Assignment 3
Design of Fixed Wing UAV
EC4.402 - Introduction to UAV Design

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1 FW-UAV Design for 3D Mapping

The following are the given requirement

$$\text{Endurance} = 60\,\text{min} \quad \text{Area of operation} = 10\,\text{Km rad.} \quad \text{Cruise speed} = 20\,\text{m/s}$$
$$\text{Flying altitude} = 100\,\text{m (from ground)} \quad \text{Climb rate} = 2\,\text{m/s} \quad \text{Descent rate} = 2\,\text{m/s}$$

It is assumed that these are the minimum values and with a greater budget these can be extended. It is assumed that some compromise on the area of operation (in terms of coverage area and not range) is acceptable.

1.1 CONOPS

CONOPS of *Concept of Operations* is the overview of the operations involved in the application of the Fixed Wing UAV (FW-UAV). The stages of operation are defined as

1. **Take-off** from ground. It is preferred to have a hand launch mechanism for take-off (bungee launch at best). Runway takeoff UAVs are least preferred (too much arrangement required for them).
2. **Climb** to the height of $100\,m$ from ground. The climb rate is $2\,m/s$.
3. **Cruise** in the area for performing mapping. It is assumed that the UAV travels in straight lines (back and forth) from one end to another end (confined in a circle - of $10\,Km$ radius).
   - It is possible to take multiple trials for covering the entire area.
   - It is preferred to have an autonomous solution, where the path is programmed and the UAV follows it.
   - A manual solution is only required as a backup.
4. **Descent** from $100\,m$ to the ground. The descent rate is $2\,m/s$.
5. **Landing** on the ground. The UAV will be at very low speeds when landing and can land on any grassland. It need not have a runway for landing (it doesn't even need wheels).

The *loitering* phase was not chosen because we decided on traveling (cruising) in straight lines, while taking turns. This is better if multiple views are required. Loitering can be chosen if the desired path is in form of expanding circles.

However, there will be no *aggressive flight maneuvers*, as the application does not desire it.

1.2 Requirement Specifications

The following can be considered the *requirement specifications* for the starting of the design phase

- **Operating velocity** can be the cruise speed of $20\,m/s$.
- **Range** can be assumed to be around $30\,Km$ (for traversals). This will depend on the sensor. Some sensors can work from far, while some will require close proximity (increasing traversal range).
- **Endurance** can be $60\,min$.
- **Payload** will be the cameras and/or LiDAR sensors (which will be used for 3D mapping). Usually, these will be well under $500\,gm$.
- **Wind** conditions will be around $5\,km/hr$ to $20\,km/hr$ [1]. They will hardly be expected to go beyond $25\,km/hr$.
- **Altitude** will be around $100\,m$ from ground, and $1000\,m$ to $3000\,m$ from sea level (mostly will be under $1500\,m$ for most commercial applications).

[1] Weather data from `https://www.meteoblue.com/en/weather/historyclimate/`

- **Safety**: The UAV must be certified for surveillance and mapping standards, as well as human operation standards. It also must have regulatory compliance with GOI (Government of India) guidelines. The following can be noted [2]
  - The drone falls in the *micro* category (weighing total of $250\,g$ to $2\,kg$).
  - Drone must have GPS, flight data logging, RTH (Return-to-home), anti-collision light, RFID and SIM with NPNT (No Permission No Takeoff) compliant software, and ID plate.
- **Maneuverability**: No agile maneuvers are needed. The drone will be oriented horizontally virtually always. Only turning maneuvers are needed.

1.3 Market Survey

senseFly eBee X

The senseFly eBee X fixed wing UAV is a hand-launched UAV suitable for mapping and surveillance applications. It is very mobile and convenient to use.

The product can be found at `https://www.sensefly.com/drone/ebee-x-fixed-wing-drone/`. Its specifications were obtained from the comparison table and datasheet at the same website.

1. *Operating velocity*: It can cruise from $11\,m/s$ to $30\,m/s$. Comfortably within our $20\,m/s$ bounds.
2. *Range*: It has a standard flight range of $37\,km$ (maximum is $55\,km$). This is well over our $30\,km$ requirement.
3. *Endurance*: It can fly for up to $90\,min$. Our requirement is only for $60\,min$.
4. *Payload*: It will carry a camera as payload. The total weight will be around $1.3\,kg$ to $1.6\,kg$. It is very easy to carry around in a bagpack.
5. *Wind*: It can tolerate wind up to $46\,km/hr$ (well beyond our maximum of $25\,km/hr$).
6. *Altitude*: Its optimal altitude is $120\,m$, we only require $100\,m$.
7. *Safety*: The UAV will require additional safety certification for India. It is certified for Canada, EU and the USA.

With the above specifications, the UAV almost exceeds our requirements. Choosing it should give very comfortable bounds, thereby allowing for greater needs in the future. Price would be around ₹ 10,00,000 (including all accessories and carrying case, with extra batteries and ground stations). This UAV is shown in figure 1a.

It has a $116\,cm$ wingspan.

Delair UX11

The Delair UX 11 fixed wing UAV is a compact hand-launched UAV suitable for mapping applications. The UAV has 3G and 4G capabilities giving it extended communication range and reducing the number of ground stations to one (receiver).

The product can be found at https://delair.aero/. Its specifications were obtained from the datasheet at the same website. Some information is also taken from its Amazon product page.

1. *Operating velocity*: The UAV can cruise at speed upto $15\,m/s$. This is a little less than our $20\,m/s$ requirement.
2. *Range*: It has a range of $53\,km$. This is well over our $30\,km$ requirement.
3. *Endurance*: It can fly for up to $60\,min$, which our exact requirement.
4. *Payload*: It will not require any external payload as the cameras are built into the UAV body. The entire UAV weighs less than $1.5\,kg$.
5. *Wind*: It can tolerate wind up to $45\,km/hr$ (well beyond our maximum of $25\,km/hr$). It can even fly in light rain.

[2] Main reference from `https://uavcoach.com/drone-laws-in-india/` and `https://digitalsky.dgca.gov.in/home`

6. *Altitude*: Its optimal altitude is $120\,m$, we only require $100\,m$.

7. *Safety*: The UAV will require additional safety certification for India. It is certified for the USA.

With the above specifications, the UAV almost meets our requirements. Choosing it for the immediate needs is ideal. Price would be around ₹ 7,00,000 (including all accessories and carrying case). This UAV is shown in figure 1b. It has a $110\,cm$ wingspan.

(a) senseFly eBee X

(b) Delair UX11

(c) WingtraOne Gen II

(d) Aeromapper Talon LITE

Figure 1: FW-UAV Market Survey

The VTOL capable WingtraOne is also a good choice. Another FW-UAV is Aeromapper Talon LITE

1.4 Airfoil Selection and sizing

The design happens in the following stages

Specifications

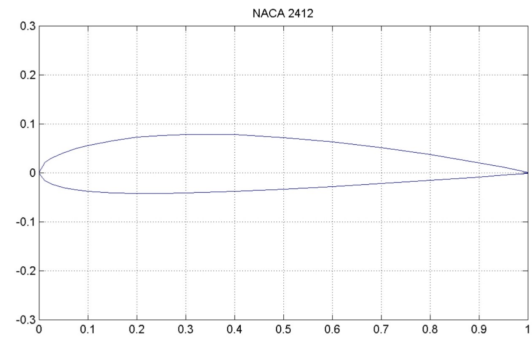
We assume a takeoff weight of $2\,kg$. The environment temperature is assumed to be $25°C$, where density of air is $\rho = 1.184\,kg/m^3$ an the dynamic viscosity is $\mu = 1.849 \times 10^{-5} kg/(ms)$ [3]. For now, the cruise speed can be $20\,m/s$.

For the starting, we will assume the wing to be rectangular and with chord length $c = \bar{c} = 0.2\,m$. Let us also assume the wingspan be to $b = 1.1\,m$. These are values taken from the UAVs in the market survey.

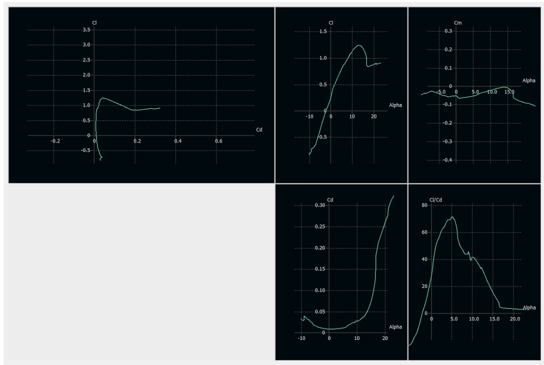
[3] Values obtained from `https://lynniezulu.com/what-is-the-dynamic-viscosity-of-air/`

Wing Design - Phase 1: Airfoil analysis

We will choose `NACA 2412` airfoil for starting the design phase (simply because it is common for remote controlled UAVs). It is shown in figure 2a.



(a) NACA-2412 Profile



(b) Airfoil analysis - 1

Figure 2: NACA-2412 Airfoil

We first analyze the airfoil in XFLR5, using `XFoil Direct Analysis`. The Reynold's number is calculated using

$$R_e = \frac{\bar{c} V_a \rho}{\mu} = \frac{0.2 \times 20 \times 1.184}{1.849 \times 10^{-5}} = 256138.45 \approx 256140 \tag{1.1}$$

The first analysis is shown in figure 2b.

We notice that highest ${}^{C_l}/_{C_d}$ occurs at $\alpha = 5°$ (best lift and least drag). The lift peaks at $\alpha = 13°$, with the drag elbowing and then increasing rapidly afterwards. This means that for this airfoil, the preferred angle of attack in the 3D plane design should be from 5° to 13°.

Noting these observations, we proceed with selecting the `NACA 2412` airfoil.

Wing Design - Phase 2: Wing from airfoil

Running an `LTT` analysis on a *wing only* model of a plane (using the wingspan $b = 1.1$ and chord $\bar{c} = c = 0.2$) yields figure 3.

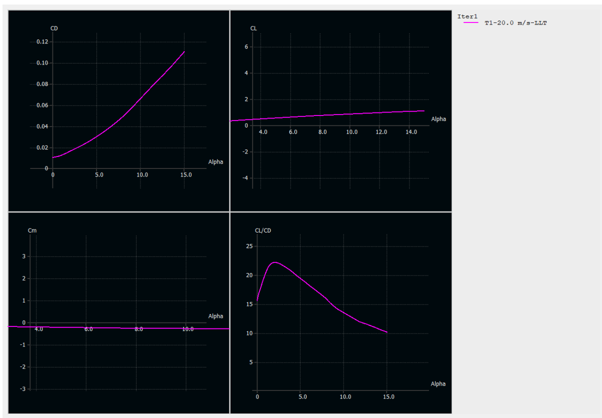


Figure 3: Wing analysis

Fitting the line and quadratic equations through graphs in figure 3, we get

$$C_{L_w} = 3.2944\alpha + 0.2951 \quad C_{M_w} = -0.5991\alpha - 0.1522 \quad C_{D_w} = 0.7666\alpha^2 + 0.2022\alpha + 0.0065 \tag{1.2}$$

We need to counter the weight for lift (when cruising at steady state). This gives us

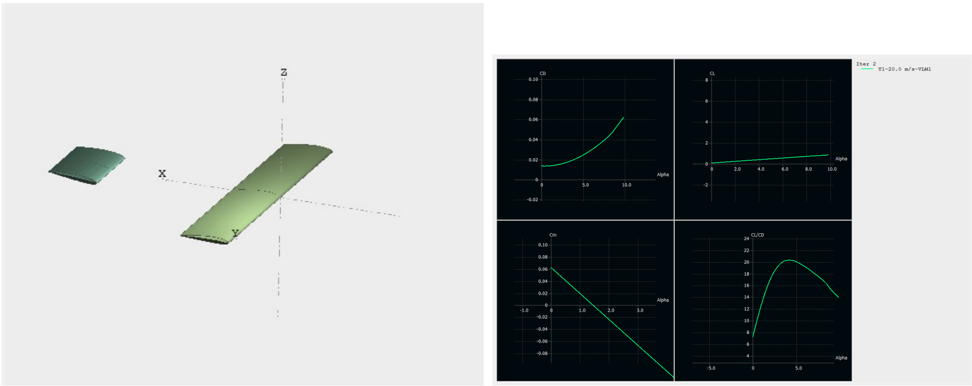
$$F_{L_w} = C_{L_w}\frac{1}{2}\rho V_a^2 S_w \Rightarrow C_{L_w} = \frac{mg}{\frac{1}{2}\rho V_a^2 S_w} \tag{1.3}$$

We get $C_{L_w} = 0.37622$ for $V_a = 20$, giving us $\alpha = 1.4°$. We can probably fly the plane with this α as well, as seen in figure 2b.

If we want the *most* optimal performance for the airfoil (highest ${}^{C_l}/{}_{C_d}$), we should choose to fly at around $16\,m/s$ (cruise). However, highest ${}^{C_L}/{}_{C_D}$ is found at around $\alpha = 2.1°$. Our $V_a = 20\,m/s$ should be manageable.

Tail Design - Phase 3: Horizontal Tail We place the tail such that at cruise speed, the pitching moment (along Y axis) is zero. The moment should be negative when α of wing increases, and should be positive when α of wing decreases from the cruise value. This will make the plane self stabilizing.

Through XFLR experimentation, we find that keeping $c = 0.2$, $b = 0.15$ for the horizontal tail is ideal (shape-wise). We place the tail $0.7\,m$ behind the wing, at a tilt of $-5°$. This is shown in figure 4a.



(a) Horizontal tail (b) XFLR Analysis

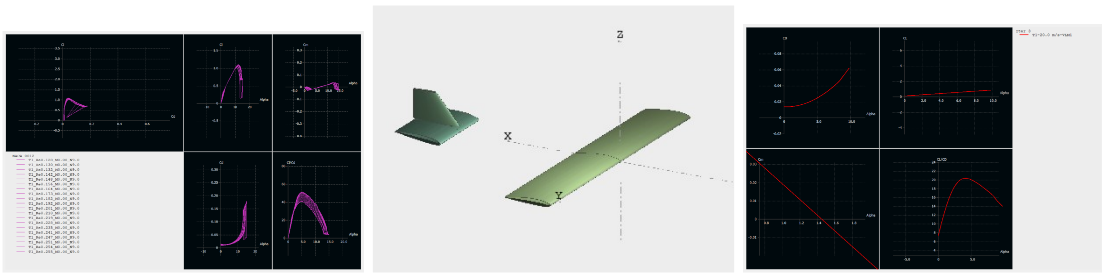
Figure 4: Wing with Horizontal tail

As is visible in the bottom left graph of figure b, the moment counters change in α and will make the plane passively stable. Minor adjustments can be done through control surface designing (elevator).

Tail Design - Phase 4: Vertical Tail

This needn't be too complicated, we don't need to make agile maneuvers. We can choose an airfoil with zero camber so that it passively doesn't add yaw, something like `NACA 0012` airfoil should work.

We run a batch analysis with a range of Reynolds number for `NACA 0012` and end up with the results in figure 5a.



(a) NACA 0012 (b) Final plane (c) XFLR Analysis

Figure 5: Final plane design
NACA 0012 airfoil for the vertical tail. The plane analysis is presented here.

We then attach the vertical tail at $0.7\,m$ X and $0.025\,m$ Z, with `NACA 0012` airfoil and taking chord 0.20 at base and 0.10 at the top (0.120 height). The final plane is visible in figure 5b.

After running analysis on the plane (we do not expect much change from previous phase), we get figure 5c.

Control Surface

The **elevator** and **rudder** are chosen at 35% and 25% of the chord length of horizontal and vertical tail respectively.

Based on historical data, we choose the **aileron** to span 37.5% of the wing, while spanning 25% of the chord.

Conclusion Notes

- We could have chosen a *sweepback* wing planform instead of a *rectangular* one. This will require a detailed batch analysis for the `NACA 2412` airfoil, as well as a more detailed review of the pitch and yaw control (as there will be no need of a tail). This will save a lot of space, but will make the design process more complicated (hence not attempted here).
- The horizontal tail could also be a zero camber one, but with a different tile angle. We went with choosing the same airfoil as the wing.
- Sometimes during analysis, we could gett a `Point out of flight envelop` error (this is because of interpolation issues). Seems like, the best fix is running a detailed batch analysis beforehand [4].

[4] From xflr5.tech/docs/