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Multi-objective Optimization of Subsonic Glider Wing Using Genetic Algorithm

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Abstract: The widespread adoption of Unmanned Aerial Vehicles (UAVs) can be traced to its flexibility and wide adaptability to various operating conditions and applications, comparably low cost of construction and maintenance and environmental friendliness as they can be easily configured for electric power. The use of electric power also favours its low noise applications such as surveillance. A major issue associated with surveillance, as addressed in this study is the compromise between Range and Endurance operation modes. The Range mode relates to being able to cover longer distances while the Endurance mode relates to spending longer times in the atmosphere for a fixed charge. Trying to balance the interplay of these parameters gave rise to a multi-objective optimization where the objectives are somewhat conflicting. This resulted in a set of Pareto solutions which are a set of design parameters (primarily angle of attack) that satisfy the joint requirements of the performance parameters of Range and Endurance. This study first considered a baseline aerodynamic design using traditional design methods. Design of Experiment techniques were then used to select the most favourable design points. This model was then used to build an input framework for Genetic Optimization algorithm deployed in the Global Optimization Toolbox of MATLAB. The result of this research shows that most of the region associated with medium angle of attack (AOA) setting (7 degrees) jointly satisfies good Range and Endurance performances with an average lift-to-drag ratio of 20 in the flight configuration considered. The implication of this result is that low velocity drag encountered in surveillance that requires a high AOA is largely reduced with the medium setting, albeit stabilized with other structural and aerodynamic settings, namely an aspect ratio of 13 and a taper ratio of 0.6.

Index Terms: Unmanned Aerial Vehicle, range, endurance, design of experiment, genetic optimization.

1. Introduction

In recent times, the aviation industry has come to depend heavily on optimization of existing designs and infrastructure to minimize the cost of maintenance and reduce or completely eliminate the need for the developing entirely and needlessly divergent design concepts. The optimization framework is generally aimed at limiting the numerical value, hence minimizing the effect of adverse performance parameters at the least possible cost to beneficial design parameters critical to performance efficiency, subject to the constraints allowable by pre-established performance/design requirements. The key word here is efficiency. The most affected factors in a typical aerodynamic optimization problem are safety and cost, primarily with regard to fuel consumption. Major ways of tackling cost are: using lightweight materials, developing energy efficient fuel systems, optimizing the flight path schedule and improving the aerodynamic properties of the aircraft [1, 2]**.** Improving the aerodynamic properties of the aircraft has proven to be the easiest and most flexible (as is seen in the available volume of research and publications in the literature)**.** Typically, a 1% increase in lift will yield a corresponding improvement of payload capability to the tune of 2 tons, with the same approach speed [3]. Another major reason for the dominance of aerodynamic approach to optimization over other approaches to aircraft efficiency improvement is that the atmosphere essentially constitutes an envelope in which the aircraft travels. Essentially, all the aerodynamic forces acting on the aircraft are dependent on the medium in which it travels, namely the atmosphere. Consequently, it is only logical to give high priority to working on an element that is so essential to the flight of the vehicle under consideration. Moreover, recent advances in the field of applied computational engineering has seen Computational Fluid Dynamics (CFD) develop into a significant complement to actual wind tunnel tests [4]. UAVs have been most especially beneficial in the area of surveillance, data acquisition and intelligence gathering, for structural safety assessment, surveying, law enforcement, goods delivery, disaster management, aerial photography and so on. For the purpose of this work, the UAV platform is being conceived for surveillance purposes, a paradigm also known as Unmanned Aerial Surveillance, [5]. Obviously, this application is quite prized by the military and some domestic applications such as environmental monitoring and atmospheric data collection. Surveillance deployment of the aircraft is also useful for surveying and assessment operations, [6,7].

The main objective of this study is to examine the optimum flight setting (captured in the angle of attack) in terms of physical wing parameters such that the Range and Endurance requirements are met for optimum performance – subject to aerodynamic, stability and structural constraints. Within this objective framework, sub-objectives include the selection of the air foil that best satisfies the desired flight characteristics and the development of the mathematical scheme that will serve as the basis for the implementation of the optimization algorithm. Furthermore, two key parameters, namely the aspect ratio and taper ratio will be initially determined from the evaluation of the lift distribution using design of experiment techniques. This framework is designed to form a robust approach for the minimization of the drag penalty associated with low-speed surveillance operations in glider flight.

1.1. Related Works

A common and powerful schema deployed in aerodynamic optimization is evolutionary algorithms (sometimes deployed within an artificial neural network infrastructure) due to their flexibility and adaptation to wide range of aerodynamic optimization problems. They also tend to score higher on overall performance. Usually, optimization algorithms are adopted to solve inverse design problems, especially parameter estimation. This works in such a way that the algorithm tries to find a set of design configuration that will satisfy a given set of predetermined performance parameters. In this way, the designer specifies a desired set of performance parameters and with the aid of the optimization algorithm, computes the air foil geometry or aerodynamic shape subject to predefined design parameters that will yield the desired performance parameters. The inverse method gives the designer significant control over the outcome of the optimization process, unlike the direct optimization method that selects an existing air foil based on its performance and tweaking its geometry to obtain the most suitable performance set [7]. However, a major drawback of the inverse method is that it tends to give unreasonable geometry if it is implemented without constraint(s). The bottom-line of the evolutionary algorithm is that if properly designed and deployed, it has been proven to significantly reduce computational cost [8, 9]. Take for example the optimization study conducted by Jianfeng *et al.* [10], where the algorithm required one-twentieth the original number of evaluations. In the course of this study, the proposed optimization tool has a robust framework for defining and implementing both performance and geometric constraints which will see off some of the loopholes pointed out above.

Yilei *et al.* [11] and Neto *et al.* [12] both adopted a multiobjective approach to the problem of aerodynamic performance optimization for glide-based vehicles, taking for example a lifting surface in ground effect (Wing-in-Ground-Effect, WIG configuration). Both studies show that a necessary component of the optimization solution is the Pareto Front, which details all possibly combinations of design parameters that appear to simultaneously satisfy all the optimization objectives. This concept will be further explored in the result of this work. However, an earlier work by Kyoungwoo *et al.* [13] already examined adding static margin as a stability criterion to the optimization constraint, especially with the study dealing with a WIG aircraft. This study on the other hand sought to extend the possibilities of flight beyond altitudes where static margin is applicable by using an aerofoil dependent stability criterion to establish the stability constraint of the wing in this case study.

On the other hand, a multipoint approach employed by Gaetan *et al*. [14] where rather than execute a 'static' (single point) optimization, a bit of dynamism that ensures an approximate coverage of the flight spectrum was adopted in the optimization such that several flight configurations were optimized for, relative to aerofoil orientation. This study showed that the result landscape seemed to favour simplicity over complexity, with the single point scenario coming tops with the largest drag reduction (the case objective). This also goes to show that the multiobjective approach, more that the multipoint approach provides a more robust framework for dealing with broad-based, multidimensional domains in a typical optimization problem. A more sophisticated alternative for implementing the multidimensionality of an aerodynamic optimization problem was presented in the work of Dileep *et al*. [15], where a shape memory alloy (SMA) was built into the upper surface of the wing to morph the wing geometry in flight and consequently, actively control the flow characteristics. This was however a single point optimization problem as the aerodynamic performance was only considered for cruise condition only. This leaves an open-ended solution where stability does not take much of a precedence as is necessary in a glide-based flight scenario.

2. Methodology

The summary of the organization of materials and methods adopted for this research work goes thus. First, the pertinent design parameters affecting wing aerodynamic performance were established, having conducted a preliminary design of the base concept, using a 2D wing section analysis software. The air foil selected was the NACA72012 profile, which was then modified due to a geometric inconvenience. The software employed for this task was Javafoil™. Afterwards, an objective function that incorporated the aerodynamic forces of lift and drag was structured to deduce a single mathematical expression for the representation of aerodynamic efficiency in terms of range and endurance. The associated constraints for the flight configuration were the developed within the framework of the objective function developed in the preceding step. Furthermore, the effect of imposing limits on the decision variables associated with the implementation of the adopted optimization algorithm was examined. The selected optimization tool was the Genetic Algorithm.

A platform for the deployment of the genetic algorithm was then selected. The Global Optimization toolbox of MATLAB® was used for the implementation. The toolbox is robust and has diverse functionalities that can be used to derive a variety of configurations that served to thoroughly explore the problem domain. The robustness of the toolbox is in the fact that it has tools for quick hyperparameter tuning without having to make extensive code alterations. It also has functions for plotting function characteristics so that the convergence of solutions can be viewed in real time. Finally, a comparison and validation of results using CFD modelling was conducted. Another means of validation explored was the actual fabrication and testing.

A design point estimation was first carried out based on the design specifications subject to stall speed, maximum speed and the ceiling of the UAV. These were computed from general relations of aircraft performance with respect to power loading and wing loading as the dependent and independent variables respectively. The equation and the values of the initial parameters used for the base design are given in table 1 while the design point estimation is shown in fig. 1.

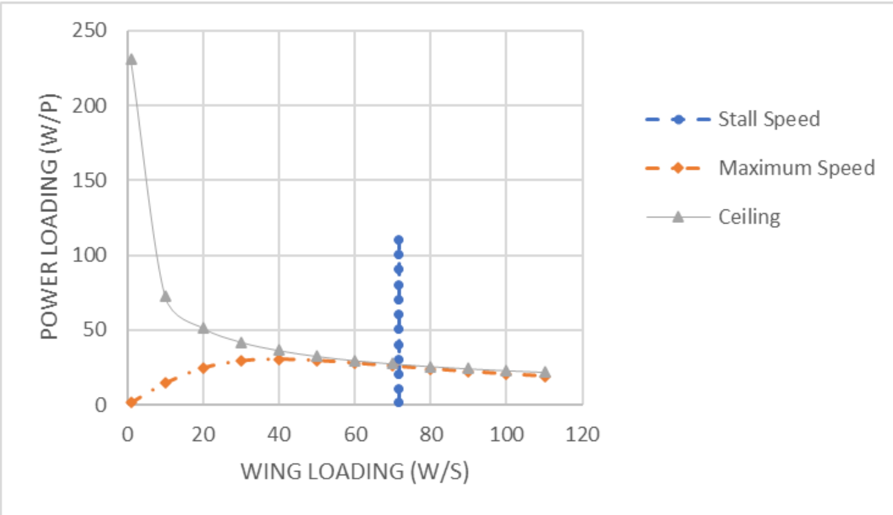

Fig.1. Design point estimation

Table 1. Mathematical Relations for parameters and their values

Parameter	Relation	Value/Basis
Stall speed (V_s)	$\left(\frac{W}{S}\right)_{VS} = \frac{1}{2}\rho_0 V_S^2 C_{L\max}$	100 Knots (51.4 m/s)
Maximum speed (V_{max})	$\frac{440}{\frac{285.94}{\left(\frac{W}{S}\right)} + 0.184\left(\frac{W}{S}\right)}$	1.1 V_s
Service ceiling	$\left(\frac{W}{P}\right)_{AC} = \frac{523}{2.266 \times \sqrt{\frac{W}{S}}}$	Absolute ceiling (where Rate of Climb = 0)
Maximum coefficient of lift (C_{Lmax})	$C\sqrt{\frac{3C_{DOL}}{K}}_{Lmax}$ Where C_{DOL} = 0.05; K = 0.033	2.12
Aspect ratio	-	15
Starting Weight	-	2 kg

Table 1 shows the mathematical relations whose combination is used to approximate the design point (fig. 1) that will be used to kick-start design analysis. The operational parameters described by the equations are the *stall speed*, *maximum speed* and the *service ceiling*. These are the fundamental requirements that are further used to determine the required power and surface area of the glider in question. As shown in fig. 1, the optimum design point is found close to (or around) the point of intersection of the three curves. Note that the curves are generated using the equations in the table.

3. Problem Formulation

3.1. Objective Function

The optimization scheme was implemented, using the objective function given in equation 1.

Objective:

$$\text{minimize}:\left[\left(\frac{C_D}{C_L}\right)^X_{endurance} + \left(\frac{C_D}{C_L}\right)^Y_{range}\right] \quad (1)$$

where $\boldsymbol{X}$ and $\boldsymbol{Y}$ are indices that describe the aerodynamic efficiency $\left(\frac{C_D}{C_L}\right)$ as it applies specifically to endurance and range performance respectively.

3.2. Aerodynamic constraints

$C_{Lmin} \geq C_{Ld}$ (The design coefficient of lift should exceed a minimum specified value)
$C_{Dmax} \geq C_{Dd}$ (The design coefficient of drag should not exceed a maximum specified value)

3.3. Structural constraint

$BM \leq BM_{max}$ (The maximum bending moment induced due to the vertical loads of lift and weight should not exceed the allowable maximum of the wing structure)

3.4. Stability constraint

$\Delta h \leq \Delta h_{max}$ (The movement of the centre of pressure along the mean aerodynamic chord of the wing as the angle of attack changes must not exceed a maximum value to entrench stability)

4. Preliminary Optimization of Base Parameters

Having conducted a preliminary design analysis to obtain base design parameters, an initial optimization to further fine tune two major parameters – Aspect ratio and Taper ratio, was conducted. For this stage, a Design of Experiment (DOE) approach is adopted. A Taguishi design with two factors (inputs), one output and nine levels are used to effectively exhaust the possibilities. The inputs are Aspect ratio and Taper ratio which were fed into a MATLAB script designed using the Lift Line Theory to generate a lift distribution profile and varied across the nine levels according to the requirements of the design. The behaviour of the lift distribution curve forms the basis for the determination of the best performance. An ideal lift distribution profile should be elliptical and have a large area under it (the larger the area, the greater the lift generated). These requirements were interpreted into three output parameters – eccentricity of the ellipse, wing coefficient of lift and curvature index (a measure of how well the profile follows an actual ellipse) - obtained from the script and the geometry of the lift distribution profile. However, for simplicity and ease of representation of the outputs on a single graph, they were lumped into a weighted sum of the three responses. The objective of the optimization scheme is to maximize the weighted sum of responses with the aspect ratio and taper ratio as decision variables. A simple optimization formulation would be:

Objective

$$\max_{AR;\,\lambda}: \text{Weighted sum of responses}$$

$Subject\ to\ (constrained\ at)$:

Planform, S = 0.01m^2
Twist angle, alpha_twist = -1 (deg)
Wing setting angle, i_w = 2 (deg)
Lift curve slope, a_2d = 5.38 (1/rad)
Zero-lift angle of attack, alpha_0 = -4 (deg)

The formulation above summarizes the initial optimization step. It summarizes the primary objective that consists of the process of plotting the base geometric objectives (aspect ratio and taper ratio) in the range stipulated by the Taguishi design. The constraints are the fixed values which are auxiliary inputs in the code used to generate the lift distribution, a sample of which is shown in fig. 6. The output of the code was examined (that is the corresponding lift distribution profile at each level of the combination of design parameters) and used to generate variables that formed the basis of the development of the pre-optimization scheme represented in a contour plot (fig. 7).

5. Derivation of Objective Functions

5.1. Endurance

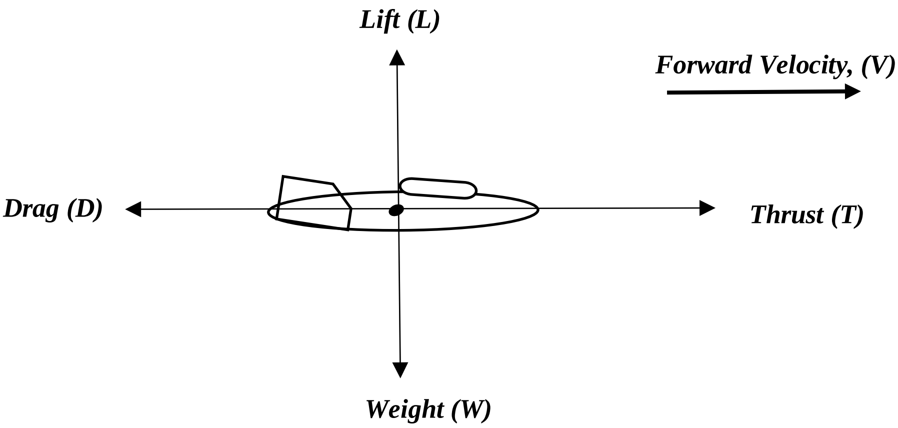

Fig.2. Aerodynamic forces in a straight level flight

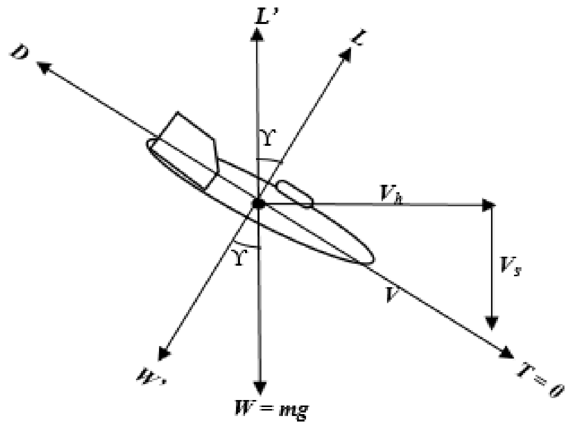

Fig.3. Aerodynamic forces in a diving flight

$$V_S = \left(\sqrt{\frac{2mg}{\rho S}}\right)\frac{C_D}{(C_D^2 + C_L^2)^{3/4}} \tag{2}$$

Given that the first identity is a constant, the sink rate then is seen to depend on: $\frac{C_D}{(C_D^2+C_L^2)^{3/4}}$

Usually for vertical motion, lift force takes precedence over drag.

That is, $C_L \gg C_D$

$$\therefore V_S \alpha \frac{C_D}{C_L^{3/4}} \tag{3}$$

Equation 3 is the first objective to be minimized.

5.2. Range

In order to derive the relationship governing the maximum range condition, we reconstruct the space diagram representing the glide dynamics as shown in fig. 4.

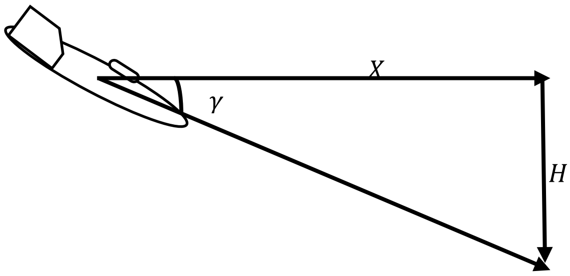

Fig.4. Simplified dynamics for diving flight

It is seen that:

$$\tan\gamma = \frac{H}{X} = \frac{D}{L} = \frac{C_D}{C_L} \tag{4}$$

where $\boldsymbol{X}$, $\boldsymbol{C_D}$ and $\boldsymbol{D}$ are associated with the range of the glider while $\boldsymbol{H}$, $\boldsymbol{C_L}$ and $\boldsymbol{L}$ are associated with the endurance of the glider.

From equation 4,

$$\therefore X = \frac{H}{\frac{C_D}{C_L}} \tag{5}$$

From equation 5, we may deduce that maximizing range, $\boldsymbol{X}$ requires the minimization of $\boldsymbol{C_D}/\boldsymbol{C_L}$. This is the second objective to be minimized.

5.3. Stability

The optimization requires that the wing meets strict stability conditions so that irrespective of the good vertical and horizontal dynamics, the aircraft should maintain strict heading and not 'fall out of the sky'. To put this in place, two points along the chord of the wing section (air foil) are defined as follows:

i. Aerodynamic center (*ac*): this is a point along the chord of the airfoil where the coefficient of moment is independent of the lift characteristic of the airfoil.
ii. Center of Pressure (*cp*): this is also a point along the chord line where the coefficient of moment of the airfoil is zero and aerodynamic influence consists entirely of the of lift and drag only.

As a result of the foregoing, the aerodynamic forces acting on the wing can coefficient be described in one of two ways: lift, drag and moment acting at the aerodynamic centre and lift and drag only acting at the centre of pressure.
The dynamics for the derivation of the stability criterion is deduced from fig. 5.

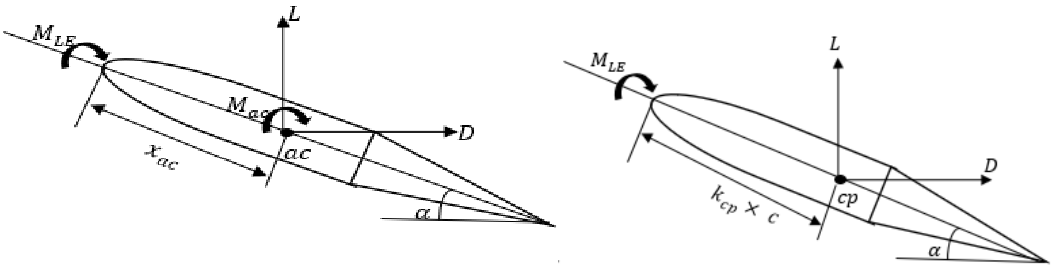

Fig.5. Air foil dynamics for stability assessment

where M_{LE} and M_{ac} are the moments about the leading edge and aerodynamic centre respectively;

$\boldsymbol{x_{ac}}$ is the moment arm of the aerodynamic center about the leading edge;

$\boldsymbol{k_{cp}}$ is the normalised position of the centre of pressure along the chord *c*; and

$\boldsymbol{\alpha}$ is the angle of attack of the airfoil/wing

Taking the moment of forces about the leading edge, we have:

$$-(L\cos\alpha + D\sin\alpha)k_{cp}c = M_{ac} - (L\cos\alpha + D\sin\alpha)x_{ac} \tag{6}$$

$$\therefore k_{cp} = \frac{x_{ac}}{c} = \frac{C_{Mac}}{C_L\cos\alpha + C_D\sin\alpha} \tag{7}$$

5.4. Aerodynamic Fitting

The fundamental relationship between the decision variables, C_L and C_D is constrained to fit the elliptical load distribution of an aerodynamically efficient wing. The relationship is quadratic and given in equation 8.

$$C_D = C_{D0} + kC_L{}^2 \tag{8}$$

where $\boldsymbol{C_{D0}}$ is the coefficient of drag independent of lift, usually at α = 0; and

$\boldsymbol{k}$ is the section drag factor given by: $\frac{1}{\pi eAR}$

6. Multipoint optimization

To determine the optimal flight condition for maximum glide efficiency, the optimization will be conducted under the multipoint scheme, with the determinant condition being the angle of attack, α. The angle of attack is therefore sampled at several points along the lift – angle of attack curve, before stall occurs. The sampling points are 2, 7 and 13. Multipoint optimization within the context of this work is similar to the definition adopted by Chai *et al.* [16]. In this sense, the scope of the optimization covers multiple geometric points/configurations, namely the three angles of attack considered.

7. Results and Discussion

7.1. Aerodynamic Pre-optimization

Table 2 shows the combination of inputs for the design of experiments described in the methodology, using the Taguishi design. The corresponding wing lift characteristic for each combination of input parameters presented is shown in Table 2. The two inputs are the first two columns of the table, fed into the MATLAB code for determining maximum lift and lift distribution. The resultant graphs (an instance of which is shown in fig. 6) were scrutinized and from them curvature indices (fourth column of the table) from each configuration were obtained. The index in each case is a measure of how the lift distribution profile fits the ideal case, the ideal case being the elliptical lift distribution. Also, from Table 2, the eccentricity (second column) of each lift distribution profile was computed being another measure of determining how much the profile matches the ideal elliptical lift distribution. These three outputs (direct and derived) were then combined into a weighted sum of an overall selection index. This index served as the input for the contour plot shown in fig. 7.

Table 2. Data of pre-optimization of design parameters and results

ASPECT RATIO ($\boldsymbol{AR}$)	TAPER RATIO ($\boldsymbol{\Lambda}$)	ECCENTRICITY ($\boldsymbol{e}$)	WING COEFFICIENT OF LIFT ($\boldsymbol{C_{LW}}$)	CURVATURE INDEX ($\boldsymbol{c}$)	SELECTION INDEX (1.2* $\boldsymbol{e}$ + $\boldsymbol{C_{LW}}$ + $\boldsymbol{c}$)
12	0.2	2.51	0.4113	0.5	3.9284
12	0.4	2.62	0.4388	0.7	4.2930
12	0.6	2.74	0.4494	0.7	4.4408
16	0.2	2.30	0.4237	0.4	3.5837
16	0.4	2.40	0.4525	0.6	3.9325
16	0.6	2.50	0.4641	0.8	4.2641
22	0.2	2.08	0.4345	0.5	3.4366
22	0.4	2.08	0.4645	0.55	3.5145
22	0.6	2.24	0.4769	0.6	3.7707

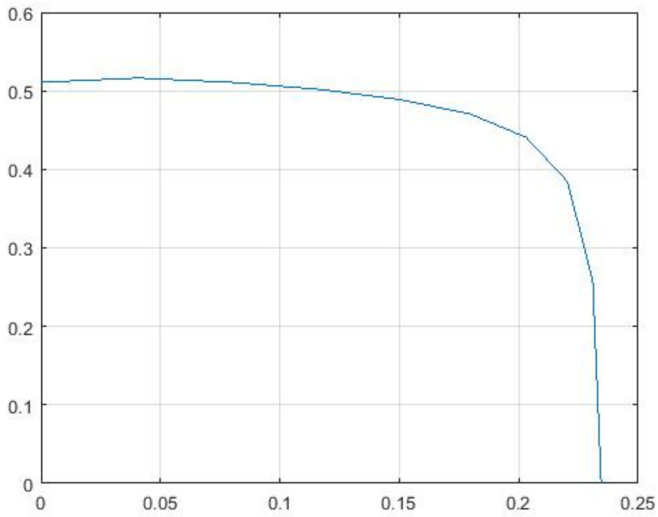

Fig.6. A wing lift distribution curve (Case: AR = 22; Λ = 0.6)

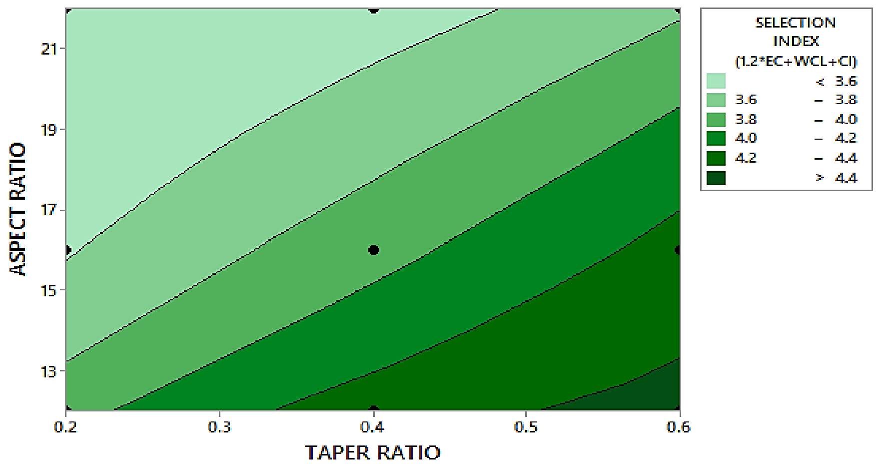

Fig.7. Pre-optimization contour plot

NB: The last column constitutes the weighted sum of responses mentioned in 4.0

On combining the results into a contour map, Fig. 7 was obtained and the optimal design point for *AR* and Λ was obtained**.**

It should be noted that the eccentricity of the wing is weighted by 20% in the selection index. This is because the application being considered has a lot to do with minimizing induced drag to maintain high endurance and range while also minimizing the structural loads acting on the wing due to lift generation. In addition, considering the fact that a high aspect ratio (longer wing span relative to the mean aerodynamic chord) is being considered relative to the aircraft size, the bending loads (which are bound to be high due to the significant moment arm in place) ought also to be minimized.

The value selected for each parameter respectively from the optimization contour map are:

$$AR = 13; \Lambda = 0.6$$

This selection corresponds to the bottom right-hand corner of the contour map. These values are seen to maximize the weighted sum of responses, hence giving the optimum performance with respect to maximum life and stall behaviour (capture by the eccentricity, wing lift coefficient and the curvature of the lift-span distribution). This fulfils the initial optimization step described in section 4.0. Furthermore, it satisfies the precondition for the evaluation of the lift distribution using design of experiment techniques as stated in one of the study sub-objectives.

7.2. Genetic Algorithm Optimization

After running the Genetic Algorithm, a set of points detailing the optimization step at each angle of attack were generated as the feasible solutions, constituting the Pareto front. The Pareto plots obtained at each angle of attack were subsequently combined in order to select the optimum operational points. This is shown in fig. 8.

The most obvious observation form fig. 8 is that irrespective of the AOA, the Pareto points seem to follow the same

(Almost logarithmic) curve. Given that these are the best results, the graph is partitioned such that each angle of attack favours a particular kind of performance – range or endurance – over the other. It is seen that low AOA favours Endurance a little over Range. This being because more Pareto points at this AOA fall within the low score region for Endurance than there are in the low score region for range. Going further down the Pareto curve, medium AOA values favour range but gives average performance for Endurance. Finally, high AOA exclusively favours range over endurance. Fig. 9 illustrates the deduced information as just explained. In addition, the relationship was correlated with a 3rd order polynomial trend line. The line has a coefficient of correlation of 0.9987. In other words, the relationship can be used to safely infer the relationship between range and endurance performance at a given AOA within the examined limits of the glider. Table 3 gives a summary of the combined performances at each angle of attack. In the table, it seen that a medium angle of attack most favours the two performances under consideration.

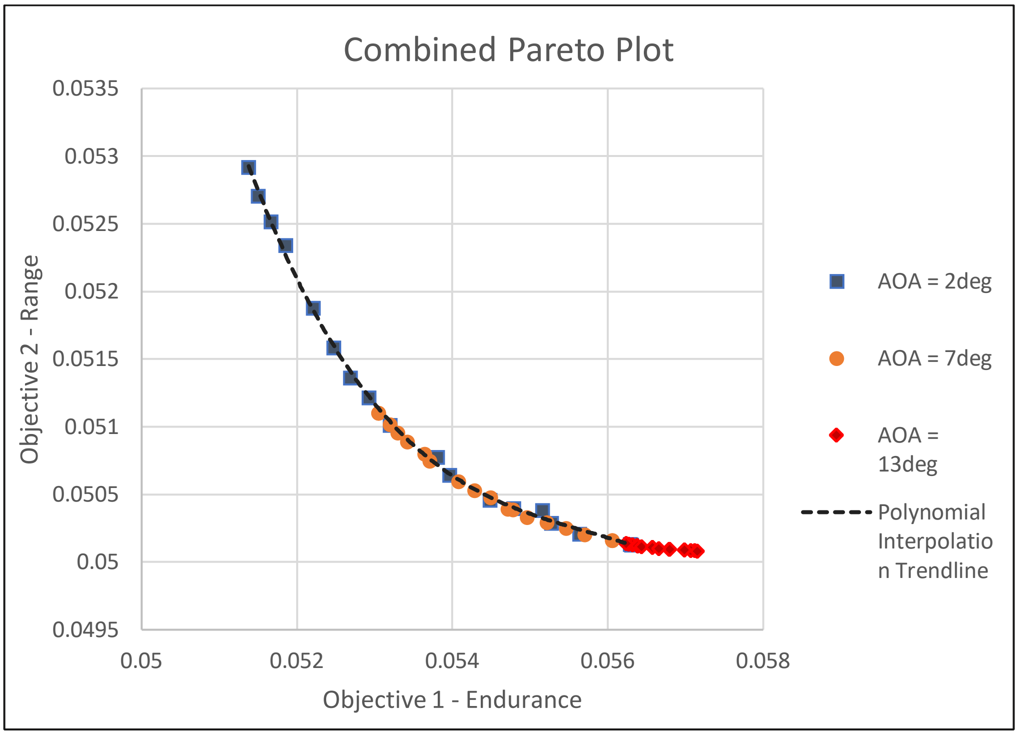

Fig.8. Combined Pareto plot

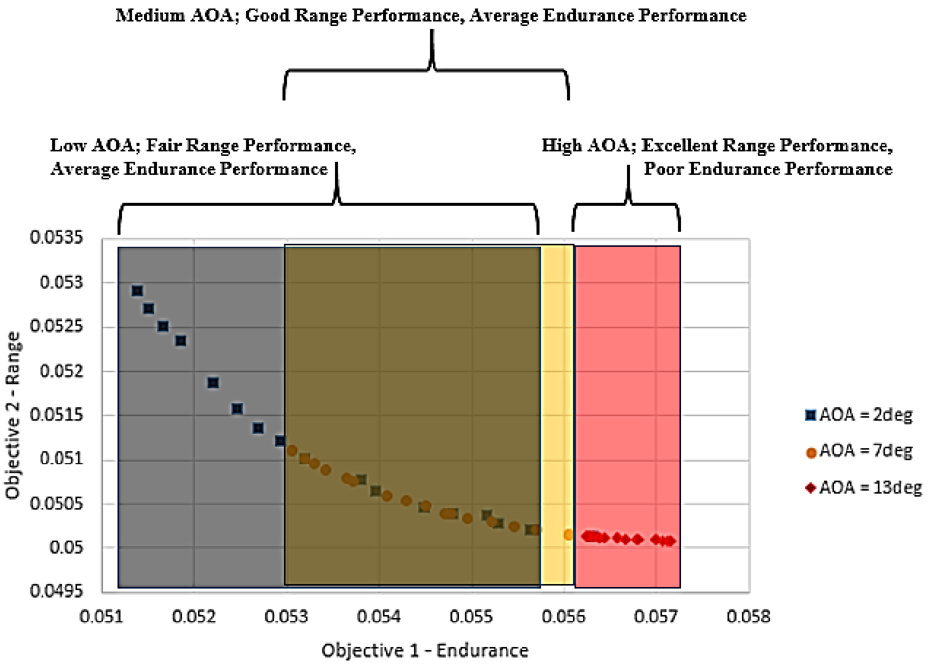

Fig.9. Relationship between AOA and Performance

Table 3. Summary of Glide Performance at the Respective AOA's

	Endurance	Range
2	Fair	Fair
7	Fair	Good
13	Poor	Excellent

7.3. Comparison with Earlier Similar Studies

By way of evaluation, two previous studies were considered. The first was conducted by Ciprian *et al.* [16] to maximize the lift-to-drag ratio of a general aviation aircraft for the range requirement. The similarity of some of the parameters considered for optimization and the response makes it ideal for this comparison which is presented in table 4. While most of the parameters are similar, the slightly greater lift-to-drag ratio may be attributed mostly to the significantly greater aspect ratio. This is justified by Oswald efficiency (e) factor which as seen in equation 8 indicates that higher values of this quantity appear to substantially affect the relationship between the coefficient of lift and the coefficient of drag.

Another study by Kandasamy *et al.* [17], shows similar behaviour. Although with similar methodology and tools, there were other responses factored into the optimization scheme apart from the lift-to-drag ratio. These included the root chord, leading edge sweep, wingspan and the taper ratio (which in the case of this study is handled with a DoE preoptimization scheme). Their approach also used two optimization algorithms namely, Gradient based solver, *fmincon* and Genetic Algorithm, *GA* (as used in this study) to conduct the optimum value search. The relative results are shown in table 5. As suggested by Ciprian *et al.* [16], the greater wingspan (consequently, greater $\boldsymbol{AR}$) explains the higher lift-to-drag ratio. Therefore, it may be said that apart from the method adopted for the optimization study, the aspect ratio is perhaps the most important parameter when optimizing for the lift-to-drag ratio of gliders [18].

Table 4. Comparison 'A' of results

Parameter	This work	Ciprian *et al.*
Angle of twist	1	2.22
Aspect Ratio	15	8
Taper Ratio	0.8	0.25
Lift slope	5.38	6.9
Mean Value Lift-to-Drag ratio	19.9	17.67

Table 5. Comparison 'B' of results

Parameter	This work	Kandasamy *et al.* (*fmincon*)	Kandasamy *et al.* (*GA*)
Taper ratio	0.8	0.6	0.6
Lift-to-Drag ratio	19.9	22.46	22.46

8. Conclusion

After the research had been conducted and validated, the following conclusions were drawn as regards the aerodynamic optimization of UAV wings for surveillance:

a) The primary geometric parameters affecting the performance of a low Mach number UAV (M < 0.6) wing with respect to Range and Endurance performance are aspect ratio and taper ratio. The parameters were found to govern the primary flow of air around the wing and consequently, generation of lift force. Their variation and combination as shown in this study gave rise to different lift characteristics that influence the overall flight behavior. The optimum values of these features as designed with respect to experiment-based optimization are 13 for aspect ratio and 0.6 for taper ratio;
b) The lift-to-drag ratio obtained as the optimum performance that jointly satisfies the range and endurance requirements by is approximately 20, at a medium (by the definition of this work) angle of attack of 7 degrees. This was as obtained subject to the imposed aerodynamic and structural constraints. It is projected that the implementation of this configuration in the prototype developed will jointly satisfy Range and Endurance requirements to minimize power consumption.
c) The setting obtained for the flight configuration, given the structure of the objective function also minimizes the drag penalty associated with the Range and Endurance behavior of the aircraft considered. This is especially useful in gliding flight for surveillance operations.
d) Furthermore, the study shows a way of finetuning the angle of attack setting of gliding flight such that the high drag penalty that would otherwise be high due to the otherwise high angle of attack. This finetuning or shall we say 'correction' was obtained using the method introduced in the initial optimization step.

e) The application of this research includes low altitude, low power crafts that rely mainly on the principle of gliding for their propulsion. This work however can be extended to include the effects of dynamic control on the stability of the aircraft, given the current flight setting. Computational fluid dynamics (CFD) studies may also be conducted to gain more insight into the workings of the fluid mechanisms that cause the behavior examined in this study.

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