Span Morphing using the GNAT Spar for a Mini-UAV: Designing and Testing

R.M. Ajaj¹, M. Bourchak², and M.I. Friswell³

¹Aeronautics and Astronautics, University of Southampton, Southampton, UK, SO17 1BJ
²Aeronautical Engineering Department, King Abdulaziz University, Jeddah, Saudi Arabia
³College of Engineering, Swansea University, Swansea, UK, SA2 8PP

Rigid wings usually fly at sub-optimal conditions which generates unnecessary aerodynamic losses represented in flight time, fuel consumption, and unfavourable operational characteristics. Large wingspans allow for good range and fuel efficiency, but lack manoeuvrability; on the other hand, low aspect ratio wings fly faster and are more manoeuvrable, but suffer from poor aerodynamic performance. Span morphing technology allows integrating both features in a single wing design and allows continuously adjusting the wingspan to match the instantaneous flight conditions and mission objectives. This paper develops a novel span morphing concept called the Gear driveN Autonomous T win (GNAT) spar for a mini-UAV. The GNAT spar allows span extension up to 25% of the original span to reduce induced drag and increase flight endurance. The GNAT is superior to conventional telescopic structures as it uses the extra space available in the other side of the wing instead of relying on overlapping structures associated with telescopic spars. In addition, it has a self-locking capability due to the low lead angle of the driving worm gear of its actuation mechanism. Aero-structural sizing and design of the concept is performed using low fidelity aerodynamics (XFLR5) and high-fidelity FE solver (SolidWorks). Furthermore a physical prototype of the concept is developed, followed by the integration of Latex flexible skin to provide the aerodynamic shape of the wing. Following from this, the design of robust control system using the Arduino Uno R3 microcontroller is discussed. Finally, benefits and drawbacks of the design are highlighted and analysed.

I. Introduction and Background

Bio-inspired by natural fliers, morphing aircraft has gained a lot of interest as a potential technology to meet the ambitious goals of the Advisory Council for Aeronautics Research in Europe (ACARE) Vision 2020 and the FlightPath 2050 documents. A morphing aircraft continuously adjust its wing geometry to enhance flight performance, control authority, and multi-mission capability (Ajaj et al., 2013a). Rigid wings are usually designed as a particular geometry which satisfies a range of flight conditions, nevertheless their performance at each condition is rather sub-optimal (Barbarino, et al., 2011). In fact, aircraft flight regimes are shifting along the mission; it means that different stages of a flight can take place at dissimilar altitudes, speeds and manoeuvring modes. An optimal wing designed for one of these stages would probably not have good performance in another, therefore actual rigid wing designs are made so that the geometry complies with all of them, limiting operational features and compromising its performance, e.g. a high aspect ratio wing can serve efficiently in a long endurance low speed applications, such intelligence, surveillance and reconnaissance, that configuration can also be beneficial for low speed approach manoeuvres, but would be detrimental when needed in a tight manoeuvring or high speed scenarios due to wing loading and structural compromises.

A span morphing wing can incorporate the features of both high and low aspect ratio wings so that the aircraft can afford the operation in both situations efficiently, reducing the effects of having a sub-optimal wing for each of the flight conditions, making this technology especially attractive for military UAV market. Increments in the wingspan represents an augmentation of the aspect ratio and wing area, hence a reduction of the spanwise lift distribution for the same resultant lift. This allows for a diminution of the wing drag, and consequently, an increment of aircraft range and endurance (Ajaj et al., 2014a). However, these variations produce a substantial increment of the wing-root bending moment due to the
larger span, therefore requiring a stiffer structure. On that behalf, the aeroelastic characteristics of the wing should be examined in order to design a wing structure compliant to the variable aerodynamic loads. Based on these consequences of span morphing, the employment of such design requires a trade-off study which allows balancing the benefits of span variations with the additional weight of the structure that will be directly driven by the changing structural requirements. Relations among these parameters will be examined in further sections. Another significant weakness of rigid wings design comes from the use of hinged control surfaces. These mechanical joints break the continuity of curvature in wing surface due to the characteristic gaps and steps present in articulated surface connections. These discontinuities impact the aerodynamic performance generating an increment of the parasite drag and therefore a higher thrust requirement. According to Raymer (2013), a wing component with a hinged control surface will have a parasite drag form factor 10% higher that the predicted taking in account merely the skin friction coefficient; this due to the extra drag of the gap between the wing and its control surface. These characteristic discontinuities, sharp edges and deflected surfaces also make aircraft more susceptible to radar signature and acoustic detection which is vastly inconvenient in certain military applications.

As a response to overcome these issues, the use of elastic skins has been considered and assessed as a solution for not only planform variations but also aerofoil alterations. According to Vasista et al. (2012), one of the main advantages of wing morphing technologies is the reduction of drag by eliminating gaps and discontinuities in wing shape created by conventional control surfaces and their actuation mechanisms by replacing them with smoothly varying gapless control surfaces, avoiding alterations of the aerodynamic contour. In fact most of the morphing technologies that have been studied so far assume the existence of an appropriate flexible skin (Barbarino et al., 2011). However the employment of these extensible materials represents numerous design challenges. Firstly, the skin should be stiff enough to withstand the characteristic aerodynamic loads of the aircraft’s flight envelope within a limited out-of-plane deformation, so that the aerodynamic performance of the wing is not affected. On the other hand the skin stiffness directly affects the actuation force, therefore the actuation mechanism selection and sizing. According to Barbarino et al. (2011), changes in wing planform area and wingspan are the primary enablers of a new class of morphing vehicles. These morphing technologies have been vastly investigated and tested, proving operational advantages and enhancement of aerodynamic efficiency. The implementation of these technologies in unmanned aerial vehicles is not yet evident in commercial systems but several developments have been documented. Most span morphing concepts have been based on telescopic mechanisms. The MAK-10 was the first aircraft designed under this concept and flew in 1931. This variable span system consisted in telescopic wing sections that were actuated pneumatically and allowed span increments of up to 62% (from 13 to 21 m) and area augmentations of 57% (Weisshaar, 2013). Blondeau & Pines (2007) demonstrated the development and testing of a telescopic wing driven by pneumatic actuators. Hollowed fiberglass wing segments were used to preserve the spanwise aerofoil geometry and the wing spars were replaced with inflatable actuators that could support the aerodynamic loads. This wing could undertake a 114% change in the aspect ratio.

II. The GNAT Spar

Nowadays the increasingly market of unmanned aerial systems and the vast demand of applications have converted UAVs in a profitable opportunity for morphing technologies to grow. Furthermore the different range of size/weight, flexibility in autonomous navigation and control, cost-effective construction, instrumentation potential and safety of operation make them an ideal test-bed for morphing wing application. Therefore, this paper focuses on applying the GNAT spar for the Tekever AR4 mini-UAV as a potential testbed for the technology. The AR4 UAV is a fully electric system that operates using a DC electric current provided by an on-board battery. The UAV specifications are listed in Table 1.
Table 1 Tekever AR4 Specifications.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTOW</td>
<td>5kg</td>
</tr>
<tr>
<td>Cruising speed</td>
<td>16 m/s</td>
</tr>
<tr>
<td>Span</td>
<td>1.8 m</td>
</tr>
<tr>
<td>Chord</td>
<td>0.24 m</td>
</tr>
</tbody>
</table>

The majority of the state-of-the-art span morphing solutions is based on telescopic mechanisms in two dissimilar forms. The first from as seen in Blondeau et al. (2003) and Blondeau and Pines (2007) where wing telescopic shells allow for a high span extension but its main drawback lays on the separation step among the sections (in chord) which generates an increment on the parasite drag and unwanted aerodynamic effects. In this form the wing skin is rigid. The other form is a telescopic or articulated spar/mechanism that is covered by flexible skin to maintain the aerodynamic shape (Ajaj et al. 2013a, 2014b). In this form, the spar/mechanism can also serve as an actuator, in which case it should be able to withstand the spanwise aerodynamic loads.

This paper will focus on the second form as it has higher aerodynamic benefits and lower structural weight. However, this paper disregards the use of telescopic or articulated spars and develops a novel concept called “Gear driveN Autonomous T win” (GNAT) spar design. The GNAT spar design utilises the available space in each side of the wing instead of using overlapping or folding the structures as it is the case with telescopic or articulated spars. The GNAT spar is capable of serving as the primary structure of the wing and as the actuation systems at the same time. According to Barbarino, et al. (2011) ideally, there should be no distinction between the structure and the actuation system in morphing wings. This multi-functionality philosophy reduces structural weight, simplifies the design, and lowers power consumption. Figure 1 shows a schematic representation of the GNAT spar.

Figure 1: Schematic of the GNAT Spar concept: original size (left), extended wing (right).

The main advantage of this design is not having the main spar split in different sections for each side of the wing which leads to a stiffer structure and the possibility to have the same spar cross-section spanwise so that it allows for the use of sliding ribs to attach the flexible skin. In this paper, span morphing occurs symmetrically on each side of the wing mainly to enhance the flight performance. Asymmetric span morphing for roll control will be investigated in future work. Symmetric span morphing significantly reduces the complexity of the structural design and actuation mechanism.

Since the UAV is electrically powered an electrical powered system is preferred, instead of a pneumatically powered system that usually requires the addition of compressors, tanks, valves and lines, which are not suitable for a small UAV like the AR4. The intended design should also be able to comply with aerodynamic and geometric requirements to maintain or enhance the aircraft actual nominal performance without major alterations. Based on these conditions, the concept uses a rack and pinion mechanism to drive each side of the GNAT
spar. The rack gear works as the main spar when the wing is extended. Sliding ribs can move spanwise to permit the actuation and keep the aerodynamic shape while being dragged by the flexible skin. The actuation of the system is achieved by the rotation of a spur gear placed between the two racks, corresponding to each of the spars, producing a symmetrical movement of both structural elements spanwise. This system is powered by a DC motor and the transmission is done via a worm gear mechanism. This gear is mounted on the same shaft as the driving spur gear as shown in Figure 2.

![Figure 2: Pinion and rack actuation system detail at wing root.](image)

The GNAT spar has a self-locking capability so that reached position is kept despite the skin axial-induced loads. Usually locking systems require the addition of control devices and therefore a robust control system and the addition of weight. The locking capability of the GNAT spar is achieved by the low lead angle of the worm gear. This type of gears is used to transmit the torque to the spur gear and allows not only a self-locking feature but an increment in the torque transmitted, which could be necessary depending on the skin axial stiffness.

### III. Aero-structural design and sizing

The highest air loads on mini-UAVs usually come from the generation of lift during an extreme gust. Therefore a 3-g gust is used as the sizing criteria for the GNAT spar. According to Megson, (2007), the structural factors needed to ensure the airworthiness of an aircraft are the limit load, which is the maximum load that the aircraft is expected to experience in normal operation, the proof load, which is the product of limit load and the proof factor (1-1.25), and the ultimate load, which is the product of the limit load and the ultimate factor (usually 1.5). The UAV must withstand the proof load without detrimental distortion and should not fail until the ultimate load has been achieved. With the aim of performing an adequate sizing and material selection of the spar and rack set, a calculation of the increment in stiffness due to the
changes in lift distribution spanwise is undertaken. In order to do so, a hypothetical wing based on the AR4 wing is designed and tested using XFLR5. XFLR5 is linear aerodynamic solver that uses XFOIL as its computation kernel with 3D wing design capability. The wing is straight untapered with NACA0012 aerofoil along its span. In order to obtain the ultimate aerodynamic loads, the lift distribution was determined for the 5kg UAV in a 3-gust scenario and speed of 16m/s. The panel forces distribution from XFLR5 is shown in Figure 3.

Figure 3: The panel forces distribution on the wing extracted from XFLR5.

Figure 4 shows the lift distribution and consequent bending moment along the span for the hypothetical wing in its original and expanded forms with variations of 25 and 50% of its span. It is evident that an increment of 50% in span results in about 50% increase in the root bending moment. This agrees with the structural requirements studied by Bae et al. (2005).
Figure 4: Lift, induced drag, and bending moment distributions along 1800mm Span with 25 and 50% span increments for a non-tapered NACA0012 wing at 16m/s from XFLR5.

Using the points of the lift distribution for the 25% extended wing, a polynomial is fitted so that lift could be expressed as a function of the span, starting in the wing root. Then, partial integrations of the polynomial function are made to obtain the nodal aerodynamic loads to size the spar. The function was integrated and evaluated in 5 equally spaced sections, assuming the existence of 5 equally spaced ribs along each side of the spar to calculate nodal loads. A safety factor of 1.5 is used in this analysis. Figure 5 shows the nodal forces that would be transferred from the skin to the spar through the hypothetical ribs.

Figure 5: Nodal aerodynamic loads for spar sizing.
A simplified model of the spar is used to run the FEA analysis as shown in Figure 6. In this model the rack is taken as a square section tube without the teeth and rigid elements are placed in the intended positions of the ribs in order to apply the aerodynamic loads in the locations where they are transferred to the spar. A subsequent FEA analysis would determine the capability of the gear and rack teeth to undertake the axial loads created by the skin in tension.

![Simplified spar model for FEA analysis.](image)

Figure 6: Simplified spar model for FEA analysis.

The point loads are applied to the spar as remote loads, taking into account the offset generated by the position of the spar away from the aerodynamic centre (assumed at 25% of the chord), so that the effects of the twisting momentum is take into consideration in this analysis. Each one of the point loads is applied by rigid connection to two of the ribs as shown in Figure 7.

![Application of aerodynamic loads along the wing semispan (left) and chordwise load offset due to distance between spar and aerodynamic centre (right).](image)

Figure 7: Application of aerodynamic loads along the wing semispan (left) and chordwise load offset due to distance between spar and aerodynamic centre (right).

The material properties for the different elements included in each side of the GNAT spar are listed in Table 2.
Two structural objectives are set in order to assess the feasibility of the design. All the elements that compose the spar should maintain stresses below the elastic limit of each material so that the stiffness of the structure complies with the airworthiness requirements. As stated before, the ultimate factor is intended to cover such items as variations of material and structural properties outside the specified limits, deterioration in service, inadequacy of load and stress analysis, and possible flight of the aircraft outside the stated design limitations (Howe, 2004). Therefore the applied loads should not create permanent deformations of the structure or cause failure. The second structural condition relies on the fact that the out-of-plane displacement of the wingtip should be less than 10% of b/2 as show in Figure 8.

![Figure 8: Wingtip out-of-plane displacement constraint.](image)

A mesh independence study is conducted in order to avoid the influence of the mesh quality in the results. Figure 9 shows the mesh convergence study performed to show the impact of mesh density on the tip displacement. Mesh convergence is achieved at 700,000 elements.
The second objective is assessed by obtaining the maximum stresses for each of the parts that compose the spar. In the following pictures, the maximum value on the scale is set to the elastic limit of each element. It is important to remark the fact that, for the carbon fibre reinforced plastic (CFRP) tube there is no difference between the elastic limit and the ultimate strength of the material due to the fact that this material doesn’t allow for plastic deformation before the failure. Figure 10 shows the von Mises stress distributions on each element of the GNAT spar.

![Figure 9: FE mesh convergence study.](image)

**Figure 10:** von Mises stress distributions on each element of the GNAT spar.

**IV. Experimental Setup**

A rectangular component made of Aluminium is used as the basis of the experimental rig to represent the fuselage. The AR4 is a high-wing UAV which implies that the actuation mechanism of the GNAT spar can be housed in the fuselage and in the overlapping area between the wing and the fuselage. Labelling of the GNAT spar different components is shown in Figure 11.
The actuation mechanism of the GNAT spar consists of a worm gear attached to the gearbox of the DC motor. The worm gear drives a spur gear which is attached to the pinion. The pinion in return drives the Delrin racks which are parts of the GNAT spar resulting in a variation in the wingspan.

A. Flexible Skin

Due to time and cost constraints, Latex was chosen to act as the flexible skin that covers the wing and provide its aerodynamic shape. Uniaxial testing of Latex specimens was performed as shown in Figure 12.

Specimens with thickness of 0.5mm and 1mm where tested up to 70% strain. All the specimens tested have a height of 100mm. 20 specimens were tested in total:

- Specimens 1-5 have a thickness of 1mm and a width of 10mm;
- Specimens 6 - 10 have a thickness of 1mm and a width of 25mm;
- Specimens 11 - 15 have a thickness of 0.5 mm and a width of 10mm; and,
- Specimens 16 - 20 have a thickness of 0.5 mm and a width of 25mm.

Figure 13 shows the stress-strain curves of the different Latex specimens. For specimens 11-15 that are 0.5mm thick and 10mm wide, initial tests showed that measured forces were very low and unsuitable for the load cell being used. The results were unreliable and so the test was not continued for these specimens.
B. Assembly and Integration

Following the uniaxial testing, 0.5mm thick Latex was chosen to act as the morphing skin of the span morphing wing. In this paper, the skin will only be applied to one side of the wing. The root rib is attached to the rig which represents the fuselage and the tip rib is fixed to the spar. All the other inner ribs between the root and tip ribs are allowed to slide on the spar in the spanwise direction. The inner ribs transfer the aerodynamic load on the skin to the wing spar and they are equally spaced from each other. The skin is bonded using epoxy to the inner ribs as shown in Figure 14. As the morphing is initiated, the spar and hence the tip rib start moving. As the tip rib starts moving it extends the skin. The bond between the inner ribs and the skin help to slide and keep the inner ribs spaced evenly apart to maintain uniform strain of the skin along the span. Since the cross-section of the spar is a square, it was difficult to find suitable ball bearing to allow the inner ribs to slide. Therefore, ball bearing frames with square cross-sections were 3D printed from ABS, lubricated, and fitted with mini-balls (refer to Figure 11).
a. The sliding ribs

b. Skin bonding to the ribs.

**Figure 14: Skin integration to the morphing spar.**

To increase the bond strength at the root and tip, the root and tip ribs consist of two minor ribs each. The skin is bonded on the top, bottom, and one side of the minor rib (tip and root). This maximises the bonding contact area between the skin and the minor ribs. Then the minor ribs are bolted together (at root and tip) to clamp the skin between them and increase the shear strength of the bond as shown in Figure 15.

**Figure 15: Root rib clamping mechanism**

Figure 16 shows the wing in the fully retracted unmorphed position and in the fully extended morphed position. The testing showed that actuators was capable of morphing the skin by 25% and showed that the skin bonding at the root and tip rib were very reliable due to the clamping mechanism.
Figure 16: Assembled wing in different morphing states.

Figure 17 shows a close-up of the wing in its fully extended state. The skin deflections in the chordwise direction are large and are easily visible due to Poisson’s ratio. Future investigation based on this paper will look at the possibility of adding chordwise running carbon fibres to the flexible skin to minimise the Poisson’s effect. When the wing is fully extended, local stresses on the ribs are higher in the trailing edge region compared to the leading edge region. This causes the ribs to bend and can jam their sliding mechanism if the ball bearings doesn’t allow for this. This can be solved by increasing the bending stiffness of the ribs or through the correct manufacturing tolerances of the bearings.
C. Control System

A robust control system is developed for the GNAT spar. It consists of a microcontroller type Arduino Uno R3 and two relay switches that help the microcontroller turning the motor on and off and changing its rotational direction. The existing control system only allows for symmetric span extensions to flight envelopes. Asymmetric span extension will require a more sophisticated control system. On this regard, the span morphing is set for three span configurations 0% 12.5% and 25%. To do so, a defined number of stages or modes refer to these levels of extensions. Ideally, a control system would autonomously vary the wing span to match the instantaneous flight conditions and operational requirements. For the construction of this prototype, microswitches at the end of each rail are installed and silicon bumps are attached in the defined positions (0%, 12.5%, and 25%) to the movable portion of the spar so that they toggle to send a 5V impulse to the controller, each time the system reaches a defined position. For prototyping purposes, two push button switches are installed so that they command the actuation in both directions (extension and retraction). The movement is stopped when both micro-switches are pushed by the positioned bumps. A nano-tech 4cell 14.8V, high discharge, LiPo battery is used to power the GNAT spar. Figure 18 shows the setup of the control system.

The experimental testing showed that it takes 27 seconds to extend the wing span by 25%. This is an acceptable actuation time when span morphing is used to enhance flight performance but will not be acceptable if it is used for roll control. In fact, the motor has its own gearbox that significantly reduces its rotational speed but maximise its torque. This is very essential to morph the flexible skin.
D. Drawbacks

One of the drawbacks of this version of the GNAT spar is the joint between the CFRP and the metallic parts of the spar. The overlapping distance within the joint is very small. In addition due to manufacturing tolerances there is a 1mm gap between the two parts of the spar. To solve this, metallic plates are fitted/inserted between the two parts to fill the gap and extend the overlapping distance of the joint. In addition, the CFRP and the metallic parts are bolted together as shown in Figure 19 to further strength the joint. However, this didn’t prove to be a very efficient solution as the CFRP part can still rotate about 5 degrees relative to the metallic part at the joint which results in a large wingtip displacement at 1g flight scenario.

![Figure 19: The joint between the CFRP and metallic parts of the GNAT spar.](image)

Another drawback of the concept is the relatively large force required to morph the wing with the flexible skin. 70 N actuation force is required to morph the wing semispan by 25%. One potential solution to reduce the actuation force is the use of flexible skin with lower Young’s modulus such as Tecoflex and Rhodorsil V-330/CA-35 Silicone elastomers.

V. Conclusions

The development of the Gear driveN Autonomous Twin (GNAT) spar for a span morphing wing was presented. Both computational modelling and experimental testing showed great potential of the concept to enhance flight performance of a mini-UAV. A novel technique was developed and utilised in integrating the flexible Latex skin to the GNAT spar while clamping it at both the wing root and tip. The GNAT spar is superior to a telescopic spar due to its lighter weight and simplified design. It also has a self-locking feature due to the low lead angle of the worm gear. This reduces the actuation power required to morphing the wing and maintains it in the desired position. The use of CFRP and AL alloys for the spar saved weight, however it resulted in a relatively unstable joint due to the short overlapping distance between the two parts and due to uncertainty in manufacturing tolerances. The current version of the GNAT spar takes 27 seconds to extend the wingspan by 25%. As the wing extends the shape of the aerofoil along the span becomes non-uniform due to the Poisson’s contractions. This will have a significant impact on the overall aerodynamic performance. The flexibility of the skin and of the spar varies for different span extensions and this was not captured in this analysis. Therefore, high-fidelity aeroelastic modelling and wind-tunnel testing are still required to have accurate assessment of the benefits of the GNAT spar concept.

Acknowledgements

R.M. Ajaj acknowledges the help and assistance of his MSc students: Mr. German Moreno-Ordonez and Mr. Mizanur Sheikh for accomplishing this research. Both German and Mizanur are MSc students at the Aeronautics and Astronautics Unit, Faculty of Engineering and the Environment, University of Southampton, UK.
References


