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Design of UAV and Optimisation using Genetic Algorithms

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Abstract : *The following paper presents a methodology for the conceptual design of an Unmanned Aerial Vehicle with generic design requirements. The design requirements were analysed to determine the constraints that bound the design space. In order to select the most optimum point from this design space genetic algorithm was employed. The algorithm generates a population of values of wing loading and power loading and selects a point that has minimum take-off weight and maximum cruise efficiency while satisfying the constraints. A MATLAB code was written for the whole design process- from requirement analysis to sizing and stability analysis. Aerodynamic analysis of the UAV has also been presented using two different analysis softwares, AVL and XFLR5 and the results have been compared. The UAV was fabricated completely in-house and has also been flight tested for more than 5 hours. It meets all the design requirements and has shown good stability and control characteristics.*

Keywords: *Artificial Neural Network (ANN), MATLAB, Back propagation algorithms, Surface Roughness.*

Nomenclature:

GTOW	= Gross Take-Off Weight= W_0
$W_{payload}$	= Payload Weight
$W_{fuelweightfraction}$	=Weight of fuel/GTOW
$W_{emptyweightfraction}$	= Empty weight fraction= W_e/W_0
AR	= Aspect Ratio
P/W	= Power Loading
V_{dash}	= Dash Speed
W/S	= Wing Loading
L/D	= Lift-to-Drag Ratio
hp	= horse power
C_L	= Coefficient of Lift
C_D	= Coefficient of Drag
C_m	= Coefficient of Moment
C_{D0}	= Coefficient of Drag at 0^o angle of attack
C_{m0}	= Coefficient of Moment at 0^o angle of attack
t/c	= thickness to chord ratio of the airfoil
C_{m0wf}	= Coefficient of Moment at 0^o angle of attack of the wing-fuselage
C.G.	= Center of Gravity
h	= distance between the C.G of the UAV and the leading edge of the wing divided by the length of mean aerodynamic chord
h_0	= distance between the aerodynamic center of the UAV and the leading edge of the wing divided by the length of the mean aerodynamic chord
η_h	= ratio of dynamic pressure at the tail to dynamic pressure at the wing.
V_H	= tail volume coefficient of the horizontal tail
C_{L_h}	= Coefficient of Lift of the horizontal tail
l	= Tail moment arm
S_h	= Surface area of the horizontal tail
c	= mean aerodynamic chord length
S	= Surface area of the wing
C_D	= Coefficient of Drag
C_m	= Coefficient of Moment
C_{D0}	= Coefficient of Drag at 0^o angle of attack
C_{m0}	= Coefficient of Moment at 0^o angle of attack

t/c = thickness to chord ratio of the airfoil

C_{m0wf} = Coefficient of Moment at 0^o angle of attack of the wing-fuselage

C.G. = Center of Gravity

h = distance between the C.G of the UAV and the leading edge of the wing divided by the length of mean aerodynamic chord

h_0 = distance between the aerodynamic center of the UAV and the leading edge of the wing divided by the length of the mean aerodynamic chord

η_h = ratio of dynamic pressure at the tail to dynamic pressure at the wing.

V_H = tail volume coefficient of the horizontal tail

C_{L_h} = Coefficient of Lift of the horizontal tail

l = Tail moment arm

S_h = Surface area of the horizontal tail

c = mean aerodynamic chord length

S = Surface area of the wing

θ = angle between the two tails

C_{tail} = chord length of the tail of the inverted-V configuration

b_{tail} = span of the tail of the inverted –V configuration

AR_{tail} = Aspect Ratio of the tail

h_{tail} = height of the tail of the inverted –V configuration

w_{tail} = Lateral distance between the tails of inverted –V configuration

α = angle of attack

C_{L_α} = Lift curve slope

X_{cg} = Position of the C.G.

X_{ac} = Position of aerodynamic center

α_h = angle of attack of the horizontal tail

X_{ac_h} = Position of aerodynamic center of the horizontal tail

e = Ostwald's efficiency factor

W_f = Width of the fuselage

L_f = Length of the fuselage

Introduction:

Unmanned Aerial Vehicles or UAVs are pilot-less aircrafts that are capable of autonomous flight and are majorly used for Intelligence, Surveillance and Reconnaissance purposes. In order to execute the mission, the UAV is required to have certain desired performance characteristics. The performance requirements bound the design space viz. the set of all points each of which yields a unique design conforming to the design requirements. A recent trend in aircraft conceptual design process is to implement accurate design tools for seeking the deterministic optimal solutions with the help of optimisation algorithms. In this paper, generic design requirements have been used as design constraints from which the design space was determined. The optimum design point was selected by implementing genetic algorithm. In order to minimise errors in designing it is imperative to follow a structured design process. The following design methodology was used for this UAV.

1. Statement of Objectives:

Table 1: Design requirements

S. No.	Parameter	Objective
1.	GTOW	<25Kg
2.	Payload weight	>5 Kg
3.	Stall Speed	<12m/s
4.	Take-off Distance	<80m
5.	Landing Distance	<80m

2. Constraint Analysis

The design requirements were analysed and conforming to the design constraints the values of wing loading and power loading were selected. These two values influence almost all design parameters hence it is necessary to select the most optimum values. The selection of optimum values of wing loading and power loading was done by employing genetic algorithm.

2.1 Constraint Identification

The following constraints were identified from the design requirements:

Stall Speed < 12 m/s
Take Off distance < 80m
Landing Distance < 80m
Load factor <2.5 (taken from empirical data for sustained turn rate)

The above constraints were written as a function of wing loading and power loading and have been mathematically represented as follows:

$$V_{stall} = \sqrt{\frac{2\frac{W}{S}}{\rho\, C_{Lmax}}} < 12$$

$$S_{takeoff} = \frac{1}{2B}\ln\left(\frac{A}{A-BV_{TO}^2}\right) < 80$$

$$S_{land} = \frac{1}{2B}\ln\left(1-\left(\frac{BV_{TD}^2}{A}\right)\right) < 80$$

Where $A = g\left(\frac{T}{W}-\mu\right)$

$$B = \frac{g\rho(C_D-\mu C_L)}{\frac{2W}{S}}$$

$$n = \sqrt{\frac{q\pi ARe}{\frac{W}{S}}\left(\frac{T}{W}-\frac{qC_{D_0}}{\frac{W}{S}}\right)} < 2.5$$

It is also required to limit the design Gross Take-Off Weight (GTOW) below 25 Kg. The relation between GTOW and empty weight fraction is as follows:

$$GTOW = \frac{W_{payload}}{1 - W_{fuelfraction} - W_{emptyweightfraction}}$$

Where, $W_{payload}$ = 5 kg

$W_{fuelfraction}$= 0. 15 (determined from historical data of similar class of UAVs)

According to design requirements payload weight is required to be greater than 5Kgs and GTOW less than 25 Kgs. So Empty weight fraction is required to be less than 0.65.

$W_{emptyweightfraction}$ is determined form the following equation.

$$\frac{W_e}{W_0} = 0.55W_0^{0.15}AR^{0.05}\left(\frac{P}{W}\right)^{0.09}V_{dash}^{0.17}\left(\frac{W}{S}\right)^{-0.05}$$

The value of $\frac{W_e}{W_0}$ should be minimised to maximise payload weight and minimise GTOW. In the above equation value of aspect ratio is also not known. So, the algorithm for selection of most optimum design point was run for all values of aspect ratio ranging from 7 to 12 with increments of 0.5. In effect, this procedure not only ensures the selection of most optimum values of wing loading and power loading but also that of the aspect ratio too.

The fitness function was to minimise the empty weight fraction and to maximise cruise efficiency $(L/D)_{cruise}$ ratio). The cruise efficiency is calculated using the following equation.

$$\left(\frac{L}{D}\right)_{cruise} = \frac{1}{\frac{qSC_{D0}}{\frac{W}{S}} + \left(\frac{W}{S}\right)q\pi ARe}$$

After determining the constraints and the fitness functions the optimum values of wing loading and values of power loading were selected by using genetic algorithm in MATLAB. The code generated random values of wing loading and power loading within the range specified and checked for fitness. Then the next generation of design points was generated using mutation and crossover operators. The design points with extremely high values of fitness function were preserved for the next generation. Hence generation after generation the value of fitness function was increased thereby finally yielding the most optimum values of wing loading and power loading.
The code for optimisation using GA was run with the following parameters:

Table 2: Genetic algorithm options used in the optimization

Parameter	Value
Population size	20
Elite count	2
Crossover Fraction	0.8
Migration Interval	20
Migration Fraction	0.2
Number of Generations	100
Time Limit	Inf.
Stall Generation limit	50
Stall time Limit	Inf.

After the MATLAB code was successfully run for all values of aspect ratio the following data was obtained:

Table 3: Results obtained after the termination of optimisation code

AR	W/S	P/W (hp/Kg)	Stall Speed (m/s)	Take off Distance (m)	Landing Distance (m)	Empty weight Fraction	L/D
7	11.06	0.059	9.50	47.50	75.80	0.650	13.15
7.5	10.96	0.053	11.1	48.76	73.70	0.649	13.83
8	6.99	0.032	7.50	45.72	46.90	0.641	15.80
8.5	8.50	0.036	8.20	48.75	56.90	0.640	16.16
9	10.11	0.040	9.11	51.20	67.60	0.644	16.12
9.5	11.32	0.043	9.50	53.60	79.90	0.635	16.10
10	10.66	0.041	9.23	52.99	71.70	0.634	16.98
10.5	10.11	0.036	9.00	52.36	67.60	0.633	17.70
11	11.31	0.044	9.50	53.69	79.90	0.649	17.70
11.5	5.43	0.022	7.01	46.39	36.20	0.636	17.20
12	11.06	0.036	9.41	57.90	74.60	0.642	17.70

3. Configuration layout

The different configurations for the placing the propulsion system like Tractor, pusher, pod-pusher and twin engine were analysed and pusher configuration was selected mainly because with pusher configuration the aerodynamic surfaces are not in prop-wash of the engine. Also, having power plant behind the C.G provides a stabilising effect to the aircraft.

For the tail configuration inverted –V type was selected after analysing pros and cons with each configuration. The selection matrix is given in the table below.

Table 4: Matrix for selection of tail configuration

Parameters	Conventional	T-tail	Inverted –V	H-tail
Manufacturability				
Sensitivity of Control Surfaces				
Prop Wash				
Weight				
Stability				
Drag penalty				
Stall Characteristics				

4. Initial Sizing

4.1 Airfoil Selection:

Airfoil of the wing and tail influence almost all the aerodynamic characteristics of the aircraft, hence the selection of 'right' airfoil is very crucial for optimum performance of the aircraft.

The following was the criteria to select the airfoil:

(i) High C_L
(ii) Low C_D
(iii) High C_L/C_D
(iv) High $C_L^{3/2}/C_D$
(v) Low C_m
(vi) High stall angle

High lift airfoils were analysed and compared in XFLR5 software as shown in figure below.

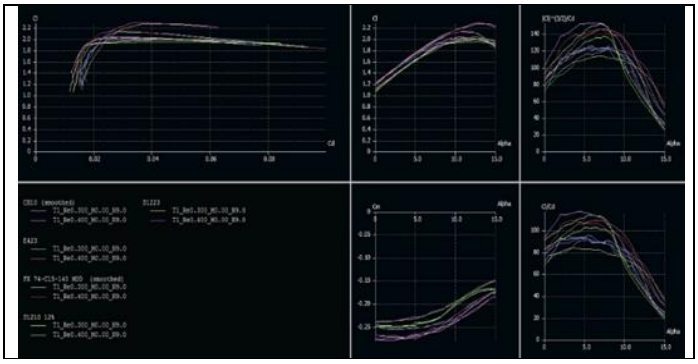

Figure 1: Analysis of airfoils in XFLR5

Table 6: Comparison of values of different high lift airfoils

Airfoil	C_{L0}	C_{Lmax}	C_{D0}	C_{m0}	Stall angle	$(C_L/C_D)_{max}$	$(C_L^{3/2}/C_D)_0$
CH10	1.194	2.024	0.016	-0.275	11	95	84
E423	1.115	2.01	0.016	-0.238	12	91	71.2
Fx-74CL5140	1.225	2.14	0.017	-0.251	12	109	78.5
S1210	1.075	1.963	0.013	-0.246	12	115	84
S1223	1.169	2.28	0.016	-0.265	13	92	77

For tail a symmetric airfoil was chosen. The airfoil should have a low drag coefficient and low moment coefficient. In addition, another tail requirement is that horizontal tail must be clean of compressibility effect. In order the tail to be out of the compressibility effect, the tail lift coefficient is determined to be less than the wing lift coefficient. To ensure this requirement, (t/c) ratio of the tail section was selected as 3% less than that of wing airfoil section. For the tail, **NACA0009** was selected.

4.2 Wing and Tail Geometry Sizing

The values of wing loading, GTOW and aspect ratio were determined in the initial stage of the design process hence the values other wing parameters can be easily calculated. The dimensions of wing are as follows:

Table 7: Values of wing parameters

Parameter	**Value**
Wing span	4.48m
Mean Aerodynamic Chord	0.42m
Tip Chord	0.34 m
Root Chord	0.49m
Aspect Ratio	10.5
Taper Ratio	0.7

The main purpose of tail is to provide equilibrium and stability to the aircraft. The equilibrium equation for longitudinal trim is given as:

$$C_{m_{owf}} + C_L(h - h_o) - \eta_h \overline{V}_H C_{L_h} = 0$$

The value of V_H was assumed as 0.7. Now,

$$\overline{V}_H = \frac{lS_h}{CS}$$

The value of *l* was assumed as 1.4m and then value of tail area of horizontal tail was calculated. Similarly the parameters for vertical tail were calculated. The parameters of the designed conventional tail were then converted to inverted-V type configuration using the following equations:

$$S_{total} = S_{ht} + S_{vt}$$

$$\theta = \tan^{-1}\sqrt{\frac{S_{vt}}{S_{ht}}}$$

$$C_{tail} = \sqrt{\frac{S_{total}}{AR_{tail}}}$$

$$b_{tail} = \frac{S_{total}}{c_{tail}}$$

$$h_{tail} = \frac{b_{tail}}{2} sin\theta$$

$$w_{tail} = b\_tailcos\theta$$

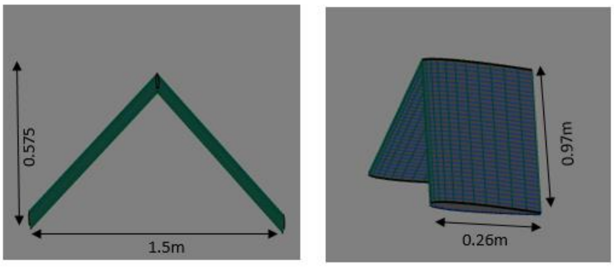

Figure 2: Dimensions of tail

Once the dimensions of the wing and tail are calculated the CAD model was designed in SolidWorks as shown in the figure below.

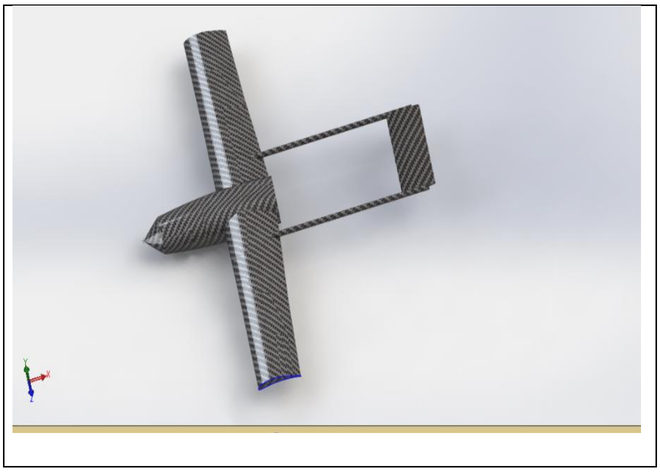

Figure 3: CAD model of the UAV

5. Aerodynamic Analysis

The UAV was modelled and analysed in XFLR5 and AVL (Athena Vortex Lattice) and the aerodynamic coefficients were determined. XFLR5 and AVL are analysis tools for wings and tails operating at low Reynolds number. The values obtained by both the softwares were compared shown in figure 6

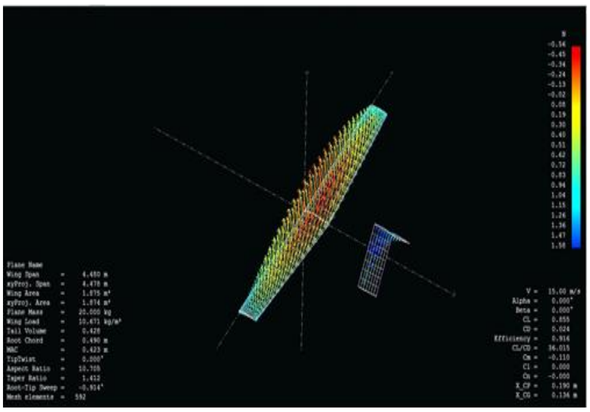

Figure 4: Analysis performed in XFLR5

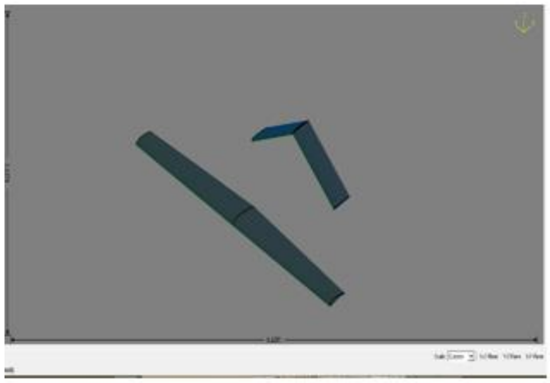

Figure 5(a): AVL Model

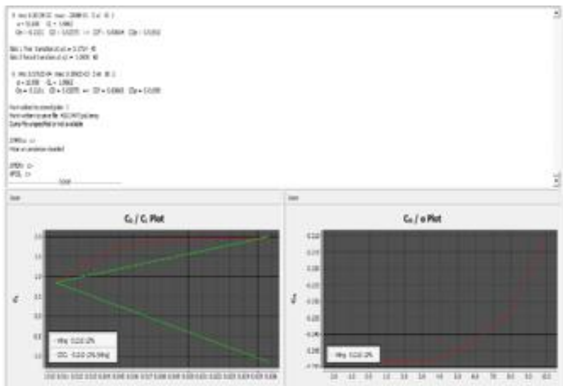

Figure5(b): AVL Results

The results obtained from both the softwares was compared as shown in the plot below:

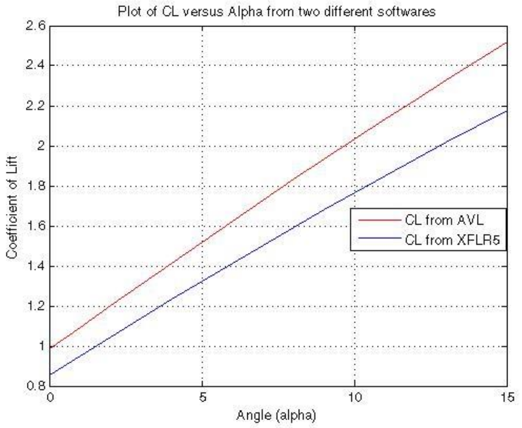

Figure 6(a) Comparison of Coefficients of Lift

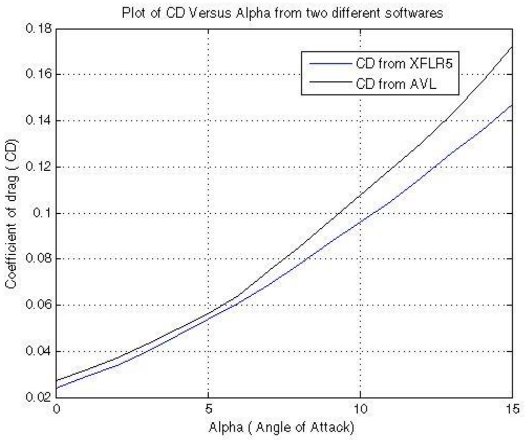

Figure 6(b): Comparison of Coefficients of drag

6. Stability Analysis

The Tail volume coefficient is an important parameter for determining the stability of an aerial vehicle and thus ensuring it is in the ballpark is crucial for stability of an aircraft. For this UAV the value of tail volume coefficient for horizontal tail is 0.7 and for vertical tail is 0.04 which is considered satisfactory.

In general terms for the aircraft to be statically longitudinally stable the following criterion should be satisfied

$C_{m_\propto} < 0$

$C_{m_\alpha} = \frac{dC_m}{d\alpha}$

This means that for the aircraft to be statically stable positive change in angle of attack should be met with negative change in moment of the aircraft and vice versa so that the aircraft returns to its original position.

$$(C_{m_\alpha})_{\text{total}} = (C_{m_\alpha})_{\text{wings}} + (C_{m_\alpha})_{\text{tail}} + (C_{m_\alpha})_{\text{fuselage}}$$

$$(C_{m_\alpha})_{wings} = C_{L_\alpha}(X_{cg} - X_{ac})$$

$$(C_{m_\alpha})_{tail} = \eta_h \left(\frac{S_h}{S_w}\right) C_{L_\alpha} \left(\frac{\partial \alpha_h}{\partial \alpha}\right)(X_{ac_h} - X_{cg})$$

$$where \left(\frac{\partial \alpha_h}{\partial \alpha}\right) = (1 - \left(\frac{\partial e}{\partial \alpha}\right) \text{ and } \frac{\partial e}{\partial \alpha} = 1.62\left(\frac{C_{L\alpha}}{\pi AR_h}\right)$$

$$(C_{m_\alpha})_{fuselage} = \left(\frac{K_f W_f^2 L_f}{c S_w}\right)$$

After substituting the values in the above equations, the following results were obtained:

Table 8: Values of Stability Coefficients

Coefficient	Value
$(C_{ma})_{wing}$	0.002915
$(C_{ma})_{tail}$	-0.043615
$(C_{ma})_{fuselage}$	0.013010
$(C_{ma})_{total}$	-0.02769

Since $(C_{ma})_{total}<0$ hence the vehicle is longitudinally statically stable.

7. Performance Calculations

The different performance parameters like Stall Speed, Take-Off distance, Landing distance, Rate of Climb and Descent were calculated. Since the calculated performance parameters satisfy the design constraints the design process was completed.

Table 9: Performance parameters

Parameter	Value
Stall Speed	9 m/s
Take-Off Distance	52.3m
Landing Distance	67.6m
Rate of Climb	4.1 m/s
Rate of Descent	3.2 m/s

Figure 8: Actual photograph of the UAV at Bhiwani airfield

8. Conclusion

The paper presented a design methodology to design a UAV with generic design requirements. The constraints were identified and values of wing loading and power loading were optimised using genetic algorithm in the initial stages of the design. This reduces the probability of the final design to be completely different from the initial draft and hence saves significant time and effort of the designer. Aerodynamic analysis using XFLR5 and AVL has also been presented. The UAV has a composite airframe fabricated completely in-house with empty weight fraction close to the estimated design value. It has been flight tested for more than 5 hours of in-air time. The UAV meets all performance requirements and satisfies all design constraints while executing a stable flight.

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