Advancements in aircraft morphing technology

Professor Fengfeng (Jeff) Xi has a passion for aerospace technology. Here, he outlines his research into the improvement of wing aerodynamics through the use of innovative wing morphing technologies.

What is ‘morphing aircraft technology’ and what are its benefits?

In general, morphing aircraft technology tries to change the shape of aircraft wings in order to optimise aerodynamic performance. The shape of the wing must change during take off, cruising and landing. Current designs only consider one condition (normally cruising), so they use high lift devices, such as flaps and slats for take off and landing.

This technology can be classified into airfoil-level morphing (2D) and wing-level morphing (3D). The former alters the chord, camber, thickness and reflex of the airfoil to modify the boundary layer and reduce drag. The latter alters the sweep, dihedral, twist and span of the entire wing to drastically reconfigure the aircraft in an effort to achieve near-optimal performance.

Optimisation of performance achieves the highest lift and lowest drag. Through the attachment of multiple actuators to the wingbox, a flexible skin (composed of smart material alloy or polymers) and an internal moving and locking mechanism, it becomes possible to move the whole structure of the wing. None of these tools are currently workable for take-off and landing. They use high lift devices, such as flaps and slats.

Could you describe your background, both educational and professional? What led to your interest in this area?

My background is actually in robotics and mechanisms, not aerospace, though I’ve always been fascinated by aerospace technology. My students and I studied the dynamics of bird flight. Birds have a very simple four-linkage type of modular wing structure. I became interested in identifying the key structure, or module, in bird wings. There is a Public Broadcasting Service Nova episode about fractals in nature, called ‘Hunting the Hidden Dimension’. It shows everything in nature has its own building blocks, i.e. modules, which can be found in cloud formations, tree limbs, in stalks of broccoli and craggly mountain ranges. These fractal-like irregular and repeating shapes are now studied in the context of a new theory called fractal geometry pioneered by Benoit Mandelbrot, a Polish-born mathematician. This concept strategically aligned with industry and led to the establishment of our current project.

How do you work with industry?

This is a Natural Sciences and Engineering Research Council of Canada (NSERC) project in collaboration with Bombadier Aerospace. The programme requires researchers to secure funding from a company and then NSERC doubles the contribution from industry. Morphing wing is strategic research from the perspective of the aerospace industry. At present we are working in Canada, but we are expanding our connections through conferences and papers. We have special connections with the University of Bristol. Each company has different methods because they have different competitive angles, so researchers must sign confidentiality agreements. We have published three high-level papers on this project, but we are only able to discuss our methods in general terms.

What are some of the mechanisms you are developing?

Variable geometry truss mechanism (VGTM) has been used in snake robots and space structures. We developed the VGTM technology so it can be adapted to wing structures, enabling them to withstand all the loading (shear/torsion, bending, tension/compression, etc.) while achieving four motions: dihedral (roll), twist (pitch), sweep (yaw) and span. By using underactuation (the theory that mechanical systems may function on a lower number of actuators than degrees of freedom) the technology doesn’t have to use all the actuators, so only some members are actuated. We use a combination of four active member and four passive links with a locking mechanism. Four passive members must be locked alternately in sequence to maintain the integrity of the structure while still providing the motion. It is also necessary to devise a strategy that considers the changes in the aerodynamic centre (the pressure for lift), and the centre of gravity, to ensure that flight stability is unaffected.

You are currently at the prototype stage. What is your end goal?

We are still trying to extend this existing project because we want to push it from Technology Readiness Level (TRL) 1-3 (Research & Development) to TRL 4-6 (Demonstration) and finally TRL 7-9 (Commercialisation). We are currently in the developmental stages of transforming theory into practice and still need to understand fatigue, safety, reliability, how to mount devices and so on. Too many actuators would incur a power-energy penalty, so we are now looking into a static balancing mechanism in addition to underactuation.

Will you be partnering with any other institutions or organisations during the course of these investigations?

We will be exploring the opportunity to collaborate with other institutions, such as the École de Technologie Supérieure (ETS) in Montreal and the University of Toronto Institute for Aerospace Studies (UTIAS) in Toronto, to combine their airfoil morphing with our wing morphing to develop a fully morphing wing aircraft.
Increasing aircraft versatility

Researchers at the Ryerson Institute for Aerospace Design and Innovation in Toronto, Canada, have been working on the development of a fully modular morphing wing, a concept which will significantly improve aircraft performance.

**AIRCRAFT DEVELOPMENT HAS**, until recently, focused on the advancement of fixed wing aircraft which have a single mission scenario as their goal for optimisation. Most often this scenario is categorised as ‘high speed cruise’, although certain types of aeroplanes, such as military reconnaissance or fighter aircraft, have other optimal configurations.

There are numerous disadvantages to designing and optimising aircraft that is limited to a particular field. Mechanisms such as wing flaps are currently used as part of adaptive airfoil geometry, and though these mediate the problem of optimising a single mission scenario, they also reduce flight efficiency and manoeuvrability. In the case of military aircraft, the reconnaissance or fighter aspect forms only a portion of the whole mission, so the efficacy of the craft’s functionality is reduced at all other times. Among other problems, this leads to increased fuel costs, as the aircraft must perform tasks which are not within its range of optimal performance.

**IMPROVING PERFORMANCE AND EFFICIENCY**

Morphing aircraft technology provides a solution to this problem by developing adaptive structures that are able to carry out multiple objectives. This technology will help to improve performance and efficiency in all flight scenarios. Morphing aircraft will have improved flight envelopes (design capabilities); augmented flight control and stealth; as well as reduced drag to improve range and reduce fuel costs. In the long term, it is predicted that morphing aircraft will replace the need for multiple aircraft with specific mission objectives, thus increasing overall cost efficiency.

There are two main branches of aircraft morphing: airfoil-level morphing and wing-level morphing.

**AIRFOIL MORPHING** affects the airfoil shape of a wing that alters local aerodynamics to improve lateral stability and manoeuvrability, while reducing air resistance (drag). Wing-level morphing affects the entire shape of the wing. It alters the twist, sweep, dihedral and span of the wing in order to optimise the wing shape for different scenarios, such as take off, cruise and landing.

**A SINGLE MORPHING METHODOLOGY**

In order to fully minimise instances of non-optimal performance during flight regimes, the actuation scheme of an aircraft must incorporate as many morphing wing capabilities as possible. Several approaches to wing morphing are currently being studied, though most current approaches focus on a single morphing methodology (sweep, dihedral, twist or span motion).

Variable sweep allows a pilot to control the speed of an aircraft, and is particularly useful for dash manoeuvres and high speed flight. The dihedral motion refers to the upward angle of a wing; a positive angle affects the lateral stability of an aircraft around its roll axis, whereas a negative angle increases manoeuvrability. The twist of a wing allows for greater control over aerodynamic forces, helping to maintain a level body. Finally, the wing span affects aspect ratio and wing loading, which enables optimisation for specific flight regimes.

There are a few studies which have combined the function of two capabilities, but none so far have succeeded in producing a morphing wing which integrates all variable capabilities.

**RESEARCH TO DATE**

Though wing morphing technology is widely regarded as an important and lucrative research venture, the majority of research to date has been theoretical and conducted in disparate areas, leading to a lack of cohesive and wider-
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scale development. Professor Fengfeng (Jeff) Xi, the Program Director for the Ryerson Institute for Aerospace Design and Innovation, Toronto, has expressed the need for systematic research into actuation methods and further development of prototypes, as he explains: “Morphing wings not only require motion capability but also sufficient rigidity to support aerodynamics and structural loads. These practical issues have not been fully explored”.

VARIABLE GEOMETRY TRUSS MECHANISMS

In collaboration with Bombardier Aerospace, Xi and his team at Ryerson, including Dr Paul Walsh, Chair of Ryerson Department of Aerospace Engineering, have focused their research on solving the problems of structural mechanism and control law development that are hindering wing morphing. Their work has led to the application of variable geometry truss mechanisms (VGTMs) to morphing technology. VGTMs are truss-based structures comprised of linear actuators which can be manipulated to control movement. The mechanisms have already contributed to many new developments, such as NASA Langley Research Center’s space crane and remote nuclear waste remediation. Xi believes that VGTMs technology can be used to fully integrate the variable capabilities of a morphing wing.

VGTMs can be integrated into existing structural components, with each module being inserted into one of the longitudinal sections that comprise the wing. They work together with extant wing structures and enable the wing to morph in sections, allowing for greater control over shape changes. There are no performance limitations with these modules; VGTMs can cater for all morphing methodologies as wings can be automatically configured and reconfigured to meet specific flight requirements.

TESTING AND MEASURING MODULES

Two VGTMs are currently being developed: the morph-specific wing module and the morph-independent module. The former considers morphing requirements of individual wing components, whereas the latter focuses on overall wing morphing requirements. Morph-specific wing modules provide a degree of freedom (DOF) for each of the four wing motions. Each module requires the same DOF, though the direction differs according to the motion. The morph-independent module coordinates the morph-specific modules, preventing the occurrence of nonlinear wing shapes.

Prototype VGTMs are also in the process of being built and tested using the Ryerson wind tunnel. They are wingtip devices which can be attached to fixed-wing aircraft to emulate many of the features of a morphing wing, including drag reduction and improved aerodynamic performance. If successful, the winglets will allow for further development of VGTMs fully morphing wings, and could be implemented on fixed-wing aircraft.

The results of the VGTM experiments are being measured through their effects upon motion, structure and aerodynamics to form a ‘kineto-structural-aerodynamics analysis’. This multidisciplinary approach allows for a balancing of the aircraft’s optimal performance, stability and fuel consumption.

FURTHER APPLICATION OF FINDINGS

In 2012, researchers at Ryerson published their first American Institute of Aeronautics and Astronautics (AIAA) Journal paper which presented a new discretisation algorithm for the development of a modular morphing wing. The algorithm uses the total curvature distribution of a known reference wing to influence the configuration of a modular morphing wing. Throughout the wing, more modules are placed in areas with larger curvature to facilitate morphing. The algorithm itself is aimed at calculating the minimum number of modules required for optimal wing performance. It is currently under development, and the researchers hope that it will form part of their overall conceptual design for a fully modular morphing wing.

In 2013, the team published a second article in the AIAA Journal that presented a variable geometry wing box design and an associated optimal motion control algorithm. By combining the principle of VGTM and under-actuation, each wing module is designed with eight trusses: four active with actuators and other four passive and lockable. There are two topologies: isostatic and hyperstatic. The first topology occurs during reconfiguration when two of the four passive trusses are locked to combine with four actuated trusses to provide six stiffness against forces and moments in three directions. The remaining two passive trusses are set free to work with four actuated trusses to provide six motions. The second topology occurs at static shape when reconfiguration is completed and all passive trusses are locked. Because of this topology change, a motion planning method called actuation sequencing was developed to morph a morphing wing through a set of intermediate poses. These calculations were validated using a prototype, which confirmed the functionality of the proposed motion control and variable topology mechanism design.

The researchers hope that the results of their work will ultimately provide a basis for long-term and sustained research and development of morphing aircraft, as well as significantly influencing the future of aircraft design and manufacturing.

DEVELOPMENT OF AN AIRCRAFT MORPHING WING USING VARIABLE GEOMETRY TRUSS MECHANISMS

OBJECTIVES

The principle of variable geometry truss mechanisms (VGTMs) will be applied to provide a systematic method for developing morphing wings. Three aspects of fundamental research will be carried out including motion, structure and aerodynamics. A new analysis method called kineto-structural-aerodynamics analysis will be developed for VGTM morphing wings.

KEY COLLABORATORS

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