Conceptual Design of Fixed-Wing UAV

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1 Introduction

Anyone who's tried to design or build a UAV will appreciate this:

> *"Time flies when we try to make things fly."*

The goal of this assignment and the accompanying session is to shorten that learning curve and give you a clear structure for thinking about the conceptual design of fixed-wing UAVs.

A design template is provided with this assignment, and completing the template ensures you've gone through the entire conceptual design process.

Work in small groups of 3–4 if you can — teamwork speeds learning and makes the whole design–build–test loop more fun. Doing it solo is also fine and will give you a deeper understanding.

2 So You Want to Build a Spy Plane?

The plane you are going to design is a classical old problem, a fixed-wing UAV for reconnaissance. It is fundamentally designed to carry a fixed payload, which means that the fuselage is already designed. Your job is to squeeze out the maximum endurance from the aircraft while keeping it easy for a human pilot to handle. For now, don't worry about the budget—let's just assume the college is footing the bill.

The mission profile for this UAV is derived from the classical aero design challenge competitions and is as follows:

1. **Hand launch phase:** You can only launch the UAV from a standing position, using one hand.

2. **Climb segment:** Reach an altitude of 30 meters.

3. **Cruise phase:** This is the main mission. You'll fly a given pattern (see Figure 1). The cruise phase starts once you've reached 30 m, and ends when your battery's state of charge (SOC) drops below 30%—you'll need that reserve energy for a safe landing.

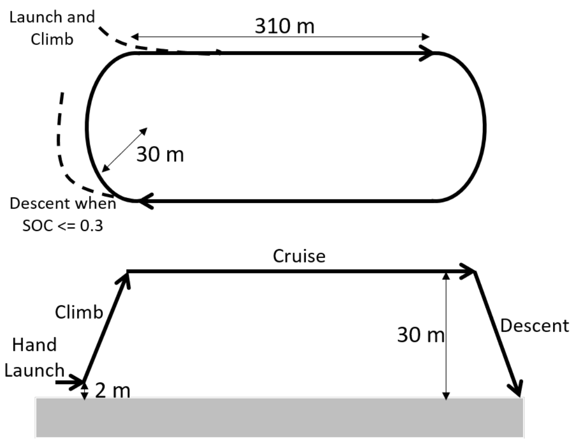

Figure 1: Mission Profile Overview: Cruise Path (top) and Full Mission Phases (bottom)

Parameter	**Value / Notes**
V_{stall}	You decide!
V_{cruise}	You decide! (must be $\geq V_{\text{stall}} + 3$)
Turn radius	30 m
Rate of climb	2 m/s
Rate of descent	2 m/s
End of Cruise	SOC ≤ 0.3

Table 1: Mission Profile Parameters

Important: All three phases—climb, cruise, and descent—will be carried out at the cruise velocity V_{cruise}. While this is not always true in practice, it simplifies the problem to selecting only one velocity of operation.

The scoring function is given as:

$$Score = 70 + 30 \cdot e^{-1.5\,(m-1.25)} - e^{4\,(V_{stall}-9)} - 100 \cdot e^{-\frac{T_{mission}}{500}}$$

In the above equation, m is the total UAV mass in kg, V_{stall} is the stall velocity in m/s, and $T_{mission}$ is the mission time in s. Key points to note in the score equation:

- UAV mass above $1.25kg$ is penalized exponentially, while mass less than that is awarded a bonus.
- Stall velocity more than $9m/s$ is penalized exponentially.
- Mission time is scored exponentially with a saturation.

Generally, missions lasting more than a couple of minutes are always executed with the help of a flight computer (most often Pixhawk). However, the hand launch phase (and even the ground takeoff roll) is very sensitive and always executed by the pilot. To ensure that the pilot can control the UAV, it is very important to keep the stall velocity V_{stall} as low as possible. Another requirement for manual control is maintaining an adequate static stability margin between 15–25% (more on this later).

The first step in designing a UAV (or a plane in general) is always deciding its purpose. This directly translates to the fuselage design, which conventionally houses the payload. For this problem, the fuselage is provided (see Figure (2)). The only flexibility you have is the boom length used to connect the empennage. You are free to choose any configuration of the empennage (T-tail, V-tail, etc.).

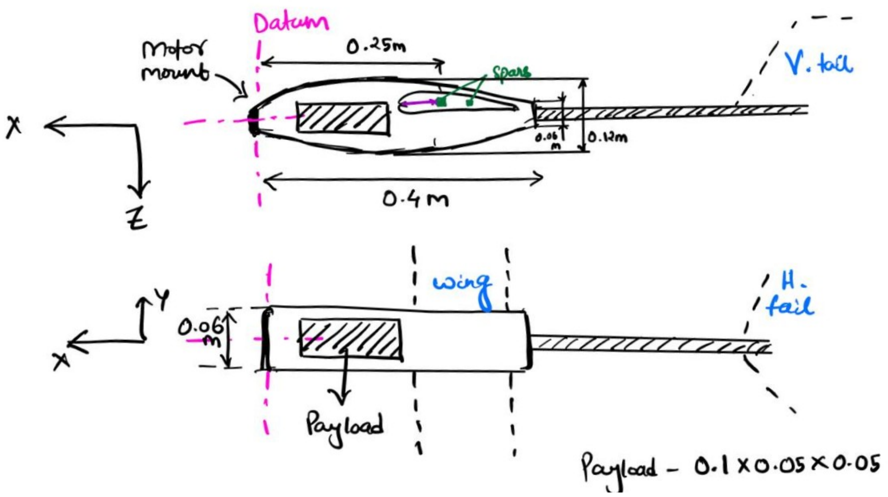

Figure 2: Fuselage sketch (not to scale)

When it comes to material selection, we restrict fabrication to PLA and 3D printing methods. From the commercial off-the-shelf (COTS) components, we have shortlisted a set of motor, battery, and propeller combinations (see Table 2). You must select one combination for your design. The rest of the electronics have been chosen for you.

That's about what you will be doing. Now, let's get into a rough highlight of how you can do it!

Note: All values are mentioned in SI units. Values for certain constants to be used on your calculations: $g = 9.81 m/s^2$, $\rho = 1.225 kg/m^3$, $\mu = 1.82 \times 10^{-5} Pa \cdot s$.

3 Guidelines and Resources

Designing a UAV is obviously a multidisciplinary challenge. Every time you look at the aircraft from the perspective of a different subsystem — whether it's propulsion, structures, aerodynamics, or avionics — you might end up with a different plane! (Check out Ideal Aircraft for a fun example.)

That's why it's super important to set clear boundaries: which decisions can be made individually by a subsystem, and which need to be made collectively, considering the UAV as a complete system. It's also important to understand the hierarchy of decision-making, so you know which choices influence others and which are constrained by prior decisions.

The guidelines and resources in this section will help you navigate the design process, understand the choices you can make at each step, and ensure that all the subsystems come together into a working UAV.

3.1 Big Picture: How We Start

The very first step in the conceptual design of your UAV is deciding on the configuration. In this challenge, most of the configuration is fixed for you (the fuselage is already designed), so your main freedom lies in the **empennage choice** — conventional, T-tail, V-tail, and so on.

Once that's settled, the next big task is **sizing**. Put simply, sizing means figuring out two key numbers:

1. The overall weight of the plane
2. The planform area of the wing

Now here's the catch: aircraft design is always an **iterative process**. That means you don't get everything right in one shot — you make an educated guess, evaluate it, and refine it.

So we start with an initial assumption about weight and wing area. Where do those assumptions come from? Usually from looking at similar aircraft, or by using reference values like *wing loading* or *wing cubic loading*. With those assumptions, you can sketch out a conceptual design.

Then comes the check: does the estimated weight converge with your assumptions? Do the performance numbers meet the requirements? What's the score?

If everything lines up — congratulations, you've got a viable design! If not (which is very normal), it's time to tweak your decision variables — maybe adjust the wing area, change the tail, or rethink the layout — and then re-run the process.

Think of it like a loop:

$$\text{Guess} \rightarrow \text{Design} \rightarrow \text{Evaluate} \rightarrow \text{Adjust} \rightarrow \text{Repeat}$$

That's how you inch closer to the best possible concept

3.2 Aerodynamics – Making It Fly

Aerodynamics plays a central role in shaping how the aircraft actually flies. Your responsibilities cover several key tasks: choosing the airfoil, defining the wing and tail geometry, checking stability, and estimating both stall and drag. In short, you're making sure the aircraft can **fly safely, efficiently, and predictably**.

1. **Airfoil Selection**: For this challenge, the choice is limited to the NACA 4-digit series. The empennage (horizontal and vertical tails) is further restricted to symmetric NACA airfoils (00xx series). To get lift and drag polars, you can either use XFLR5 or access them from airfoiltools.com. *Don't forget*: the Reynolds number (Re) must be calculated based on velocity and a characteristic length (e.g. chord for airfoils, mean aerodynamic chord (MAC) for wings, fuselage length, etc.).

2. **Wing Sizing**: Here you decide on the wing and tail geometry — parameters like wing area, span, aspect ratio, and taper ratio. There are no strict limits on wingspan, so you have freedom to explore different configurations. Your choices should be based on fundamental principles of conceptual design and configuration trade-offs.

3. **Drag Estimation**: Finally, you'll estimate drag across different phases of flight. This step is critical, since the propulsion calculations depends on your results to size the powertrain and estimate power requirements. Lee Nicolai's White Paper provides an empirical method, with further references for more detailed approaches.

4. **Static Stability**: Every aircraft needs to be stable in flight, and that's where the tail comes in. A straightforward way to size it is by using the tail volume coefficient method. For conventional UAVs, typical values are around V_H=0.45–0.55 for the horizontal tail and V_V=0.035 for the vertical tail.

   Of course, checking stability is an iterative process. Using these typical values should get you pretty close, and with a few iterations you'll be able to converge on a good design. The key steps are to calculate the neutral point and then choose a center of gravity (CG) location that provides a suitable stability margin.

   A good reference for this process is Anderson's Flight Mechanics textbook, though XFLR5 can also be used to run the analysis. (note that we are restricting ourselves to static longitudinal stability only).

5. **Stall Velocity**: The stall velocity (and equivalently $C_{L_{max}}$) must be determined for your airfoil and wing design. Keep in mind: 2D lift curves from airfoil data need to be corrected for 3D finite wing effects. A solid reference for this process is again Lee Nicolai's White Paper.

3.3 Propulsion – Powering Your Spy Plane

In propulsion, your job is to select a powertrain (motor, propeller, battery) combination. For simplification, we are restricting your choices to a set of 3 motors, propellers, and batteries. The specifics are mentioned in Table (2).

Component	**Data**	**Mass[g]**
Motor (Tmotor)		
AT2317 880KV	(Link)	79
AT2312 1250KV	(Link)	60
AT2308 1450KV	(Link)	47
Propeller (APC)		
APC Thin Electric 8x6	-	15
APC Thin Electric 9x6	-	19
APC Thin Electric 10x4.7	-	24
Battery (Genxpower)		
Genx 3S1P 3300mAh 40C	(Link)	285
Genx 3S1P 5200mAh 40C	(Link)	420
Genx 4S1P 3300mAh 40C	(Link)	380

Table 2: Available Powertrain Components

You can refer to Gabriel Staples equation to calculate the dynamic thrust curve. Your goal is to find the power required by the propulsion system during various flight phases. Here is how you can do it:

- For each phase, you must calculate the dynamic thrust (thrust at the particular cruise velocity) to satisfy steady level flight conditions. The RPM should be varied for the chosen propeller so that you achieve the desired dynamic thrust.
- You then take the static thrust for that thrust curve and interpolate the power drawn by the motor using the specification datasheet provided in the website (refer to the vendor links in Table (2) for your chosen motor).
- Repeat this for all the flight phases. The power values you give will be used in the endurance estimation in performance calculations later.

Remember, your powertrain choice significantly affects the final endurance of your airplane and thus your score! Pick wisely.

3.4 Structures – Keeping It All Together

In real aerospace projects, structures are one of the most safety-critical systems. That's why companies often have more structural analysts than concept designers — keeping things from breaking is serious business!

But since we're only working at the conceptual design level here, we won't dive into finite element analysis or stress plots. For us, structures mainly show up in two key ways:

- Weight

- CG balance

Estimating the airframe weight is actually pretty straightforward. You can use the density of PLA along with the infill parameters (see Table (3) to get a good estimate. This estimated weight is then compared against the weight assumptions you made at the start of the design. If your estimated weight matches up reasonably well with the sum of all component weights, great — that means your initial assumptions about size (which come from weight and planform area) were on track. You can use the below equations to estimate the boom, wing and tailplane masses respectively.

$$m_{boom} = \rho_{CF} \cdot l_{boom}$$

$$m_{wing} = \rho_{PLA} \cdot (t_{skin} \cdot S_{wet,wing} + 8\% \cdot V_{wing})$$

$$m_{TP} = \rho_{PLA} \cdot (t_{skin,TP} \cdot S_{wet,TP} + 8\% \cdot V_{TP})$$

The tailplane mass equation is applicable for the horizontal and vertical tails (apply it separately for each case). The Table (3) below lists the parameters of above equations.

Variable	**Parameter**	**Value**
ρ_{CF}	linear density of ϕ 18mm carbon fiber rod	0.085kg/m
l_{boom}	boom length	your value
ρ_{PLA}	density of PLA	1260kg/m^3
t_{skin}	wing skin thickness	0.0004m
$S_{wet,wing}$ and $S_{wet,TP}$	wetted wing and tailplane area	your values
V_{wing} and V_{TP}	wing and tailplane internal volume	your values
$t_{skin,TP}$	tail-plane (HT and VT) skin thickness	0.0004m

Table 3: Mass equation parameters

Component	**Mass (kg)**	**X Distance from Datum (m)**
Motor	x	0.02
Electronic Speed Controller (ESC)	0.04	-0.03
CG of Payload	0.3	x
Actuator 1, 2 (for ailerons)	0.02	-0.3
Actuator 3, 4 (elevator and rudder)	0.02	-0.35
Radio Rx	0.03	-0.37
Fuselage Shell	0.35	-0.2

Table 4: Fixed component mass and X distance from Datum

Next comes the classic airplane puzzle: where to put everything. You'll need to shuffle the components inside the fuselage so that the final CG ends up where the stability requirements demand. If the numbers don't converge — meaning the weights don't add up, or the CG is off target — then it's back to the drawing board. In that case, you'll need to rethink either your initial sizing assumptions or your chosen configuration.

Important note: Table (4) shows the mass and relative CG positions of some components from the datum, but it's not the full story. To calculate the overall CG, you'll also need to include the battery, wing, tail boom, and empennage. We've fixed the quarter-chord location of the wing, and you can assume a linear taper for the fuselage from the maximum thickness to the tail end. This is especially helpful when deciding where to place the payload and battery, so everything balances nicely.

3.5 Performance – Can It Actually Fly the Mission?

Once you've got a design in mind, the next big question is: **can this plane actually fly the mission profile?** That's what performance estimation is all about.

By this point, you already have a plane and know its stall velocity. You also get to make one more decision based on your understanding of flight mechanics: selecting the cruise velocity, V_{cruise} . Just remember, it must be at least 3 m/s greater than the stall velocity to ensure safe and controllable flight

The main task now is simulating the mission. In simple terms, that means checking whether the electrical energy required to fly the mission is less than the energy stored in the battery.

Here's the basic math:

- Energy available in the battery (Joules):

$$E_{\text{battery}} = V_{\text{avg}} \times \text{Capacity (Ah)} \times 3600$$

- Energy consumed in a phase:

$$E_{\text{phase}} = P_{\text{battery}} \times t_{\text{phase}}$$

Add up the energy consumed across all the mission phases, and then compare it with the battery's available energy.

A small but important detail: the calculation above assumes that each phase of the mission is in *static equilibrium*. In other words, we treat the mission as a series of quasi-steady phases and ignore the dynamics. This works perfectly fine for most phases like climb, cruise, and descent.

But not for hand launch. That one's messy because the aircraft is accelerating, so technically you'd have to model it as a dynamic system. For now, we'll keep life simple and just ignore it — though in practice, hand launch is often the most restrictive part of the whole mission!

Now, here's another twist: in our problem, the mission profile doesn't fully define the cruise duration. Cruise ends only when the SOC drops to 30%.

To figure that out:

1. Divide the total energy and the consumed energy by the average battery voltage. This converts them into charge.

2. Use the difference between available and consumed charge, and normalize it with the total available charge, to find the SOC.

3. Adjust the cruise time until SOC hits exactly 0.3.

And that's it — performance estimation basically boils down to solving for the cruise time that brings the SOC down to 30%.

4 Conclusion

Congrats if you've made it this far — and double congrats if you were able to complete the design template! You probably tackled this either entirely with manual calculations or maybe with a bit of coding.

If you used coding, that's fantastic! In the upcoming session, we'll explore how to execute the entire conceptual design process using very basic coding, which will give you superpowers to quickly assess and compare a vast number of design concepts.