Design of UAV's and MAV's - AS5213

AS5213

Group - 13

Design Report

Week 4

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Important Equations

- Lift

$$Lift = \frac{1}{2} * C_L * \rho * A * V^2 \tag{1}$$

- Drag

$$Drag = \frac{1}{2} * C_D * \rho * A * V^2 \tag{2}$$

- Drag coefficient

$$C_D = C_{D0} + k * {C_L}^2 \tag{3}$$

$$k = \frac{1}{\pi * e * AR} \tag{4}$$

- Drag coefficient

$$C_D = C_{D0} + k * {C_L}^2 \tag{5}$$

$$k = \frac{1}{\pi * e * AR} \tag{6}$$

- Power in cruise

$$P = D * v \tag{7}$$

$$P = \frac{1}{2} * (C_{D0} + (\frac{1}{\pi * e * AR}) * {C_L}^2) * \rho * A * V^3 \tag{8}$$

- Turn rate

$$w = \frac{g * \sqrt{n^2 - 1}}{v_\infty} \tag{9}$$

- Turn radius

$$w = \frac{{v_\infty}^2}{g * \sqrt{n^2 - 1}} \tag{10}$$

- Oswald's Efficiency Factor

$$e = 1.78[1 - 0.045(AR)^{0.68}] - 0.64 \tag{11}$$

- Skin Friction Coefficient

$$C_{f,laminar} = 1.328/\sqrt{R_e} \tag{12}$$

- Zero Lift Drag

$$C_{D_0} = C_{fe}\frac{S_{wet}}{S_{ref}} \tag{13}$$

- Reynolds Number

$$R_e = \frac{V.I}{\nu} \tag{14}$$

- Raymer Empirical equations(For straight wings)

$$e = 1.78(1 - 0.045A^{0.68}) - 0.64 \tag{15}$$

- Raymer Empirical equations(swept wing $\phi_{LE} > 30°$)

$$e = 4.61(1 - 0.045.A^{0.68})(cos\phi_{LE})^{0.15} - 3.1 \tag{16}$$

Symbolic notations

- C_L = Co-efficient of lift
- C_D = Co-efficient of Drag
- n = Load factor
- ρ = Density
- A = Section area
- AR = Aspect ratio

1 Mission objective

1.1 Problem Statement

Monitoring and surveillance (MS) encompass the observation and analysis of extensive areas of interest. This broad term applies to various contexts, such as protected regions like wildlife sanctuaries and coral reefs, as well as areas prone to natural disasters, where real-time data collection enhances predictive capabilities for anticipating and responding to such occurrences.

1.2 Why this problem needs attention

Monitoring wildlife sanctuaries is crucial for several reasons, as it helps in the conservation and protection of biodiversity. Here are some key reasons why monitoring wildlife sanctuaries is important:

- **Biodiversity Conservation:** Wildlife sanctuaries are designated areas to protect and conserve the natural habitats of various species. Regular monitoring allows authorities to assess the health and diversity of the ecosystems within these sanctuaries. It helps in identifying any threats or changes in biodiversity, allowing for timely interventions to protect endangered species.
- **Illegal Activities:** Wildlife sanctuaries are often targeted by poachers, illegal loggers, and other criminal activities. Monitoring helps in detecting and preventing such illegal activities, safeguarding the flora and fauna within the sanctuary.
- **Habitat Health:** Monitoring helps in evaluating the overall health of the habitat, including factors such as water quality, vegetation cover, and soil conditions. This information is essential for managing and maintaining a balanced ecosystem.
- **Population Dynamics:** Tracking the population dynamics of various species within a sanctuary is crucial for understanding their behavior, reproductive patterns, and overall health. It aids in implementing effective conservation strategies, such as habitat restoration or reintroduction programs.
- **Climate Change Impact:** Wildlife sanctuaries are not immune to the impacts of climate change. Monitoring helps scientists and conservationists understand how climate change affects different species and ecosystems. This knowledge is vital for adapting conservation strategies to mitigate the effects of climate change.
- **Research and Education:** Monitoring provides valuable data for scientific research, helping researchers better understand ecological processes, species interactions, and the overall functioning of ecosystems. This information can also be used for educational purposes, raising awareness about the importance of wildlife conservation.

- **Adaptive Management:** Regular monitoring allows for adaptive management, where conservation strategies can be adjusted based on the changing conditions within the sanctuary. This flexibility is essential for addressing emerging threats and challenges.
- **Policy and Planning:** Monitoring data contributes to evidence-based decision-making in the development of policies and management plans for wildlife sanctuaries. It helps authorities allocate resources effectively and implement measures that are grounded in scientific understanding.

In summary, monitoring wildlife sanctuaries is essential for maintaining the health and balance of ecosystems, protecting endangered species, and ensuring the long-term sustainability of biodiversity. It plays a vital role in conservation efforts and supports the broader goals of preserving natural habitats and promoting ecological integrity.

1.3 Mission Statement

To tackle this issue, we propose a lightweight monitoring/surveillance UAV with rapid turnaround times. The vehicle would fly around and over a designated area of interest and acquire important data - primarily in the form of pictures and terrain information - over long spans of time.

1.4 Requirements

- One of the most important aspects that will drive the design of such an aircraft will be endurance. We wish to fly for uninterrupted periods of time.
- Rapid turnaround time aiding in quick re-deployment.
- House good quality instruments for image capture and terrain estimation.
- Lightweight.

The following section details about a prospective mission profile for our aircraft.

2 Mission profile

2.1 Mission phases

- **Take-off** - Accelerating on the runway until liftoff and subsequently retracting the landing gear.
- **Climb** - Rise to the desired altitude required for the mission.
- **Cruise** - Level flight till the area of interest.
- **Loiter** - It is the most important aspect of our mission and most of the UAV's flight time is spent in loiter mode.

- **Descent** - Dropping altitude to ground level.
- **Landing** - Deployment of landing gear and deceleration to a halt.

2.2 Mission info-graphics

Given figures try to depict trajectory of mission of a UAV in a scenario that is according to the mission profile.

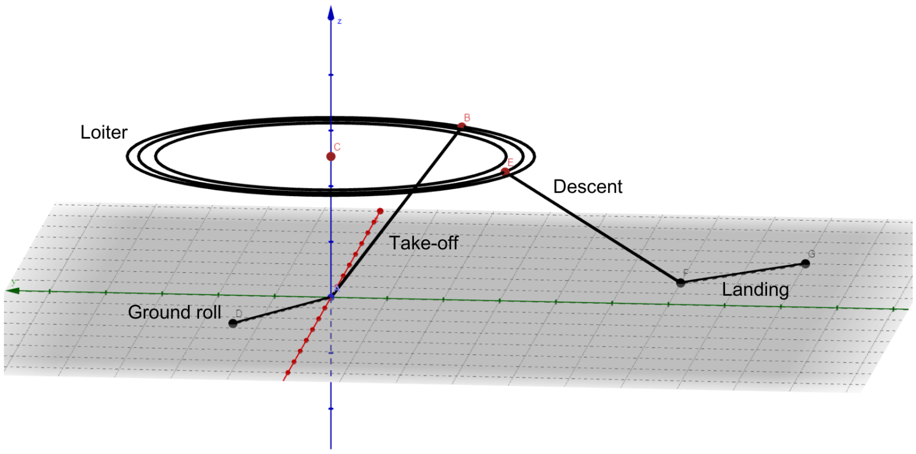


Figure 1 – Geometric view

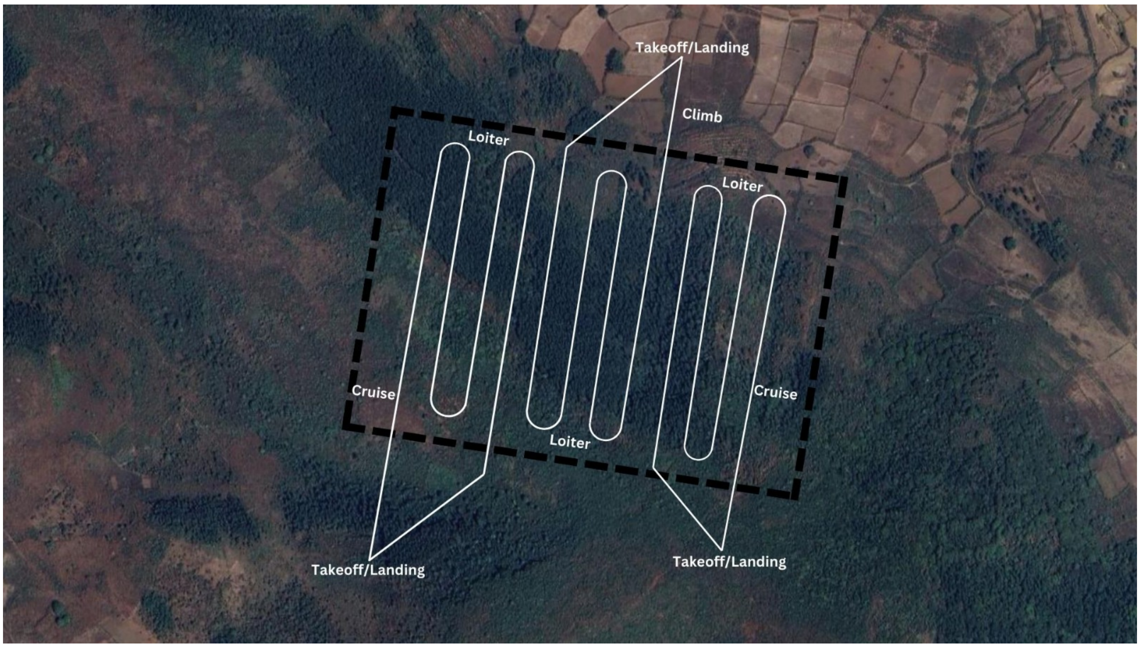


Figure 2 – Terrain / Geographic view

3 Estimation of parameters:

A general estimate of desired flight parameters (Range, approximate cruise speed, endurance was estimated as follows:
Average area of a forest in India is 1 million hectares, which is 10^4 km^2. Let us approximate a forest to be of an approximate square geometry of 100 km x 100 km.

Considering a solution for surveillance of forests using a UAV as per our mission statement, we plan a model where 15 UAV's in the skies for a duration can suffice for the surveillance of the entire forest.

Now considering forest to be an approximate square geometry of 100 km x 100 km, field of vision of each UAV spanning about 3 km of ground, the forest can be classified to 33 strips each of 100 km length and 3.3 km width. The 15 UAV's in the model would be monitoring about 2 strips each.

Consider the following parameters:

- Endurance of each UAV = e hr's
- Speed of each UAV corresponding to maximum time of flight = s km/h

We can thereby develop a relation:

$$e * s = 200 \tag{17}$$

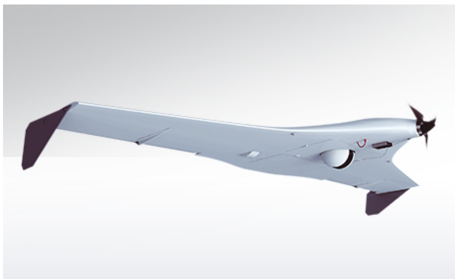
Now, choosing/fixing the preferred range for one of the above parameters wihh thereby give out the range of the other. We choose the flight speed to be in the range 10 - 25 m/s (36 - 90 km/h) which implies the endurance of each UAV should be around 2.2 - 5 hours.

Thereby we proceed ahead to research on UAV's with an endurance of about 2 - 5 hours and flight speeds of about 10-25 m/s.

4 UAV Study

4.1 Data of similar UAV's

Data of UAV's which are used actively in environments with the same natural prospects as our problem statement have been collected and analysed. The following are the images of the UAV's.
Each of their sources is linked in the caption of the figure



(a) ZALA 421-04M

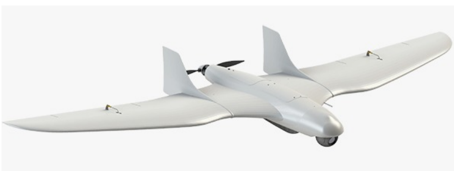
(b) Crex B

(c) Vrabac

(d) Borey 20

(e) Albatross

(f) Boeing Insitu



(g) A1-CM Furia

(h) TAI-Pelikan

(i) TAI-Marti

(j) RQ-20 Puma

Figure 3 – Similar UAVs. (References are contained within image captions).

4.2 Parameters for selection, Categorization and classification of UAV's

A substantially produced UAV was categorized similar to the UAV we aim to design for out problem statement based on following paramenets:

- **Weight** : UAV's with an ideal weight of 5-20 kg.
- **Endurance** : An endurance of at least 1hr is expected considering it's used for surveillance purposes. Following our estimations, UAV's with endurance in range 2-5 hours are considered.
- **Operational height / Ceiling** : UAV's with an operational height of 150 m - 1 km were considered with a maximum ceiling of around 2 km - 3 km. These parameters are considered keeping in view that the UAV would be required to perform several tasks related to imaging and detection.
- **Speed** : UAV's with operational speeds in the range 10-25 m/s, to ensure the quality and resolution of the data collected through camera and sensor modules is not compromised.

4.3 Further information on data of similar UAV's

4.3.1 Ceiling

In certain UAV's from the above mentioned list, exact details of ceiling wasn't mentioned in catalogue, hence the data provided is the data of the suggested operational ceiling provided by the company.

4.3.2 Range

In certain UAV's their range is restricted based on the farthest for which a smooth data transmission is possible which is majorly dependent on communication modules (LoRa etc) and antennae used (Omni, Yagi, uni etc) and not on power-plant. Considering communication an important prospect, we proceeded with the available data of range.

Range of certain UAV's wasn't specified, in those scenarios, we estimated the maximum possible range based on cruise speeds, endurance, MTOW.

4.4 Comparison chart

The following table has data of UAV's with similar mission profiles and with similar parameters like operational ceilings, range and endurance. All the UAV's listed are fixed wing and are manufactured on a substantial scale and are widely available for commercial purchase.

Similar mission profile UAV's data									
S.no	UAV Designation	Empty weight	Powerplant weight	Payload weight	MTOW in kg	Endurance in hr	Range in km	Speed in m/s	Ceiling in km
1	Albatross	4.4	-	5.1	10	3	180	17 - 33	0.15 - 5
2	Boeing Insitu	14		5	26.5	1.5 - 4	250	18.9	-
3	A1-CM	3.5	-	0.6-1	5.5	3	200	18	-
4	TAI-Pelikan	20	-	6	35	6	320	33	1.52
5	TAI-Marti	9			12	1	-	27	0.9
6	RQ-20 Puma	4.2	-	-	7	2	15	10 - 23	0.15 - 3
7	Vrabac	6.17	1.3	1.5	9	1	50	17-33	0.3-0.5
8	ZALA 421-04M	3.47	1.03	1	5	1.5	15	17-27	3.6
9	CREXB	1.5	-	-	2.2	1.25	10	10	3.1
10	Borey 20 UAV	8.7	-	4	26	5	400	20	3.5

Table 1 – UAV Technical Specifications

In the above table consisting of data of different UAV's. All the data presented above has been collected from valid and reliable sources and the hyperlinks redirecting to the sources have been attached for all the UAV's.
All the weights mentioned are in kilograms. Exact data of power-plant weight of several UAV's wasn't available in the catalogues so approximations have been considered in a few cases based on the data of MTOW, Payload capacity and Empty weight.

5 UAV Mission Phases

Estimated durations for each of the phases of the mission are given as follows, this is only a preliminary flight estimate based on the mission profile

UAV Mission Phases and Duration's		
S.no	Mission Phase	Duration in minutes
1	Ground-roll	30 seconds
2	Climb and cruise	3 - 5 minutes
3	Loiter	2 - 4 hours
4	Descent	3 - 5 minutes
5	Landing	30 seconds

Table 2 – UAV Mission Phases and Durations

Cruise and loiter: After observing data from similar UAV's and making a detailed assesment of our mission profile, a cruise altitude of around 300m is found suitable. This altitude gives enough freedom and clearance to UAV's path from any natural disturbances and would be suitable to work with thermal sensors, imaging modules and other mapping equipment.

6 Payload selection

Visible camera : We have selected **DJI Zenmuse P1** based on several factors. It is specifically designed for aerial photography. It comes with an integrated 3-axis mechanical gimbal for image stabilization. It is also lighweight (**800g**) and cheap when compared to it's competition.

Figure 4 – DJI Zenmuse P1

Multispectral camera : For terrain mapping, complementing visible range camera we have chosen **Sequoia RedEdge P**, which is capable of capturing images in five spectral bands and also has a built-in thermal sensor. Also comes with an integrated gimbal which is simple to mount with the UAV. Weight of the camera is **350g**.

Figure 5 – Sequoia RedEdge P

LiDAR : LiDAR offers highly detailed 3D models of the terrain, including elevation, vegetation cover, and even small objects. For terrain with dense vegetation or uneven surfaces, LiDAR can penetrate foliage and capture accurate elevation data, while traditional visual mapping might struggle. We have chosen **DJI Zenmuse L2** which weighs at **0.91 kg**. It is compact and lightweight, suitable for complex terrain and wildlife analysis.

Figure 6 – DJI Zenmuse L2

Total payload weight $= 0.91 + 0.35 + 0.8 =$ **2.06 kg**

7 Power requirements and energy estimation

Estimation of power required by the UAV to complete the mission is vital in battery weight estimation, and battery selection. This plays a crucial role in estimating a lot of factors including the total weight.

The power required to perform the entire mission is broken down into segments relating it with power required during each phase of the mission, and it's estimated as follows:

7.1 Ground roll

To conservatively estimate energy requirements during ground roll, we assume the following;

- Taking Stall speed = 12m/s, we assume lift off speed to be 1.2 times the stall speed $V_{Liftoff} = 14.4m/s$
- In the real world, the UAV is expected to start from rest and then accelerate to this $V_{Liftoff}$. For our initial energy requirement estimation, we take the speed of the entire stretch to be $V_{Liftoff}$. This also ensures that friction is taken care of.

These assumptions are valid and give us more energy than would be needed in the real case, hence acting as a factor of safety. Moreover, this stage of the flight would account for less than 5 percent of the total energy requirement.

$$Power = Thrust \times Velocity$$

$$Power = Drag \times V_{Liftoff}$$

$$Power = \frac{W_{Total}}{\frac{L}{D}} \times V_{Liftoff}$$

$$Energy = \frac{W_{Total}}{\frac{L}{D}} \times V_{Liftoff} \times Time \tag{18}$$

7.2 Climb

Considering climb, the UAV should climb to an altitude of 300 m (Cruise altitude). After being airborne, the UAV should clear obstacles (most likely to be trees), hence distance travelled while airborne to safely clear an obstacle plays a crucial role as it determines the approximate length of airstrip required. We hence decided to consider a climb performance such that the distance travelled while airborne to safely clear an obstacle is not very large, Considering the parameters such that the UAV can takeoff on an airstrip as short as 100 metres,

Distance travelled while airborne = 100 m
Height of obstacle = 20 m

Height of obstacle is considered 20 m as after research, it is found to be the average height of a tree in Indian forests.

$$V sin(\theta) \times t = 20 \tag{19}$$

$$V cos(\theta) \times t = 100 \tag{20}$$

$$tan(\theta) = 0.2 \tag{21}$$

$$Climbangle = 11^0 \tag{22}$$

As most airfoil's stall around an angle of 15 degrees, a climb angle of around 11 degrees which we require according to the above approximation can be considered a safe climb angle as even in case of a disturbance due to horizontal wind, it has still has a margin where it may not stall. (Although direction of thrust vector, placement of wing, and airfoil affect this, climb at 11 degree angle can be taken as a safe approximate which would hold in extreme cases as well.)

Now coming to climbing to 300 m, as assumed, the UAV is expected to reach this altitude in around 2 minutes as mentioned in flight profile.

$$V(sin(11)) \times 120 = 300 \tag{23}$$

$$Climbvelocity(V) = 12.5m/s \tag{24}$$

Force due to drag on the UAV can be given as:

$$D = \frac{C_D}{C_L} \times W \tag{25}$$

Now power required can be estimated as:

$$Power = v \times \frac{C_D}{C_L} \times W + v \times W \times sin(\theta) \tag{26}$$

$$Power = 12.5 \times \frac{C_D}{C_L} \times W + 12.5 \times W \times sin(\theta) \tag{27}$$

The value of C_D/C_L is chosen 1/20 after taking reference from [4] page number 3.

7.3 Cruise and Loiter

After climbing to the required altitude, the next thing the UAV is required to do is reaching the desired location via level flight (cruise) followed by occasional level turns and then back to cruise. This phase is predominantly cruise. The following are the main considerations for power estimation:

- Cruise time = 2 hours
- Cruise altitude = 300 m
- Density of air = 1.188 kg/m^3
- Cruise speed = 20 m/s
- Angle of attack = 5^0

$$P_{cruise} = DV$$

$$P_{cruise} = D \times (\frac{L}{L}) \times V$$

$$P_{cruise} = \frac{W_0}{\frac{L}{D}}V$$

$$P_{cruise} = 20 \times W_0 \times \frac{C_D}{C_L}$$

The value of C_D/C_L is chosen 1/25 after taking reference from [4] page number 3.

7.4 Level turns

We fix to a turn rate of around 12 degrees per second, completing a turn in a span of 30 seconds. For turn, we choose the value of C_L/C_D of 20 for turn after referring to [4] page number 3

The turn is being taken at a bank angle of 30 degrees. Turn velocity can be evaluated as:

$$v = \frac{gTan(\theta)}{\omega} \tag{28}$$

$$v = 27m/s \tag{29}$$

Power during this phase evolves out to be:

$$P = \frac{C_D}{C_L} \times W_0 \times 27 \tag{30}$$

7.5 Descent

As shown in 27, we assume descent requirements are similar.

7.6 Landing

As shown in 18, we assume landing requirements are similar.

8 Battery

Recent developments in lightweight electric motor and battery design are making feasible the use of electric propulsion from storage batteries. In particular the improvement in rechargeable battery performance through use of Li–S (lithium sulphur) Li-Po (Lithium Polymer) technology has reduced the mass/energy ratio to about one-quarter that of other battery types. The resulting performance of a high-technology battery-motor combination may be seen to be marginally better than the rotary engine.

Considering these factors, a LiPo battery based propulsion system has been opted for our UAV. Other battery sources including ones such as Ni-Mh, Ni-Cd are compared less safer than LiPo, have less energy density and constitute substances which are toxic/poisonous to nature.

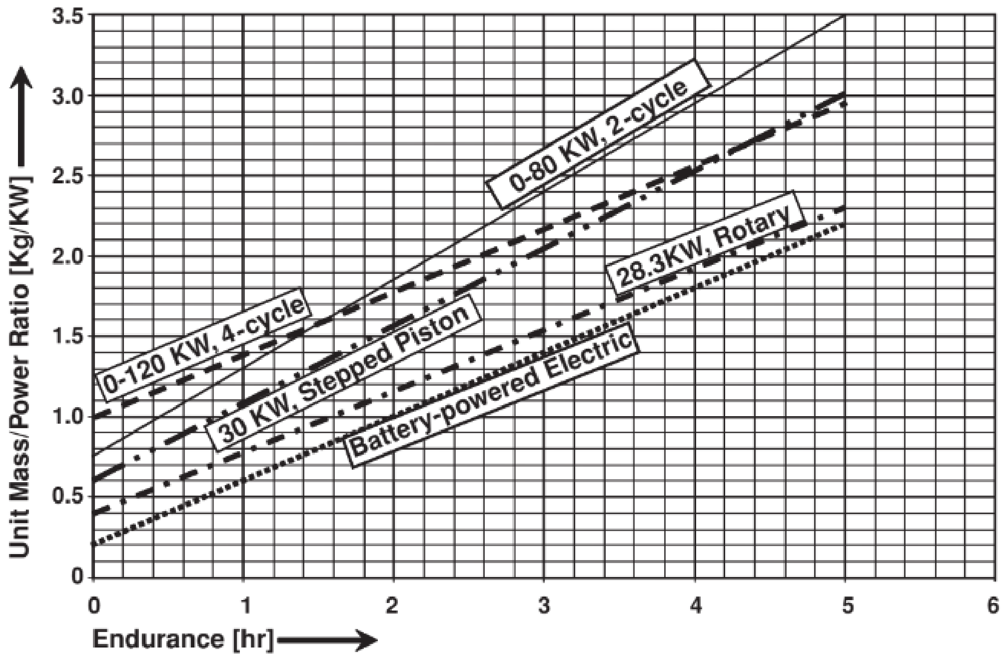


Figure 7 – Graph taken from Reg Austin Unmanned Aircraft Systems, page no. 290 [5]

8.1 Battery weight estimation

- From the energy requirements of each stage of flight, we get an estimate of the total energy required to carry out one cycle of our mission (In terms of the total weight of the aircraft).
- If we divide this quantity by the energy density rating (250 W h /Kg here) of an appropriate battery, we estimate the battery weight needed to carry out our desired mission.
- Dividing this value by the total weight of the aircraft, we get the battery weight fraction. This will serve as an input to the interactive weight estimation process.
- A 10% safety factor is considered in our energy requirement. Additionally, we've taken efficiencies of motor components and battery power delivery as 0.8 and 0.9, respectively.
- Fraction turns out to be 0.13

```
%% Energy and Battery Weight Fraction Estimation
Mass = 10; %(Can be anything, will be cancelled in the final
    battery weight estimation)
W = Mass*9.81;
LbyD = 10;

Ptakeoff = (W/(LbyD*2))*1.2*12;
Etakeoff = Ptakeoff*30;

P_climb = (12.5/(LbyD*2))*W + W*12.5*sind(11);
E_Climb = P_climb*120;

P_CruiseLoit = (20/(LbyD*2))*W;
E_CruiseLoit = P_CruiseLoit*2*60*60;

P_Turn = 27 * W/((2\sqrt(3))*25);
E_Turn = P_Turn*90;

Total_Energy = 2*Etakeoff + 2*E_Climb + E_CruiseLoit + E_Turn;

Battery_Energy_Density = 250; % W h/ Kg
Battery_Weight = Total_Energy*1.1/(0.9*0.8*Battery_Energy_Density
    *60*60);
Battery_Weight_Fraction = Battery_Weight/Mass;
display(Battery_Weight_Fraction);
```

9 Empty weight estimation:

We undertake empty weight estimation by looking at historical data from previous successful UAVs as shown in 5.
The generic form of how empty weight fraction varies with total weight is given by the relation:

$$\frac{W_{empty}}{W_{total}} = AW_{total}{}^{L} \tag{31}$$

Where A and L are some constant coefficients. It is important to note that L is expected to be a negative number to ensure convergence (Will be talked about in section 8.3)

9.1 Empty weight fraction vs Total weight

Plotting (from our data collection) the required values, we get the following:
Running an optimization (fmincon in MATLAB) that reduces the least squares error for input parameters A and L.

```
sol = fmincon(@(X) find_AL(X,MTOW,Empty_Weight./MTOW),[1,0]);
function cost = find_AL(X,MW,frac)
A = X(1);
L = X(2);
y = A*MW.^L;
error = (frac-y)./y;
cost = error*error';
end
```

Running the above script the appropriate Take of Weights and Empty Weight fractions, we get the following values:

$$A = 0.8993, L = -0.1594 \tag{32}$$

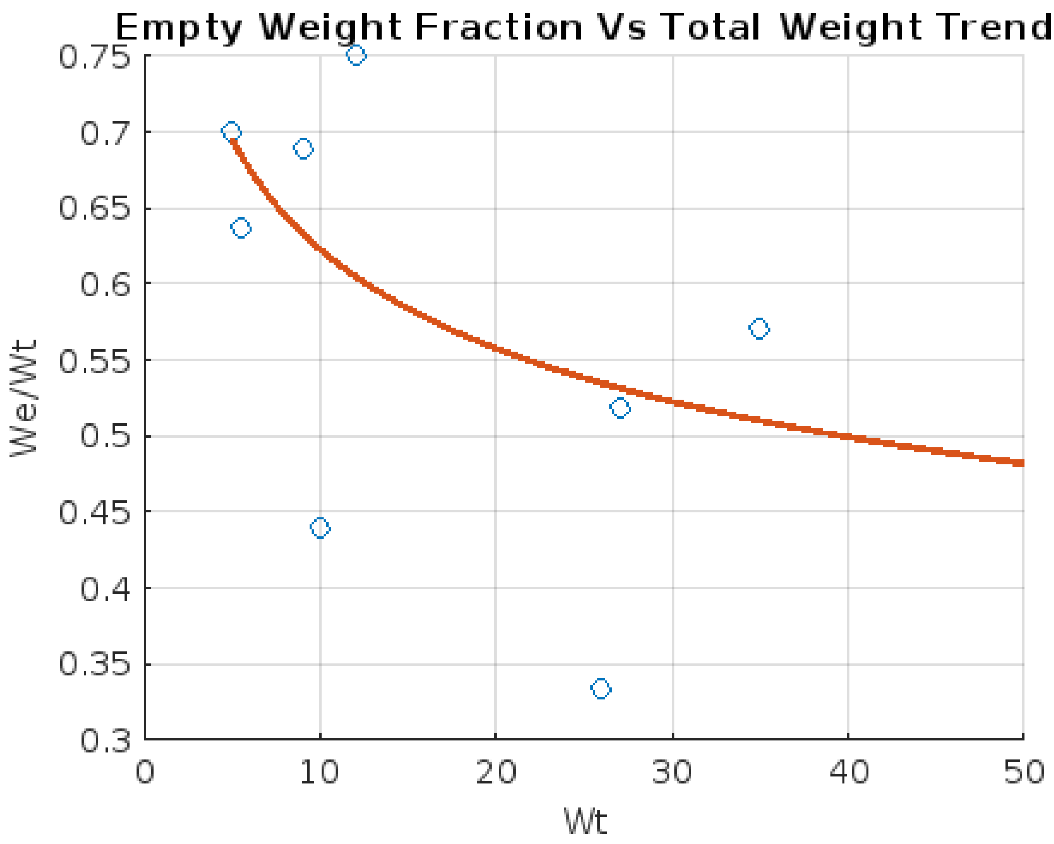


Figure 8 – Empty Weight Trend

9.2 Estimated total weight

With the values of A, L, and a battery weight fraction estimated, we are now ready to do an iterative preliminary weight estimation as given in Raymer <INSERT BIB>.
Before we do so, let us familiarize ourselves with the various quantities involved.

$$W_{total} = W_{empty} + W_{battery} + W_{payload} \tag{33}$$

Rearranging the terms, we get the following

$$W_{total}(1 - \frac{W_{empty}}{W_{total}} - \frac{W_{battery}}{W_{total}}) = W_{payload} \tag{34}$$

This expression gives us the algorithm that will be used to propagate our iterative process.

$$W_{totali+1} = \frac{W_{payload}}{(1 - \frac{W_{empty}}{W_{totali}} - \frac{W_{battery}}{W_{totali}})} \tag{35}$$

where i denotes the iteration number.
Executing the above algorithm until a user-specified convergence is achieved, we get the following plot.
Weight converges to **10.21 Kg**.

```
%% Iterative Loop to find initial estimate of weight
A = sol(1);
L = sol(2);
W_p = 2.5; % Kg (We have to find this)
Battery_Weight_Fraction; % (Calculated in Battery Estimation)

w1 = 5; % Kg (Just an initial guess)
i = 1;
diff = 10;
figure
array = [i w1];
hold on
grid on
while abs(diff)>0.00001
    empty_frac = find_empty_frac(A,L,w1);
    w2 = W_p/(1-Battery_Weight_Fraction-empty_frac);
    diff = (w2-w1)/w1;
    w1 = w2;
    i=i+1;
    array(i,:) = [i w1];
    if i>100
        break
    end
end
display(w1)

display(w1) % This is our initial weight estimate
```

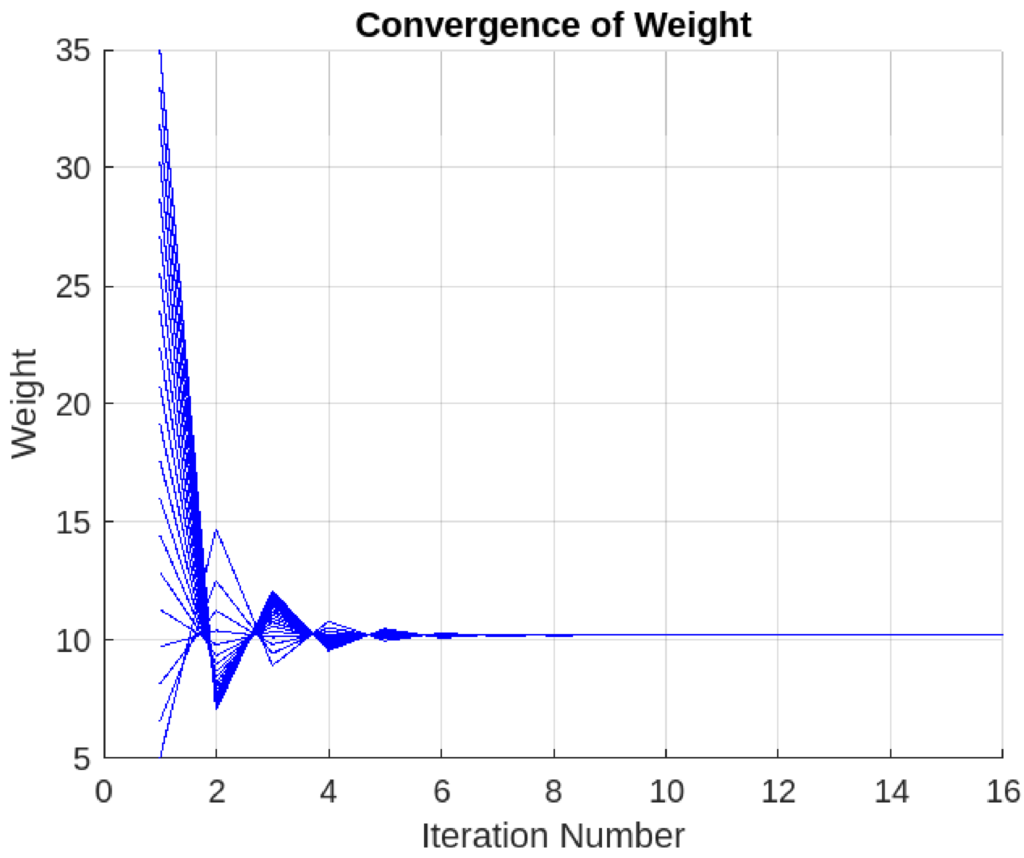


Figure 9 – Weight Estimate Convergence

10 Estimations and approximations:

The only estimate considered while evaluating the weight fractions of battery is the ratio of $\frac{C_L}{C_D}$. Other approximations and values are only to make the mission profile simpler and to design a system with parameters such that it's performance is better.

To give an example, velocity of UAV during climb is taken to be 12.5 and that value is reached while starting from a situation to have a shorter distance travelled while being airborne, in order to successfully clear an obstacle.

11 Powerplant Estimation

11.1 Oswald's efficiency factor estimation:

There are two sets of empirical equations for evaluating oswald's factor for straight and swept wings.

For straight wings

$$e = 1.78(1 - 0.045AR^{0.68}) - 0.64 \tag{36}$$

For swept wings with sweep greater than 30 degrees

$$e = 4.61(1 - 0.045AR^{0.68})\cos\phi^{0.15} - 3.1 \tag{37}$$

The UAV collected have a sweep angle less than 30 degrees (with only 1 exception) so the first expression 36
Using this we can also find K:

$$K = \frac{1}{pi \times e \times AR} \tag{38}$$

11.2 Cd_0 Estimation:

The expression for Cd_0 is as follows [11]:

$$Cd_0 = C_f \frac{S_{wet}}{S_{ref}} \tag{39}$$

- Where C_f is Coefficient of Skin Friction. For laminar flow:

$$C_f = 1.328/\sqrt{Re}$$

$$Re = V \times l/\nu$$

- $\frac{S_{wet}}{S_{ref}}$ depends on the relative areas of the total surface area and the wing platform area.

11.3 Analytical approach for $(\frac{L}{D})_{Min.P}$

Endurance for a propeller based aircraft is given by

$$E = \frac{\eta_{\text{pr}}}{c}\sqrt{2\rho_\infty S}\frac{C_L^{3/2}}{C_D}\left(W_1^{-1/2} - W_0^{-1/2}\right)$$

For maximum endurance, we have $\left(\frac{C_L^{3/2}}{C_D}\right)_{\max}$

11.3.1 Climb

We require to clear heights and soar to the required altitude as fast as possible for which we need maximum rate of climb. For a propeller based aircraft we have velocity at maximum rate of climb as

$$V_{(R/C)_{\max}} = \left(\frac{2}{\rho_\infty} \sqrt{\frac{K}{3C_{D,0}}} \frac{W}{S} \right)^{1/2} = 15m/s$$

(design choice for week 1 and 2)

$$(R/C)_{\max} = \frac{\eta_{\mathrm{pr}} P}{W} - V_{(R/C)_{\max}} \frac{1.155}{(L/D)_{\max}}$$

Which can be rewritten as

$$(R/C)_{\max} = \frac{\eta_{\mathrm{pr}} P}{W} - V_{(R/C)_{\max}} \left[\sqrt{\frac{KC_{D,0}}{3}} + \sqrt{3KC_{D,0}} \right]$$

k and $C_{D,0}$ were obtained from the previous section.

11.3.2 Cruise

Most of our mission is revolving around cruise. In cruise/level flight we have

$$L = W = \frac{1}{2} \rho_\infty V_\infty^2 S C_L$$

$$\Rightarrow V_\infty = \sqrt{\frac{2W}{\rho_\infty S C_L}}$$

We know

$$P_R = T_R V_\infty = \frac{W}{C_L/C_D} V_\infty$$

$$\Rightarrow P_R = \frac{W}{C_L/C_D} \sqrt{\frac{2W}{\rho_\infty S C_L}}$$

$$P_R = \sqrt{\frac{2W^3 C_D^2}{\rho_\infty S C_L^3}}$$

It is desirable to fly at minimum power consumption and this occurs at

$$\left(\frac{C_L^{3/2}}{C_D} \right)_{\max} = \frac{1}{4} \left(\frac{3}{K C_{D,0}^{3/2}} \right)^{3/4}$$

To obtain this we differentiate $\left(\frac{C_L^{3/2}}{C_D}\right)$ with C_L and equate it to zero.

$$\frac{d\left(C_L^{3/2}/C_D\right)}{dC_L} = \frac{(C_{D,0} + KC_L^2)\left(\frac{3}{2}C_L^{1/2}\right) - C_L^{3/2}\left(2KC_L\right)}{C_{D,0} + KC_L^2} = 0$$

Leading us to

$$\boxed{C_{D,0} = \frac{1}{3}KC_L^2} \Rightarrow C_L = \boxed{\sqrt{\frac{3C_{D,0}}{K}}}$$

Now for the $\frac{L}{D}$ vs $\sqrt{AR}$ plot we need to obtain $\frac{L}{D}$ at $\left(\frac{C_L^{3/2}}{C_D}\right)_{\text{max}}$

$$\frac{L}{D} = \frac{C_L}{C_D} = \frac{C_L}{C_D, 0 + KC_L^2}$$

$$= \frac{C_L}{\frac{1}{3}KC_L^2 + KC_L^2} = \frac{3}{4KC_L}$$

$$\Rightarrow \boxed{(\frac{L}{D})_{MinP} = \frac{1}{4}\sqrt{\frac{3}{KC_{D,0}}}}$$

These are tabulated in 11.5 and the required L/D values are plotted against $\sqrt{AR}$ in 14.

11.3.3 Turn:

Updating from previous week's Turn Calculation, we assumed a maximum load factor of 3 in our turn calculation of power and energy.

11.4 Area estimation

Estimation of area's are done using fusion canvas and open J. Details that are knowm for all the UAV's are that of Span and Aspect ratio. Images of most UAV's are available on the internet and sketches, CAD files of some were available.
The estimation is done in the following way:

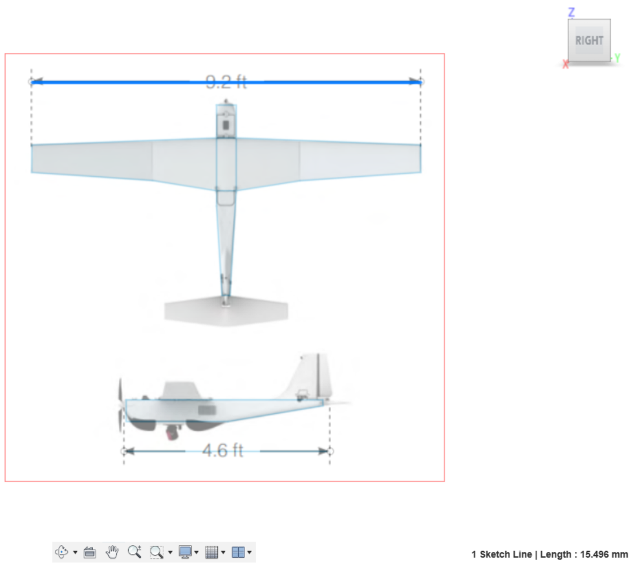


Figure 10 – Dimensioning on Fusion 360 canvas

The dimension from fusion canvas 15.49 m gives us the scale factor to draw a comparison to the actual UAV, this scale factor can now be used to evaluate the dimensions of aircraft, including root chord, tip chord, planform area, wing wetted area, fuselage projected areas and fuselage wetted area.

Estimatng from CAD files
Scaled down CAD models for some UAV's were provided by trusted sources, estimation of span, and other factors are done thereby based on the CAD files.

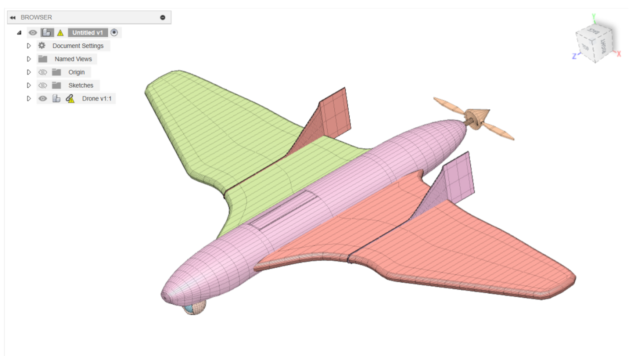


Figure 11 – Dimensioning on Fusion 360

Estimatng from OpenVSP

Models of UAV's can be imported to OpenVSP and estimation of projected areas can done thereby based on the files.

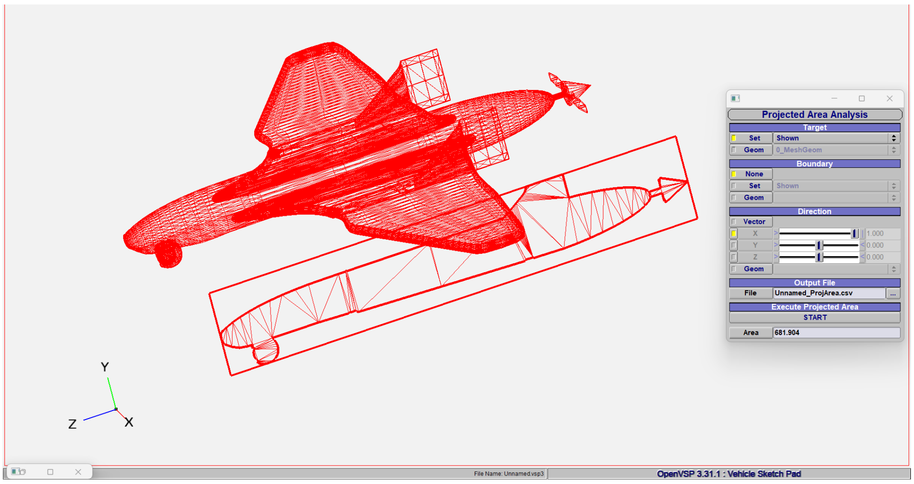


Figure 12 – Dimensioning using OpenVSP

Reference and wetted area are calculated according to methods discussed in section 11.4 [10]
The excel sheet with the evaluated data is linked **here**.

	A	B	C	D	E	F	G	H	I
1	UAV	Wing area exposed	Reference area	Wetted area for wing		Fuselage top area	Fuselage side area	Mean area	Wetted area for fuselage
2	Albatross	6838	6838	13696.514		1184	555	869.5	2956.3
3	Boeing Insitu	8268	9394	16536		3302	3302	3302	11226.8
4	CREX-B	3825	332	7650		NA	NA	NA	
5	Vrabac	7500	7930	15000		930	3200	2065	7021
6	Tai Marti	7530	7530	15060		875	1046	960.5	3265.7
7	RQ20 Puma	7832	8368*	15664		1641	1608	1624.5	5523.3
8	Tai Pelikan	9600	9600	19200		Na	NA		0
9	A1-CM	8010	9710	16020		2703	1921	2312	7860.8
10									
11									
12	All area's are in cm^2								
13									

Figure 13 – Calculations

11.5 Flight Parameter Estimation for Data Collected

UAV	Dimensions	Parameters
	• Span = 4.3 m • Mean chord = 0.36 • Area = 1.59	• AR = 12 • e = 0.7060 • k = 0.0376
	• Span = 3.2 • Root chord = 0.3 • Area = 0.64	• AR = 16 • e = 0.6122 • k = 0.0325
	• Span = 15m • Mean chord = 0.23 • Area = 12.29	• AR = 18.3 • e = 0.5618 • k = 0.0310
	• Span = 1.7 m • Mean chord = 0.225 • Area = 0.379	• AR = 7.62 • e = 0.8213 • k = 0.0509
	• Span = - • Mean chord = - • Area = -	• AR = - • e = - • k = -

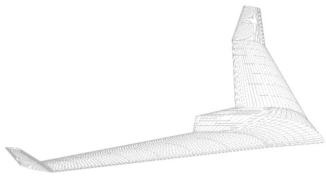
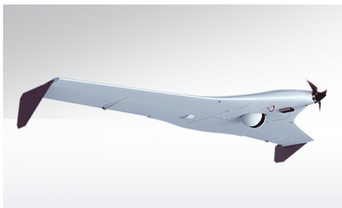
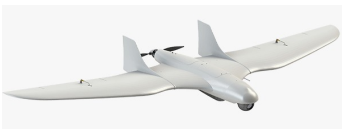
	• Span = 2.36 • Mean chord = 0.371 • Area = 0.733	• AR = 7.6 • e = 0.8218 • k = 0.0509
	• Span = - • Mean chord = - • Area = -	• AR = - • e = - • k = -
	• Span = 2.8 m • Mean chord = 0.25 • Area = 0.8 m^2	• AR = 9.8 • e = 0.7618 • k = 0.0426
	• Span = - • Mean chord = - • Area = -	• AR = - • e = - • k = -
	• Span = 2 m • Mean chord = 0.2 m • Area = 0.3 m^2	• AR = 13.33 • e = 0.6739 • k = 0.0354

Table 3 – Aspect ratio Specifications

11.6 Flight Parameter Estimation for our design (Drawing parallels from data collection)

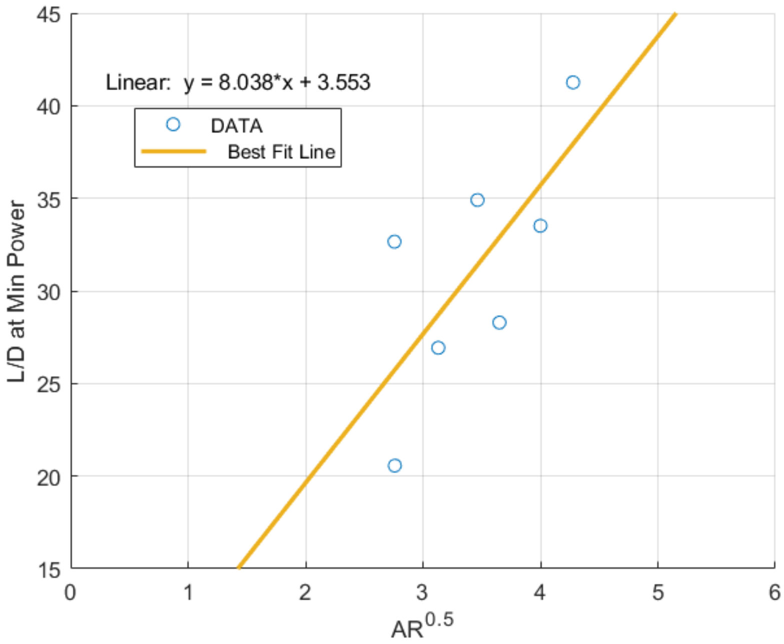


Figure 14 – Operating L/D Variation with AR

- Taking the mean of $\frac{L}{D}$ from the data points in the graph: **28.09**
- Corresponding to this $\frac{L}{D}$, the Aspect ratio we require is computed: **11.80**.
- Taking this AR, we compute Oswald's Efficiency factor using equation 36.

$$\boxed{e = 0.7110}$$

- From 38,

$$\boxed{K = 0.0379}$$

- In 39 we assume a flight taking place over a generic forest in India. Temperatures are taken at $15C$, ν at this temperature is taken to be:$15.53 * 10^{-6}$

$$\boxed{C_{D0} = 0.0074}$$

$\frac{P}{W}$ Calculation:

$$(R/C)_{\max} = \frac{\eta_{\text{pr}} P}{W} - V_{(R/C)_{\max}} \left[\sqrt{\frac{KC_{D,0}}{3}} + \sqrt{3KC_{D,0}} \right]$$

We desire a maximum climb rate of 2.86 m/s at a velocity of 15 m/s (design choice from week 1 and 2). With this we obtain the maximum power drawn from the powerplant for our design choice at $(R/C)_{\text{max}}$.

$$2.86 = \frac{P_{drawn}}{W} - 15 \left[\sqrt{\frac{0.0849 \times 0.0087}{3}} + \sqrt{3 \times 0.0849 \times 0.0087} \right] \tag{40}$$

$$\frac{P_{drawn}}{W} = 3.8014$$

Maximum Thrust Required: Out of all the mission stages, "climb" requires the highest thrust, which, in our case, comes out to be

$$T_{max} = \frac{P_{max}}{V} = \frac{P_{climb}}{V_{climb}} = \frac{380.7551}{15} = 25.383N \tag{41}$$

This dictates the choice of the propeller.
This will serve as our design point at this stage of the course. We shall use these parameters in our updated power and energy calculations in the following section. To see the plotting code, click on the image caption in this page.

11.7 Propeller Orientation and Positioning

We wish to build a flying wing type of UAV (which gives good endurance among other classes of UAVs). The key criteria that will drive our decision of propeller placement will be stability and aerodynamic efficiency.

11.7.1 Pusher Vs Puller (Tractor) Configuration:

A puller propeller typically has the engine behind it and near the front of the aircraft so that its thrust pulls the aircraft forward. A pusher typically has the engine in front of it and is at the rear of the aircraft so that its thrust pushes it forward. We have decided to go for a Puller configuration due to the following reasons:

- Puller propellers face the incoming flow without any disturbances, leading to better aerodynamics and propulsion efficiency. With a pusher propeller system placed at the tail, the flow coming into the propeller would be altered due to interactions with the fuselage.
- Placing the propellers in front of the nose (Puller) shifts our center of gravity forward. This is desirable when it comes to the static stability of the aircraft. We want our center of gravity to be as forward as possible compared to the neutral point to have a better stability margin.

- With a Puller Propeller system, the wings, and the fuselage interact with the downwash of the propellers, thereby energizing it. This leads to better performance.

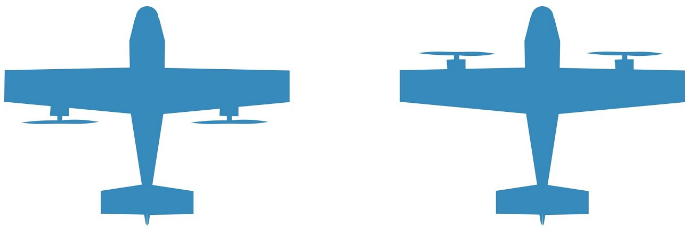


Figure 15 – Pusher (left) Vs Puller (right) Configuration [12]

11.7.2 Single Vs Distributed Propulsion:

Single propulsion systems and distributed propulsion systems represent two distinct approaches in designing UAVs, each with its own set of advantages and disadvantages.

- A single propulsion system, typically a single engine with one or more propellers, is simpler and often more cost-effective. It's easier to maintain and has a straightforward design.
- Distributed propulsion systems involve multiple propulsion units distributed across the UAV's airframe. This approach enhances redundancy, as the failure of one unit does not necessarily lead to a complete loss of power. It also allows for innovative designs, such as vertical takeoff and landing (VTOL) capabilities.
- Distributed propulsion systems can be more complex, increasing manufacturing and maintenance costs. Additionally, the increased number of components may lead to a heavier overall system, impacting efficiency. Single propulsion better for simpler applications.
- Moreover, placing multiple propeller units at the wings (which are expected to be moderately swept back for our design) pushes the center of gravity towards the tail. This is undesirable from a stability point of view for a flying wing configuration aircraft.

We have decided on an undistributed propulsion system because of our stability requirements.

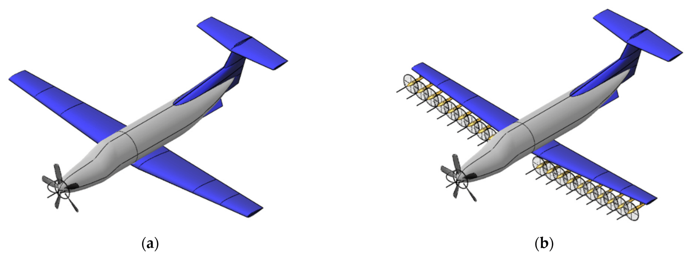


Figure 16 – Undistributed Vs Distributed Propulsion System [10]

11.8 Propeller selection: **NOTE: Data presented is for static tests.**

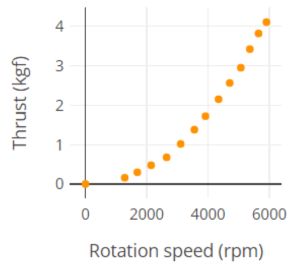
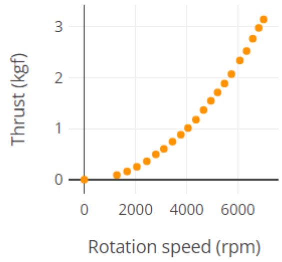
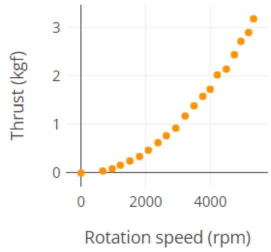
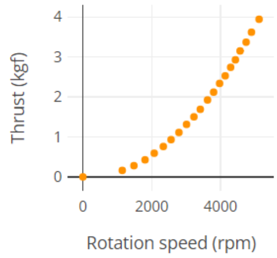
Propeller	Characteristics	Thrust curve
T-Motor P16x54	• Diameter (in) = 16 • Pitch (in) = 5.4 • Weight (gr) = 28 • Material = Carbon fibre	
T-Motor FA162x53	• Diameter (in) = 16.2 • Pitch (in) = 5.3 • Weight (g) = 37 • Material = Carbon fiber with foam or balsa core	
T-Motor MF1806	• Diameter (in) = 18.4 • Pitch (in) = 6.6 • Weight (g) = 37 • Material = Polymer propeller (+CF)	
T-Motor P20X6	• Diameter (in) = 20 • Pitch (in) = 6 • Weight (g)= 47 • Material = Carbon fiber with foam or balsa core	

Table 4 – Propeller test data for selection

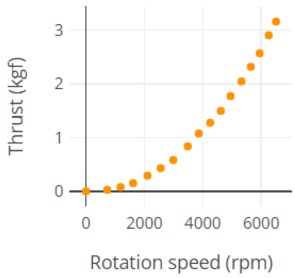
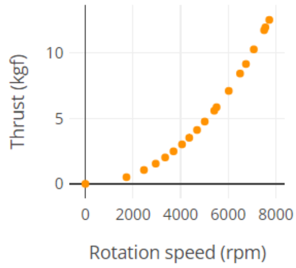
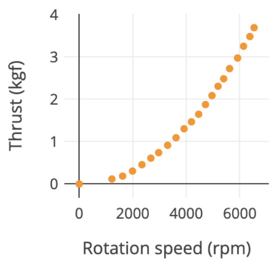
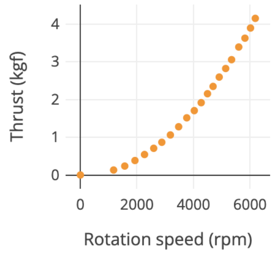
Propeller	Characteristics	Thrust curve
APC 16x55MRP	• Diameter (in) = 16 • Pitch (in) = 5.5 • Weight (g) = 45 • Material = Nylon	
Xoar PJN	• Diameter (in) = 21 • Pitch = 8 • Weight (g) = 69 • Material = Beech Wood	
T-Motor P17x58 propeller	• Diameter (in) =17 • Pitch (in)= 5.8 • Weight (g)= 28 • Material = Carbon fiber with foam or basla core	
T-Motor G18x59	• Diameter (in)= 18 • Pitch (in)= 5.9 • Weight (g)= 3.4 • Material = Carbon fiber with foam or balsa core	

Table 5 – Propeller test data for selection

Links for the propeller's and test data are provided in first column, attached along with the name of the propeller. Link's to support for all the dimen-

sions and material are attached to the Diameter item in the second column (Suitable motor combinations are as well is provided in the same web page.)
We have chosen T-Motor P16 x 54 as it matches our requirements the best.

(a) T-Motor P16 X 55 Propeller

(b) U7 490kV Motor

Figure 18 – Propeller and battery

Justification:
Maximum thrust required for our mission is 2.58 kgf, the propeller we choose has an optimal thrust (suggested operation thrust for max efficiency) of 2.6 kgf as listed in it's data (Linked in the second column of table). It is also capable of producing maximum thrust up to 7 kgf and sustain for the bending loads and moments due to aerodynamic forces without any permanent deformations.

Hence we select this propeller due to the factors of ideal operational thrust being close to the thrust that we require and for having a good available margin between maximum capable thrust and required estimated thrust (in case the actual thrust required slightly varies from the estimated one, the design still would be on the safer side)

The current selection of motor is **T-Motor U7 490kV**. The tests for the propeller choosen are as well performed using the same motor, which is one of the main reasons for selecting it. It also has better efficiency compared to other motors which were used to test the propeller (data is linked in column 1 of table).

12 Battery Data

Links for the battery data from the below table are provided in first column, attached along with the name of the battery.
From 11.6 we require maximum thrust of 25.383 N which corresponds to **2.5875 kgf**. Allowing for a margin, we accounted the calculations for a thrust of 2.8 kgf (10 percentage higher than what we would need)

Battery	Characteristics	Battery Image
GENX 6S 10000mAh	• Capacity(mAh) = 10000 • Nominal Volatge(V) = 22.2 • Discharge Rate = 25C • Weight(g)=1332	
GENX 6S 16000mAh	• Capacity(mAh) = 16000 • Nominal Volatge(V) = 22.2 • Discharge Rate = 5C • Weight(g)=1500	
TATTU 10000mAh 6S	• Capacity(mAh) = 10000 • Nominal Volatge(V) = 22.2 • Discharge Rate = 25C • Weight(g)=1386	
HRB 6S 10000mAh	• Capacity(mAh) = 10000 • Nominal Volatge(V) = 22.2 • Discharge Rate = 25C • Weight(g)=1362	

Table 6 – Battery data for selection

13 Battery selection

- Visible Range Camera: 20W
- Multi-Spectral Camera: 10W
- Lidar: 30W
- Avionics = 15(flight controllers) + 25(control surfaces)
- Total power consumed by auxiliary systems = 100W
- Maximum power consumed by T-Motor P16x54 (selected propeller) = 497.74W ≈ 500W. (This is during climb during which we won't need to switch on the payload).
- Estimated peak power requirement (climb) = 550W
- Estimated cruise power requirement = 73.3422 + 100 ≈ 175W.
- Estimated takeoff power requirement = 158.66 + 40 ≈ 200W.
- Estimated turn power requirement = 297 + 100 ≈ 400W.

16.1 contains a snippet of code to compute these power requirements at different stages of flight.
To match these power requirements for the entire mission time we have come up with several feasible batteries (sec. 12) and have concluded that **GENX 6S 16000mAh** is the most suitable.

Justification:

- Wh rating of the battery = nominal voltage (V) × capacity (Ah) = 22.2 × 16 = 355.2 Wh
- Continuous max discharge = 5C
- This implies we get a maximum continuous discharge of 80 A, which is more than required.
- Maximum power output = 5 × 16 A × 22.2 V = 1776 W. This is again more than required.
- In cruise we need 175W that implies feasible cruise time = $\frac{355.2}{175} \approx 2$ hrs (meeting our mission requirement).

14 Updated weight

After feeding the code with new values of power required, the updated total weight of the UAV is 10.86 kg (from 10.21) with battery weight fraction of 0.1552. This fraction corresponds to an allowable battery weight of 1.69 kg's. Our current battery selected as stated in section 13, complies with this (It has as weight of 1.50 kg's).

15 Wing Loading Estimation:

Wing loading refers to the ratio of the weight of the aircraft to the reference area.

$$\boxed{\frac{W}{S}}$$

This factor greatly influences crucial performance metrics such as stall speed, climb rate, takeoff and landing distances, and turning capability. [5]
Each stage of our flight will give an optimal wing loading magnitude. This week's computations are based on the T/W ratios derived from the previous week.
It is also important to note that if one particular flight segment is giving a starkly lower or higher value of optimal wing loading, it is imperative to try and pick another value.
Different stages of flight can have different conditions. How can we uniformly compare values of wing loading? We define a reference state of flight against with we compare an equivalent magnitude of wing loading. However, for our design, we do not need to go down this path, as we are operating a battery-powered flight.

15.1 V_{Stall} Constraint:

Wing loading has direct implications on stall speed and approach speed (Which is usually a factor of magnitude more than stall speed, 1.1-1.3). To find an appropriate wing loading we decide on a V_{Stall} (based on mission requirements and historical data).
We take this value to be 12m/s. (refer 4.4)
We know L = W:

$$\boxed{W = L = q_{\text{stall}}\, SC_{L_{\max}} = \frac{1}{2}\rho V_{\text{stall}}^2\, SC_{L_{\max}}}$$

Now the quantity remaining unknown is $C_{L_{\max}}$. Usually without any use of lift-enhancing devices, $C_{L_{\max}}$ is about 1.3-1.5.
Let's take 1.5 and analyze what value of wing loading we land up at.

$$\boxed{\frac{W}{S} = \frac{1}{2} 1.21 \times 12^2 \times 1.5 = 130.68 N/m^2}$$

130.68 is quite a low value. This points out towards a need to enhance the max value of C_{Lmax}. This can be achieved by using standard lift-enhancing devices such as flaps, slats, spoilers, winglets, vortex generators, etc. According to [6], with the aid of these devices, we can get values of C_{Lmax} up to 5. For short take-off UAVs it is about 3. Using this, we get:

$$\boxed{\frac{W}{S}_{stall} = \frac{1}{2}1.21 \times 12^2 \times 3 = \mathbf{261.36}N/m^2}$$

This value ($261.36N/m^2$) is more appropriate for UAVs of our desired size.

15.2 Take off/ Landing Constraint:

The liftoff speed for a nominal takeoff is

$$\boxed{V_{TO} = 1.1V_{Stall}}$$

Our mission objective requires the UAV to clear a height of 20m in a ground roll of 200m. Near the tropical evergreen forests the maximum altitude on average is 60m above sea level, which implies there isn't much variation in density from the sea level. For a propeller based UAV, the take off parameter (TOP) is given by

$$\boxed{TOP = \frac{W/S}{\sigma C_{L,TO} HP/W}}$$

where,

TOP	=	takeoff parameter
W/S	=	wing loading
σ	=	density ratio given by ratio of air density at takeoff altitude and air density at sea level ≈ 1
HP	=	horsepower in take off = 0.268 hp
$C_{L,TO}$	=	coefficient of lift at take off which is maximum lift coefficient divided by 1.21 (since V_{TO} = 1.1 V_{stall}) = $\frac{3}{1.21}$ = 2.479

Take off distance = 656.168 ft, which corresponds to a TOP value of 70 (approx)

$$\boxed{\frac{W}{S}_{TO} = (\text{TOP})\sigma C_{L_{\text{TO}}}(\frac{\text{hp}}{W}) = \mathbf{93.02}\frac{N}{m^2}}$$

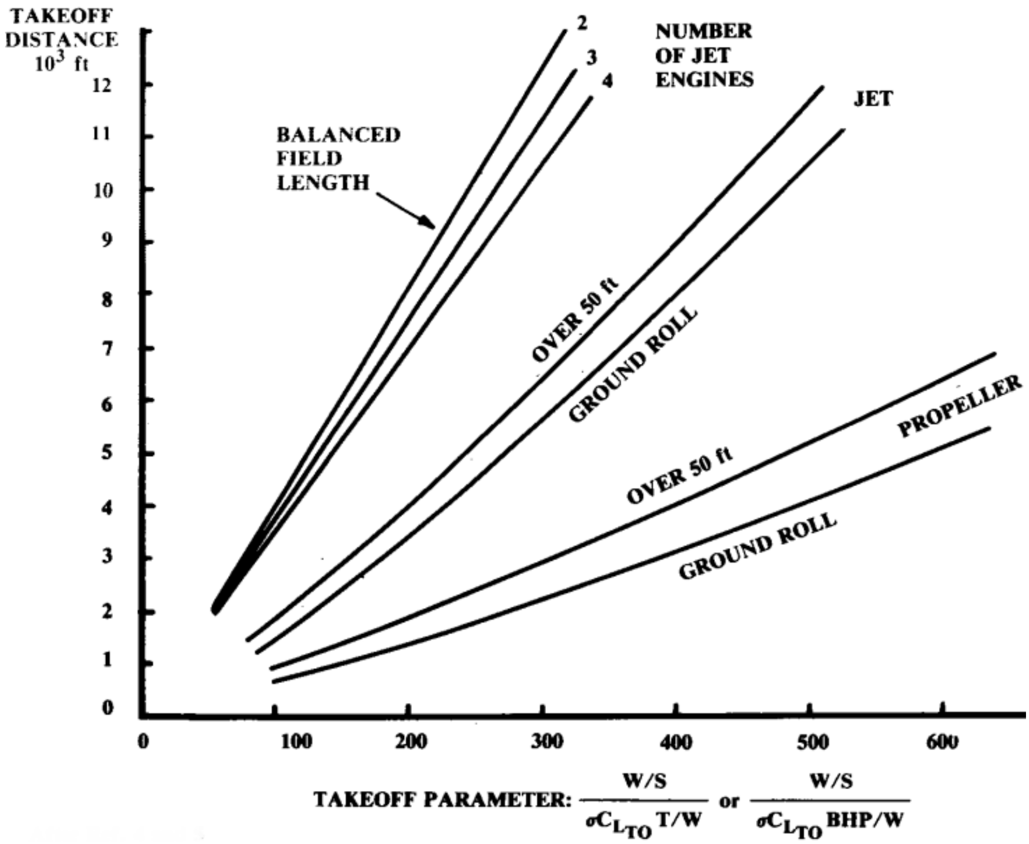


Figure 19 – Plot for a comparison chart of Takeoff distance vs Takeoff parameter taken from - Raymer page no 88 [6]

15.3 Cruise/Loiter Constraint:

In our mission profile, we require the UAV to cruise/Loiter the forest region for around 2 hours and make necessary observations on the terrain. Mission phase constrains and conditions are listed as follows.

- Weight of the UAV is almost constant through out the Cruise/Loiter given the fact that the propulsion system is electric. (Battery weight during discharge only decreases slightly, so UAV weight can be taken to be constant.)
- C_{D0} and e values for the current iteration of the UAV are 0.0074 and 0.711 respectively.
- V_{cruise} for the current iteration of the design is 20 m/s

Wing loading for max endurance
From the above listed first mission condition that weight of the UAV is constant throughout the mission, we can start wing loading estimation for maximum endurance as follows

Velocity can be expressed as

$$v = \sqrt{\frac{2W}{\rho S C_L}}$$

Power required is

$$P = \sqrt{\frac{2W^3 C_D^2}{\rho_\infty S {C_L}^3}}$$

Hence the minimum power, i.e maximum endurance is for a case where $\frac{{C_L}^{\frac{3}{2}}}{C_D}$ is maximum
The maximum value of $\frac{{C_L}^{\frac{3}{2}}}{C_D}$ can be obtained as

$$(\frac{{C_L}^{\frac{3}{2}}}{C_D})_{max} = max(\frac{\sqrt{C_L}}{\frac{C_{D0}}{C_L} + \frac{1}{\pi e AR} C_L})$$

$$(\frac{{C_L}^{\frac{3}{2}}}{C_D})_{max} = \frac{1}{4}(\frac{3}{K {C_{D0}}^{\frac{3}{2}}})^{\frac{1}{4}}$$

Substituting this value of $\frac{{C_L}^{\frac{3}{2}}}{C_D}$, we get the expression for least power, i.e the scenario corresponding to maximum endurance as

$$v = (\frac{2}{\rho_\infty}\sqrt{\frac{k}{3C_{D0}}}\frac{W}{S})^{\frac{1}{2}}$$

The wing loading corresponds to the minimum power consumption and maximum endurance is thereby given by

$$\boxed{\frac{W}{S}_{cruise} = q\sqrt{3\pi e(AR)C_{D0}} = \mathbf{185.1} N/m^2} \tag{42}$$

Substituting required values into eq. 42
Where

- q = $\frac{1}{2}\rho_\infty {V_\infty}^2$
- AR = Aspect ratio
- e = efficiency factor

Substituting the values, the wing loading comes out to be **185.1** N/m^2.

15.4 Turn Constraint:

Considering the turn constraints of the mission,

- Turn rate = 12^0 per second
- Bank angle = 30^0

- Velocity of turn = 27 m/s

From the above parameters, load factor can be evaluated as

$$n = \frac{1}{\cos(30^0)} \tag{43}$$
$$n = 1.154$$

Value of q can be calculated as:

$$q = \frac{1}{2}\rho v^2 \tag{44}$$

After substituting the required values, value of q comes out to be **441.045** N/m^2. Expression for wing loading during turn is given by (Expression taken from Raymer page no 96 [6])

$$\boxed{\frac{W}{S}_{turn} = \frac{q}{n}\sqrt{\pi AReC_{D0}} = 168.7N/m^2} \tag{45}$$

From the above expression, the wing loading is **168.7** N/m^2

The above equation, maximises the sustained turn rate regardless of the thrust available. This equation may give low wing loading values as it may utilise only a fraction of available thrust depending on the chosen parameters (Mentioned in Raymer page no 97 [6]). But clearly that isn't the case observed here, as the wing loading is decently high (**168.7 N**/m^2**)**

Since to make sure that all the available thrust is utilised, we obtain the wing loading by equation thrust and drag, which yields the following equations: (Chosen from Raymer page no 97 [6]

$$T = qSC_{D_0} + qS\left(\frac{C_L^2}{\pi ARe}\right) = qSC_{D_0} + \frac{n^2W^2}{qS\pi ARe}$$
$$\frac{T}{W} = \frac{qC_{D_0}}{W/S} + \frac{W}{S}\left(\frac{n^2}{q\pi ARe}\right)$$
$$\frac{W}{S}_{turn} = \frac{(T/W) \pm \sqrt{(T/W)^2 - (4n^2C_{D_0}/\pi ARe)}}{2n^2/q\pi ARe} = \mathbf{239.79} or \mathbf{118.8} N/m^2$$

15.5 Climb/Glide Constraint:

Gliding flight is similar to climbing flight with the thrust set to zero.The direction of the gliding angle γ is assumed to be reversed from that used for climb.

$$D = Wsin\gamma$$

$$L = W cos\gamma$$

$$\frac{W cos\gamma}{W sin\gamma} = \frac{1}{tan\gamma} = \frac{1}{\gamma}$$

The "glide ratio" is the ratio between horizontal distance travelled and altitude lost, and is equal to the lift-to- drag ratio.To maximize range from a given altitude, the glide ratio should be maximized.

$$V_{maxL/D} = \sqrt{\frac{2W}{\rho S}\sqrt{\frac{K}{C_{D_0}}}}$$

$$C_{L_{maxL/D}} = \sqrt{\frac{C_{D_0}}{K}}$$

$$(L/D)_{max} = \frac{1}{2\sqrt{C_{D_0}K}}$$

The time a glider may remain in the air is determined by the "sink rate"; the vertical velocity V_ν, which is negative in this case. Sink rate is the air- craft velocity times the sine of the glide angle.

$$V_\nu = V sin\gamma = sin\gamma\sqrt{(\frac{W}{S})\frac{2cos\gamma}{\rho C_L}}$$

$$sin\gamma = \frac{D}{L}cos\gamma = \frac{C_D}{c_L}cos\gamma$$

$$V_\nu = \sqrt{\frac{W}{S}\frac{2cos^3\gamma C_D^2}{\rho C_L^3}} = \sqrt{\frac{W}{S}\frac{2}{\rho(C_L^3/C_D^2)}}$$

$$\frac{W}{S} = V_\nu^2 \times \frac{\rho(C_L^3/C_D^2)}{2}$$

Taking $V_\nu = 2.86m/s$ based on our design choice in week 1 and 2.

$$\boxed{\frac{W}{S}_{climb} = (2.86)^2 \times \frac{1.21 \times (22.039)}{2} = \mathbf{109.064N/m^2}}$$

The lift coefficient for minimum sink rate is solved for by maximizing the term involving C_L and C_D.

15.6 Maximum Operational Ceiling Constraint:

At the maximum operational ceiling we have,

- V = 20 m/s
- q = $\frac{1}{2}\rho V^2$ = 242 Pa
- G = 0 (Max Rate of Climb)

From Raymer, [6] page number 99, at absolute ceiling condition:

$$W/S = q\sqrt{\pi AReC_{D_0}} = 242 \times \sqrt{\pi \times 11.8 \times 0.711 \times 0.0074} = \mathbf{106.87\frac{N}{m^2}}$$

$$\Rightarrow \boxed{\frac{W}{S}_{ceiling} = \mathbf{106.87\frac{N}{m^2}}}$$

As suggested in raymer there is an alternate way to obtain wing loading in case the above equation yields a very low value, it clearly is not the case as a wing loading of **106.87** N/m^2 is not very low. The alternate way is presented as follows

$$\frac{W}{S}_{ceiling} = qC_L = 242\sqrt{\frac{3C_{D,0}}{K}} = 242\sqrt{\frac{3 \times 0.0074}{0.0379}} = \mathbf{185.2\frac{N}{m^2}}$$

The initial calculated wing loading of **106.87 N/m^2 is considered for evaluation.**

15.7 Results of W/S Estimation from data computed above:

$$\frac{W}{S}_{TO} < \frac{W}{S}_{Climb} < \frac{W}{S}_{turn} < \frac{W}{S}_{cruise} \approx \frac{W}{S}_{ceiling} < \frac{W}{S}_{stall}$$

We choose the least wing loading value to ensure that the wind is large enough for all flight conditions.

$$\Rightarrow \boxed{\frac{W}{S} = 93.02N/m^2}$$

$$\Rightarrow S = 1.145m^2$$

And with an aspect ratio of 11.8, we get wing span as

$$b = \sqrt{S} \times AR = 3.67m$$

16 Appendix

16.1 Power Requirement for various flight stages

```
%% Code Snippet for finding Power and Energy requirements at
    different stages of flight
Mass = 10.21;
W = Mass*9.81;
LbyD; % Got from previous part of the code, from the plot of L/D Vs
     sqrt(AR)

Ptakeoff = (0.5*10.21*14.4^2)/10 + 14.4*10.21*9.81/LbyD
Etakeoff = Ptakeoff*10;

P_climb = Power_during_climb
E_Climb = P_climb*120;

P_CruiseLoit = (20/(LbyD))*W
E_CruiseLoit = P_CruiseLoit*2*60*60;

P_Turn = 27*3*W/((LbyD))
E_Turn = P_Turn*90;

Total_Energy = 2*Etakeoff + 2*E_Climb + E_CruiseLoit + E_Turn
```

17 Contributions:

17.1 Week2

- **Hrishav Das:** Compiling data into Matlab Script, generating plots, takeoff, and landing power requirement formulation.
- **Chandra Hasa:** UAV data collection, payload selection, cruise and loiter power requirement formulation, document formatting.
- **Balaji Naidu P:** Climb and Turn performance and power requirements, Data collection and compilation, Performance and powerplant study of similar UAV's, document formatting.
- **Avneesh Kumar:** UAV data collection,design making and formatting,Payload instrument selection,document formatting.
- **Vishwajeet Shukla:**
- **Karri Deepak:**

17.2 Week3:

- **Hrishav Das:** Computed the flight parameters and generated $\frac{L}{D}$ vs $\sqrt{AR}$ plot, mission section's power estimation, decision on undistributed and puller propulsion, documenting the report on LaTeX.

- **Chandra Hasa:** Geometry estimations for similar UAVs, derived expressions for required $\frac{L}{D}$; power for climb and cruise, power estimation for all components (flight + auxiliary systems), battery selection and justification, documenting the report on LaTeX.
- **Balaji Naidu P:** Area estimations using fusion 360, openVSP, mission section's power, Battery selection and endurance estimation, propeller data collection and selection, dimensioning, documenting the report on LaTeX
- **Avneesh Kumar:** Battery data collection and selection, Propeller data collection and selection, dimensioning, documenting the report on LaTeX
- **Karri Deepak:** Similar Aspect ratio UAV study and data collection, CL/CD, $CL^{\frac{3}{2}}$/CD variations study based on research articles.
- **Vishwajeet Shukla:**

17.3 Week4:

- **Hrishav Das:** Wing loading for V_{stall} constraints, wing loading for ceiling, wing loading for turn, documenting the report on LaTeX
- **Chandra Hasa:** Wing loading for take-off/ landing, wing loading for turn, comparative analysis of wing loading for all stages and span evaluation, documenting the report on LaTeX
- **Balaji Naidu P:** Wing loading for cruise and loiter, wing loading for turn, documentation of report on LaTeX
- **Avneesh Kumar:** Wing loading for climb and glide, documentation of report on LaTeX
- **Vishwajeet Shukla:**
- **Karri Deepak:**

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