Morphological Design and Analysis of Aircraft Wings

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ABSTRACT

When developing the aircraft profile mission, one would want to achieve the most advantageous flight aerodynamic parameters for each specific segment. Nowadays traditional air vehicles and particularly their wings are not designed to satisfy the most optimal conditions for each segment but only designated to achieve sub-optimal performance of the entire flight envelope, putting the major focus on one or two crucial settings to achieve an overall consensus. A morphing wing is a concept that allows wing's transformation in flight so that the overall aircraft performance in terms of both mechanical behaviours and aeroelastic conditions is significantly enhanced. In this paper a thorough analysis of aircraft wings development in terms of existing morphing technologies was carried out using the Morphological Analysis Design method as initiated by Fritz Zwicky in 1930s, to get a comprehensive understanding of morphing technologies in aircraft wings development and to categorise the variable parameters of solutions. The Morphology is referred as a study of the simplicity, basic arrangements of all objects. Not only taking into account general structures such as aspects of geometry, geology or biology but also looking at more abstract interrelations between structures, ideas or any additions of substance. In this study, the analysis encompassed different mission segments to ensure the most crucial performance metrics and their variables were taken into account for fixed wings operation in subsonic region. An extended analysis using RQ-21A Blackjack selected as an aeroplane scope, highlighted performance improvements in both aerofoil and planform/out-of-plane morphing the Morphological Analysis starting with an initial set of 576 solutions. The discussion of possible as well as misjudged concepts is presented using comparative non-dimensional aerodynamic performance metrics.

KEYWORDS: Morphing, Morphological analysis, Wing Design

1 INTRODUCTION

Flight performance has been a matter of the utmost importance since the earliest development of any aircraft. Dependent on the aircraft's profile mission, one would want to achieve the most advantageous flight aerodynamic parameters for each of them. However, there are several constrains so that it can fulfil the mission with increased payload at faster speeds. Nowadays traditional air vehicles and particularly their wings are not designed to satisfy the most optimal conditions of each flight segment. They are only designated to achieve sub-optimal performance of the entire flight envelope, putting the major focus on one or two crucial settings to achieve an overall consensus [1]. As the demand for commercial and military air transport capabilities increase, the investigation into cost-effective solutions that enhance aircraft performance becomes more and more vital. The estimates give the image of as little as 1% decrease in aerofoil drag could give the total saving of $140 millions per year when analysing US transport feel with the cost of fuel of $0.70 per gallon [2]. The nature has been immensely inspirational for aircraft designers for years. Not only the simplicity but mainly the aerodynamic efficiency, that is the most significant characteristic of all flying species, became the major background for aircraft designers to resemble the nature creations [2]. A simple bird can provide an ideal state conditions for an aircraft wing as it can drastically reshape itself to satisfy the most optimal geometrical requirements for all flight conditions [1]. Falcons are one of the most important examples as they have the ability for long endurance loitering with the aid of e.g. air currents and for swift morphing of their body to strike their detected prey [2]. The challenge of transforming the geometry of an aircraft wing has been investigated as early as at the beginning of 20th century with the Wright brothers' development of the heavier-than-air The Wright Flyer aircraft. It was claimed as one of the firsts attempt at controlling the structural flexibility by using manpower to twist the wing to influence roll properties [3]. This can be treated as one of the first usages of morphing technologies in aircraft wing development. A morphing wing is a concept that allows wing's transformation in flight so that the overall aircraft performance in terms of both mechanical behaviours and aeroelastic conditions is significantly enhanced [4]. The shape and structural flexibility were found during aircraft design optimisation to be the two key elements influencing the performance, hence changing the geometry in flight is the major focus of reference when one speaks about aircraft morphing [3],[5]. Within the literature there are proposed several classifications of techniques to obtain a morphing wing that could focus on the level of morphing classifying transformations as large, medium or small [1] or group all morphing capabilities in aerofoil, planform or out-of-plane alterations [2],[6]. The classification represented in Table 1 will be here object of study expanding on the meaning of each morphing idea and explaining the aerodynamic effects as referred to actuation and skin coverage methods.

Table 1: Classification of geometrical wing morphing aspects [6]

Shape Morphing Wing	**Aerofoil Adjustment**	Camber Variation
		Thickness Variation
	Planform Alteration	Span Variation
		Chord Length Variation
		Sweep Angle Variation
	Out-of-plane Transformation	Twist Variation
		Dihedral / Gull Variation
		Spanwise bending

Some historical aspects regarding the morphing technology evolution are discussed in Section 2, followed by a presentation of the Morphology Analysis Design Method [7] in Section 3. The application of this method for the development of morphing wings is presented in Section 4, followed by conclusions and possible future work ideas. Extended analysis and results are presented in [8], which formed the basis of the present work.

2 MORPHING TECHNOLOGIES

For the most vital comprehension of morphing developments, the existing constrains and limits of various designs should be reviewed. One of the most famous examples developed in 1970s is the Grumman F-14 Tomcat, widely known just as F-14. Its specific construction allowed the wings sweep angle to vary between 20° to 68° degrees, which provides the most optimal lift-to-drag ratio in flight configuration [1]. The idea of planform alteration that succeeds in the variable sweep angle comes from the need for both the most optimal low-speed operation during take-off and landing as well as high-speed for fast cruise, even at supersonic conditions. Particularly for the second flight operation there is an advantage of delaying the drag rise at Mach numbers approaching 1.0 due to the alteration of wing sweep. To contrast these great performance advantages that would be highly favourable especially for military application one must consider what are the drawbacks of running an aircraft with such applications in place. In the Grumman F14 Tomcat case, the biggest penalty was the additional weight and the complexity of an aircraft, what not only lowers the fuel efficiency but in longer term, increases the cost of running the aircraft. All the F-14's became retired by US Navy in 2006 due to high maintenances required that were not only complex but also not cost-effective. Unfortunately, even its replacement F/A-18E did not exceed the specification due to reduced payload by smaller fixed wings [1]. Despite having represented The Wright Flyer from the beginning of 20th century many could find other examples of even earlier advancements of not only the technological advancements in aeroplane technology but also the history of the world. Starting with Icarus that comes from Greek mythology, attempts at both flying and resembling the nature were mentioned such as those represented by primitive feathers glued with wax to create bird-like wings [9]. The early aviation also brings a history of Otto Lilienthal from 1881 whose systematic bird studies succeeded in a series of simple but elegant gliders. He discovered the curved shape of bird's wings was the key element to the secret of flight. Having applied it to aircraft shape would harness the success for a flying machine, Lilienthal is claimed to be the first to underpin the principles of the force of lift as there was very first realisation of how the shape of wing affects the flow surrounding the wing [10]. As early as in 1914, Gallaudet D-1 has been a subject to variable wing tips study what was further studied by North American XB-70 Valkyrie in 1964 [11]. The span extension could be observed from 1931 when Makhonine MAK-10 was implemented with telescopic wing allowing up to 62% in retraction and the variable sweep was used 20 years before Grumman F14 Tomcat for Bell X-5 operated exclusively by NACA High-Speed Flight Station between 1952-1955 [12]. More complex and unusual configurations which can be mentioned are the Goodyear Inflatoplane, the concept of an inflatable aeroplane produced from 1952 and sponsored by United States Army, or the NASA AD-1, the concept of an asymmetric-oblique sweep that works like a pair of scissors to enhance low-to-high speed performance, both with potential usage in other vehicle configurations [13]. The current state of the art in aircraft design presents many interesting solutions which are under investigation and development. In this paper the main focus is the subsonic wing design and possibilities to use morphing techniques to create concept solutions with enhanced performances during the flight envelope, starting from existing configurations and varying their design characteristics within the framework of a powerful design methodology.

3 MORPHOLOGICAL DESIGN ANALYSIS

The modelling tool to assess the constrains of morphing wing technologies will be Morphological Analysis as initiated by Fritz Zwicky in 1930s, a Swiss astronomer and a professor of Astronomy at California Institute of Technology [7], and further studied by different several institutions such as California Polytechnic State University San Luis Obispo [14] and Swedish Morphological Society [15]. Morphology is referred as a study of the simplicity, basic arrangements of all objects. Not only by taking into the account general structures such as the aspects of geometry, geology or biology but also looking at more abstract interrelations between ideas or any additions of substance. General Morphological Analysis has been established as a method for describing, structuring and investigating the finite set of possible relationships within often non-quantifiable problem with high complexity factors [7]. The approach the Fritz Zwicky undertook comprised of five iterative steps:

(1) Clear and concise formulation of a problem to be investigated,

(2) Analysis of all Morphological Analysis Field descriptive parameters that could possibly be of an importance for providing the solution to the problem,

(3) Construction of a Morphological Box, a multidimensional matrix that describes all of the solutions to the problem as based on pre-defined parameters,

(4) Examination of every solution within the Morphological Box to determine their performance with respect to each other,

(5) Evaluation of the most viable solutions to the investigated problem as based on the performance between each solution for pre-defined descriptive parameters within Morphological Analysis Field.

To clarify the process, an example of one of the most significant investigations carried out as a preparatory step towards defining a new propulsive system [15] is presented. The Morphological Analysis Field variables were set as *Initial Energy Form, Transmission* and *Final Storage Form* that simplified provides 5 equal solutions for each of the variables such as *Kinetic, Electrical, Chemical, Thermal* and *Nuclear*. The simplified Morphological Box, called in other words as a Morphological Analysis Field for the exemplar problem is represented in Table 2. As indicated, the top row contains *Variables* and each row underneath represents singular *Solutions.*

Table 2, A simplified Morphological Analysis Field used for defining a new propulsive power in 1960s [15].

Descriptive Parameters ↓	**Variations →**				
d1	**d1.1**	**d1.2**	**d1.3**	**d1.4**	**d1.5**
Initial Energy Form	Kinetic	Electrical	Chemical	Thermal	Nuclear
d2	**d2.1**	**d2.2**	**d2.3**	**d2.4**	**d2.5**
Transmission Energy Form	Kinetic	Electrical	Chemical	Thermal	Nuclear
d3	**d3.1**	**d3.2**	**d3.3**	**d3.4**	**d3.5**
Final Energy Storage Form	Kinetic	Electrical	Chemical	Thermal	Nuclear

The example of an overall solution d1.1, d2.2, d3.3 that is highlighted in cells above provides a configuration of *Initial Energy Form* as *Kinetic*, *Transmission Form* as *Electrical* and lastly *Final Storage Form* as *Chemical*. Nowadays such a configuration is widely known as a hydroelectric energy generation stored in a battery. Another instances to spot within the solutions space could be an internal combustion energy stored in a flywheel (*Chemical – Thermal – Kinetic*) or a simple refrigerator (*Electrical – Chemical – Thermal*). The maximum amount of arrangements depends on the size of a matrix, that in given case could provide 125 (5x5x5) possible configurations. The exploration of given results enables the assessment of not only currently existing solutions to stated problems but it also may allow the discovery of undeveloped paths that were not taken into consideration before. The introduced form of Morphological Analysis is used for the investigation of morphing technologies existence in aircraft wings development. In order to follow the *5 Iterative Steps* as described by Fritz Zwicky, there is a need for an additional tool to reduce the number of final possible configurations and overcome the practical limits of the original method. For this reason, Cross-Consistency Assessment (CCA) has been put in place to study whether the combinations of all provided solutions are actually plausible and are not contradictory. Obtaining of the CCA eliminates any inconsistencies between particular configurations and ensures the remaining ones are logically consistent [16]. By performing the CCA, the analysis of a solution space with the established Morphological Box may allow easier designation of any undeveloped results and a possible room for improvement to overcome existing challenges and derive vital performance analysis.
In the present study, following the Morphological Analysis methodology, a comprehensive study of the morphing technologies was carried out: classifying the variable parameters of solutions within geometrical shape morphing for aerofoil, planform and out-of-plane majoring alterations (Table 1), evaluating the goals of different technologies, underlining the relationships between identified solutions' categories to eliminate any inconsistencies, and establishing a benchmark of flight mission aerodynamic performance metrics that will be further used to assess viable solutions. A solution space of morphing ideas was created identifying any undeveloped technologies or areas that could be applied differently based on configuration simulation, and performing a comparison of performance against the set benchmark using mathematical formulations referred to the aerodynamic effects and computational study in Xfoil [17] and XFLR5 [18] programmes, with a goal to underline the principles of applicable actuation systems and material capabilities for the favourable solutions and forecast of future state-of-art technologies that could enhance flight capabilities.

4 RESULTS

As described in [14] the construction of analysis field consists of descriptive parameters or variables that are abstract enough to cover a wide variety of objects, but specific enough to be applicable. The problem has been formulated and thoroughly studied outlining the challenges and limitations in Section 3 and on that basis there was created a Morphological Analysis Field or as referred by others a Morphological Box. In order to get the best understanding of the possible concepts to be generated using Morphological Analysis there were not included the methods of actuation and possible skin types. The variety of morphing alternations may not be possible to achieve with the same actuation method and including them for every parameter studied would create high-level of complexity of the analysis. For the reason, only 'what' – aerodynamic performance is discussed within Morphological Analysis and 'how' – is summarised for selected configurations. The classification of morphing technologies introduced the most important parameters for the purpose of benchmark analysis described in Section

1. There were identified four descriptive parameters directly referring to wing morphing capabilities, d2-d5 and one parameter that puts the wing into the context of the type of aircraft it could be used for referred to as d1. The Morphological Box is outlined in Table 3 with full specification of all possible solutions for all descriptive parameters as listed. The reference aeroplane, d1 that would be the subject of wing's application is deemed to have one, two or zero fuselages, so called 'flying wing'. Aerofoil morphing, d2 is concerned with changes applied to leading edge, trailing edge or a full camber transformation. Planform morphing concerns two parameters such as span, d3 and sweep d4. For span morphing there are concerned two generic ideas of uniform extension such as in [19] or [20] and non-uniform that relates mainly to separate winglets represented in [21]. Sweep angle morphing represents a summary of ideas within forward, backward and asymmetric also called oblique transformation. Lastly, out-of-plane morphing d5, has been combined for both dihedral and gull degrees, representing straight dihedral for an entire wing alteration, tip dihedral and gull morphing as represented in [22].

Table 3: Morphological Analysis Field for studied morphing technologies.

Descriptive Parameters ↓	**Variations →**				**Variations Count**
d1 Aeroplane	**d1.1**	**d1.2**	**d1.3**		**k1 = 3**
Number of Fuselages	None – Flying Wing	One	Two		
d2 Aerofoil	**d2.1**	**d2.2**	**d2.3**	**d.2.4**	**k2 = 4**
Morphing Camber	None	Leading Edge	Trailing Edge	Entire Camber	
d3 Planform	**d3.1**	**d3.2**	**d3.3**		**k3 = 3**
Morphing Span	None	Uniform	Non-Uniform		
d4 Planform	**d4.1**	**d4.2**	**d4.3**	**d4.4**	**k4 = 4**
Morphing Sweep	None	Forward	Backward	Asymmetric 'Oblique'	
d5 Out-of-plane	**d5.1**	**d5.2**	**d5.3**	**d5.4**	**k5 = 4**
Morphing Dihedral/Gull	None	Straight Dihedral	Tip Dihedral	Gull	
					Total k = 576

Having established the complete Morphological Analysis Field, the spectrum of all solutions have been summarised providing the total of 576 solutions that can be achieved within the analysis, what gives 192 configurations for each type of the fuselages. Additionally, as described in [14] focused mainly on architectural projects, in order to provide the highest accuracy of multi-dimensional design analysis there were added variants that allow the lack of certain type of morphologies. It increases the dimensionality of different non-quantifiable configurations that could be analysed either by random selection, constraint imposition or preference ordering in order to remove bias and prejudice from design. As introduced by Zwicky and further studied by Swedish Morphological Society, there is an inevitable need to minimise the number of all possible solutions through cross-consistency analysis of solution's feasibility what overcomes the practical limits of the original Morphological Analysis developed in 1930s [16]. Additionally, as presented in the Phase 1, SUGAR – Subsonic Ultra Green Aircraft Research, a similar approach was used not only to study the compatibility of proposed solutions but also the enhancement that favourable configurations could impose on dynamic decision making [23]. The report carried out in-depth analysis of airline current market outline to design a new aeroplane concept, also covering variable camber and planform wing morphing. It depicted that medium size airliners will be almost 50% off all air vehicles entering service from 2030. It enforced additional efforts on a right identification of relations between solutions to start their evaluations.

Having listed the all descriptive parameters and variants in the matrix represented in Table 3, the incompatible configurations were decided to be the following:

1. d1.1 Aeroplane Fuselage, None – Flying Wing
    a. d1.1 x d2.4 – Aerofoil Morphing, Entire Camber
    b. d1.1 x d3.3 – Planform Morphing, Non-uniform Span
    c. d1.1 x d4.2 – Planform Morphing, Forward Sweep
    d. d1.1 x d4.3 – Planform Morphing, Backward Sweep
    e. d1.1 x d5.2 – Out-of-plane Morphing, Straight Dihedral
    f. d1.1 x d5.3 – Out-of-plane Morphing, Tip Dihedral
    g. d1.1 x d5.4 – Out-of-plane Morphing, Gull
2. d5.4 Out-of-plane Morphing, Gull
    a. d5.4 x d1.1 – Aeroplane Type, No Fuselage – Flying Wing
    b. d5.4 x d1.1 – Aeroplane Type, Two Fuselages
    c. d5.4 x d4.2 – Planform Morphing, Forward Sweep
    d. d5.4 x d4.3 – Planform Morphing, Backward Sweep
    e. d5.4 x d4.4 – Planform Morphing, Oblique Sweep

Further, the overall number of conflicting solutions gave the total of 264, what by taking out all of them from the available solution of morphological box, left 312 feasible solutions out of initial 576. There will be also performed an additional analysis to confirm the CCA task was performed correctly by confronting the performance of removed configurations. Out of remaining 312 solutions, 156 were compatible for d.1.2 an aeroplane type with one fuselage. Moreover, for the purpose of maximisation the performance analysis in order to satisfy benchmark criterion, there were further eliminated all non-morphing solutions from the morphological space, such as d2.1 – Zero Aerofoil Camber Morphing, d3.1 – Zero Planform Span Morphing, d4.1 – Zero Planform Sweep Morphing and d5.1 – Zero Out-of-plane Dihedral/Gull Morphing. Having done that, the final 36 solutions were obtained for one fuselage aeroplane, extended to 72 solutions. To give some more details, the following 6 solutions were decided for further consideration as an initiation point of morphological space analysis:

1) d1.2 x d2.4 x d3.2 x d4.2 x d5.2: Wing with entire camber morphing aerofoil that can uniformly expand span and transform to forward swept position at straight dihedral angle.
2) d1.2 x d2.4 x d3.2 x d4.2 x d5.3: Wing with entire camber morphing aerofoil that can uniformly expand span and transform to forward swept position at wing tips dihedral angle.
3) d1.2 x d2.4 x d3.2 x d4.3 x d5.2: Wing with entire camber morphing aerofoil that can uniformly expand span and transform to backward swept position at straight dihedral angle.
4) d1.2 x d2.4 x d3.2 x d4.3 x d5.3: Wing with entire camber morphing aerofoil that can uniformly expand span and transform to backward swept position with wing tips at dihedral angle.
5) d1.2 x d2.4 x d3.3 x d4.3 x d5.3: Wing with entire camber morphing aerofoil that can non-uniformly expand span and transform to backward swept position with wing tips at dihedral angle.
6) d1.2 x d2.2 x d3.2 x d4.3 x d5.3: Wing with leading edge camber morphing aerofoil that can uniformly expand span and transform to backward swept position with wing tips at dihedral angle.

Table 4: Cross-Consistency Assessment for the developed Morphological Analysis Field

1 Compatible Solution 0 Incompatible Solution		d1 Aeroplane – Number of Fuselages			d2 Aerofoil – Morphing Camber				d3 Planform – Morphing Span			d4 Planform – Morphing				d5 Out-of-plane – Morphing Dihedral/Gull			
		None - Flying Wing	One	Two	None	Leading Edge	Trailing Edge	Entire Camber	None	Uniform	Non-Uniform	None	Forward	Backward	Oblique	None	Straight Dihedral	Tip Dihedral	Gull
		d1.1	d1.2	d1.3	d2.1	d2.2	d2.3	d2.4	d3.1	d3.2	d3.3	d4.1	d4.2	d4.3	d4.4	d5.1	d5.2	d5.3	d5.4
d1	d1.1	**1**																	
	d1.2	0	**1**																
	d1.3	0	0	**1**															
d2	d2.1	1	1	1	**1**														
	d2.2	1	1	1	0	**1**													
	d2.3	1	1	1	0	0	**1**												
	d2.4	0	1	1	0	0	0	**1**											
d3	d3.1	1	1	1	1	1	1	1	**1**										
	d3.2	1	1	1	1	1	1	1	0	**1**									
	d3.3	0	1	1	1	1	1	1	0	0	**1**								
d4	d4.1	1	1	1	1	1	1	1	1	1	1	**1**							
	d4.2	0	1	1	1	1	1	1	1	1	1	0	**1**						
	d4.3	0	1	1	1	1	1	1	1	1	1	0	0	**1**					
	d4.4	1	1	1	1	1	1	1	1	1	1	0	0	0	**1**				
d5	d5.1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	**1**			
	d5.2	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	**1**		
	d5.3	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	**1**	
	d5.4	0	1	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0	**1**

7) d1.2 x d2.4 x d3.2 x d4.2 x d5.2: Wing with entire camber morphing aerofoil that can uniformly expand span and transform to forward swept position at straight dihedral angle.
8) d1.2 x d2.4 x d3.2 x d4.2 x d5.3: Wing with entire camber morphing aerofoil that can uniformly expand span and transform to forward swept position at wing tips dihedral angle.
9) d1.2 x d2.4 x d3.2 x d4.3 x d5.2: Wing with entire camber morphing aerofoil that can uniformly expand span and transform to backward swept position at straight dihedral angle.

10) d1.2 x d2.4 x d3.2 x d4.3 x d5.3: Wing with entire camber morphing aerofoil that can uniformly expand span and transform to backward swept position with wing tips at dihedral angle.
11) d1.2 x d2.4 x d3.3 x d4.3 x d5.3: Wing with entire camber morphing aerofoil that can non-uniformly expand span and transform to backward swept position with wing tips at dihedral angle.
12) d1.2 x d2.2 x d3.2 x d4.3 x d5.3: Wing with leading edge camber morphing aerofoil that can uniformly expand span and transform to backward swept position with wing tips at dihedral angle.

The computational performance evaluation was split across all described morphing segments to get an understanding of how different solutions generated contribute towards the performance improvement. The benchmark study was selected to be RQ-21A Blackjack UAS introduced in 2014, an unmanned aerial surveillance vehicle produced by Boeing Insitu, with the capabilities of the maximum endurance of 16h with operating up to ceiling of 20,000ft [24].RQ-21A creates an ideal benchmark plane to understand how wing morphing could improve its overall performance as its fuselage design allow the wing to be easily replaced if further wind tunnel analysis was required, as represented in Figure 1. For the study the aerofoil shape was assumed to be NACA 0012 and the specifications of wing with removed winglets were increased by factor 1.6 for chord and 1.531 for wing span to simplify the computational analysis.

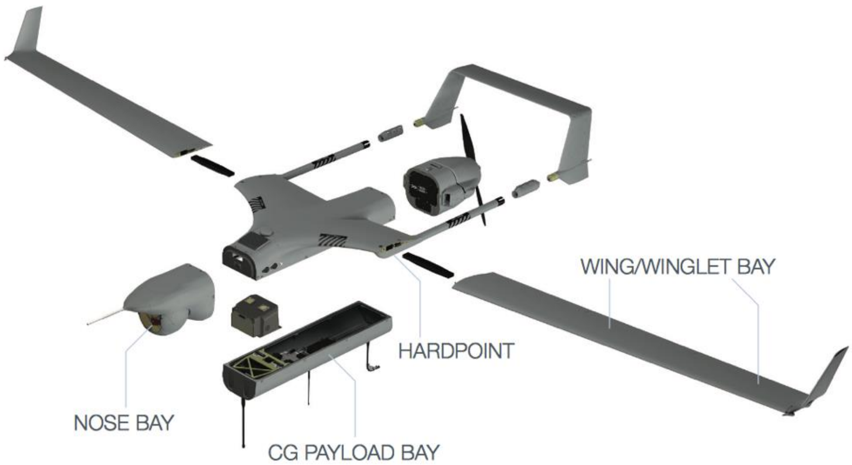

Figure 1: RQ-21A [24].

Table 5: RQ-21A [24] wing parameters used for the optimisation process.

Wing Span	**4.9**	**m**	**7.5**	**m**	**+53.1%**
Chord	0.3125	m	0.5	m	+60%
Aspect Ratio	15.68		15.0		-4.3%
Taper Ratio	1		1		
Total Length	2.5	m	4	m	+60%
OEW	36.7	kg	58.7	kg	+60%
MTOW	61	kg	97.6	kg	+60%
Max Payload	17.7	kg	28.3	kg	+60%

A similar investigation has been conducted in [25] taking BQM-34 Firebee UAV as the study scope. In order to learn and compare the results, similar settings for Mach numbers were used at the selected mission profile segments presented in Table 6. An extended set of simulations were carried out using

XFLR with the initial configuration allowing a comparison of the different design solutions discussed in Tables 3,4.

Table 6: Testing conditions for selected benchmark mission profiles.

Mission Segment	Unit	Take-off	Range			Endurance	
Altitude	ft	0	0	29520	59040	29520	59040
	m	0	0	9000	18000	9000	18000
Mach No.		0.2	0.3	0.6	0.7	0.7	0.7
Speed at SL	m/s	340.3	340.3	303.8	295.1	303.8	295.1
Speed at altitude	m/s	68.06	102.09	182.28	206.57	212.66	206.57
Reynold No.	$x10^6$	2.33	3.49	2.85	0.88	3.33	0.88
Test Reynolds No.	$x10^6$	2.50	3.50	3.00	1.00	3.50	1.00

A number of airfoils were analysed the best performance being achieved for NACA6412 and FX74-CL5-140 aerofoils, having 6% and 10% effective camber respectively. The greatest improvement has been observed across 4 and 6% camber for high-altitude endurance and high-altitude range achieving between 40-100% improvements giving superior results, with NACA6412 having better performance than FX74-CL5-140 in all range related missions. From previous evaluations the cases selected were "d3.2, d4.2, d5.2"; (2) "d3.2, d4.2, d5.3"; (3) "d3.2, d4.3, d5.2" and (4)/(6) "d3.2, d4.3, d5.3". The testing constraints were set at Reynolds No. $3x10^6$ to resemble flight conditions of Mach No. 0.25 at sea-level altitude or Mach No. 0.6 at MA, medium altitude 9000m as introduced within aerofoil optimisation. The benchmark aerofoil has been selected as NACA6412 to provide the most optimal effective camber performance without the need of achieving 10% effective camber. The results have been constrained for 1/3 AR, aspect ratio increase up to 20 from initial AR 15, and 2/3 increase of AR up to 25. The taper ratio has been set as 1, chord length at constant 0.5m and the inertia of the wing has been selected at one-quarter chord length with corresponding 1/3 and 2/3 OEW weight increase for AR 20 and AR 25 from initial OEW.
The results were obtained for tip to root sweep angle Λ varied from -15° forward sweep angle, d4.2 up to 30° backward sweep angle, d4.3 and dihedral angle Γ that was varied for straight alteration, d5.2 up to 10° and 45° wing tip, d5.3. The 1/3 increase of AR from 15 to 20 has shown the increase in both range and performance factors of +36% and +40% respectively. The computational analysis in Xfoil for aerofoil morphing in Reynold No. between 1.00 $x10^6$ - 3.50 $x10^6$ showed a great advantage of an effective camber transformation from 0% to up to 6% for range and 10% for endurance improvement. Further use of flow control such as AHLLE MOLEC could enhance lift improvement by at least 95% when compared to traditional Kruger flaps in take-off segment. XFLR5 was used to perform a comparison of different planform for Reynold No. 3.0 $x10^6$ that has shown up to 140-180% improvement across all mission segments when allowing 2/3 aspect ratio expansion, root to sweep angle variation between -15° and 15°, straight dihedral of 0-10° and tip dihedral of up to 45°.

5 CONCLUSIONS

An initial study for performance improvement using airfoil, planform and out-of-plane shape morphing has been carried out using the Morphological Analysis giving a set of 576 possible solutions based on the aerodynamic performance calculations, the mass constraints and actuators capability not being considered. A reduced set of configurations allowed the analysis of performance obtained through different morphing options in combinations as derived using the Morphological Analysis.

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