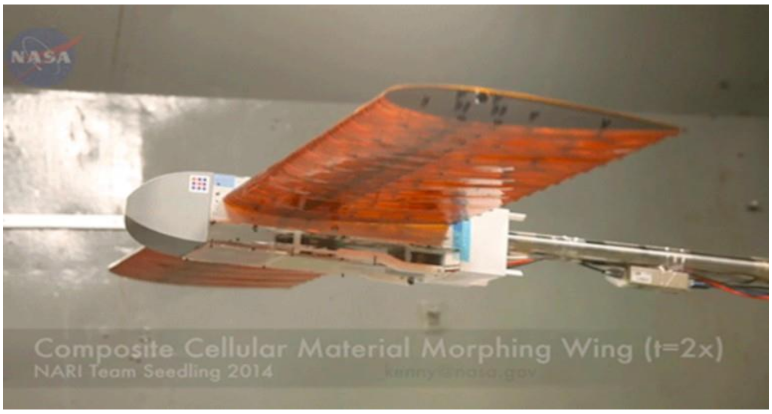

Figure 1 Overview of the NASA, morphing wing model

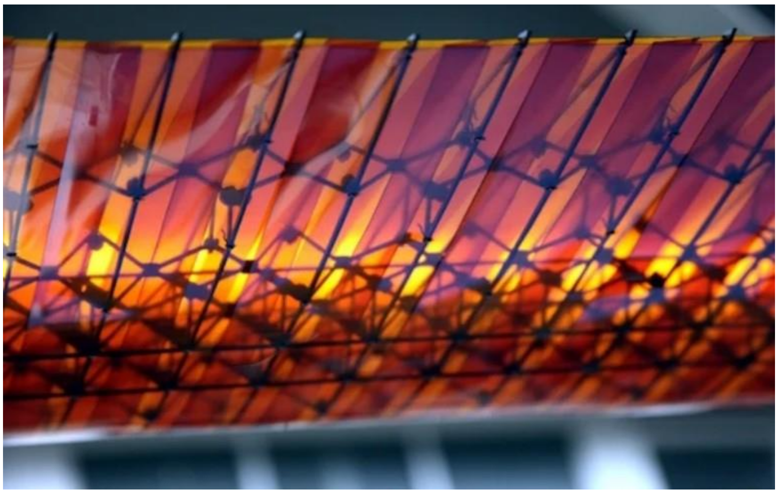

Figure 2: NASA, morphing wing structure

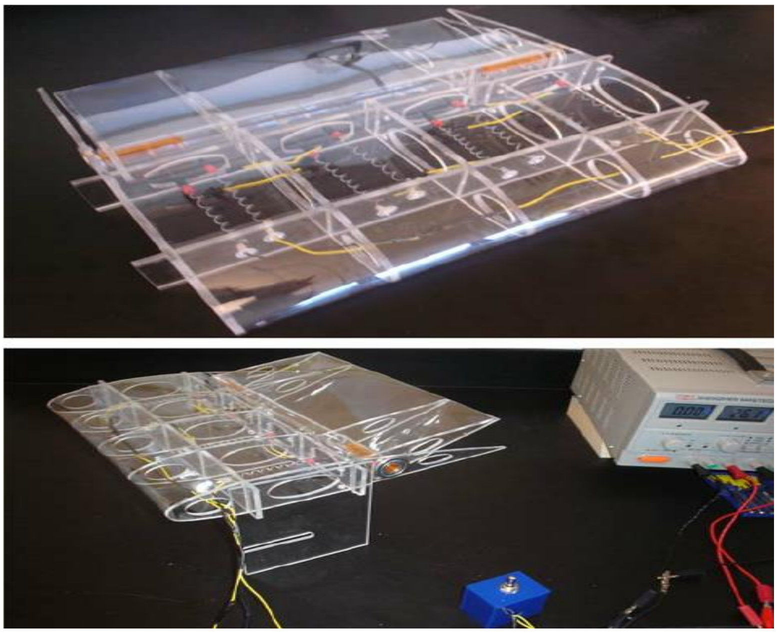

Figure 3: Smart wing structure

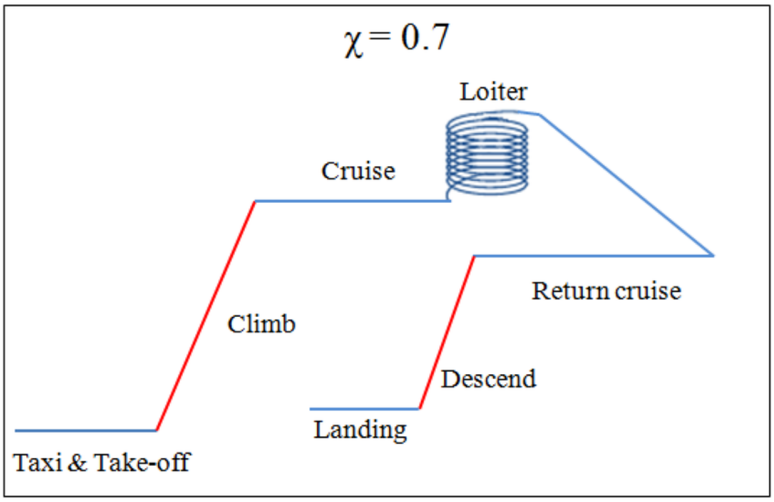

Figure 4: Mission Profile of Surveillance UAV

2. MATERIALS AND METHODS

The introduction of intelligent materials substantially aided the morphing technology, leading to a more straightforward, lightweight, and reliable structural design. Characterising "smart" materials is difficult. Because they can adjust to changes in their surroundings, smart materials are "living," as opposed to static, or "dead," materials [12]. Thus, smart materials are both structural and active materials. Heat, light, heat waves, electricity, magnetism, strain, and microwave radiation are some of the stimuli. Currently, smart materials include SMA, SMP, electro-active polymers, optical fibres, electro- and magneto-rheological fluids, ferroelectric, piezoelectric, and magneto-strictive materials, as well as multifunctional nanocomposites. Smart structures include corrugated structures, variable-stiffness tubes, auxetic honeycombs, and multi-stable structures.

Usually, smart materials and structures form a smart system. Figure 1 shows how intelligent materials and structures, similar to those found in humans, may perceive their surroundings, send a chemical or physical reaction to the brain for decision-making (control), and then use their muscles to carry out activities (actuation). Ligaments and fibrous bands connect each part (structures), and the nerves carry the information. Among the many special qualities of smart materials is shape memory, which is the capacity to return to a particular shape following deformation. Sensitivity to external stimuli like light, heat, magnetic fields, or stress, Self-healing: the capacity to fix damage or fissures by themselves, the capacity to conduct electricity is known as conductivity, Sensing: ability to detect and respond to changes in their environment, Actuation: ability to produce movement or mechanical action as a result of a stimulus. The key characteristics of smart materials and structures include self-sensing, which allows the system to produce electric or magnetic signals in response to environmental changes or undergo strain that can be measured to characterize the environment [13], and self-actuating, which, when activated, automatically produces an output such as a force, displacement, heat, or light [12] and self-adaptive—the system has the ability to modify its geometry in response to its surroundings [14].

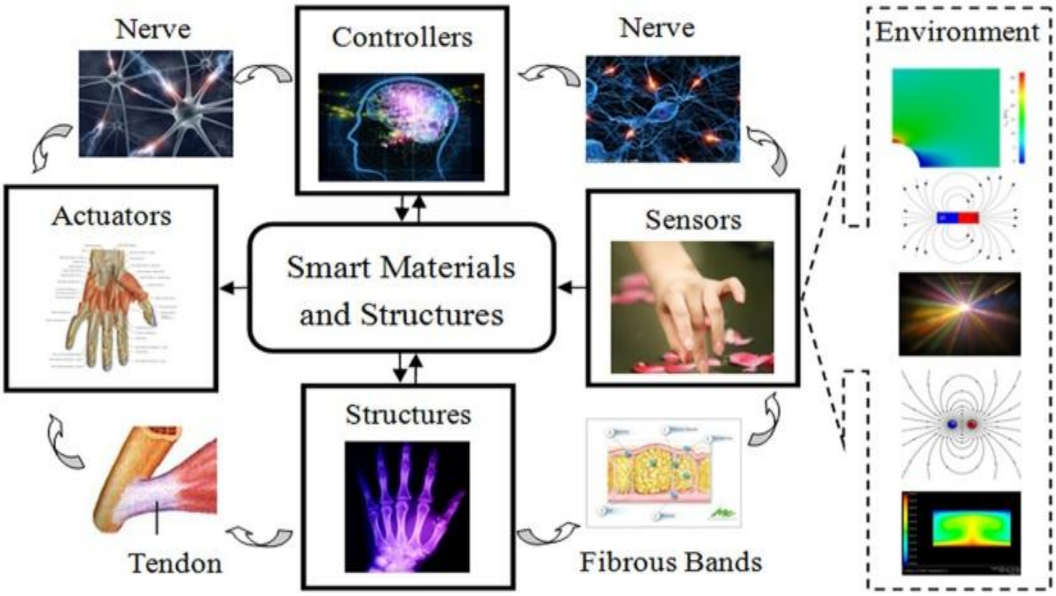

Figure 4. Smart materials and structures

2.1 Shape memory alloys

The shape memory effect refers to the capacity of metallic alloys such as NiTi, NiTiCu, and CuAlNi to resume their original shape after deformation when heated. The transition points are the austenite start and finish temperatures (A_s and A_f) and the martensitic start and finish temperatures (M_s and M_f). During a training cycle, a SMA acquires a stabilized strain that can be recovered at temperatures higher than Mild steel. SMA can work even under high applied loads and enormous inelastic deformations because of its super-elasticity, which allows it to resist high stresses without failing or undergoing plastic deformation [15]. High output forces, high energy densities, huge recoverable strains, controllability, and the ability to produce both one-way and two-way memory effects make SMA highly desired for actuators. Aerospace morphing structures already make extensive use of SMA. SMAs are most recognized for their use in a Boeing commercial airplane's engine nozzle to lower jet noise [16]. The Boeing Company and Texas A&M University conducted extensive simulations and theoretical work [17]. Variable-geometry chevrons, which were mounted on a 777-300 model with GE-115B engines and activated by a SMA, underwent full-scale flight tests in August 2005. Figure 5 displays photos of the chevrons. The findings showed that there was a noticeable decrease in cruising noise. The fan stream and free stream air are better mixed due to the chevrons.

The wing geometry can also be changed with SMA actuators. Research has been done on a variable-sweep wing on the spar that is managed by SMA.To increase lift, a morphing trailing edge was created using SMA wire in a number of additional. There have been several studies on segmented morphing trailing-edge concepts that result in a greater trailing-edge angle. To improve the lift-to-drag ratio, a similar strategy can be applied to the leading edge. Using SMA actuators, Cornell University created a Hyper-Elliptic Cambered Span wing.By improving yaw control when in the furled condition, this morphing wingtip can significantly increase maneuverability. Groups of SMA actuators have been used to create a morphing-airfoil wing for subsonic cruise flight conditions. Under quasi-constant lift conditions, the drag in wind tunnel trials decreased from 14.5% to 26.7%, with an average of 18.5%. SMA torque tube actuators have been used to provide helicopters with nearly ideal blade twist in hover and cruise flying situations. SMA actuators have also been used in bionic flapping wings.

Figure 5. Full-scale flight tests of SMA-actuated variable-geometry chevrons on a Boeing 777-300ER

2.2 Piezoelectric materials

One recent development in history is the discovery of piezoelectric materials. Although the hypothesis of piezoelectric materials was developed in the 18th century, formal discovery of these materials did not occur until the 19th century. In 1880, the Curie brothers made the discovery of a crystal exhibiting piezoelectric characteristics. Applying a voltage to a piezoelectric material can result in strain of up to 0.1% [18]. Piezoelectric stack actuator can be created by stacking layers of these crystals. Piezoelectric composites can be created by combining piezoelectric fibers with matrix. Larger strains and different motions can be produced by these composites. The shape memory effect refers to the capacity of metallic alloys such as NiTi, NiTiCu, and CuAlNi to resume their original shape after deformation when heated.

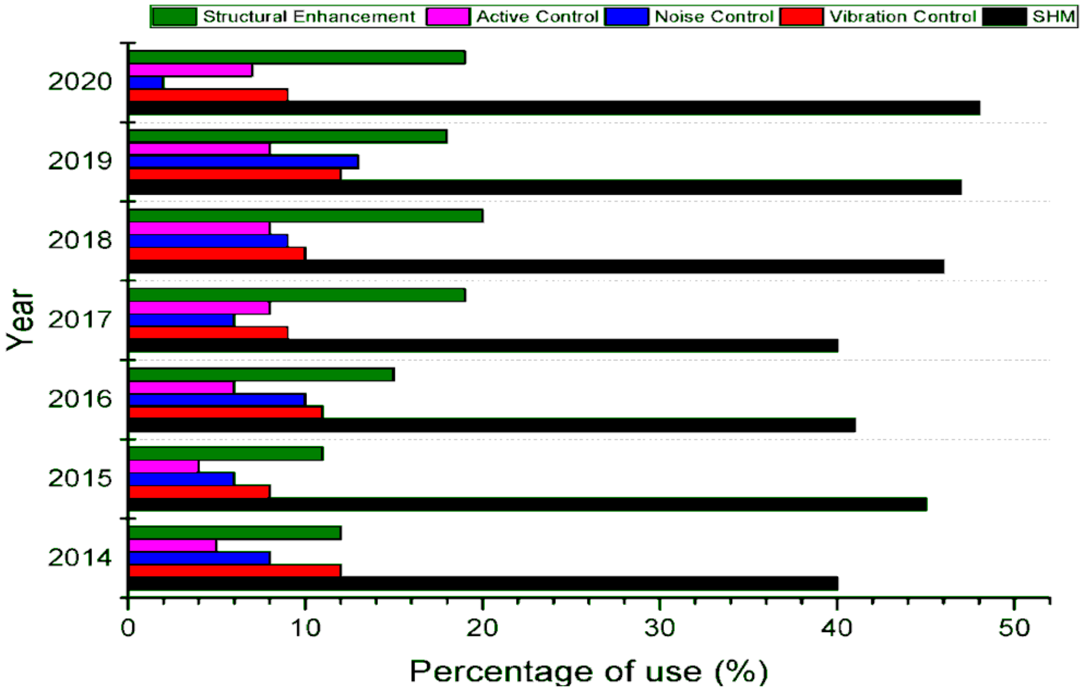

Figure 6. Trends in piezoelectric research [19]

2.2.1 Natural Piezoelectric materials

In general, piezoelectric materials fall into two categories: crystalline and non-crystalline. Some naturally occurring minerals, such as tourmaline, quartz, and Rochelle salt, possess piezoelectric properties. Additionally, there are also non-crystalline materials that display piezoelectricity, including silk, certain types of wood, rubber, and bone among others. What all of these materials have in common is that when a stress is applied, it results in a net polarization of the material's structure.

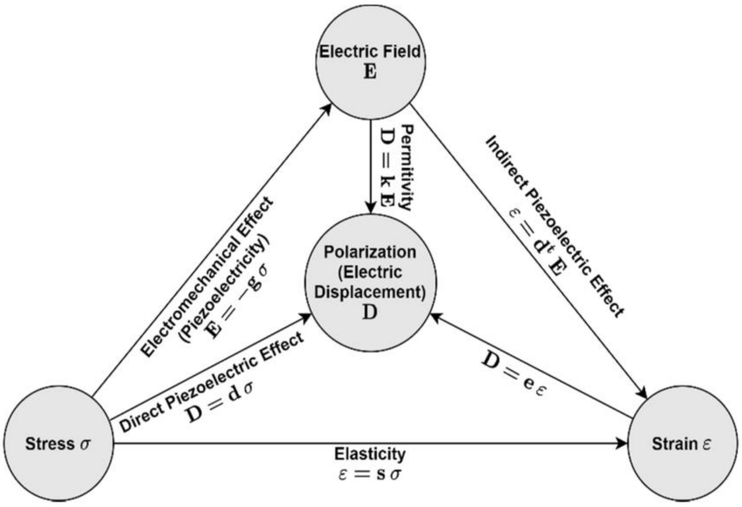

Figure 7: Voltage –stress strain for piezoelectric materials [19]

2.2.2 Synthetic piezoelectric materials

Synthetic piezoelectric materials, on the other hand, are not naturally occurring and have been created through human effort to attain mechanical and piezoelectric properties that are absent in natural piezoelectric materials. Most synthetic piezoelectric materials are ferroelectric ceramics. Some of the most commonly used synthetic piezoelectric material include: Lead Zirconate Titanate (PZT), Barium Titanate (BaTiO3), Lead Metaniobate (PMN), Lead Lanthanum Zirconate Titanate (PLZT) and the list of materials may not be exhaustive and the relevance of each material may vary depending on the specific application.

2.2.3 Piezoelectric ceramics

Piezoelectric ceramics have been utili sed to power hydraulic pumps due to their high frequency responses and huge output forces. The following is the operating concept. One-way valves connect a hydraulic system to a chamber that has an inlet and an outlet. In response to a periodic voltage, the piezoelectric ceramic actuator cyclically alters the chamber's volume by moving a metal membrane. The liquid moves from the intake to the outlet due to the pressure differential [20]. In the stopped condition, these pumps have reached maximum flow rates of 2300 cc/min and output pressures surpassing 200 bar. A remotely piloted vehicle's morphing wing effectively employed a piezoelectric hydraulic pump in order to enhance vibration, noise, and aerodynamic performance, piezoelectric ceramics have also been utilised as linear actuators in helicopter rotor systems. Raising the output of piezoelectric ceramic actuators—whose maximum extension strain is currently barely 0.1%—would be a significant technological advancement. As seen in Figure 4, a BK117 S7045 prototype.Aircraft in Europe successfully employed a variety of piezoelectric actuator types, including the O type, the L-L type [21], and the X-type actuators. According to the results, installing an active-flap rotor reduced vibrations by up to 90%, to less than 0.05 g. In order to quickly and precisely control the configuration of a morphing structure, several researchers have developed piezoelectric actuators based on a "step and repeat" driving strategy, which means actuators generate displacement pulses by repeatedly performing motions in an insistent manner. This results in larger linear displacements and larger output forces [22].

2.2.4 Piezoelectric composites

Piezoelectric composites have been used to lessen vibration and noise in helicopter rotors. Flight testing has demonstrated the viability of these designs. Piezoelectric composites were used in several experiments to alter the lift, drag, and pitching moment of a micro air vehicle's (MAV) wings by altering its camber [23]. By altering the trailing edge close to the wingtips, roll and pitch were managed. A MAV using piezoelectric composites to control the elevators was constructed and tested in a wind tunnel [24]. In a different investigation, the composites were included into a flexible flapping wing at 20° pitch angles, 10 m/s flow velocity, and an 8 Hz flapping frequency to change the camber and increase lift by up to 20.8%.

2.2.5 Shape memory polymers

A shape memory polymer (SMP) is a type of polymer that exhibits the form memory phenomenon, much like a SMA. SMPs can recover substantially on a macroscopic level following exposure to an external stimulation (e.g., heat, electricity, light, magnetism, microwaves, moisture, or a change in pH) [25].

Figure 5. Micro air vehicle controlled by piezoelectric materials on the ground and in flight [23]

SMPs are commonly employed as actuators in weightless environments, or deployable space structures [25]. However, due to their changeable stiffness, SMPs have a lot of potential for applications that call for a morphing skin. SMP morphing skins can accommodate morphing structures because they can sustain substantial deformations (up to 100% strain) in the elastic state and aerodynamic loads in the glassy state [26]. Carbon, glass, or elastic fibres have been combined with SMP resin to create SMP composites, which improve the SMP's mechanical properties.

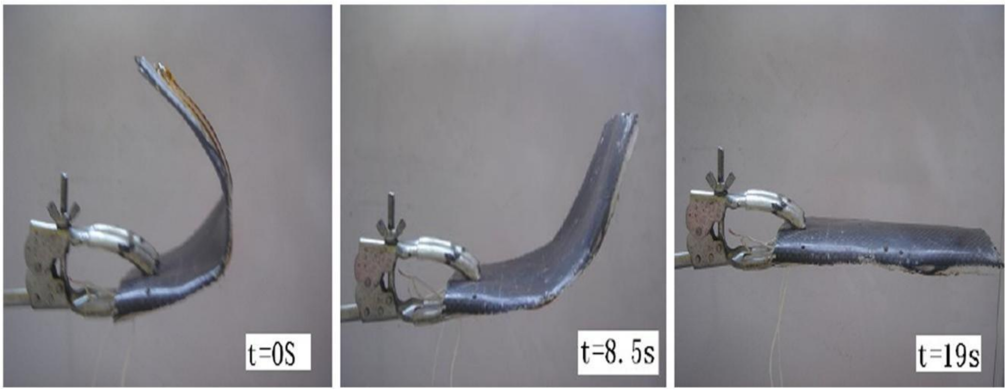

Figure 6. Wing with SMP composite skin

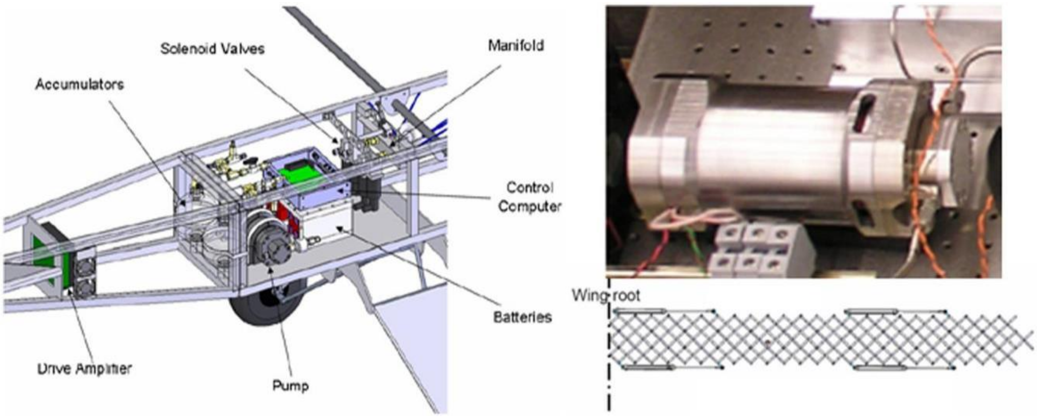

Figure 7. Shape memory composite wing skin [25].

2.2.6 *Electro-active polymers*

Electrical stimulation of an electro-active polymer (EAP) can result in a notable change in size or form, with strains as high as 300% [28]. Polyvinylidene fluoride (PVDF), ionic polymer–metal composites (IPMCs), dielectric elastomers (DE), and other comparable materials are examples of EAP materials. Low weight, low power consumption, quick reaction, and adaptability are just a few of the many benefits that EAPs offer as actuators [29]. Flapping wing MAVs have made use of EAPs [30]. To get the MAV airborne, just a 2.5–4 V sinusoidal pulse was needed to create enough lift from the flapping wings.

2.2.7 Magnetostriction

The property known as magneto-striction occurs when a substance is exposed to a magnetic field and changes in size or shape. At ambient temperature, terfenol-D (chemical composition: $Tb_{0.3}Dy_{0.7}Fe_{1.9}$), a common magnetostrictive material, experiences a significant induced strain in a low-intensity magnetic field [31]. It was shown that a Terfenol-D-based linear step actuator performed exceptionally well, with a maximum force of 410 N, a range of motion of 45 mm, a maximum speed of 60 mm/min, and 95 W of power[32]. Hydraulic pumps have been powered using magneto-strictive materials [33]. Actuators are now the most common use for smart materials. When compared to traditional electromotors, smart materials have higher power density, higher output force (SMA, piezoelectric materials, and magnetostriction materials), higher output displacement (SMP, EAP, and MFC), higher output frequency.

2.2.8 Optical fibers Sensors

FBG sensors can be used to track the shape of morphing wings. Using FBG sensors, the strain in a hinge or metal plate has been used to calculate deflections in variable-camber wings (Figure 9) [34]. A neural network and a variety of FBG sensors can be used to track the precise shape of a twisting wing that is driven by SMAs [35]. FBG sensors can also be used to measure the form of an SMP, and they may find use in a folding skin.

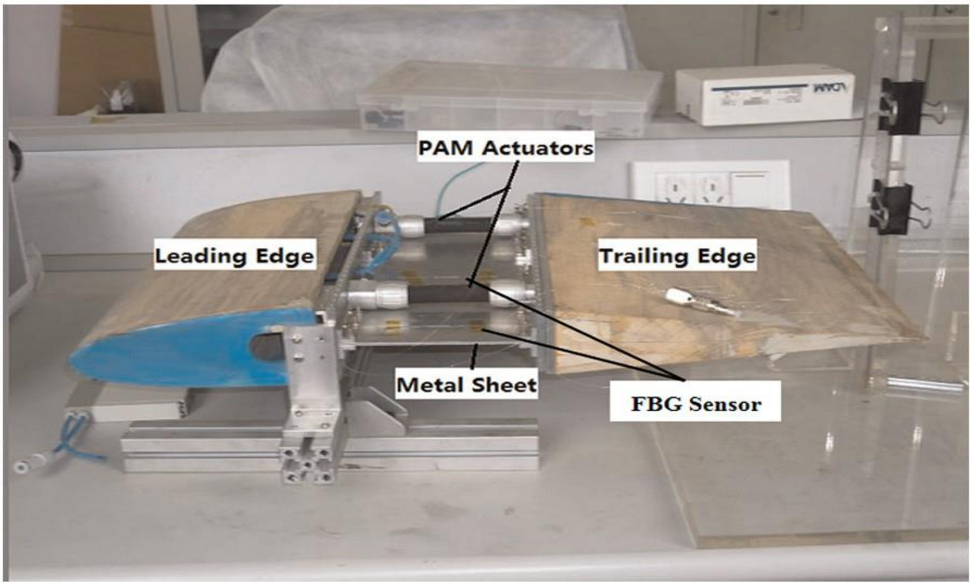

Figure 8. Model of a flexible, variable-camber wing monitored by an FBG sensor [36]

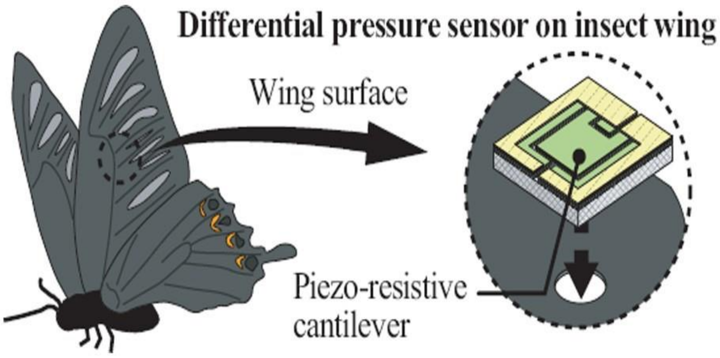

Figure 9. Piezoelectric differential air-pressure sensor for an insect wing [37].

2.2.9 Electro-active polymers

EAPs can produce electrical signals and are applicable to flexible constructions and high strain conditions, much like piezoelectric materials. A flying wing MAV with EAP sensors on its wings is depicted in Figure 11 [38]. The EAP sensors provided the lift during flight. Flight tests and a wind tunnel test confirmed these findings. Vibrating structures can likewise be monitored with EAP sensors [39].Another key characteristic of smart materials is self-sensing. Smart materials can sense environmental factors including temperature, stress, strain, and the location of structural deterioration.

2.3 Structures

Auxetic honeycomb structures have a negative Poisson's ratio because, in contrast to regular honeycomb structures, they have a broader width when stretched [40]. For morphing structures, auxetic honeycomb architectures offer further benefits [41]. A variety of auxetic structure types, such as chiral honeycombs [43], cross-shaped honeycombs, and reentrant hexagonal honeycombs [42], have been used in the construction of variable-camber wings. Variable-span morphing wings have made use of honeycombs with a zero Poisson's ratio [43]. Figure 12 shows a 100% extension variable-span morphing wing [44]. Variable-chord wing structures have been made using similar methods [15, 44]. Pressured air has been added to the sealed honeycombs of adaptive wings to provide the best possible configuration for a particular flight scenario.

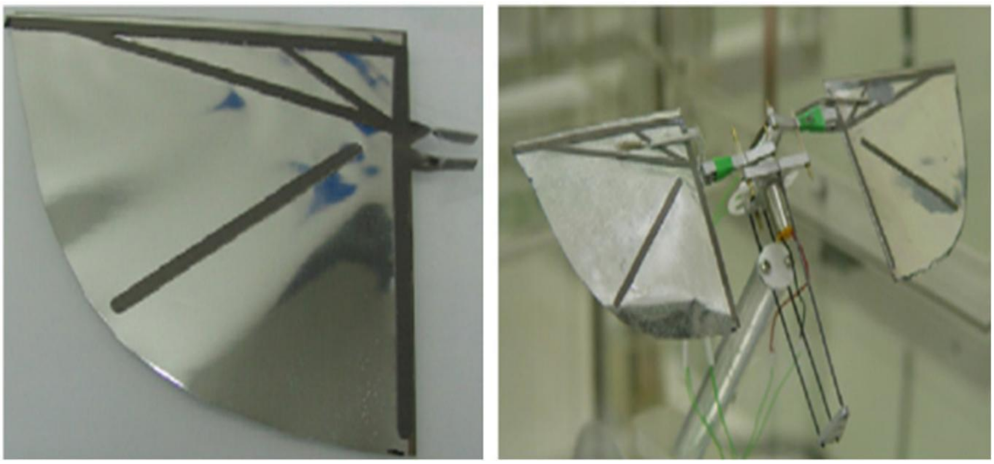

Figure 10. EAP sensors on a flapping wing MAV [38].

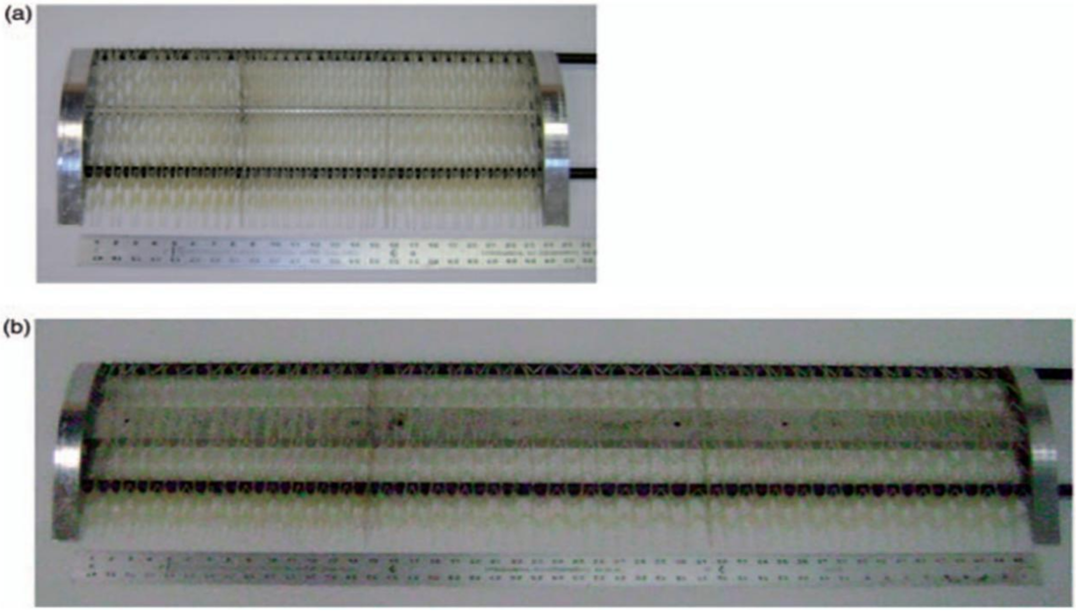

Figure 11. Variable-span morphing wings based on zero-Poisson's-ratio honeycombs: (a) Contracted state and (b) Extended state [45]

2.3.1 Variable-stiffness tube structures

The structure needs to be both robust and flexible because morphing architectures are incompatible. It is necessary to have a structure with changeable stiffness. As mentioned in the section "Shape memory polymers," these materials have varying stiffness. The creation of a structure using a flexible matrix and tubes with varying stiffness is covered in this section. Variable-stiffness tubes come in three varieties. Pneumatic tubes, often known as pneumatic muscle fibers, are the original kind. Pneumatic muscle fibers that shorten in response to air pressure demands have been employed as actuators [46]. The tube's rigidity drastically varies during this procedure. A morphing skin with a transverse stiffness ratio of up to 120 can be created by adding pneumatic muscle fibers to a flexible matrix [19,47]. Additionally, this morphing skin served as both an actuator and a skin in a variable-camber wing structure. Tensile experiments revealed that a morphing skin made using SMP composite tubes had a modulus ratio of 59.6 in one set of research [47]. Images showing the out-of-plane deformation when the tube was heated under uniform loads are shown in Figure 13**.**

Fluidic flexible matrix composite (F2MC) tubes are the third kind of variable-stiffness tubes. Because of the fluid's unique anisotropic tube shape and incompressibility, applying pressure to it results in a significant increase in stiffness. A skin composed of F2MC tubes can have a modulus ratio of up to 55.5, while the theoretical maximum is 120 [19, 47]. F2MC-reinforced SMP composites can be created by using SMPs for the matrix in order to get a higher modulus ratio [47]. These materials can survive conditions that could harm an F2MC since their modulus ratio can reach 140**.**

2.2.2Multi-stable Structures

Two or more stable states make up a multi-stable structure, which can quickly change between them when activated. For morphing wing UAVs, multi-stable structures have been employed [50]. Variable-sweep wings have been built using multi-stable frameworks. The wings were able to go from straight to fully swept in tests [51]. In order to control a UAV, a twisting structure based on bi-stable structures operated by MFCs has been created [52]. A bi-stable adaptive morphing-airfoil wing that alternates between rigid and compliant modes has been designed. The first layer of material is structurally joined to a support beam at a second temperature that is greater than the first temperature in an earlier manufacturing procedure. While an actuator is made to function at a first working temperature, this enables the support beam to be under compression at the first temperature without flexing [53]. The PBP mechanism enhances tip rotation by up to 40% and allows for tip deflection of up to 45° [54].

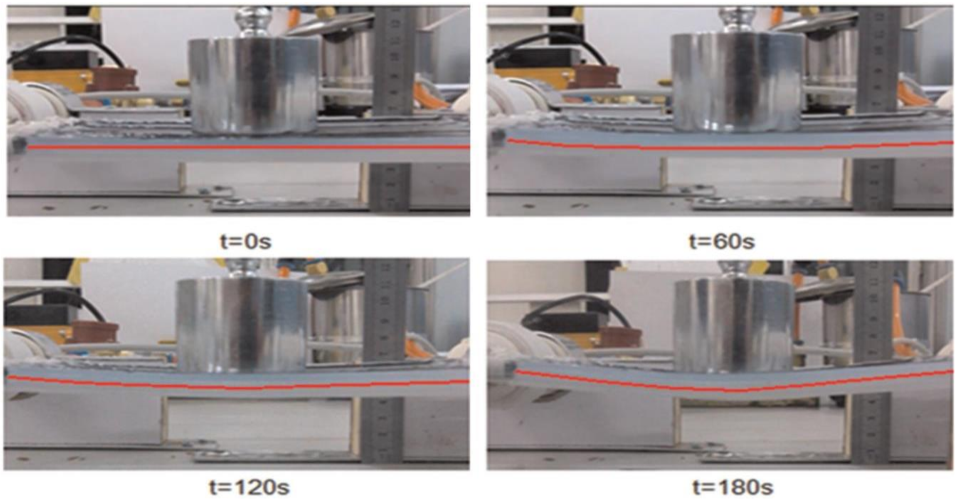

Figure 12. Deformation using SMP composite tubes in a morphing skin [47]

2.2.4 Corrugated structures

Corrugated structures have the ability to expand or shrink significantly in a single direction. Additionally, these structures can be bent or folded. Like streamlined airfoils, eddies form across the corrugated surface within a certain range of Reynolds numbers. Corrugated skins can be used to cover morphing trailing-edge structures [55]. Corrugated structures can be smoothed in two ways. One approach is to cover the structure with a segmented skin that resembles fish scales, and another is to fill it with flexible rubber [56]. A corrugated morphing winglet with a dihedral angle shift of 0.52 rad and a twist angle change of 0.055 rad is shown in Figure 14 [57]. The characteristics of deformability and design ability are what set smart structures apart from conventional bearing structures. The foundation of actuators and sensors for various deformation structures of morphing aircraft is a framework that can carry and deform. Although the bearing and deformation capacity of these modern lightweight deformation structure designs are good, there are still certain issues with the connection between deformation structures and smooth configuration that need to be resolved. The following are two possible solutions. First, by figuring out a legitimate way to attach flexible skin to deformation structures, smooth configurations might be achieved. Second, looking for theoretical backing to create irregular designs that perform well on certain unique aerodynamic efficiency.

Figure 14. Demonstration of extension and canting of a morphing winglet with a corrugated structure [57]

3. CONCLUSION

This article reviewed the use of smart structures and materials in morphing aircraft. Numerous micro-, unmanned and full-size aircraft already use these materials, indicating the enormous potential of intelligent materials and structures in morphing aircraft.Multi-scale design and multidisciplinary research should be taken into consideration in order to fully utilize these devices, and the following issues should be resolved:

- The performance of existing smart materials could be enhanced by amputation, grafting, recombination technologies, or molecular-scale material alteration.
- To make smart composites multifunctional, additives such as carbon nanotubes, carbon black, graphite, ferrous particles, and nickel powders could be included.
- Bitable structure actuators made from MFCs can be used to create novel structures employing a variety of smart materials.

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