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Span Morphing using the GNATSpar Wing

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Rigid wings usually fly at sub-optimal conditions generating unnecessary aerodynamic loses represented in flight time, fuel consumption, and unfavourable operational characteristics. High aspect ratio wings have good range and fuel efficiency, but lack manoeuvrability. On the other hand, low aspect ratio wings fly faster and are more manoeuvrable, but have 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, the **G**ear drive**N** **A**utonomous **T**win **Spar** (**GNATSpar**) for a mini-UAV. The GNATSpar can be used to achieve span extensions up to 100% but for demonstration purposes it is used here to achieve span extensions up to 20% to reduce induced drag and increase flight endurance. The GNATSpar is superior to conventional telescopic and articulated structures as it uses the space available in the opposite sides of the wing instead of relying on overlapping structures and bearings. In addition, it has a self-locking actuation mechanism due to the low lead angle of the driving worm gear. Following the preliminary aero-structural sizing of the concept, a physical prototype is developed and tested in the 7'x5' wind-tunnel at the University of Southampton. Finally, benefits and drawbacks of the design are highlighted and analysed.

I. Introduction and Background

Continuous demands to enhance flight performance and control authority have focused the interest of aircraft designers on span morphing [1,2] . Wings with large spans have good range and fuel efficiency, but lack manoeuvrability and have relatively low cruise speeds. By contrast, aircraft with low aspect ratio wings can fly faster and become more manoeuvrable, but show poor aerodynamic efficiency [3]. A variable span wing can potentially integrate into a single aircraft the advantages of both designs, making this emerging technology especially attractive for military UAVs. Increasing the wingspan, increases the aspect ratio and wing area, and decreases the spanwise lift distribution for the same lift. Thus, the drag of the wing could be decreased, and consequently, the range or endurance of the vehicle increase. Unfortunately, the wing-root bending moment can increase considerably due to the larger span. Thus the aerodynamic, structural, aeroelastic, and control characteristics of the vehicle should be investigated in the design of variable-span morphing wings. Most span morphing concepts are based on a telescopic mechanism, following the ideas of Ivan Makhonine, a Russian expatriate, where the wing outer panel telescoped inside the inner panel to enable span and wing area changes. The MAK-10 was the first design with a telescopic wing and it first flew in 1931. The mechanism was powered pneumatically and enabled span increases up to 62% (from 13 to 21m) and area increases up to 57% (from 21 to 33m2) [4]. Blondeau et al. [5] designed and fabricated a three segmented telescopic wing for a UAV. Hollow fiberglass shells were used to preserve the spanwise aerofoil geometry and ensure compact storage and deployment of the telescopic wing. To reduce the weight, they replaced the wing spars with inflatable actuators that could support the aerodynamic loads on the wing (in excess of 73kg/m2). Their telescopic spar design consisted of three concentric circular aluminium tubes of decreasing diameter and increasing length, connected by ceramic linear bearings, and deployed and retracted using input pressures of 345–483kPa (50–70psi). The wing could undergo a 114% change in the aspect ratio, while supporting aerodynamic loads.

Blondeau et al. [6] adopted two identical telescopic spars instead of one, mechanically coupled by the ribs, to prevent wing twist and fluttering. The new prototype could undergo a

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230% change in aspect ratio, and seam heights were reduced giving less parasitic drag. In its fully deployed condition the telescopic wing could achieve lift-to-drag ratios as high as 16, which was similar to its solid foam-core wing counterpart. The most dramatic morphing wing involving span change that has been realized as a wind tunnel prototype is the Agile Hunter by Lockheed Martin [7-9]. Funded by DARPA within the MAS program, the prototype was based on a military UAV capable of folding the inner sections of the wing near to the fuselage, to reduce the surface area and drag during transonic flight at low altitude (also called a Z-wing). The major challenge was the realization of suitable hinges that connect the two wing portions; the hinges have to sustain the aerodynamic loads but offer a smooth, continuous aerodynamic surface. Several materials were considered, including silicone-based and Shape Memory Polymer skins. Wind tunnel tests at Mach 0.6 showed a morphing capability from 0° to 130° over 65s with a controllable, reliable and precise actuation. Bae et al. [10] performed both static aerodynamic and aeroelastic studies on the wing of a long-range cruise missile and highlighted some of the benefits and challenges associated with the design of a morphing wing capable of span change. The total drag decreased by approximately 25%, and the range increased by approximately 30%. The aeroelastic analysis showed that the flexibility of the morphing wing structure increased as the wingspan increased. At a given flight condition, the deformation from the aerodynamic loads was much larger than that of the conventional wing. Static aeroelastic considerations that a variable-span wing requires increased bending stiffness because the bending deformation is more significant than twist. Ajaj et al. [11] developed the Zigzag wingbox concept that allows the wing span of a medium altitude long endurance (a MALE) UAV to be varied by 44% (22% extension and 22% retraction). The Zigzag wingbox consists of a rigid part and a morphing part. The morphing part consists of various morphing partitions where in each partition there are two spars each consisting of two beams hinged together. Each morphing partition is covered by flexible skin and is bounded by two ribs through which the spars are connected. Furthermore, Ajaj et al. [12] developed the Compliant Spar concept that allows the wing span to be varied to provide roll control and enhance the operational performance for a medium altitude long endurance (MALE) UAV. The Compliant Spar is made of compliant joints arrange in series to allow it to be flexible under axial (spanwise) loads but at the same time stiff enough to resist bending loads. Each compliant joint consists of two concentric overlapping AL 2024-T3 tubes joined together using elastomeric material. Under axial (spanwise) loading, the elastomeric material deforms in shear allowing the overlapping distance between the tubes to vary and hence the length (in the spanwise direction) of the joint/spar to vary. A more extensive review on span morphing technology (applications and concepts) for both fixed-wing and rotary-wing aircraft is given in Barbarino et al. [13].

II. The GNATSpar Wing

The majority of the state-of-the-art span morphing concepts use telescopic and articulated mechanisms. Telescopic mechanisms tend to be heavy due to the need for minimum overlapping distance and bearings/lubriction between the different telescoping stages/sections. Furthermore, the telescoping stages/sections need to be of different cross-sectional areas to fit inside each other which increases their complexity and reduces their structural stiffness. The "**G**ear drive**N** **A**utonomous **T**win **Spar**" (GNATSpar) design, proposed here, overcome the need for telescopic and articulated mechanisms by utilising the available space in the opposite sides of the wing. In other words, the spar in each side of the wing is longer than the semi-span and the extra portion of the spar is stored in the opposite side of the wing and the wing-fuselage interface as shown Figure 1.

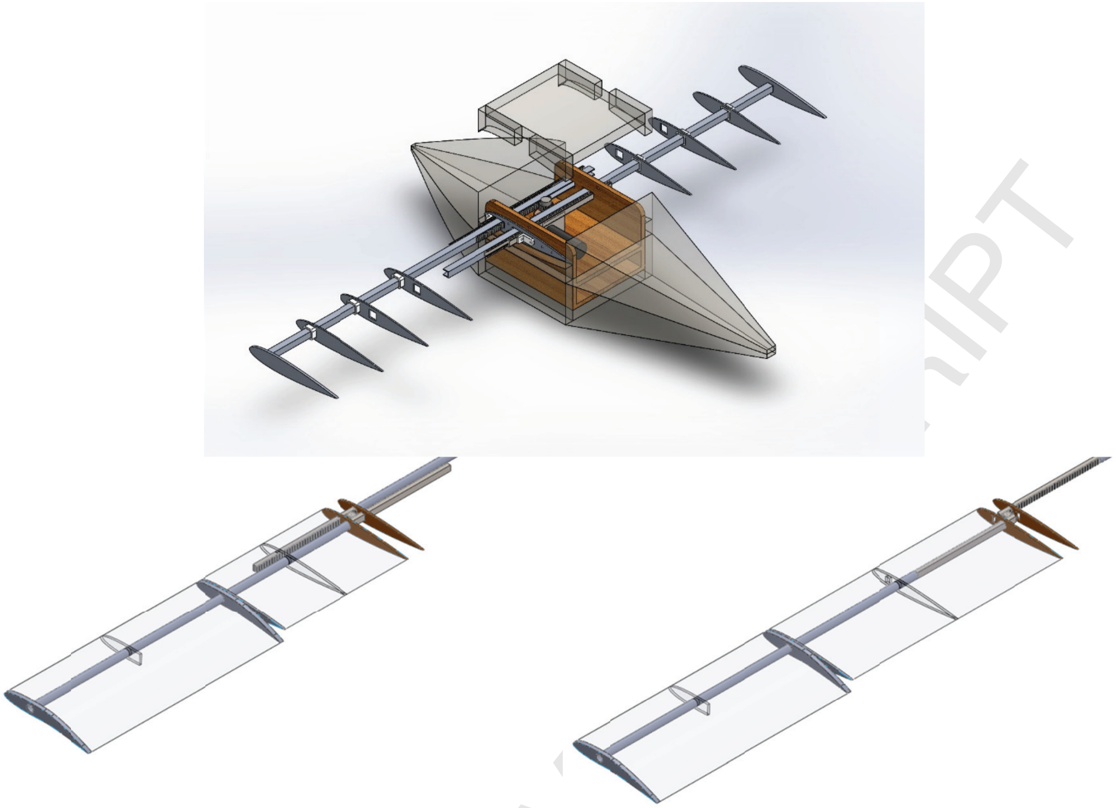


Figure 1: Schematic of the GNAT Spar concept.

The GNATSpar design allows having a uniform cross-section spar along the wing semi-span which is not possible with telescopic designs. The GNATSpar is a multifunctional morphing concept because it serves as the primary structure in the wing and as the actuation system to achieve span extension. This multi-functionality is achieved by having the inboard portion of the GNATSpar acting as a rack so a rack and pinion mechanism can be used to actuate the design as shown in Figure 2. With the GNATSpar design, the actuation system can be positioned in the wing-fuselage interface, hence reducing the complexity of the design and structural weight. This paper focuses on symmetric span morphing to enhance the flight performance of air-vehicles. This implies that the spars in the starboard and port wing can be actuated together where one actuator drives the pinion and the pinion drives the rack on each spar simultaneously allowing an overall span extension. The GNATSpar can also be used for asymmetric span morphing with slight modification to the actuation system but this will be investigated in future studies.

The GNATSpar will be covered by flexible elastomeric skin to allow span variations while maintaining the aerodynamic profile of the wing. The flexible skin is supported by a number of ribs. These ribs are bonded to the flexible skin and as the GNATSpar moves some of them slide on the spar to allow the skin to deform uniformly. The actuation system used consists of a pinion gear placed between the two racks, corresponding to each of the spars, producing a symmetrical movement of both spars. A spur gear and the pinion mounted together on the same shaft. Then, a DC motor drives the spur gear via a worm gear and the spur gear drives the pinion and hence the racks.

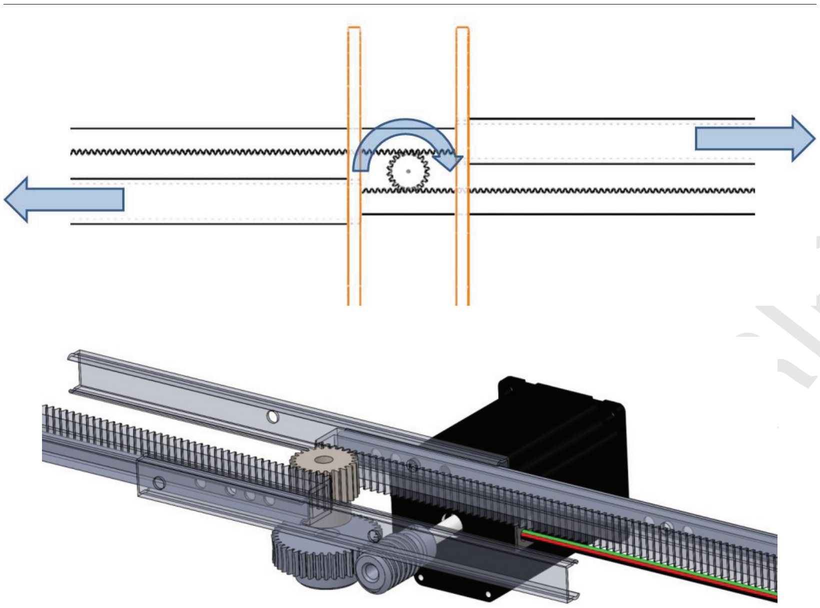


Figure 2: Rack and pinion actuation system for the GNATSpar.

The GNATSpar design has a self-locking capability due to the low lead angle of the worm gear. This self-locking capability implies no actuation energy is needed to overcome the flexible skin elastic loads to keep the spar in the desired locations (span extension). This paper focuses on utilising the GNATSpar on a representative electrically-powered, mini-UAV with a rectangular, straight wing. The UAV's specifications are listed in Table 1.

Table 1: The mini-UAV Specs.

Parameter	Value
MTOW	5kg
Cruising speed	15 m/s
Span	1.25 m
Chord	0.24 m

III. Aero-structural design and sizing

Aero-structural sizing of the GNATSpar wing is performed to ensure it can withstand extreme aerodynamic, actuation and skin elastic loads during the mechanical and wind-tunnel testing planned. The XFLR5 aerodynamic solver is used to determine the aerodynamic forces and moments on the wing. XFLR5 is linear aerodynamic solver that uses XFOIL as its computation kernel with 3D wing design capability. A straight, untampered rectangular wing with a NACA0012 aerofoil is modelled in XFLR5. The aerodynamic loads associated with maximum span extension (20%) at a 3-g gust scenario are the limit aerodynamic loads. These limit loads were amplied by 1.5 safety factor to determine the ultimate loads [15]. The ultimate loads are then converted into nodal forces applied at the wing ribs. A simplified cad model of the spar,used in FEA analysis, is shown in Figure 3. In this model the rack is taken as a square section tube while rigid elements are used to simulate the sliding ribs through which the aerodynamic loads are transferred to the spar. The axial loads from the skin strecthing and actuation are combined with the aerodynamic loads. Furthermore, a subsequent FEA analysis is conducted to determine the capability of the gear and rack teeth to undertake the axial loads created by the skin streching and actuation.

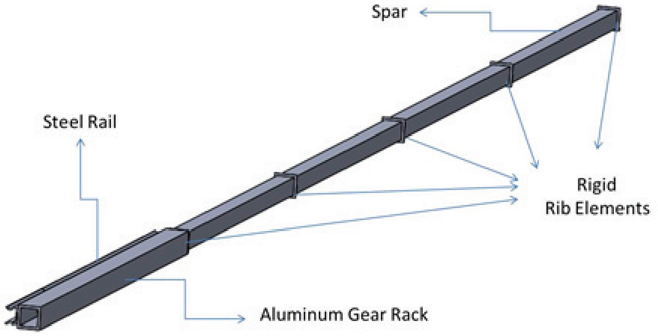


Figure 3: Simplified spar model for FEA analysis.

The spar of the port wing is located at 25% of the chord while the spar of the starboard is at about 40% of the chord. This implies that the starboard spar will experience higher torsional load due to its offset from the aerodynamic centre and must be designed to withstand them. Therefore, the nodal loads are applied at an offset to the spar to simulate the actual scenario as shown in Figure 4.

Figure 4: Nodal aerodynamic loads along the wing semispan.

Two structural objectives are set in order to assess the feasibility of the design. First, all the elements that compose the spar should maintain stresses below the elastic limit of each material at the limit loads. The second objective is that at 1-g flight, the wingtip out-of-plane deformation (when fully extended) should be less than or equal to 10% of the semi-span as shown in Figure 5.

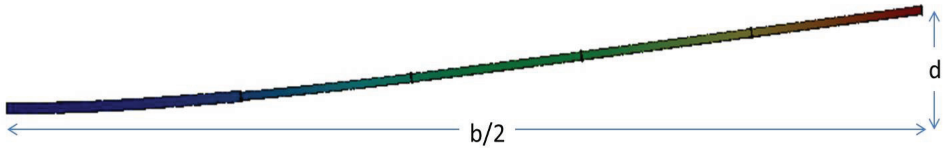


Figure 5: Wingtip out-of-plane displacement constraint.

A mesh convergence study was conducted to avoid the influence of the mesh size and density on the results. The sizing process indicated that a spar whose depth is 15mm and thickness is 1.5mm is required to withstand the loads. On the other hand, the spanwise and chordwise lift distribution were used to estimate the flexible skin out-of-plane deformations for different span extensions. The analysis showed that as the wingspan extends the out-of-plane deformations of the skin reduce significantly. Therefore, it was decided to add a 5% pre-tension into the skin to limit its deformations when the wing is fully retracted (0% extension).

IV. Prototype Manufacturing and Integration

A. Flexible Skin

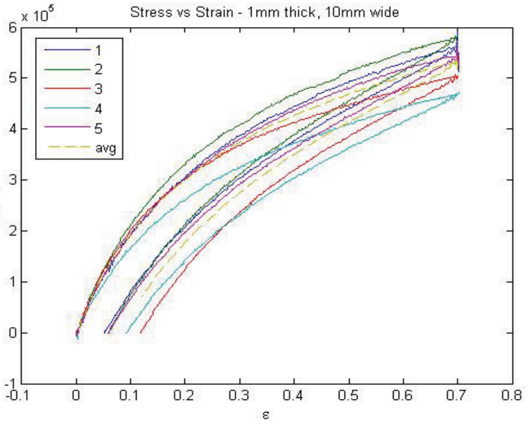
Due to time and cost constraints, Latex was chosen as the flexible skin that covers the wing and maintains its aerodynamic shape. Uniaxial testing of 20 Latex specimens was performed as shown in Figure 6 to determine the mechanical properties of the skin; hence, the size of the actuation system (mainly the motor and gear ratio).

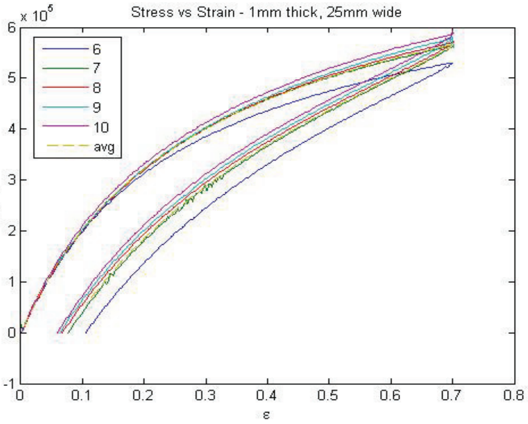
Figure 6: Uniaxial testing of Latex using the Instron 5569 test rig.

Specimens with thicknesses of 0.5mm and 1mm where tested up to 70% strain. All the specimens tested are 100mm long:

- Specimens 1 - 5 are 1mm thick and 10mm wide
- Specimens 6 - 10 are 1mm thick and 25mm wide;
- Specimens 11 - 15 are 0.5mm thick and 10mm wide; and,
- Specimens 16 - 20 are 0.5mm thick and 25mm wide.

Figure 7 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. In Figure 7, the curves with “avg” legend represent the mechanical behaviour of the skin with 90% confidence levels.





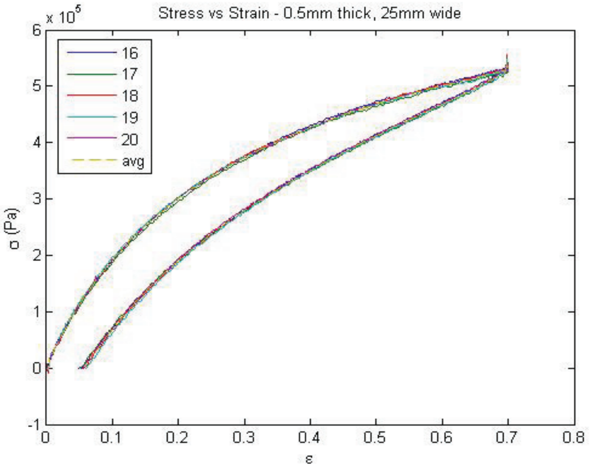
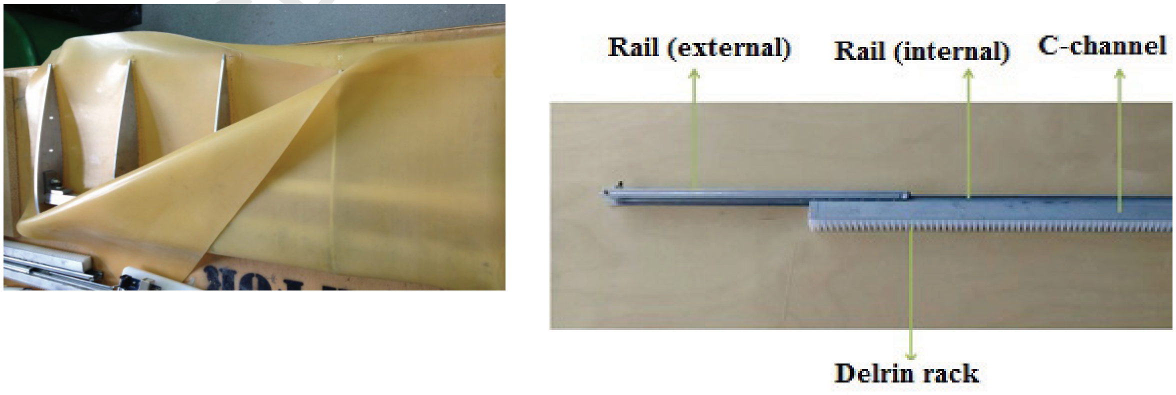


Figure 7: Stress strain curves of the different Latex specimens

B. Assembly and Integration

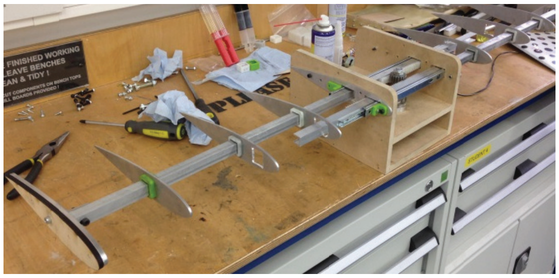
Following Latex uniaxial testing, 0.5mm thick Latex sheet was chosen to act as the morphing skin (Figure 8a). The loads from the skin are transferred to the spar through ribs. On each side of the wing there is 5 ribs. The root ribs are fixed to the wooden fuselage frame and each spar is attached to both root ribs (to maximise its bending stiffness) via a steel rail that allows the spar to slide relative to these ribs (Figure 8b). The rails transfer the loads from the spars to the wooden fuselage and maintain the chordwise positions of the spars.

The tip rib is fixed to the end of the spar while the other three intermediate ribs are attached to the spar via ball bearings so they can slide on the spar in the spanwise direction. The sliding ribs transfer the aerodynamic loads from the skin to the wing spar and they are equally spaced from each other. The skin is bonded using epoxy to the ribs as shown in Figure 8a. As the span extends, the spar and hence the tip rib (on each side of the wing) start moving. As the tip rib moves it forces the skin to extend. The bond between the sliding ribs and the skin slides and keeps these ribs spaced evenly apart to maintain uniform strain of the skin along the span. Since the spar has a square cross-section, it was difficult to find suitable ball bearings to allow the ribs to slide it. Therefore, ball bearing frames with square cross-sections were 3D printed from ABS, lubricated and fitted with mini-balls. The spars are Aluminium, square cross-section beams where the inboard portion of each spar is machined to achieve a C-channel cross-section. In the C-channel, Delrin racks are housed (bonded and screwed) for actuation purposes.



a. The Latex skin.

b. Spar inboard portion.



c. Components of GNATSpar.

Figure 8: Assembly and Integration of GNATSpar.

The joint between the skin and the root rib and between the skin and the tip rib experience large shear stresses due to the elastic loads of the skin as the span extends. To maximise the shear strength of these joints, the root and tip ribs (on each side of the wing) are split into of two minor ribs each. The skin is bonded on the top, bottom, and one side (depth of the rib) of one of the minor ribs (tip and root). This maximises the bonding contact area between the skin and the minor ribs. Then the minor ribs are bolted together to clamp the skin between them and increase the shear strength of the joint as shown in Figure 9.

Figure 9: Skin-ribs clamping mechanism.

Figure 10 shows the wing in the unmorphed position and in the fully extended position. It is evident from Figure 10 that the motor selected is capable of morphing the skin by up to 20% and that the skin joints at the root and tip are reliable due to the clamping mechanism developed.

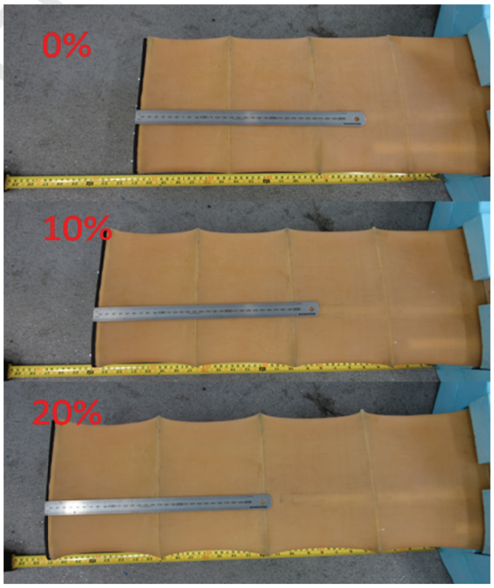


Figure 10: GNATSpar at different span extensions.

Figure 11 shows a close-up of the wing in its fully extended state. The skin deflection along the chordwise direction is large due to the large Poisson's ratio of Latex. 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 ratio effect.

Figure 11: Poisson's contraction of the skin when fully extended.

C. Control System

Figure 12 shows the setup of a robust control system developed for the GNATSpar. It consists of an Arduino Uno R3 microcontroller and two relay switches that help the microcontroller switching the motor on and off and changing its rotational direction. This control system allows only symmetric span extensions but can be adjusted to allow for asymmetric extensions. Three span extension configurations, corresponding to 0% 10% and 20%, are set in the controller as stages or modes. Ideally, a control system would autonomously vary the wing span to match the instantaneous flight conditions and operational requirements. A micro-switcher at the end of each rail (root ribs) is installed and silicon bumps are created on the sides of each spar in the defined positions (0%, 10%, and 20%). As the spar extends and reach one of the defined positions, the micro-switcher toggles to send a 5V impulse to the microcontroller. Two push button switches are used to command the actuation in both directions (extension and retraction). The actuation is terminated when both micro-switchers are pushed by the positioned bumps. Finally, a nano-tech 4cell 14.8V, high discharge, LiPo battery is used to power the GNATSpar.

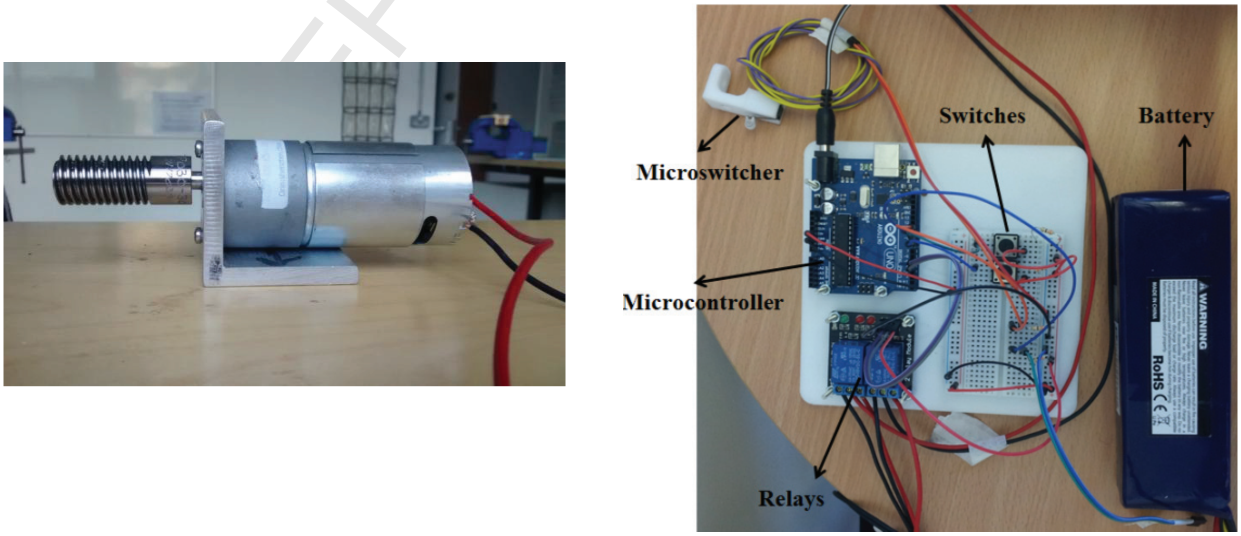


Figure 12: The control system for the GNATSpar.

It takes 18.5 seconds to extend the wingspan by 20%. According to Ajaj et al. [16,17], this actuation time is acceptable for symmetric span morphing used to enhance flight performance (but not for asymmetric morphing used for roll control) especially that this actuation time is less than 0.2% of the UAV's endurance. The DC motor has a built-in gearbox (Figure 12) that significantly reduces its rotational speed but maximises torque, which is optimum for stretching the skin.

D. Mechanical Testing

Mechanical testing is performed to determine the variation of bending stiffness with span extension. A 3kg load is applied on the wingtip (tip rib) and the wingtip out-of-plan defections are measured for the different extensions. Figure 13 shows the variation of the normalised bending stiffness of the GNATSpar wing with span extension. It should be noted that the 3kg tip load generates higher bending loads on the wing root than the 1-g flight condition.

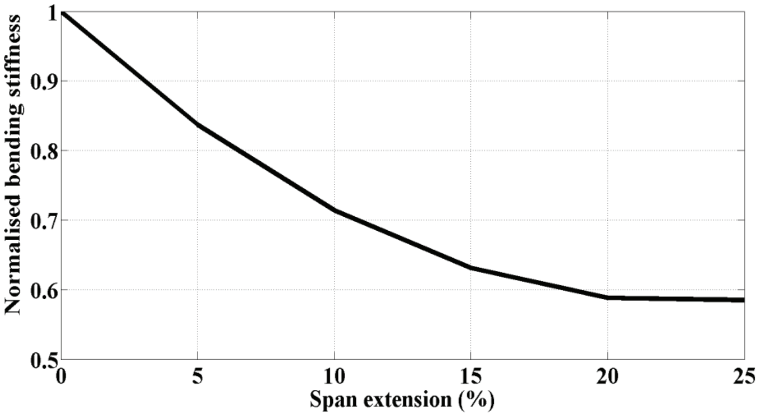


Figure 13: Bending stiffness of the GNATSpar versus span extension.

At 20% span extension, the bending stiffness of the GNATSpar drops by 40%. This drop has a significant impact on the aeroelastic behaviour of the wing.

E. Wind-tunnel Testing

Following the mechanical testing, wind-tunnel testing is performed. The high-speed section of the 7'x5' wind-tunnel at the University of Southampton is used. A representative fuselage cover made from foam is manufactured modularly to house both the GNATSpar wing and the wooden fuselage frame and maintain smooth aerodynamic profile around them as shown in Figure 14.

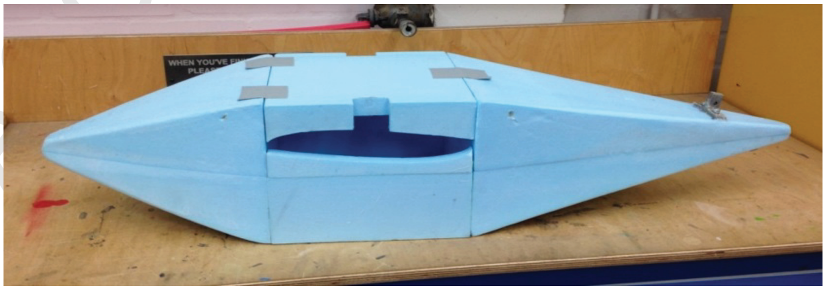


Figure 14: The GNATSpar integrated in the mini-UAV.

The model setup in the wind-tunnel is shown in Figure 15. The high-speed section of the tunnel uses a 3-component weight beam balance in the tunnel roof.

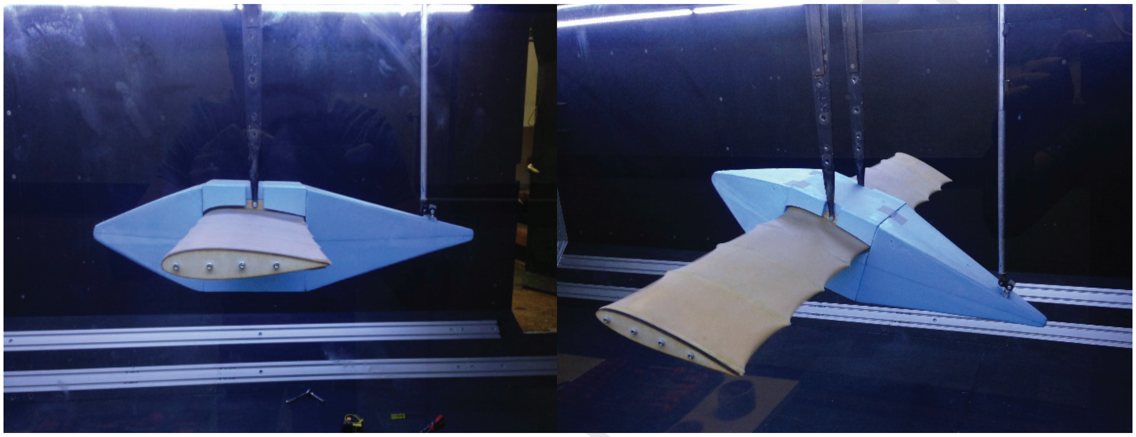
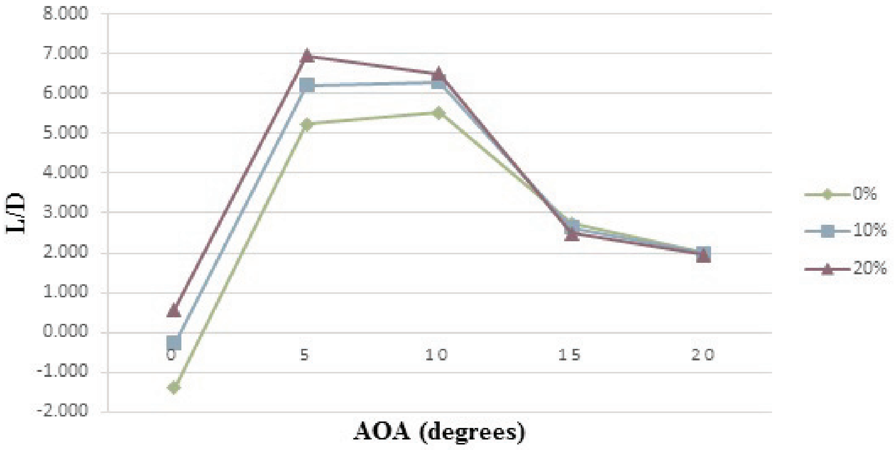
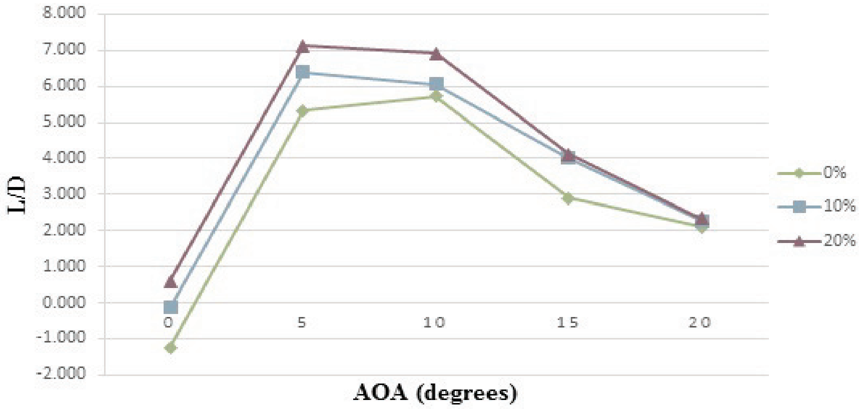


Figure 15: The GNATSpar Wing in the 7'x5' wind-tunnel.

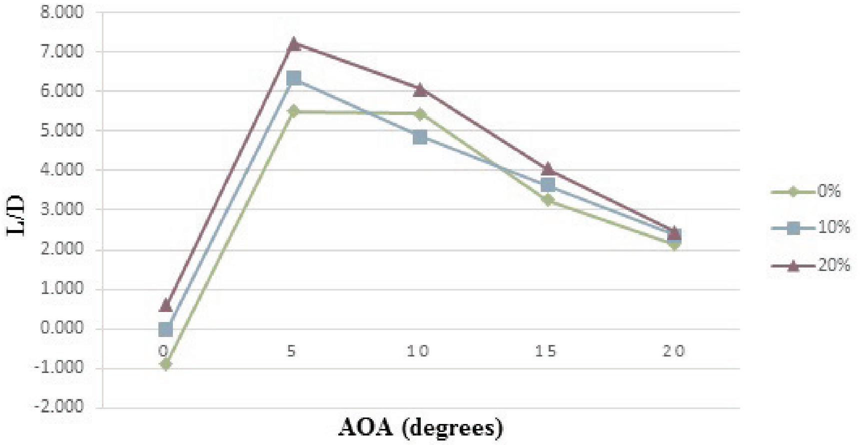
Three span extensions corresponding to 0%, 10% and 20% are considered during wind-tunnel testing. For each span extension, the AOA is varied from 0° to 20° with a step of 5° and the airspeed is varied from 10m/s to 20m/s with a step of 5m/s. The testing is performed quasi-statically where the wingspan is extended to the desired position before the wind-tunnel testing commences. Figure 16 shows the aerodynamic efficiency of the GNATSpar wing for different span extension at different operating conditions.



a. At 10m/s



b. At 15m/s



c. At 20m/s

Figure 16: Aerodynamic efficiency versus AOA for different span extensions.

It is evident from Figure 16 that span extension increases the aerodynamic efficiency of the UAV. It should be noted that for a 20% span extension at 20m/s, the wing aeroelastic deformations become large and if the airspeed is increased to 25m/s the wing started fluttering due to the large aerodynamic loads and lower stiffness of the wing. This was noticed during testing but was not considered further because the UAV is not designed to fly at 25m/s. The overall aerodynamic efficiency of the model is low due to the fuselage configuration being an aerodynamically inefficient, bluff body. However, the aim of the study is not to design an optimum fuselage configuration but to capture the sensitivity of the aerodynamic efficiency to span extension. It should be noted that stretching the flexible skin has an impact on the effective camber of the wing as shown in Figure 16. As the span extends and the skin stretches,α_o the zero lift angle of attack, increases as well.

V. Conclusions

The **G**ear drive**N** **A**utonomous **T**win **Spar** (GNATSpar) was designed, manufactured, integrated and tested. The GNATSpar is superior to conventional telescopic and articulated structures as it uses the space available in the opposite sides of the wing instead of relying on overlapping structures and bearings. In addition, it has a self-locking actuation mechanism due to the low lead angle of the driving worm gear. This reduces the actuation power required to morphing the wing and maintains it in the desired position. Following the preliminary aero-structural sizing of the concept, a physical prototype is developed and tested in the 7'x5' wind-tunnel at the University of Southampton. The span extension increased the aerodynamic efficiency of the UAV. The GNATSpar requires relatively large force required to morph the wing with the flexible skin. 55N actuation force was required to morph the wing semispan by 20%. 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. In addition, as the wing extends the shape of the aerofoil along the span becomes non-uniform due to the Poisson's contractions. Future work will focus on building three of non-morphing, rigid wings with spans corresponding to 0%, 10% and 20% span extensions. These wings will have with rigid skins. Wind-tunnel testing of these wings will be conducted and aerodynamic efficiency will be measured. This will allow estimating the impact of the flexible skin on the aerodynamic efficiency of the wing.

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