Preliminary Sizing of an Agricultural Aircraft

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Abstract: This paper aims to preliminary size an agricultural aircraft that meets the agricultural requirements in Sudan and could be manufactured locally and be equipped with an engine that works with cheaper type of fuel (Jet-A1). The specifications have been obtained from existing similar aircraft designs working in Sudan then the standard design procedure has been reproduced. The aerodynamic parameters have been obtained using FLUENT. The primary results were found qualitatively acceptable but need extensive verification. Finally a UAV down-scaled model has been constructed and a flight test has been carried out and the aircraft taxed, took off and landed safely. That indicated a good aircraft configuration.

Keywords: Agricultural aircrafts, aerodynamics, wing, fuselage, tail unit design.

Nomenclature
I_h Incidence angle
Λ Sweep angle
λ Taper ratio
Γ Dihedral angle
L_f Fuselage length
d_f Fuselage diameter
θ_{fc} Fuselage cone angle

Abbreviations
AERO-RC   All engine operative-Rate of climb
H.T   Horizontal tail
M.A.C   Mean aerodynamic chord
V.T   Vertical tail

1. Introduction
Agricultural aviation usually refers to agricultural, forestry, fishing and public health types. It is in fact an aerial application; i.e. the distribution of chemicals and seeds from the air on the surface of the land or water, or on vegetation plants. One should nevertheless remember that agricultural aviation also includes such work as aerial survey for agricultural purpose such as land use, livestock inventories, detection of crop diseases, locust detection and fire patrols.

The need of new design comes from high direct operation cost that arises from high costly fuel consumption and expensive spare parts.

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2. Preliminary Sizing

2.1 Specifications

Name of project	SEAD-8
Payload (liquid chemical)	2204lb
Crew weight (one pilot)	220.4lb
Range	460 Mile
Endurance	3 hours
Initial rate of climb	1170ft/s
Service ceiling	10,000ft
Absolute ceiling	25,000ft
Field length	3280.8-3937 ft
Field width	32.8-49.2 ft
Power plant	One Turboprop engine using Jet-A1 fuel type

A/C must meet FAR-23 requirements for stall, cruise speed, T.O landing distance, climb rate.
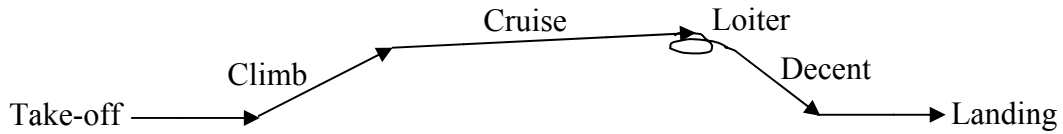
2.2 Aircraft Weight Estimation
The takeoff weight is given by [1];

$$W_{T.O} = W_{O.E} + W_F + W_{PL} \tag{1}$$

$$W_{O.E} = W_E + W_{TFO} + W_{CREW} \tag{2}$$

The fuel weight W_F (as fraction of $W_{T.O}$) can be obtained from mission profile of aircraft that is shown in Fig. 1 following standard procedures as detailed in [1].


Fig. 1   Mission profile for SEAD-8

2.3 Estimating Aircraft Design Parameters
The estimated aircraft weight has been obtained from the intersection between algebraic and logarithmic lines as in Fig. 2, while constants A and B were obtained from [1]. Different values of wing loading (w/s), power loading (w/p) and maximum lift C_{Lmax} have been calculated according to FAR23. Then the design parameters (*wing area, take-off power, maximum lift coefficient for clean, take-off and landing configuration and wing aspect ratio*) have been obtained by selecting the appropriate point (intersection between two blue lines) as illustrated in Fig. 3 based on the highest wing loading and lowest power loading.
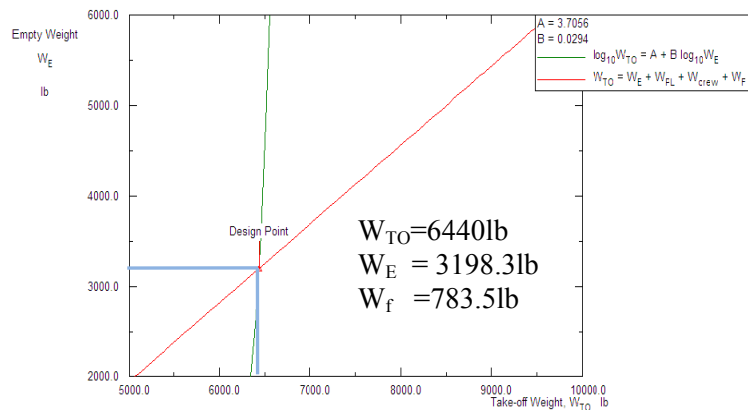
Fig. 2   Weight trend for SEAD-8
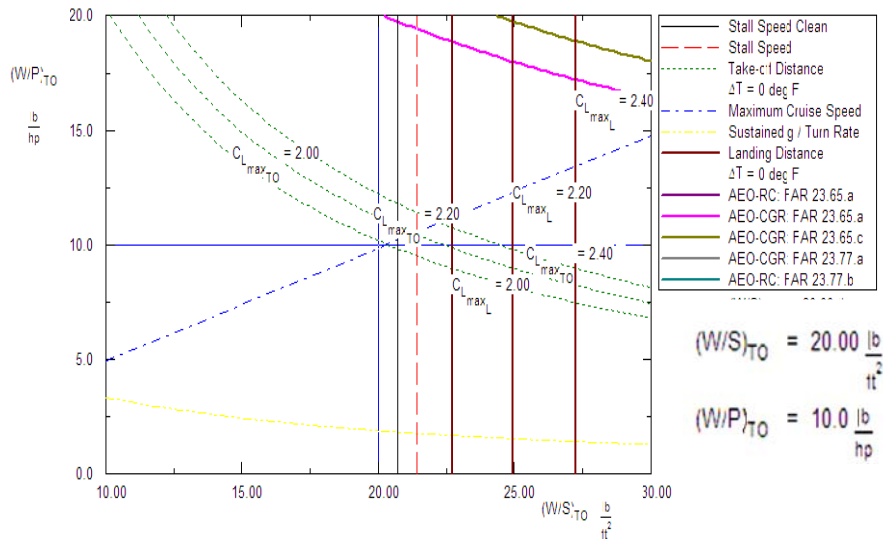
Fig. 3   Design point according to maximum W/S and minimum W/P

The wing area and power required can be determined as follows;

$$S = \frac{W_{TO}}{\left(\frac{W}{S}\right)} = 6440 \Big/ 20 = 322 \quad ft^2 \tag{3}$$

$$P = \frac{W_{TO}}{\left(\frac{W}{P}\right)} = 6440 \Big/ 10 = 644 \quad hp \tag{4}$$

C_{Lmax} values are from Fig. 3.

Clean   = 1.7
Take-off   = 2.0
Landing   = 2.2

And the appropriate value of aspect ratio AR = 6.

Table (1) compares SEAD-8 with medium weight category agricultural aircraft.

Table 1   Comparison between SEAD-8 and other Ag-aircrafts

| Type	Max T.O. Weight	Empty Weight	Wing loading	Wing area	Power loading	Max Cont. Power	Hooper load	V_S
	Lb	lb	lb/ft^2	Ft^2	lb/hp	Hp	lb	kts
Ag-Cat 'Fat Cat'	4500	2455	13.72	328	5.99	657	2000	68
Zlin Z-137T	5566	2900	14.20	392	9.28	600	1984	-
Ayres S2R	6000	3600	18.40	326	8.00	700	4638	77
Sead-8	**6440**	**3198.3**	**20.0**	**322**	**10.0**	**644**	**2204.6**	**60**
750XL AG	7500	3825	28.01	267.8	10.00	633	4410	69

2.4 Arrangement of the Major Aircraft Components
The preliminary arrangement of major components involving *'fuselage configuration', 'engine type, number of engines and engine disposition', 'wing type and disposition', 'empennage type and disposition', 'landing gear type and disposition'* is discussed in the following sections.

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2.4.1 Fuselage layout design

Design of cockpit and fuselage layout

Fuselage is carrying one pilot and his equipment and chemical tank (hopper) systems. The fuselage geometric parameters shown in Fig. 4 for agricultural aircraft were chosen as displayed in Fig. 5 from statistical study but both the ratio of length of fuselage cone to maximum diameter and angle of cone $\frac{l_{fc}}{d_f}, \theta_{fc}$ are out of range due to nose L.G. configuration.
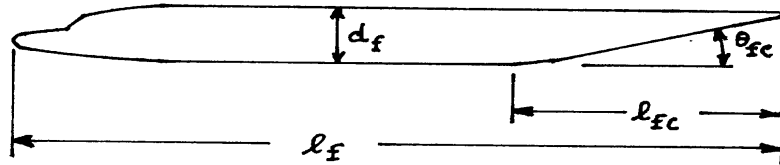
$$\frac{L_f}{d_f} = 5 - 8, \quad \frac{L_{fc}}{d_f} = 3 - 4, \quad \theta_{fc} = 1^o - 7^o$$

Fig. 4   Geometric parameters of the fuselage, [2]

$$\frac{l_f}{d_f} = 5.375, \quad \frac{l_{fc}}{d_f} = 2.5$$
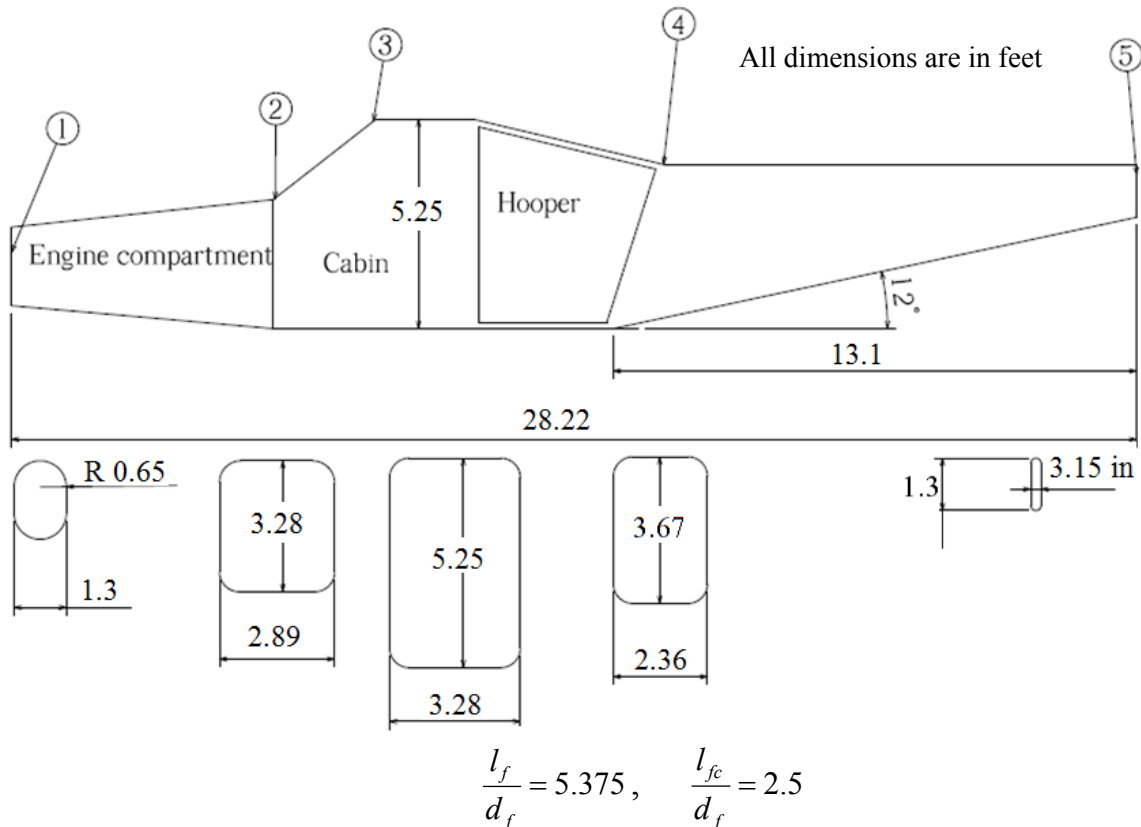
Fig. 5   SEAD-8 fuselage layout and section design

### 2.4.2 Selection of propulsion system type

A tractor installed propeller type with two blades has been selected. The blade-power-loading (P_{bL} 5.0) , the propeller diameter is calculated from:

$$D_P = \{4P \max/(\pi n_P P_{bl})\}^{0.5} = 9.2 \, ft = 2.8 \, m \tag{5}$$

4

Accordingly a Pratt & Whitney PT6A-34AG engine (Fig. 6), has been selected which has the specifications listed in Table 2.

Table 2   Engine Specification

Model	PT6A-34AG
Power SHP	750 SHP
Power BHP	670 BHP
Diameter	19 "
Length	62 "
RPM	2200
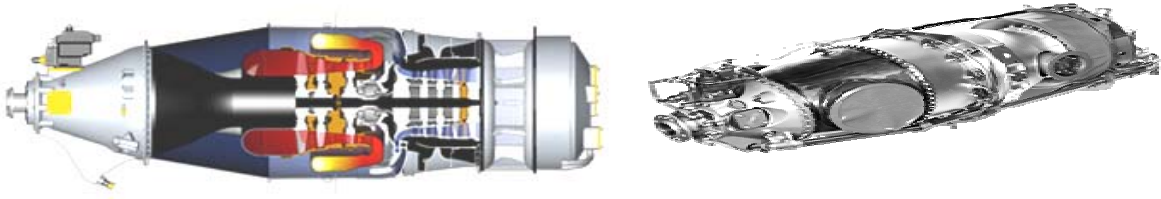
Fig. 6   SEAD-8 engine layout

2.4.3 Wing planform design and sizing and locating lateral control surfaces

The wing is characterized by *wing area (S), Aspect ratio (A), Sweep angle ($\Lambda_{C/4}$), Thickness ratio (t/c), Airfoils, Taper ratio (λ_W), Incidence angle (i_w), Twist angle (ε_i), Dihedral angle (Γ_W) and Lateral control surface size and layout.*

2.4.3.1 Wing sizing

The wing has been chosen as a low cantilever type. The wing span has been calculated from aspect ratio as 44 ft with mean Chord 7.3 ft.

The geometric characteristics have been selected from a comprehensive statistical study for similar types as;

Sweep angle $\Lambda_{C/4}$ = Zero
Taper ratio (λ_W)   = 1.0
Thickness ratio (t/c) = 0.12
Airfoil selection: = NACA 4412 (agree with clean C_{Lmax}) [8].
Incidence angle: (i_w) = 3 deg.
Dihedral angle: (Γ_W) = 3

2.4.3.2 Sizing high lift devices

Computing the required value of increment section lift coefficient (ΔC_L), which the flaps must generate and relating this value to flap type, flap angle and flap chord, as in Fig. 7.
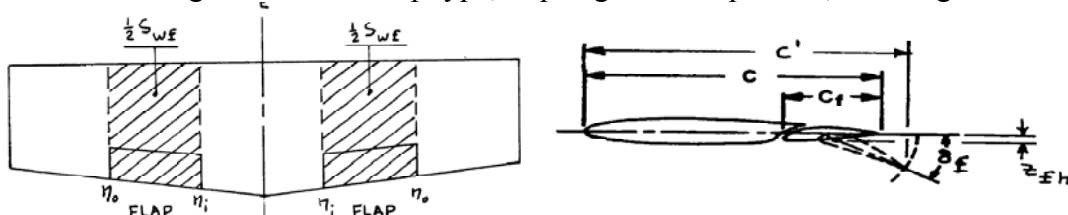
Fig. 7   Flapped wing area and flap stations and parameters [2]

$$\Delta C_{l\max} = (\Delta C_{L\max})(S / S_{wf})(K_\Lambda)$$

(6)

where ΔC_L (0.3) at T.O. and (0.5) at landing and K_Λ is (0.92).

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$$\Delta C_L = C_{L_\alpha} \alpha_{\delta_F} \delta_F \tag{7}$$

$$C_{L_{\alpha F}} = C_{L_\alpha} (\bar{C}/C) \tag{8}$$

$$(\bar{C}/C) = 1 + 2(Z_{fh}/C) \tan(\delta/2) \tag{9}$$

From statistical study as detailed in ref. [2]:

Distance ratio	$Z_{fh}/c = 0.1$
Flap chord to m.a.c ratio	$C_f/C = 0.25$
Flapped wing area	$S_{wf}/S = 0.33$
Flap deflection in T.O.	$\delta_{fTO} = 10$ deg.
Flap deflection in landing	$\delta_{fL} = 15$ deg.

$$S_{wf}/S = (\eta_0 - \eta_i)[2 - (1 - \lambda)(\eta_0 - \eta_i)]/(1 + \lambda) \tag{10}$$

Flap stations as in (Fig. 7) $\eta_i = 0.12$, $\eta_o = 0.45$

Figure 8 describes wing plan form with flap with supposed location of front and rear spars in dashed lines while the fuselage station in dotted line.
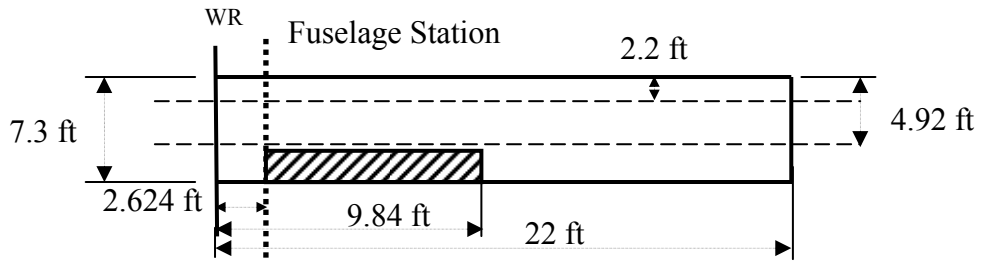
Fig. 8 Wing dimensions

2.4.4 Empennage design
The empennage has been sized as a conventional configuration, the canard configuration has not been adopted, and the tail unit position is in rear of fuselage [2].

2.4.4.1 Horizontal tail sizing
The required parameters to size H.T is wing area, wing m.a.c. H.T volume $V_h = 0.4$ and distance from C.G to H.T m.a.c. $X_h = 14$ft and H.T. aspect ratio $A_h = 3$ and elevator area to H.T area $S_e/S_h = 0.25$ selected from statistical study as follows;

$$S_h = \frac{V_h S C}{X_h} = 67.2 \, ft \tag{11}$$

$$A_h = b^2/S_h \tag{12}$$

Airfoil selection:	= NACA 0009
H.T span, b_h	= 14.2 ft
H.T chord, C_h	= 4.7 ft,
Elevator area, S_e	= 16.8 ft^2,
Elevator chord, C_e	= 1.5 ft,
Elevator span, b_e	= 14 ft,
$I_h = 0$, $\Lambda_{c/4} = 0$, $\lambda_h = 1$,	

2.4.4.2 Vertical tail sizing

As previous, the required parameters to size H.T is wing area, wing span, V.T volume V_v= 0.022 and distance from C.G to V.T m.a.c. X_v= 13 ft and V.T. aspect ratio A_v= 1.3 and elevator area to V.T. area S_r /S_v= 0.3 selected from statistical study [2].

$$S_v = \frac{V_v S b}{X_v} \tag{13}$$

$$A_v= b^2/S_v \tag{14}$$

Airfoil selection: NACA 0012
V.T area, S_v = 23.98 ft^2
V.T span, b = 5.6 ft
Rudder area, Sr = 7.2 ft^2
Rudder chord, C_R = 1.3 ft
V.T tapper ratio, λ_v = 0.74
V.T sweep angle, $\Lambda_{c/4}$ = 15 deg.

$$C_{root} = 2S/b(1+\lambda) \tag{15}$$

Rudder root chord, C_{root} = 5 ft
Rudder tip chord, C_{tip} = 3.7 ft

$$C_{Mean} = \frac{2}{3}C_{root}(1+\lambda+\lambda^2) \quad Y = \frac{b}{6}(1+2\lambda)/(1+\lambda) \qquad [7] \tag{16}$$

V.T mean chord, C_{Mean} = 4.38 ft

2.4.4.3 Landing gear disposition

Two geometric criteria that need to be considered in deciding the disposition of the landing gear strut are:

i- Tip-over criteria

The main landing gear must be behind the aft C.G location, the (15°) angle which usually represents the relation between main gear and aft C.G. as clear from Fig. 9.

ii- Ground clearance criteria

The lateral ground clearance angle and the longitudinal ground clearance angle apply to tricycles. Accordingly, the following values have been determined;
Longitudinal ground clearance criterion:- Base=11.8ft, distance enough to prevent nose-over and to prevent tail from touching the ground Fig. 9.
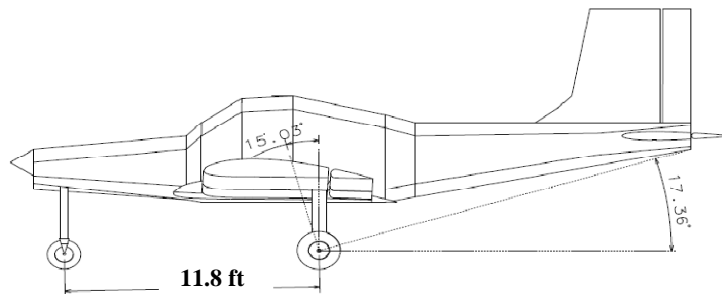
Fig. 9   Landing gear lateral tip over criteria

Lateral ground clearance criterion
Angle 54° is quite enough to avoid tip-over (protect wing tips from touching ground when aircraft is turning).Track=11.8ft (distance between wheels) is enough to create the angle as in Fig. 10.

54°
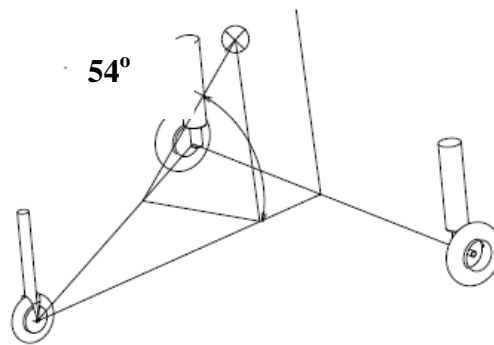
Fig. 10   Landing gear longitudinal tip over

2.5 Aircraft Weight and Balance

The initial component weight breakdown is shown in Table 3 using weight prediction methods [5]. The center of gravity location has been determined as shown in Table 3 below.

Table 3   SEAD-8 C.G. location (forward or afterward)

Component	Weight lb	X in	Y in	W_iX_i lb.in	W_IY_i lb in
Horizontal tail	83.51	327.3	3.2	27332.82	267.232
Vertical tail	35.79	301.7	78.0	10797.84	2791.62
Fuselage	355	118.4	66	42032	23430
Wing	891.1	111.8	3.2	99624.98	2851.52
Main gear	173.52	149.6	-26.0	25958.59	-4511.52
Nose gear	43.38	12.6	-39.4	546.588	-1709.17
Fixed equips	712.4	94.5	102.4	67321.8	72949.76
Engine	851.6	5 0.4	20.5	42920.64	17457.8
Foreword C.G.	**3198.3**	**100.1**	**36.3**		
Pilot	220.4	118.1	31.5	26029.2	6942.6
Fuel	783.5	126.0	3.2	98721	2507.2
Chemical load	2204.6	163.8	26.8	326280.8	57319.6
Aft word C.G	**6406.8**	**120**	**28.8**		

2.6 Aircraft Overall Configuration

Autodesk® AutoCAD has been used to draw the aircraft external layout as illustrated in Fig. 11.

3. CFD Predictions

Due to symmetry, only half model is used as displayed in Fig. 12 and demonstrates the surface mesh of half model while Fig. 13 shows the mesh of the entire domain.

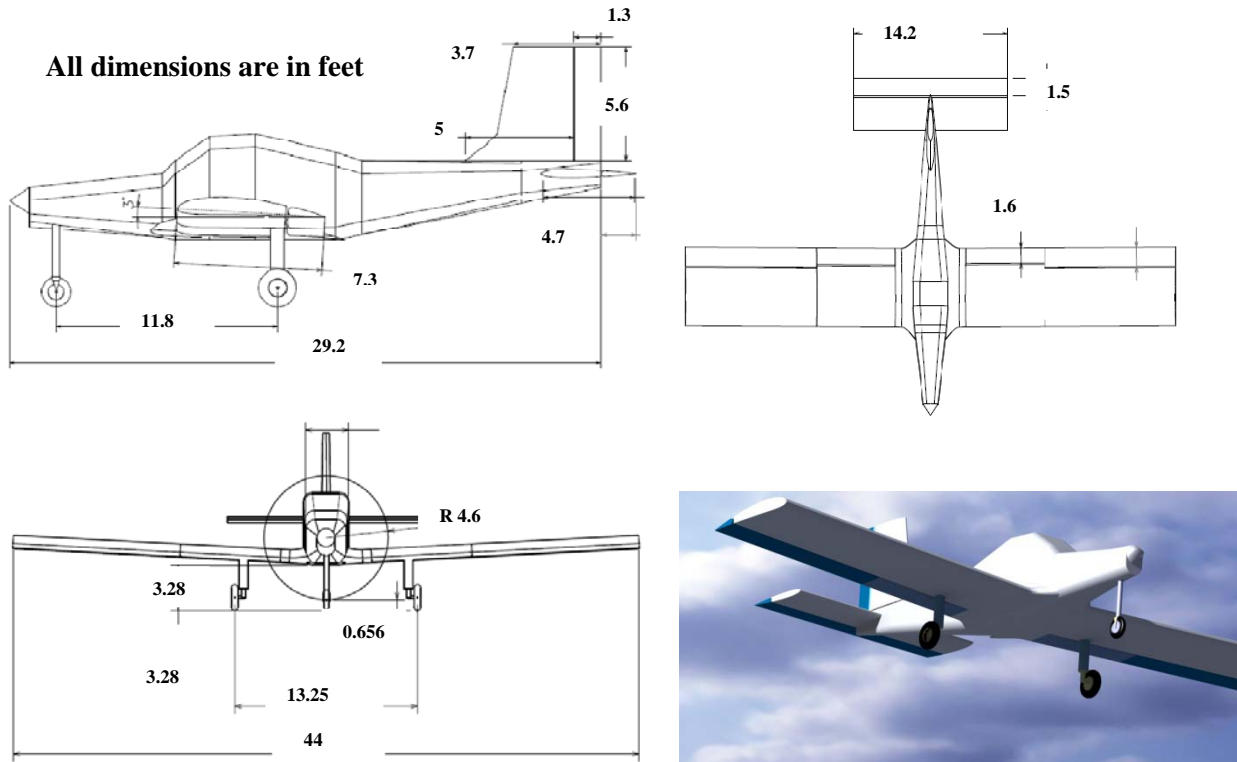Table 4 lists the resulted lift, drag and moment coefficients for three different values of angle of attack.

All dimensions are in feet
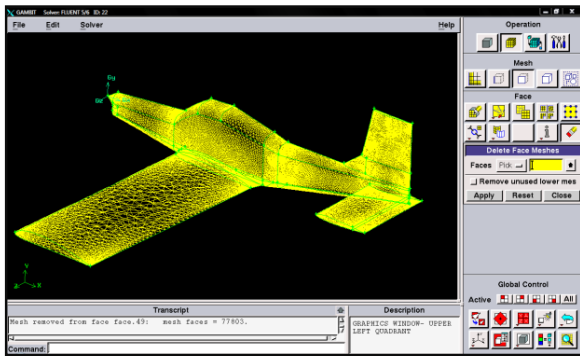

Fig. 11   SEAD-8 3-D view

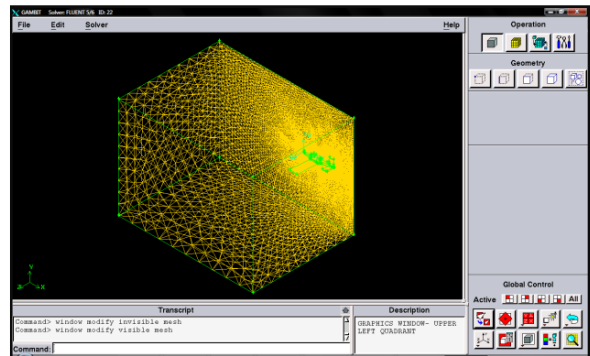

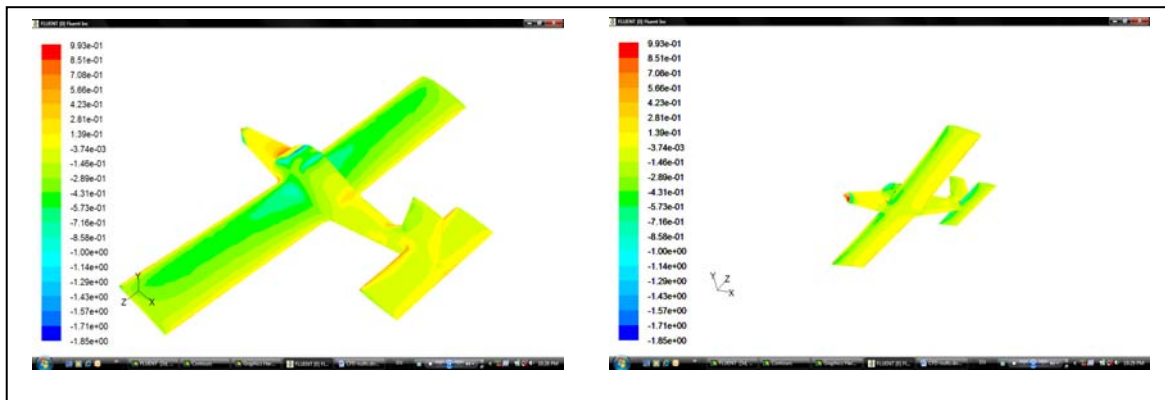Fig. 12   SEAD-8 meshed surface

Fig. 13   Meshed domain

Fig. 14   Pressure distribution on upper and lower surfaces.

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Table.4 Aerodynamic derivatives obtained form CFD

Angle of attack, [deg]	C_L	C_D	C_M
-4	0.0911467	0.02471999	0.0010672
0	0.0089899	0.25545	0.023397
4	0.25544468	0.0233903	0.01571

4. Aircraft Testing as a UAV

Due to practical reasons the actual aircraft size was difficult to be manufactured and tested. A scaled down aircraft model has been manufactured as a UAV to prove that the aircraft is flyable. The scale factor 1:6.5 (N = 15%) has been used to fabricate the model [9]. To ensure the dynamic similarity of the flow, there are two criteria, namely geometrical similarity and flow similarity parameters; i.e. Reynolds number and Mach number. For low speed Reynolds number similarity is more significant.

$$Re = \frac{\rho V d}{\mu} = \frac{\rho V_m (0.15d)}{\mu} \tag{17}$$

Because the test was made in the atmosphere ρ and μ are the same for the full scale and down-scaled model, the difference will appear mainly in the velocity e.g. $V_{s\ model} = 0.15 V_{s\ actual}$.
The aircraft weight and wing area were found from;

$$L_m = L_A N \tag{18}$$

$$S_m = S_A N^2 \tag{19}$$

$$W_m = W_A N^3, \tag{20}$$

W_m=21.735 lb

Figure 15 shows shabloons which were made and used to fabricate wing and fuselage.

Fig. 15   SEAD-8 shabloons

Assembled UAV is ready to test for flying as shown in Fig.16 and was successfully taxed, took-off as demonstrated in Fig. 17 and smoothly maneuvered as displayed in Fig. 18 and then safely landed as clear in Fig. 19. That confirmed that the external configuration was quite acceptable.

5. Conclusion and Recommendations

According to the assumed customer specifications, the paper has undertaken the tasks of weight estimation, fuselage layout design, wing sizing, high lift device sizing, empennage design, landing gear disposition, weight and balance, CFD predictions, UAV manufacturing. Stability issue has to be addressed in a more extensive approach. Namely DATCOM is suggested for determining stability derivatives. These issues are subject to comprehensive analysis being conducted presently by the authors and will be published later.

6. References

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Fig. 16   SEAD-8 as UAV

Fig.17   UAV at take-off

Fig. 18   UAV at maneuvering

Fig. 19   UAV at landing