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Project: Development of a Tilt-rotor VTOL UAV

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Abstract

This report is to identify the key aspects in developing a Tilt rotor VTOL UAV. Eventually building a fully flyable and autonomous UAV.

Initially, i will begin with a background and literature review into the fundamentals of quadcopter and airplane flight.

Development of the UAV will begin with determining the airframe dimensions and proportions. Using dimensional values similar to known airframe of similar flight characteristics can ensure that the UAV will inherit good fight performance.

Once dimensions are worked out CAD modelling can start. The CAD model must be designed to fit within the design specification requirements of this craft, these including the need to be as light as possible to be able to generate large quantities of lift during flight.

CFD analysis on the model can be done on completion of the final CAD of the UAV, without needing access to a wind tunnel, a simulation can be performed on the airflow around the UAV. The analysis will show how streamlined and aerodynamic the aircraft is. Any issues discovered on the UAV leading to poor aerodynamics can be refined and optimised through CAD and re-simulated through CFD.

Fabrication of the craft will begin by using 3D printed components, carbon fibre tubing and light weight model aircraft film for the wings. The 3D printed parts are designed as structural components for the UAV but will also accommodate the electronics, specific placement of the electronics is important as it will affect the centre of gravity.

Prior to the UAV's maiden flight, a series of setup and configuration to both the hardware and software is required. Making sure all hardware is properly connected within the UAV, software configuration of the UAV's flight controller will setup the craft to be able to receive input control and output control to actuators, motors or any component. Autonomous flight is possible through the use of GPS.

Initial flights will determine the true lift capability and flight efficiency of the UAV.

Once satisfactory flight characteristics are obtained through flight tests, analysis of blackbox data, and tuning of the UAV software configuration, flight durations of a predetermined flight path with various payloads weights can be recorded to find what is the maximum weight that can be carried for the longest amount of time.

Key Words: UAV, tilt-rotor, quadcopter, airplane, stress analysis, configuration, 3D printing, carbon fibre, foam, CAD, autonomous, flight efficiency.

Acknowledgement

As the author of this report I would like to thank Dr Yahya Zweiri for his vast knowledge in UAV and mechatronic systems, his expertise was extremely helpful throughout the duration of this project.

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Chapter 1 Introduction

Background

UAVs, otherwise known as Unmanned Aerial Vehicles, are machines that can fly without needing navigational inputs of an on-board pilot. Flight is achieved either autonomously by using on-board microprocessors to read sensor signal inputs and control actuator outputs, or through piloted remotely by a human operator. UAVs remove the need to carry a pilot and so are able to smaller and much more cost effective than conventional manned aircraft.

Due to UAVs unique and advanced capabilities, their usage is wide spread in fields such as; military, reconnaissance, natural disasters, monitoring environments, and agriculture.

Most UAVs fall into one of two categories, fixed wing planes or multi-rotors. Fixed wing UAV planes are advantageous in applications concerning a need for constant forward flight or carrying heavy payloads, where as multi-rotor UAVs are beneficial for more precise flight movements in X, Y and Z axises, as well as hovering abilities.

Multi-rotors are the most commonly used type of UAV due to ability to move in any axis, however, powering multiple motors for sustained flight is extremely power intensive meaning flight times for small to mid size multi-rotor UAVs range from 5 to 45 minutes **[1]**, this is because of a high rate of discharge on the batteries, compared to fixed wing UAV which are capable to sustain flight for much longer durations, achieved by creating lift under their wings.

A Tilt rotor UAV is a fixed wing plane that utilises propulsion systems normal to the Z-axis of each wing tip to perform vertical take-off much like a multi-rotor. VTOL is very useful in situations where little to no runway is able to be used. Once at altitude the UAV will transition to forward flight by tilting its motors and thus propulsion normal to the Y-axis of the aircraft. Once in forward flight the aircraft can use lift generated by the wing, in turn reducing the need for power output to propulsion systems and reducing the discharge rate on the battery. From this, longer flight times are possible whilst also having vertical take off capability.

Aim

For this project I am interested in prototyping and manufacturing a flyable autonomous UAV. My aim is to develop a tilt rotor UAV to demonstrate vertical lift off, autonomous flight, and enhanced flight duration. Advancements in these technologies will yield more efficient UAVs.

Objectives

- Design and development of a lightweight aircraft.
- CAD modelling for use of CFD simulations.
- Use additive manufacturing, 3D printing, for rapid prototyping and fabrication of required components.
- Identify an airfoil profile that will provide sufficient lift and gliding at low air speeds.
- Configure PixHawk flight controller to control servo actuators, motor operation, tilt rotor features and autonomous flight through GPS.
- Refinement and tuning of UAV flight characteristics.

Classification of Unmanned Aerial Systems

- Very small UAVs
- Small UAVs
- Medium UAVs
- Large UAVs

Due to advancements in technology it is difficult to only classify UAVs according to size as smaller and light-weight UAV can have as much of a tactical advantage as larger UAVs. Instead, UAVs can be categorised by their deployment range and flight endurance **[2].** This UAVs discussed here are most military used, privately made UAVs may not follow the same classification.

- Low cost close-range UAVs

These appear very similar to model airplanes as being small and light weight is what is required. UAVs of this class are for use in non tactical situations as they are limited to an approximate range of 5 km, and a flight endurance of about 20 to 45 minutes. This does make them ideal for close range reconnaissance missions. It is a low cost UAV for the military, priced at $10,000 (2012 estimate). Examples of UAVs in this class are the Raven and Dragon Eye.

Figure X: Raven UAV
https://

- Close-range UAVs

Similar to UAVs such as the Raven or Dragon eye, these UAVs are small in size. However, they are not constrained to being low cost, as such, this class is capable of extended flight endurance time of 1 to 6 hours and a range of 50km. Also used for reconnaissance and surveillance tasks, but in situations where longer flight must be sustained.

- Short-range UAVs

Short range UAVs are classed to have a minimum usable range of 150 km, along with endurance times of up to 8 to 12 hours. Again these UAVs are used for reconnaissance and surveillance purposes but with requirements to travel further distances.

- Mid-range UAVs

The mid-range UAVs are capable of very high speeds. Due to their speed they are able to travel for long distances of up to 650 km. This is traded with a compromise on endurance.

- Endurance UAVs

This class makes up for the lack of endurance on mid-range UAVs. They can display an average flight endurance of 36 hours but a reduced radius 300 km. The UAV can be operated at extreme altitudes of 30,000 feet, higher than most other classed. Because of this fact they are commonly used for reconnaissance, surveillance, and meteorological purposes.

According to the U.S. Department of Defense, there are 5 categories of UAVs, as shown in Table 1:

Table 1: UAVs Classification according to the US Department of Defense (DoD)

Category	Size	Maximum Gross Takeoff Weight (MGTW) (lbs)	Normal Operating Altitude (ft)	Airspeed (knots)
Group 1	Small	0-20	<1,200 AGL*	<100
Group 2	Medium	21-55	<3,500	<250
Group 3	Large	<1320	<18,000 MSL**	<250
Group 4	Larger	>1320	<18,000 MSL	Any airspeed
Group 5	Largest	>1320	>18,000	Any airspeed

*AGL = Above Ground Level
**MSL = Mean Sea Level
Note: If the UAS has even one characteristic of the next level, it is classified in that level.
Source: "Eyes of the Army" U.S. Army Roadmap for UAS 2010-2035

Classification According to Size

Very small UAVs

The very small UAV class applies to UAVs with dimensions ranging from 1-50 cm long.
UAVs of this size use mechanisms for flight similar to that found in insect. The most popular means of propulsion are flapping or rotary wings.
Due to their small size and weight, they are hard to notice. Hence why application for this UAV can range from spying to biological warfare.
Depending on how manoeuvrable the UAV need to be will depend on whether it uses flapping or rotary wings
Flapping wing-based designs can provide more precise movement allowing the UAV to land on small surfaces.

Examples of very small UAVs;

- Israeli IAI Malat Mosquito (35 cm wing span. 40 minutes flight endurance).
- US Aurora Flight Sciences Skate (60 cm wing span, 33 cm length).
- Australian Cyber Technology CyberQuad Mini (42x42 cm square).

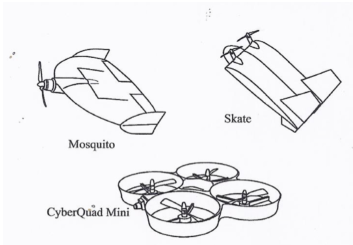


Figure 1.1: Examples of very small UAVs

Small UAVs


Figure 1.3: A US army RQ-7 Shadow
Source: Olive-Drab

A small UAV is categorised by having any one of it dimensions within the range of 50cm and 2m.
Due to their increased size, this class of UAV using fixed wings unlike the very small UAVs. Fixed wings are necessary as they will be able to provide the lift needed to allow flight. These UAVs are still small enough to be hand launched, removing the need for a runway for take off.

Examples of small UAVs;

•RQ-11 Raven, by US Aero Vironment (wingspan of 1.4 m and length of 1m).
•US Army RQ-7 Shadow

Medium UAVs

Medium UAVs are too heavy to be carried and thrown as their size class makes them just smaller than conventional light aircraft. Wing spans for this class can range from 5-10 m, generating enough lift to carry payloads from 100 to 200 kg. Payload can range from cargo, to sensory equipment, and even small weaponry.

Newer examples medium UAV are;
- Israeli-US Hunter and the UK Watchkeeper.

For reference, the Hunter UAV has a wingspan of 10.2 m with a length of 6.9 m.

Medium UAV used in the past include;

- US Boeing Eagle Eye
- RQ-2 Pioneer
- BAE systems Skyeye R4E
- RQ-5A Hunter.

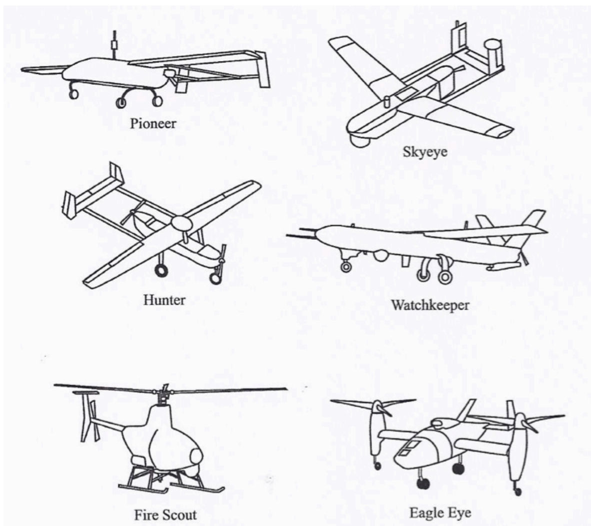


Figure: 1.6 Examples of medium UAVs
Source: Paul Fahlstrom and Thomas Gleason, 2012, Introduction to UAV Systems, 4th edition, Wiley

Large UAVs

Any UAV with a dimension larger than 10m is classed as a large UAV.
This class is most commonly used by the military as a means of reconnaissance as well as within offensive missions, their large size makes them capable of holding large payload and so weapon systems can be installed.

Large UAV examples include;

- US General Atomics Predator A and B
- US Northrop Grumman Global Hawk

Figure 1.8: NASA's Global Hawk
Source: NASA

Multi Rotor Fundamentals

Frame Types

These are the 3 main types of multi rotor configurations. Each name referring to the number of arms that the multi rotor uses. Adding more arms and subsequently more motors to the craft, additional redundancy is gained.

For example, with a Hexacopter you can lose signal to up to 2 of the 6 motors before flight performance is significantly negatively affected.

Quad-copters have a number of different frame configurations. The most common types are shown in the illustration below. Quad X configuration is a popular choice as most of the weight is centralised giving a centre of gravity that lies in the middle of the craft. Having a centralised c.o.g ensures good flight characteristics in all axis', as opposed to an off centre c.o.g which will yield off balance movements in the axis'. [3]

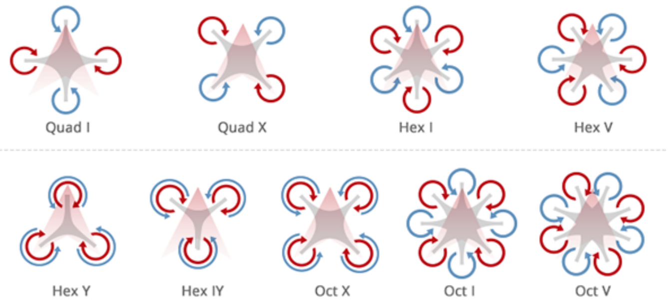
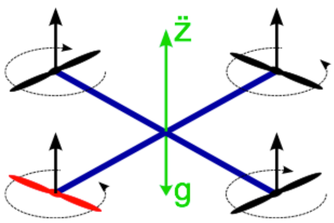


Figure X: Multi Rotor Frame Types



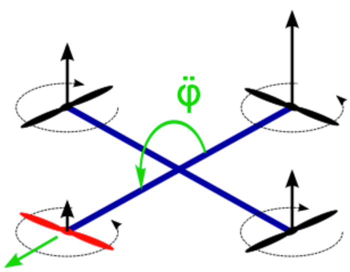
(a) Upward movement

Altitude

All motors spin simultaneously at the same rotational speed.
Varying the throttle output to the motors will affect lift to weight ratio.

The craft will ascend if thrust is more than the weight of the craft and descend if less.

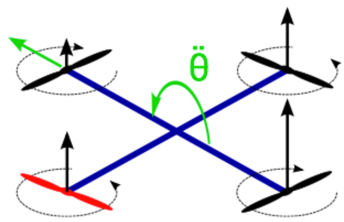
Pitching, and Rolling



(b) Pitch and lateral movement

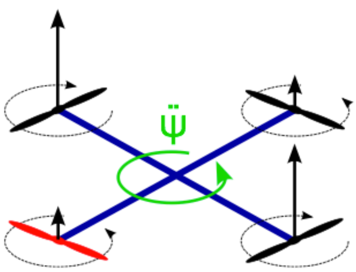
Only two motors spin simultaneously at the same rotational speed.

Varying the pitch or roll output will cause the other two motors to proportionally and inversely change their rpm. As shown in the figure, 2 motors spin the same, whist one increases its rpm and the other decreases.



(c) Roll and lateral movement

The craft will pitch up or down around the axis between the two 'simultaneous' motors.



(d) Yaw and rotational movement

Yawing

Two sets of two motors spin simultaneously at the same rotational speed. One set of motor are at a high rpm whilst the other set is at a lower rpm.

Yaw is achieved by using the common rotation direction of a motor, a resultant force is tangential to the direction of spin of the motor and by Newtons 3rd law, an equal and opposite force is generated around the mid-origin of the multi rotor. This force allows the craft to yaw clockwise or anticlockwise.

Typical Electronic Wiring for a Quadcopter

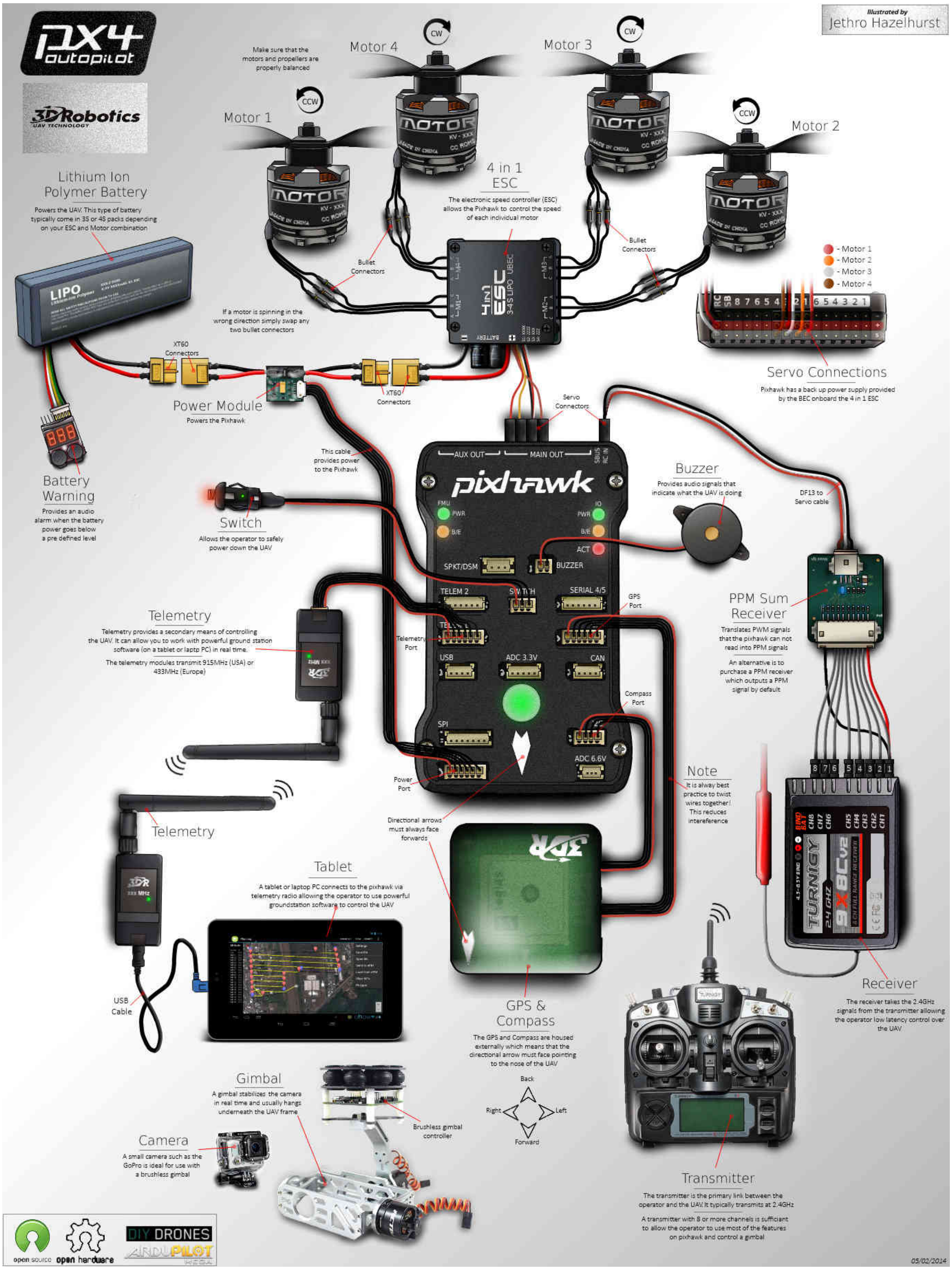


Figure X: Quadcopter Pixhawk Wiring

<u>**Airplane Fundamentals**</u>

Unlike a multi rotor, an airplane uses it propulsion system mostly for forward thrust and manipulates the airflow around the craft through control surfaces in order to pitch, bank, and yaw. The most integral control surfaces are elevators and rudders on the tail and ailerons on the wings.

Deflecting a control surface up will reduce the amount of lift generated on that wing or tail, vice versa, moving a control surface downwards would increase the amount of lift generated **[4]**.

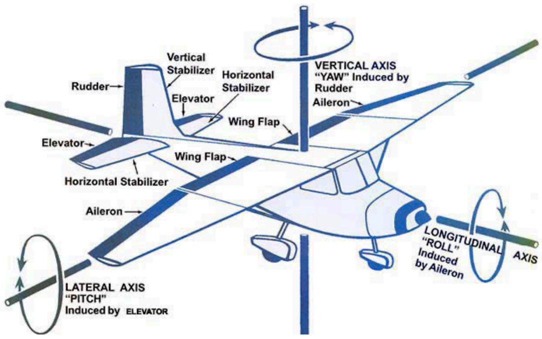


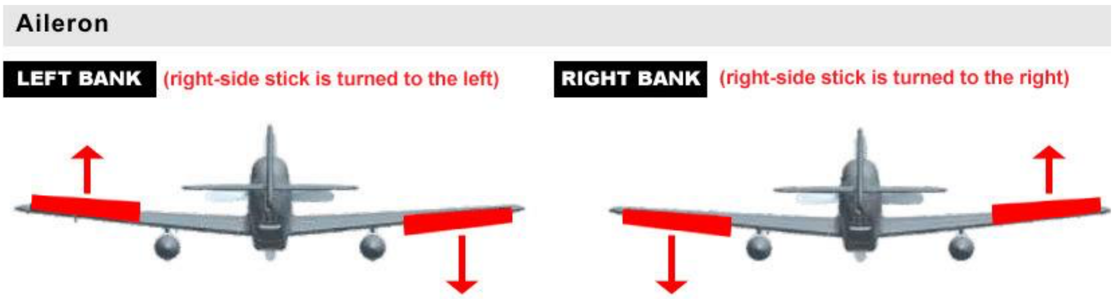
Figure X: Airplane Axis' and control surfaces
https://iacvirar.com/wp/wp-content/

Pitching

As the elevator is turned upwards, lift is created on the top side, pushing downwards on the tail causing a 'pitch up' rotation around the c.g of the aircraft

Rolling

Ailerons bank the aircraft by tilting in opposing directions, lift pushes up on one wing and down on the other.



Yawing

A rudder will yaw the aircraft just as how the elevators allow pitch, by rotating the craft around its c.g.

Figure X.1, X.2, X.3: Stick movements and control surfaces
https://cdn.shopify.com/s/files/1/1052/4162/files/stick-control-diagram_1024x1024.jpg?v=1477417882

<u>**Typical Electronic Wiring for an Airplane**</u>

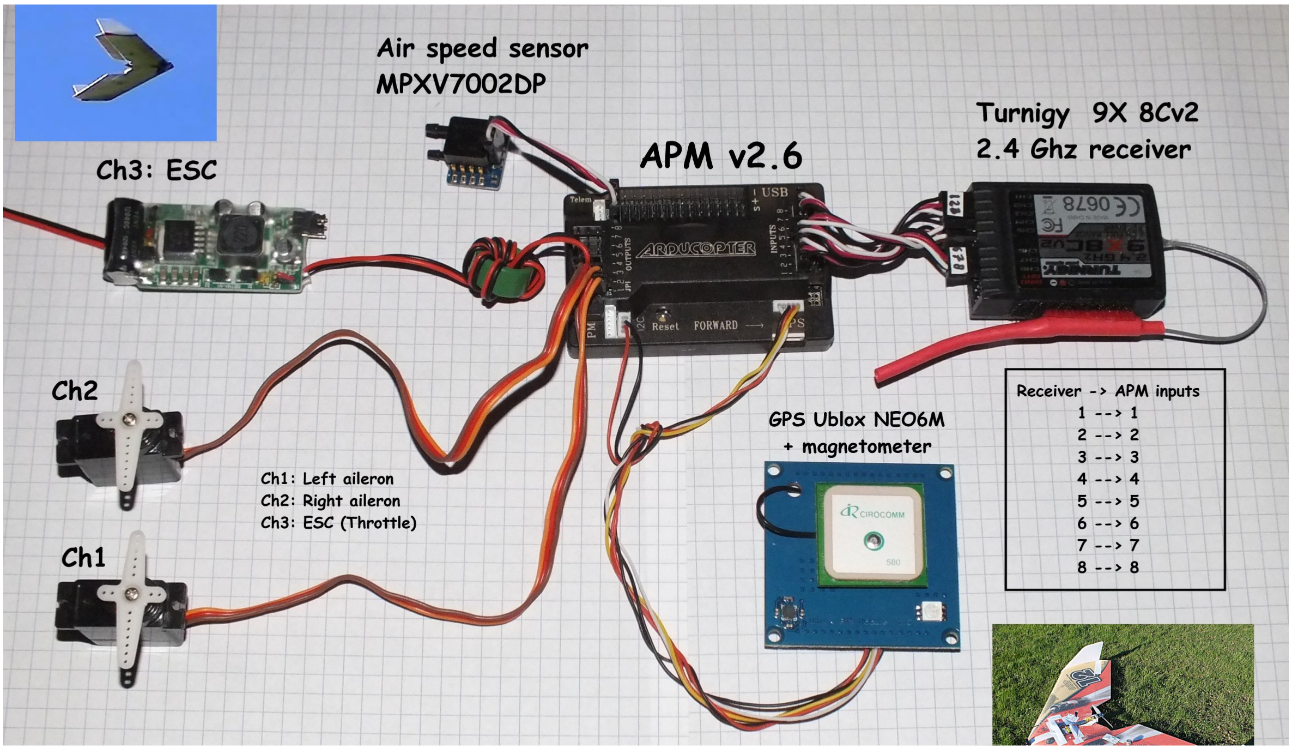


Figure X: Wiring for RC Plane
https://raw.github.com/jlnaudin/x-drone/master/MaxiSwift/APMv26MaxiSwift.jpg?width=750

VTOL Fundamentals

Figure X: V-22 Osprey https://

VTOL stands for Vertical Take-Off and Landing. Aircraft that utilise VTOL, such as the V-22 Osprey, have flight characteristics of both Planes for forward flight, and helicopters / multi rotors for vertical flight.

VTOL requires the use of actuators to tilt the motors from a vertical position, for take-off, to a horizontal position, for forward flight.

VTOL has many benefits as well as drawbacks. Most importantly, aircraft with VTOL capabilities are able to perform lift-off without a run-way as lift doesn't need to be generated from the wings during vertical flight. In this regard, this ability is invaluable for military situations where airports aren't available yet large cargo still needs transportation. The drawback is that a lot of energy and fuel is used during vertical flight as lift is solely generated by propeller thrust, not from the wings. This puts a limitation on the weight of the craft, as the craft must be light enough so that the lift-to-weight ratio is sufficient enough to perform VTOL manoeuvres but must still be carrying enough fuel or cargo onboard to make the aircraft justifiable for its mission and purpose. **[5]**

Transitioning during VTOL flight is an important procedure. A fast transition of tilting the motors from a vertical position to horizontal could be catastrophic as the aircraft can nose-dive and lose altitude momentarily, this is due to the fact that the aircraft wings will require some amount of horizontal movement through the air to generate lift.

Therefore it is suggested that the VTOL transition is split into 3 main angles of attack for the motors.
Vertical flight will use a 90 degree upward tilt to generate vertical acceleration but no horizontal acceleration.
The transition phase will use 45 degree AoA as this will provide the aircraft with equal vertical and horizontal acceleration, during this transition phase the wings will begin to generate lift as the velocity of airflow increases.
Once the wings are able to achieve the minimum lift required to hold the aircraft altitude, the motors are finally tilted to their horizontal position of 0 degree. From this point on, the wings are generating vertical lift whereas the motors are providing horizontal thrust.

The same must be done in reverse when performing a vertical landing. The transition phase's 45 degree tilt will reduce the aircraft's velocity horizontally resulting in less overshoot past the designated landing site. Thrust will also be vectored downwards resulting in increased stability vertically.

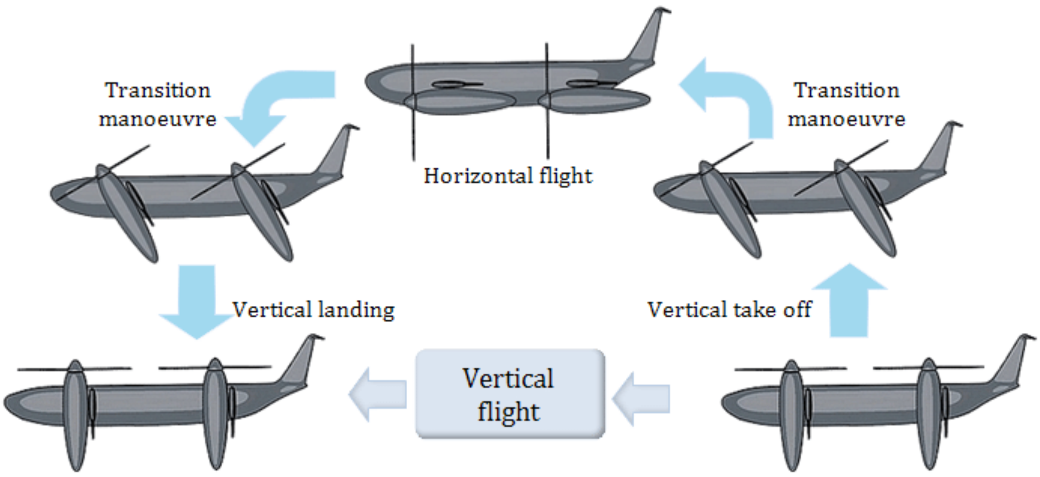


Figure X: VTOL Flight Transitions

Common RC Components

- **Flight controller (FC)**

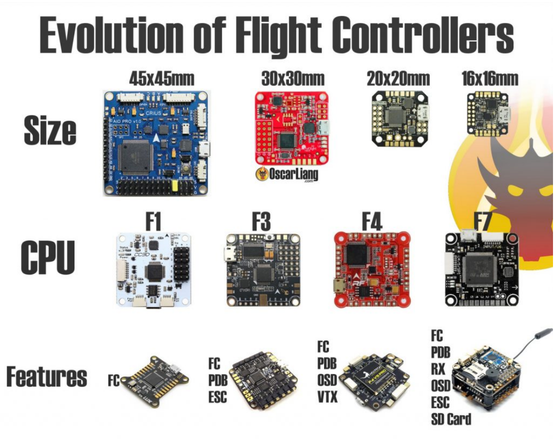


Figure X: Types of Flight Controllers

The flight controller is the main microprocessor on the craft that is able to control the quadcopter. Using sensors, actuators (motors, servos), and PID loops and code, the flight controller can take input controls from either a human operator through a receiver or input from onboard software and make flight possible. [6]

Many quad-copters use an onboard gyro and accelerometer to determine the crafts angular position with respect to X,Y and Z axis, using a PID loop the FC can determine a suitable RPM for each individual motor so that the craft can sustain a stable hover in a dynamic environment.

Additional peripheral sensors can be connected to ports on the FC. To better aid with autonomous flight performance, sensors such as GPS, Sonar, Barometers and Magnetometers, can be connected and configured for use by the FC.

As shown in the illustration, FCs come in many options to accommodate different areas of usage. The CPU is where all sensor inputs are quantified and calculations for outputs occur.

Faster CPUs like an F4 or F7 are required in racing drones where there is a necessity for very fast input and output control. Conventional quadcopters can benefit from cheaper F1 and F3 FCs as data doesn't need to be computed as quickly, investing in more features instead will allow use of more features.

- **Electronic Speed Controller (ESC)**

ESCs connect the FC to the brushless motors, ESCs will carry the output signals from the FC to the motors but will also provide the necessary voltage and amperage to the motors from the battery. The ESCs will take DC from the battery and convert it into an AC that can be used to spin the motor.

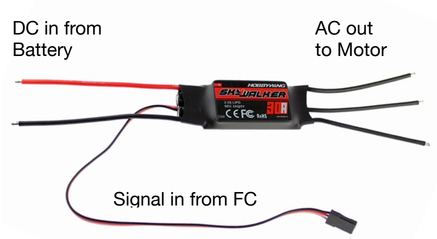


Figure X: ESC
https://www.google.com/url?

- **Power Distribution Board (PDB)**

This is a small basic component that will take raw voltage directly from the batteries and convert that power to any format required by other components. For example, the flight controller must only be supplied with 5volts where as the ESCs require 12volts or full battery voltage. Any major component that requires power is usually supplied through the PDB.

- **Radio Transmitter and Reciever (RX/TX)**

A transmitter is used by a pilot to wirelessly control a craft through radio signals. Using radio signals that match the frequency of a receiver, the transmitter is able to wirelessly transmit signal commands to the vehicle/craft. These commands are sent over channels. Throttle, Yaw, Pitch, and Roll are the four main channels used to control a quadcopter.

Figure X: Transmitter
https://www.getfpv.com/

Figure X: Receiver

The radio receiver is connected to the flight controller of the RC craft. It will receive incoming signals from the transmitter, interpreting each channel, and passing the command to the FC where output signals are then sent to servos, motors, or any other device.

• **Battery**

Figure X: LiPO Battery
https://www.hobbyrc.co.uk/

Lithium Polymer batteries are the most popular option when it comes to developing robotic or RC vehicles. Especially in RC projects, these batteries are favourable due to their ability for high energy density and high discharge rates.

Each cell of a LiPO battery holds a nominal storage voltage of 3.7v. To create more powerful battery packs, multiple cells can be connected in series. The number of cells within a pack is denoted by the amount and followed by ’S’. For example, a 14.8 volt battery is made up of 4 3.7v cells and so is called a ‘4S LiPO battery’. Battery voltage is important as it determines the RPM of a brushless motor (RPM = motor Kv * Voltage). [7]

Apart from voltage, battery capacity can be measured in milliamp hours. It describe how much current the battery can supply per unit of time. A battery with a capacity of 1500 mAh or 1.5Ah will be able to output a current of 1.5A for 1 hour, or 3A for 30 minutes, or 6A for 15 minutes, etc. Batteries with higher capacities are able to provide higher amperage for longer lengths of time, essentially increasing the flight time, however bigger batteries come at the expense of being heavier and negatively affecting flight performance.

• **Motors**

Brushless DC motors are able to rotate by supplying a current to the windings in the stator, which generates an electromagnetic field. Permanent magnets within the rotor are attracted/repelled by this electromagnetic field causing rotation of the rotor shaft around the stator.

As the shaft turns, inertial energy from the rotation places the next set of magnets along the windings electromagnetic field where the magnets are once again attracted/repelled. This occurs repeatedly whenever a current is applied to the motor, allowing continuous rotation. [8]

The constant velocity of a motor is referred to by its “Kv”. It is measured by the rpm of that motor when 1V is applied with no load.
For example, a 1500Kv motor powered by an 11.1V 3S battery would spin at 16,650 rpm (1500 x 11.1). [9]

A low Kv motor uses thinner wire but has more winds, meaning it can provide high voltage at low amps, more torque, and turn a larger propeller. On the other hand, a high Kv motor uses thicker wire but fewer winds, that yield high amps at low voltage and can rotate a smaller prop at high RPM.

• **Propellers**

Propellers can mostly be categorised by their diameter and pitch. Diameter being the circular area and the pitch refers to the length of the propeller’s twist section. Propellers generate thrust much like how wings generate lift, each blade has an airfoil profile. Using rotational motion, a propeller will move through air or any other fluid. How aggressively it can pull/push the fluid is determined by the pitch of each blade. Pitch is what creates the Angle of Attack for each blade. [10]

Large diameter propellers generate more thrust but at the expense of requiring more torque from the motor. Propellers with high pitch values are able to move through the fluid rapidly.

Pitch can be thought of as a corkscrew where the propeller with a high pitch will be able to travel the same distance as a lower pitch prop but in less rotations, hence if both propellers of different pitch spun at the same RPM, the higher pitch can travel further in the same amount of time.**[11]**

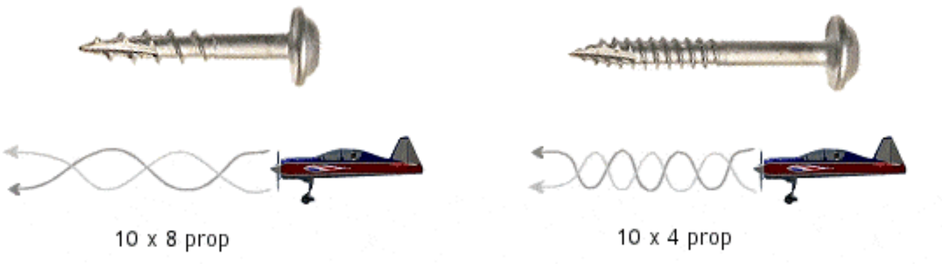


Figure X: Propeller Pitch
https://www.droneomega.com/quadcopter-propeller/

For example, a heavy lift quadcopter will preferentially use large diameter propellers to make sure enough thrust is generated but will have a relatively low pitch as speed isn't a priority plus it reduces the strain of the motors.
On the other hand, a racing drone will use smaller diameter props since most racing drone weigh <1kg, higher pitch props are needed to be able to withstand and utilise speed from the high RPM motors.

Planforms

Findings from a review of ‘Aircraft Performance and Design, 1998’ [12] and ‘The Design of an Airplane, 2001’ [13] of different wing planforms are outlined above. Each profile yields both advantages and disadvantages, and so it is necessary to select a suitable planform based on parameters set by the mission requirements of the UAV.

An elliptical planform is the most favourable choice, as they have the lowest induced drag, meaning a higher lift coefficient, and they have an even stall pattern across the span of the wing. However they are much more complex to design and fabricate, further increasing the risk of problems later on in development.

Use of a rectangular planform is the most feasible, they still provide advantages such as low risk of tip stall occurring due to constant Reynolds number values across the span of the wing.

Tapering a rectangular planform will further optimise the wing by reducing induced drag and smaller bending moments.

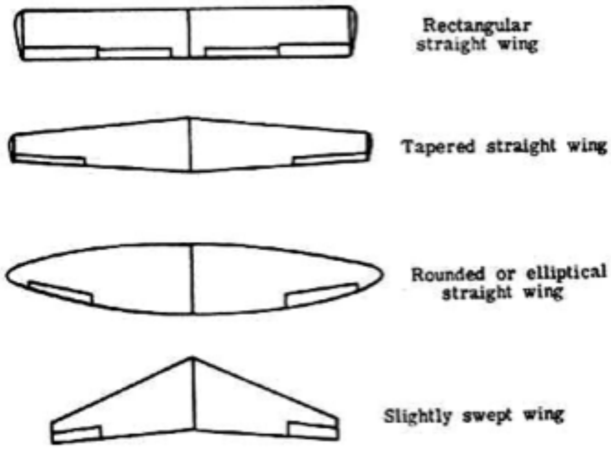


Figure X: Planform Type Shapes
http://www.stengel.mycpanel.princeton.edu/

Profile	Advantages	Disadvantages
Elliptical	1. Lowest induced drag 2. Stalls evenly across spans	1. Difficult to fabricate
Rectangular	1. Constant Re reduces risk of tip stall 2. Easy to fabricate	1. Higher induced drag 2. Higher bending moments
Tapered	1. Lower induced drag than rectangular planform 2. Smaller bending moment	1. Risk of tip stall
Combined Rect. & tapered	1. Approach advantages of elliptical 2. Easier to fabricate	1. Hazards of tip stall remains

Figure X: Planform Types Advantages and Disadvantages
source UAV wing design and manufacturing singapore uni disso

Wing aspect ratio

Choosing an appropriate aspect ratio for the wings will mean referring back to the mission requirements of the UAV;

- slow cruising speed 5-20m/s
- Manoeuvrability is not a priority
- Long endurance flight, maximum lift

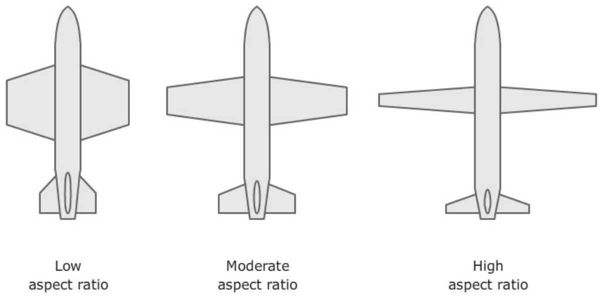


Figure X: Wing Aspect Ratio
https://www.sciencelearn.org.nz/resources/

High aspect ratio wings are used in gliders or slow moving aircraft. They provide more lift and allow longer flight endurance.
Low aspect ratio wings are used in fighter jets and missiles as this AR allows for good manoeuvrability and fast roll rates.

High to Moderate aspect ratio wings [14]

Stability: Long narrow wings give a plane more stability since additional lift is generated along the wings and can correct angular deviations in the roll axis. Because of this, high aspect ratio wings aren't very manoeuvrable.

Less induced drag Due to high AR wings being much narrower than low AR wing, they possess less induced drag. Induced drag occurs when turbulent regions of high pressure air under the wing come up over the trailing edge and onto the top of the wing into the low pressure zone disrupting the wings ability to create lift.

Less fuel consumption: As a result of less induced drag, more aerodynamic lift can be created for the wings, and thus less energy or fuel is required to maintain altitude for flight.

Using Aspect Ratio to determine chord length

Based off of findings from Mohammad H. Sadraey [15], the aircraft types that follows similar design specifications to the UAV have an aspect ratio between 5 and 9.

No	Aircraft type	Aspect ratio
1	Hang glider	4-8
2	Glider (sailplane)	20-40
3	Homebuilt	4-7
4	General Aviation	5-9
5	Jet trainer	4-8
6	Low subsonic transport	6-9
7	High subsonic transport	8-12
8	Supersonic fighter	2-4
9	Tactical missile	0.3-1
10	Hypersonic aircraft	1-3

Figure X: Typical Aircraft Type

For a rectangular wing plane, the formula for Aspect Ratio is given by;

AR = s / c

s = Span **c = Chord length**

Given that I am limited to a maximum wing span of 1m due to the Carbon Fibre wing tube length, I am limited with the range in which i can set the chord width to be.
Although Gliders also follow similar design specifications as the UAV, their AR values are so high that small wing spans of 1m will require a chord width of 50mm to 25mm. This will result in negligible lift forces and will be excluded from consideration.

To calculate minimum and maximum chord width I can rearrange the AR formula.

Min C = S / AR
= S / 40 = 1000mm / 9
= 111.1 mm

Max C = S / AR
= S / 5 = 1000mm / 5
= 200 mm

A chord width of **150mm** is selected given an AR of 6.6. This places the wing characteristics of the craft to be similar to Hang gliders, Homebuilt's, and General Aviation types. These types of aircraft manoeuvre at slower roll rates compared to aircraft with higher AR (tactical missile @ 0.3-1) but have the advantage of being able to generate higher amounts of lift at slower speeds making them ideal for long range flights.

Airfoils

Shape	Key characteristics	Applications
Heavily Cambered	High L, low D, low C_M	Wings on high endurance UAVs, RC sailplanes
Moderately Cambered	High L, low D, moderate C_M	Wings on short range UAVs, RC sports plane
Symmetrical	Moderate L, Moderate D, low C_M	Horizontal and Vertical Tail, Aerobatics

Figure X: Airfoil Shape Characteristics

Summary of Low-Speed Airfoil Data
MichaelS. Selig, James J. Guglielmo, Andy P. Broeren and Philippe Giguere

Referring back to the UAV's mission requirements and parameters, the aircraft is specified as a RC sailplane/trainer configuration with a short to mid range flight endurance. Results extracted from findings in 'Summary of Low-Speed Airfoil Data' [16] have been display in the table above.

From this it can be concluded that a moderately to heavily cambered airfoil is an optimal choice for what is required.

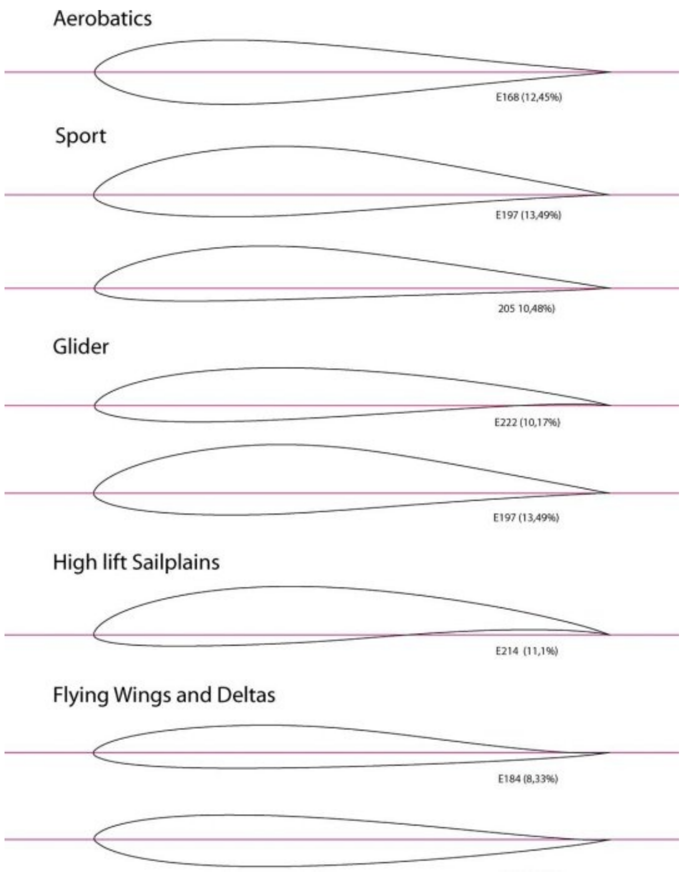


Figure X: Airfoil Types

https://www.google.com/url?sa=i&url=https%3A%2F%2Fwww.pinterest.com%2Fpin%2F696087686137294390%2F&psig=AOvVaw1dwLEiMC8YuQkKJySo3Pjn

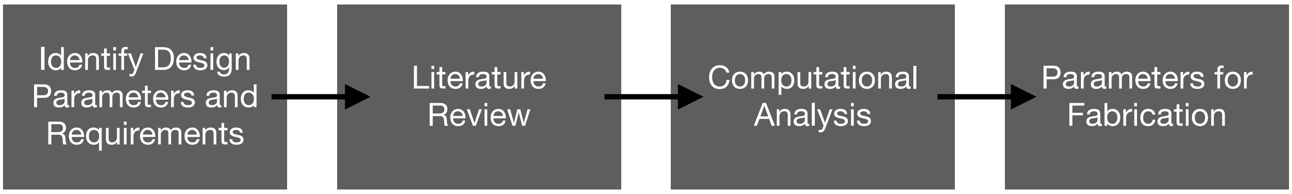
Chapter 3 Design and Analysis

Methodology

The design stage of this project involves manipulating the physical geometry of an aircraft to affect its aerodynamics. The UAV's flight characteristics will have a direct effect on its performance, stability and most importantly its mission capabilities.

By referring to the mission capabilities of this UAV, a range of desirable parameters for the design, performance, and stability of the aircraft can be identified.
Through the use of literature review and fundamental theory, a selection of optimum parameters are made for each mission requirement.

Computational analysis will be used to refine the options and to justify final selection
With parameters generated, fabrication can begin.



<u>Requirements and Parameters</u>

Mission Requirements

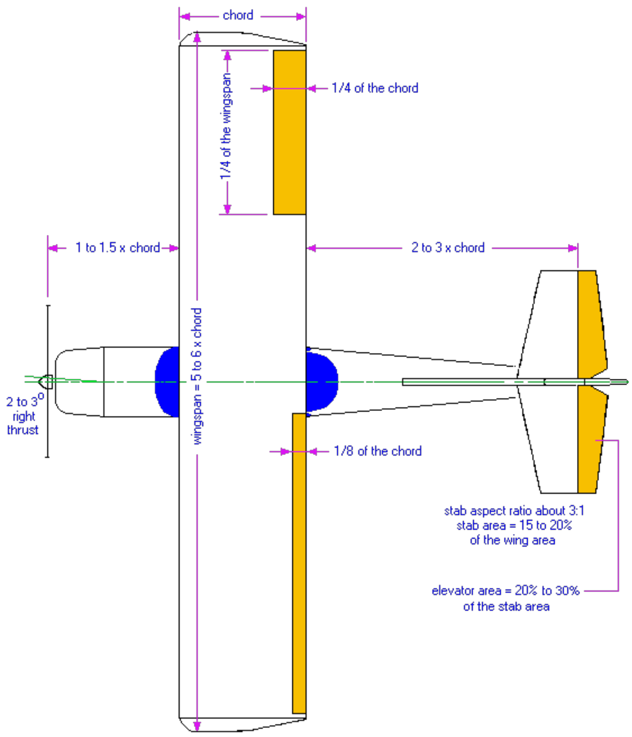
Mission requirements of the UAV will dictate its design and hardware requirements. Below is a table of the mission requirements of the UAV.

	Specification
Designated Task	Short - Medium Range Waypoint Navigation, possible surveillance and rescue mission usage.
Payload	Total weight < 1kg
Wing Span	High Wing
TakeOff/Recovery	Vertical Take Off and Landing capability
Manoeuvrability	Turning radius < 1km
Range and Endurance	Using GPS, range can be large but battery power only allows 10-15 minute flight times
Altitude and Cruising Speed	500ft-1650ft (150m-500m); 5-20 m/s

Determining Airframe Dimensions

To begin designing the UAV, fundamental parameters such as dimensions are vital in determining all other parameters.

Using the image below for reference, dimensions can be determined for the UAV. Using dimensional values advised it can be assumed that the UAV will have flight characteristics similar to that of a Trainer/Glider.



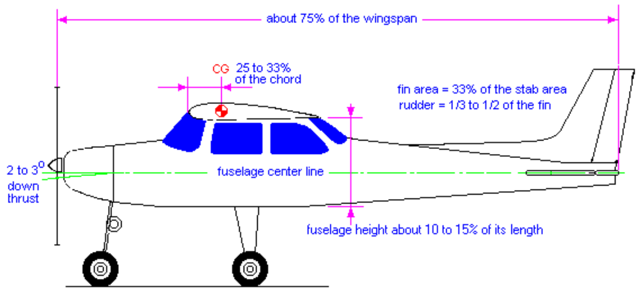
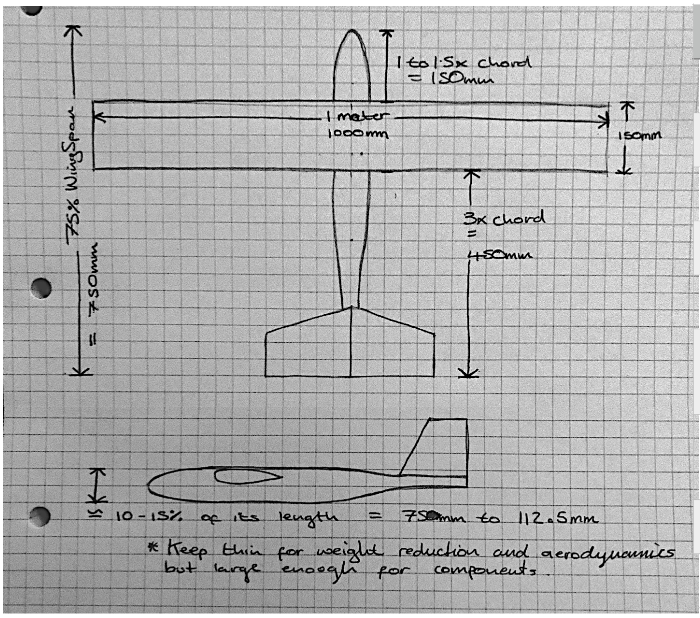


Figure X: Typical Dimensions of a Trainer Airframe
https://cdn.instructables.com/FN5/QE3N/IP45JH8S/FN5QE3NIP45JH8S.LARGE.gif?



Parameters	Specification
Aspect Ratio	6.6
Wing Chord	0.15m
Wing Span	1m
Fuselage Diameter	0.075m - 0.1125m
Fuselage Length	0.75m
Wing leading edge distance from Fuselage tip	0.15m
Wing trailing edge distance from Fuselage end	0.45m
C.G to tip distance	0.1875m
C.G to tail distance	0.5625m

Critical Performance Parameters

Aircraft Lift (Cl vs a)

$$C_L = C_{l_\alpha} \frac{AR}{AR + 2} \alpha$$

Range and Endurance (Cl vs Cd and Cl/Cd)

Range

$$R = \frac{V_\infty}{c_t} \frac{L}{D} \int_{W_1}^{W_0} \frac{1}{W} dW = \frac{V_\infty}{c_t} \frac{C_L}{C_D} \int_{W_1}^{W_0} \frac{1}{W} dW$$

Endurance

$$E = \frac{1}{c_t} \frac{C_L}{C_D} ln \frac{W_0}{W_1}$$

*Signal strength between tx and rx is limiting factor
*battery capacity (calculations on energy draw)

Determining Stability Requirements

Longitudinal Stability

Slope of aircraft pitching moment curve

$$C_{n_\beta} = C_{n_{\beta_{wf}}} + C_{n_{\beta_v}}$$

Contribution to pitching moment from wing and tail

$$C_{m_{\alpha_w}} = C_{L_{\alpha_w}}\left(\frac{x_{NP}}{\bar{c}} - \frac{x_{cg}}{\bar{c}}\right) \; ; \; C_{m_{\alpha_t}} = -\eta V_H C_{L_{\alpha_t}}\left(1 - \frac{d\varepsilon}{d\alpha}\right)$$

Lateral Stability

Slope of aircraft pitching moment curve

$$C_{n_\beta} = C_{n_{\beta_{wf}}} + C_{n_{\beta_v}}$$

Contribution to yawing moment from vertical tail

$$C_{n_{\beta_v}} = V_v \eta_v C_{L_{\alpha_v}}\left(1 + \frac{d\sigma}{d\beta}\right)$$

Slope of aircraft rolling moment curve is largely dependent on wing dihedral

$$C_{l_\beta} = -C_{L_\alpha}\Gamma.\frac{2\int_0^{b/2} c(y)\,dy}{Sb}$$

Criteria for static stability is given by

$$C_{m_\alpha} < 0, C_{n_\beta} > 0, C_{l_\beta} < 0$$

Reynolds Number Based on Specification

The Reynolds number is calculated from:

$$Re = \frac{\rho v l}{\mu} = \frac{v l}{\nu}$$

Where:

v = Velocity of the fluid
l = The characteritics length, the chord width of an airfoil
ρ = The density of the fluid
μ = The dynamic viscosity of the fluid
ν = The kinematic viscosity of the fluid

Estimated MinV = 5m/s (11mph)
Estimated MaxV = 20m/s (45mph)

V average = 12.5 m/s (28mph)

V = 12.5 m/s (22.4mph)
l = 0.15m
v = 1.4207 x 10^-5

Re = (12.5 * 0.15) / (1.4207 x 10^-5) = **131,977**

Kinematic Viscosity

Example kinematic viscosity values for air and water at 1 atm and various temperatures.

Air

Kinematic Viscosity m^2/s	°C	°F	
1.2462E-5	-10	14	Use
1.3324E-5	0	32	Use
1.4207E-5	10	50	Use
1.5111E-5	20	68	Use

Water

Kinematic Viscosity m^2/s	°C	°F	
1.6438E-6	1	33.8	Use
1.267E-6	10	50	Use
9.7937E-7	20	68	Use

Figure X: Kinematic Viscosity
http://airfoiltools.com/calculator/reynoldsnumber?

Airfoil Comparison

Figure X: Gemini Sailplane Airfoil
http://airfoiltools.com/polar/details?polar=xf-

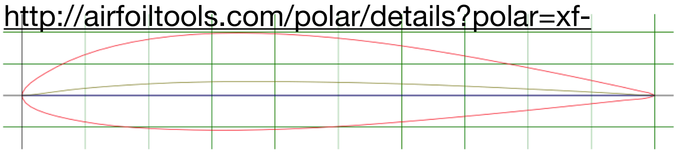
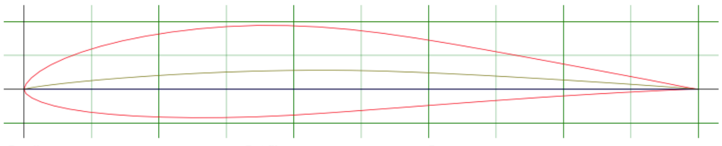


Figure X: E197 Sailplane Airfoil



Airfoil	Reynold Number	Max Cl/Cd
Gemini	100,000	47.3 at aoa = 9.25 deg
	200,000	66.9 at aoa = 7.25 deg
E197	100,000	52.5 at α=9°
	200,000	77.6 at α=8°

Re =100,000	E197	Gemini
Max Cl	**1.1873**	1.1762
Max Cl / Cd	**52.51 at α=9°**	47.28
Cl at aoa = 9 deg	**1.1819**	1.1580
Max Cl / Cd at aoa = 9 deg	**52.51**	1.158/0.02458 = 47.11
Stall Angle	13	**14**
Stall Pattern	gentle over 4 deg	**gentle over 5 deg**

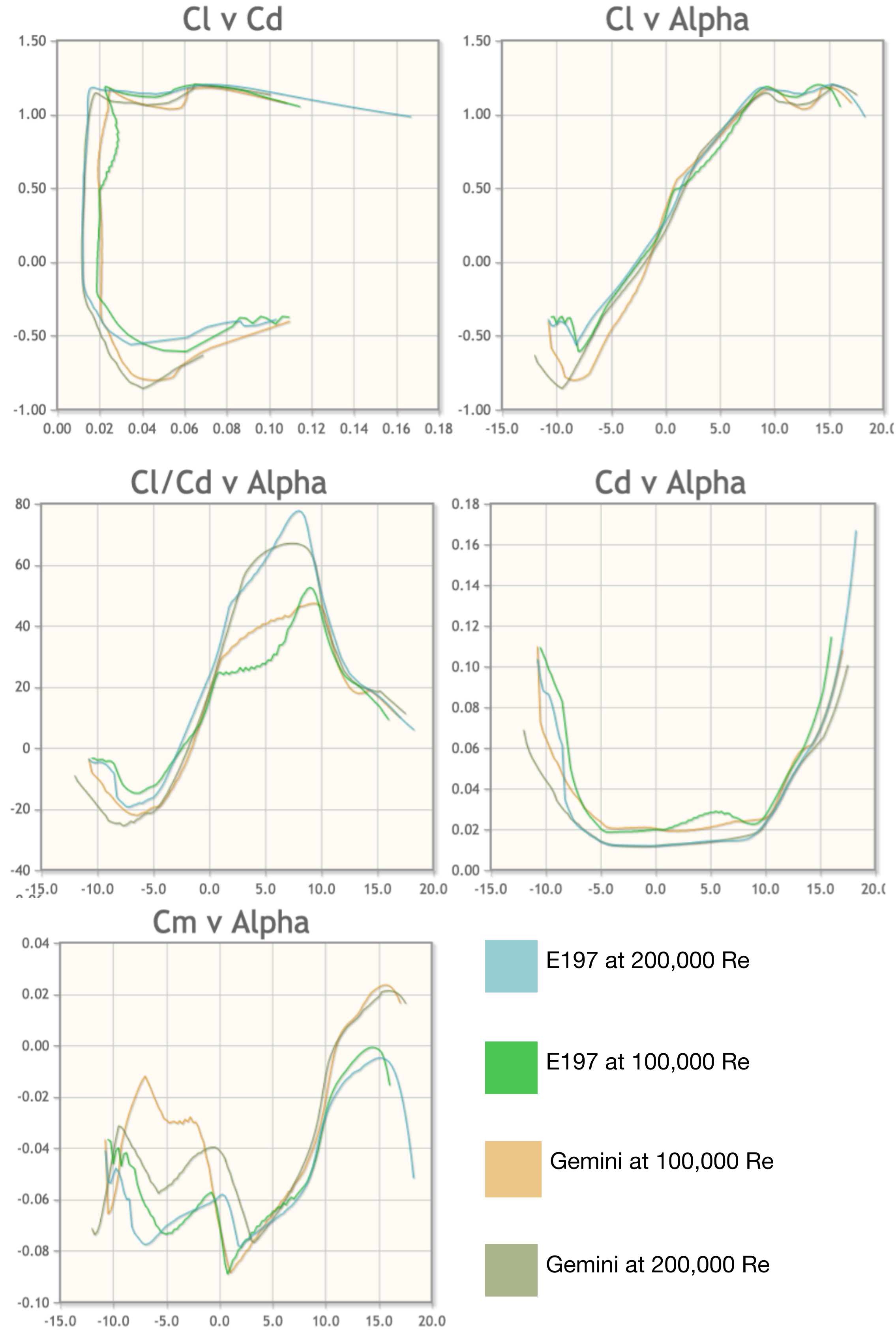


Figure X: Graph Plots for Gemini and E197 Airfoils
http://airfoiltools.com/polar/details?polar=xf-geminism-il-100000

Comparing both airfoils shows that E197 yields more favourable lift values than the Gemini. Most particularly was the fact that Cl was higher for the E197 at angle of attack ranges of 5 - 10 deg.

Thrust to Weight Ratio

The thrust to weight ratio of an aircraft is important as it determines whether the craft has enough thrust to generate a lift force. If the amount of thrust is less than the aircraft weight, the aircraft will have difficulty taking off.

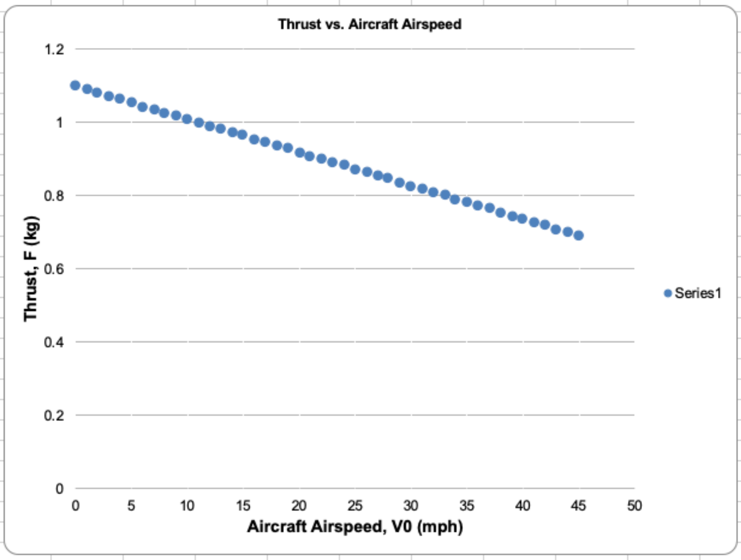
Using an estimate of the overall weight of the UAV and an approximation of the the amount of thrust generated, the thrust to weight ratio can be found.

From my findings **[Xhttps://www.flitetest.com/articles/propeller-static-dynamic-thrust-calculation]**, a general formula using propeller diameter, pitch, and motor RPM can be used to calculate the static and dynamic thrust at different speeds.

$$F = 1.225\frac{\pi(0.0254\cdot d)^2}{4}\left[\left(RPM_{prop}\cdot 0.0254\cdot pitch\cdot\frac{1min}{60sec}\right)^2 - \left(RPM_{prop}\cdot 0.0254\cdot pitch\cdot\frac{1min}{60sec}\right)V_0\right]\left(\frac{d}{3.29546\cdot pitch}\right)^{1.5}$$

Gabriel Staples, 2013. http://electricrcaircraftguy.blogspot.com/

	x		y		
	Aircraft Airspeed, V_0 (m/s)	Aircraft Airspeed, V_0 (mph)	Dynamic Thrust, F (N)	Dynamic Thrust, F (g)	Dynamic Thrust, F (kg)
Static Thrust -->	0	0	10.7851394	1099.403	1.099403
all others are dynamic thrust	0.44704	1	10.696073	1090.323	1.090323
	0.89408	2	10.6070065	1081.244	1.081244
	1.34112	3	10.51794	1072.165	1.072165
	1.78816	4	10.4288736	1063.086	1.063086
	2.2352	5	10.3398071	1054.007	1.054007
	2.68224	6	10.2507406	1044.928	1.044928
	3.12928	7	10.1616742	1035.849	1.035849
	3.57632	8	10.0726077	1026.769	1.026769
	4.02336	9	9.98354124	1017.69	1.01769
	4.4704	10	9.89447477	1008.611	1.008611
	4.91744	11	9.8054083	999.5319	0.999532
	5.36448	12	9.71634184	990.4528	0.990453
	5.81152	13	9.62727537	981.3736	0.981374
	6.25856	14	9.5382089	972.2945	0.972294
	6.7056	15	9.44914244	963.2153	0.963215
	7.15264	16	9.36007597	954.1362	0.954136
	7.59968	17	9.2710095	945.057	0.945057
	8.04672	18	9.18194303	935.9779	0.935978
	8.49376	19	9.09287657	926.8987	0.926899
	8.9408	20	9.0038101	917.8196	0.91782
	9.38784	21	8.91474363	908.7404	0.90874
	9.83488	22	8.82567717	899.6613	0.899661
	10.28192	23	8.7366107	890.5821	0.890582
	10.72896	24	8.64754423	881.503	0.881503
	11.176	25	8.55847777	872.4238	0.872424
	11.62304	26	8.4694113	863.3447	0.863345
	12.07008	27	8.38034483	854.2655	0.854266
	12.51712	28	8.29127837	845.1864	0.845186
	12.96416	29	8.2022119	836.1072	0.836107
	13.4112	30	8.11314543	827.0281	0.827028
	13.85824	31	8.02407897	817.9489	0.817949



Propeller Inputs					
diam, d (in):	4.8	pitch (in):	3.6	RPMs:	35520

Part	X	Weight
Front Section	1	19 grams
Mid Section	1	70 grams
Tail Section	1	89 grams
1m CF Tube	2	2 x 50 grams =100 grams
Wing Rib	8	8 x 31 grams = 248 grams
Tail Tilt Mechanism	1	15 grams
Wing Tilt Mechanism	2	2 x 25 grams = 50 grams
Motor	3	3 x 33.8 grams = 101.4 grams
Servo	3	3 x 20 grams = 60 grams
ESC	3	3 x 6.8 grams = 20.4 grams
Battery	2	2 x 150 grams = 300 grams
Pixhawk FC	1	38 grams
Additional Misc (Estimation)		150 grams
Estimated Total Weight		**1,260.8 g** **1.26 kg**

Weight of the UAV was calculated after the CAD had been completed. Using the 3D printer slicing software i was able to figure out the approximate weight. Density of plastics x Volume to be printed.

Weight = 1.26 kg
Thrust = 0.845 kg X 2motors = 1.69 kg

Thrust to Weight = 1.3 : 1

- (min)------------Trainer > 0.3 : 1
- (preferred)-----Trainer = 0.8 : 1
- (min)--------------Sport > 0.8 : 1
- (preferred)-------Sport = 1.3 : 1

Based on values for typical aircraft, a 1.3 :1 is great, even if the UAV is not to behave like a sports plane it is reassuring to understand that the plane shouldn’t have any problem creating sufficient amounts of lift. It also means that the aircraft is capable of carrying additional payload weight, additional batteries would yield even longer flight endurance times.

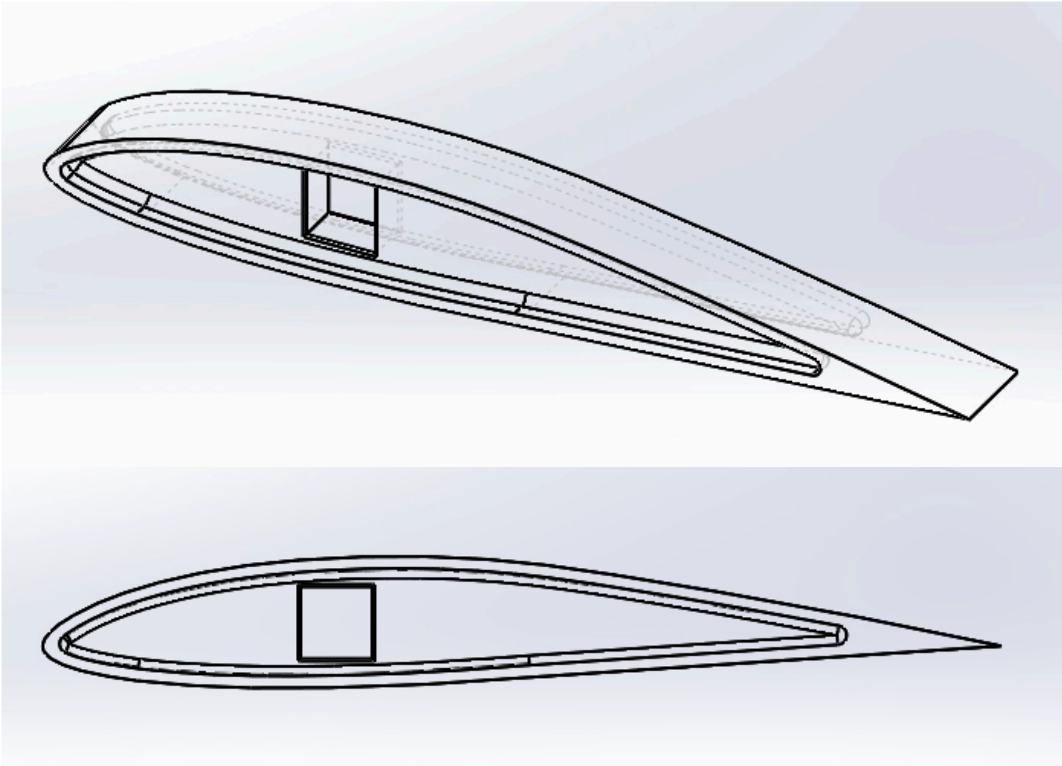


Figure - CAD Wing Rib Mrk.1

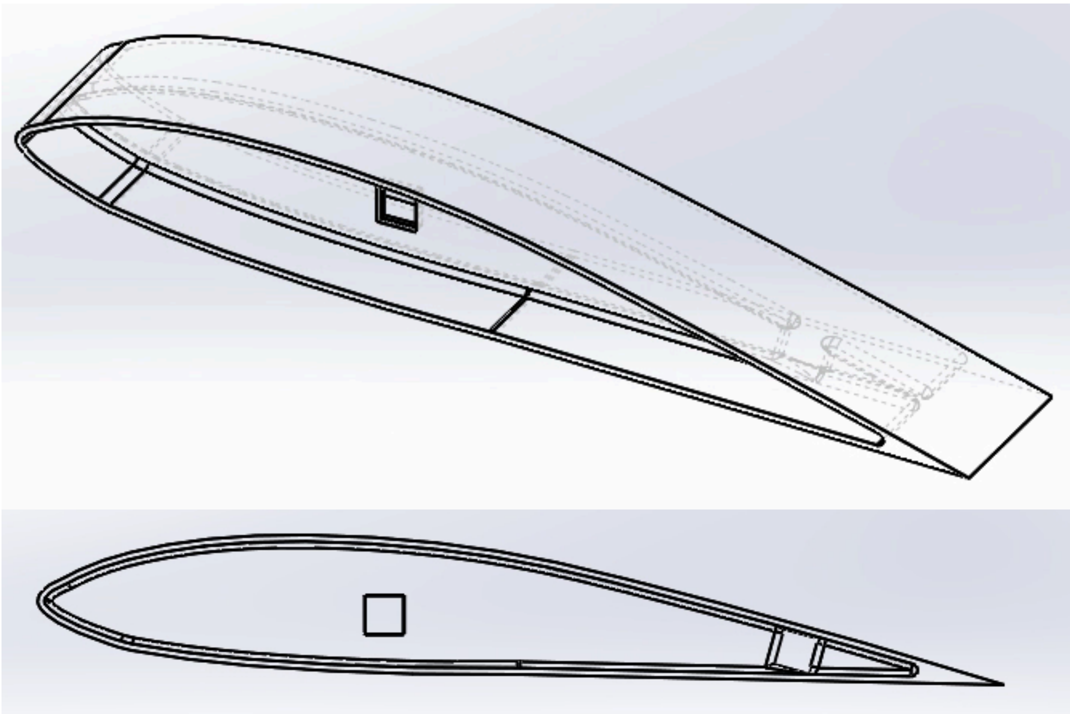


Figure - CAD Wing Rib Mrk.2

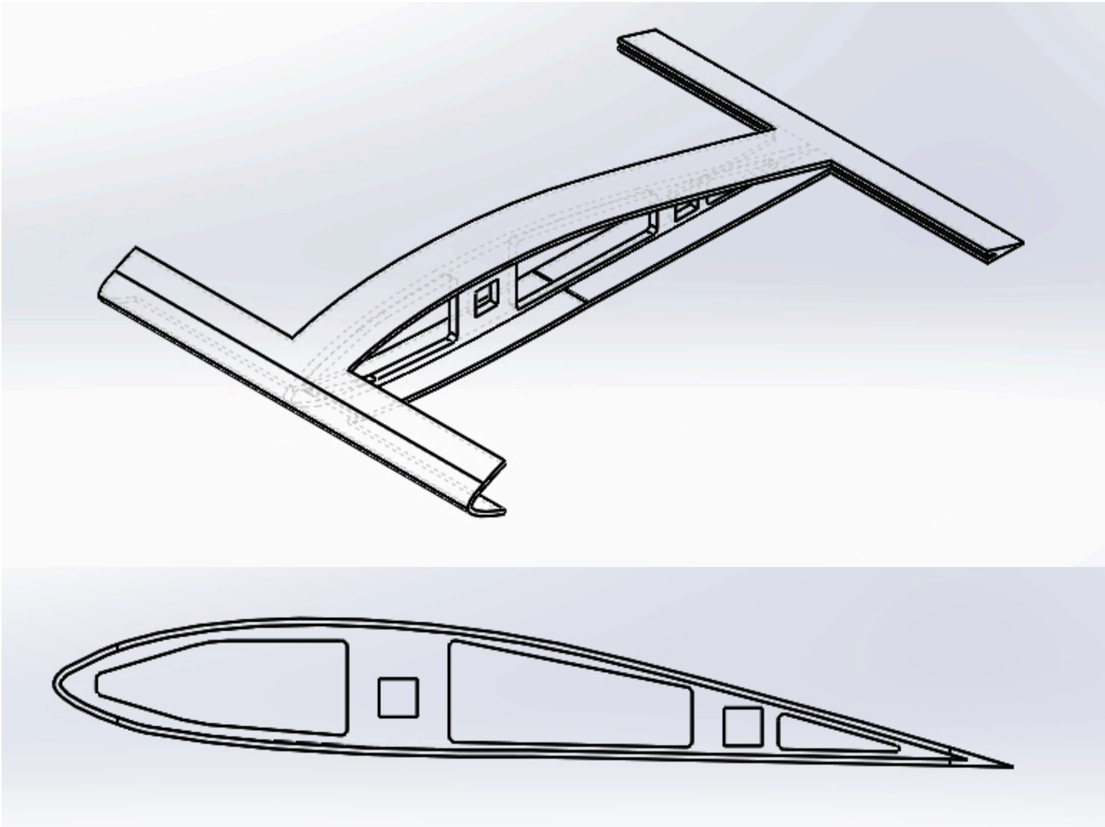


Figure - CAD Wing Rib Mrk.3

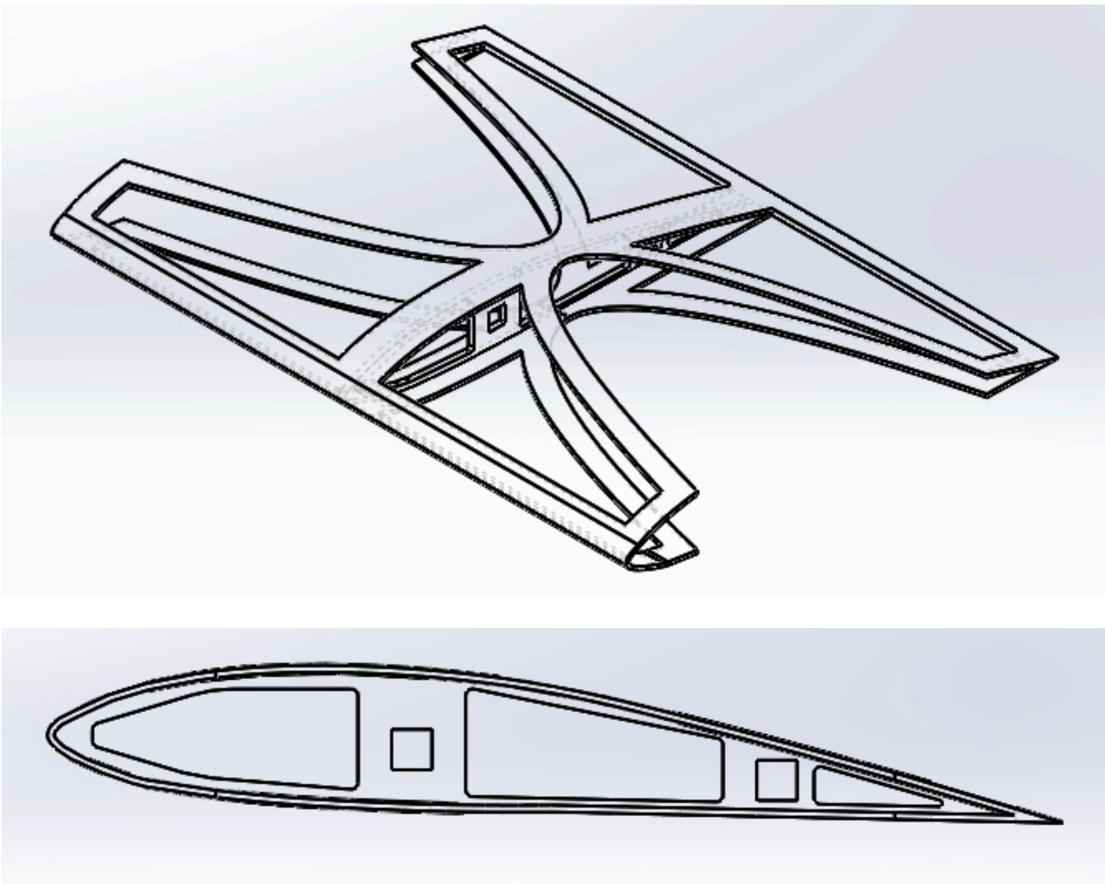


Figure - CAD Wing Rib Mrk.4

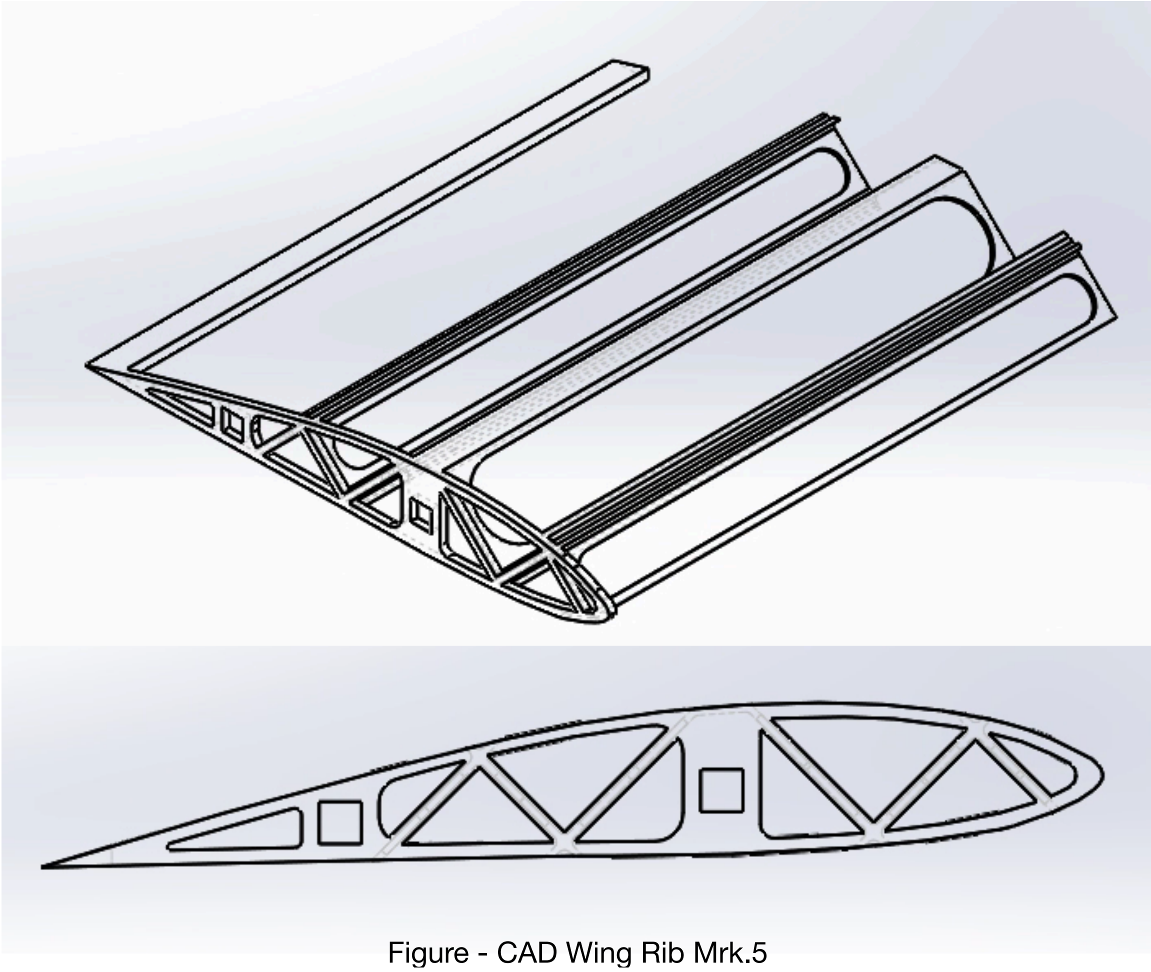


Figure - CAD Wing Rib Mrk.5

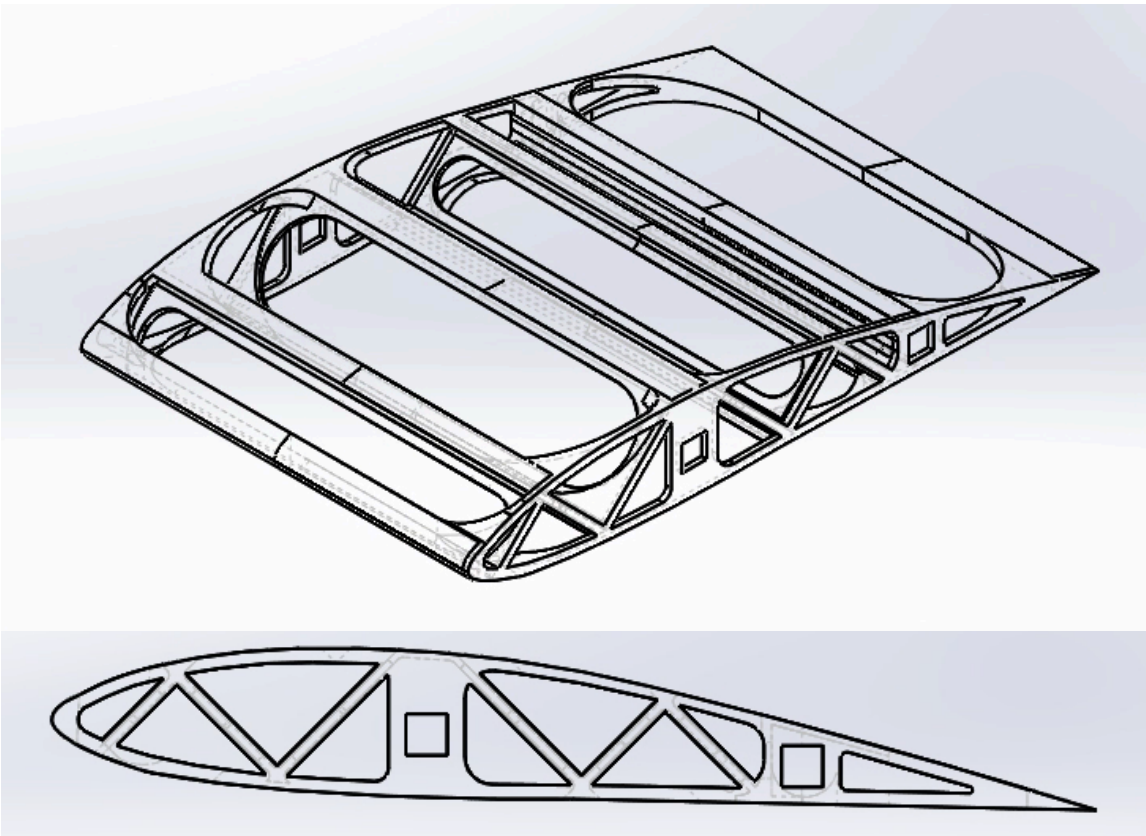


Figure - CAD Wing Rib Mrk.6

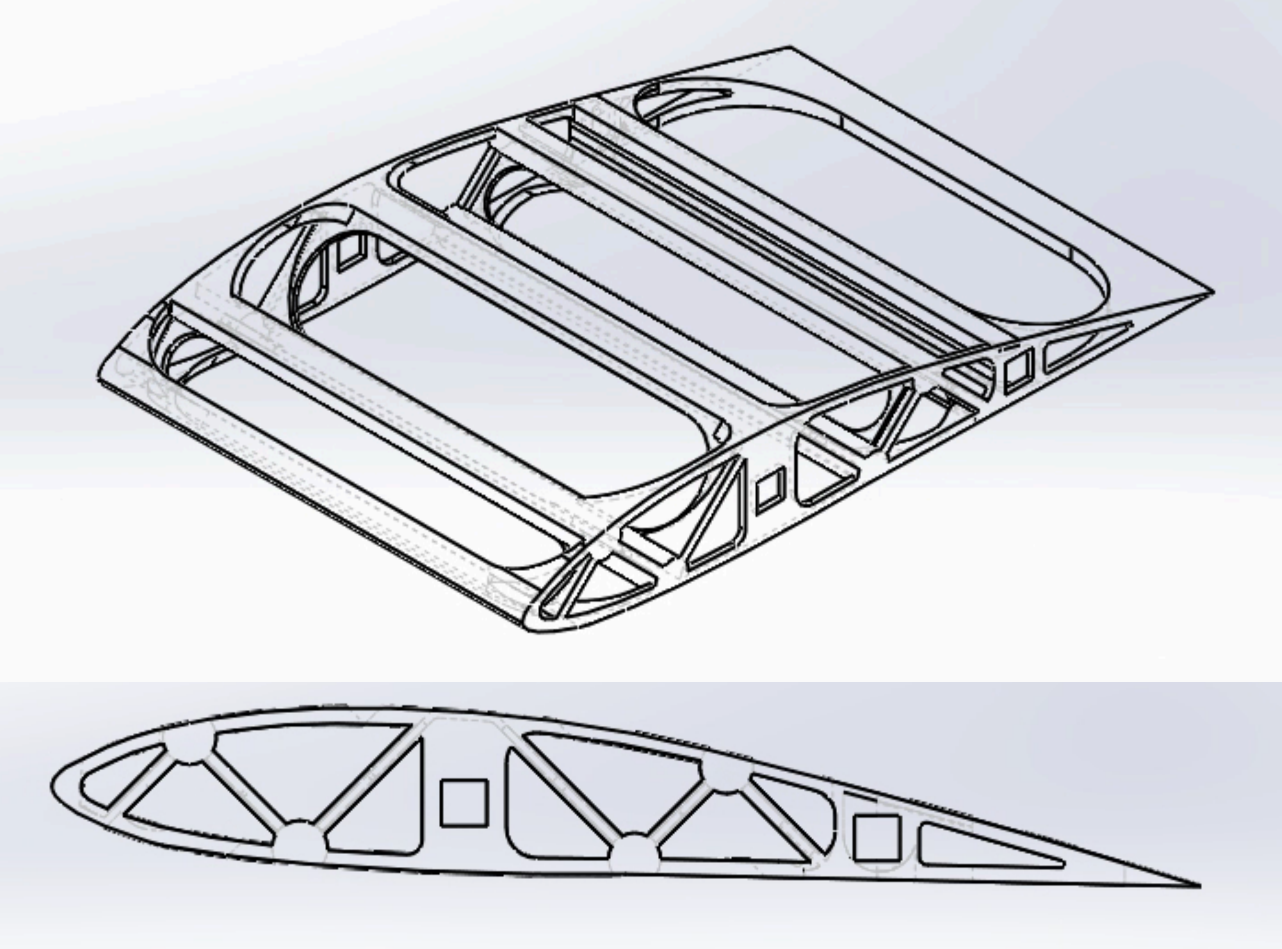


Figure - CAD Wing Rib Mrk.7

CAD - Fuselage

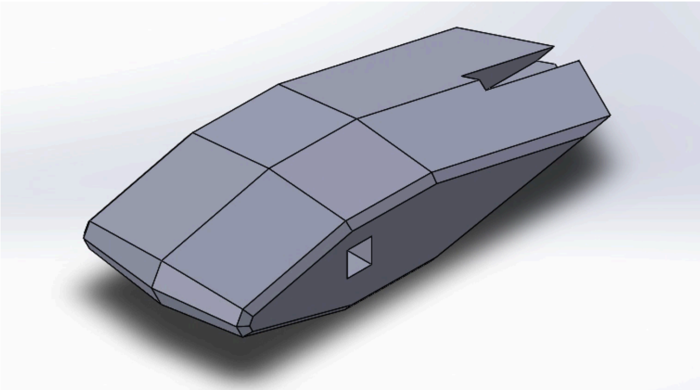


Figure - CAD Fuselage Mrk.1 (Isometric View)

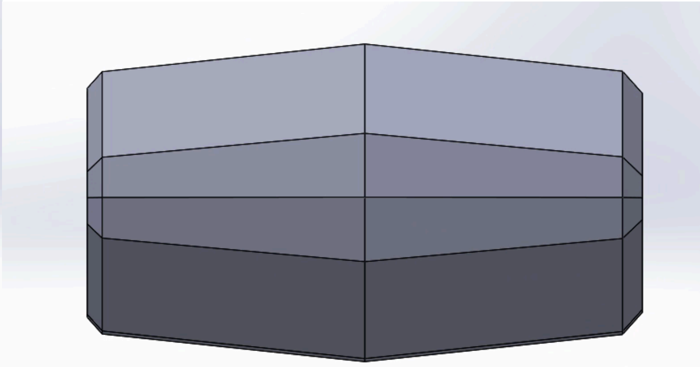


Figure - CAD Fuselage Mrk.1 (Front View)

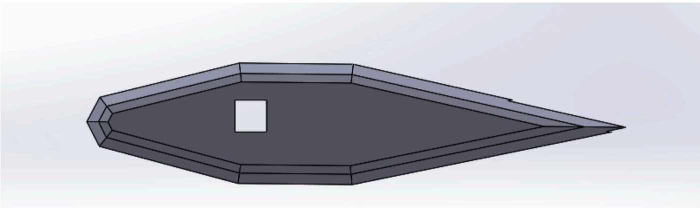


Figure - CAD Fuselage Mrk.1 (Side View)

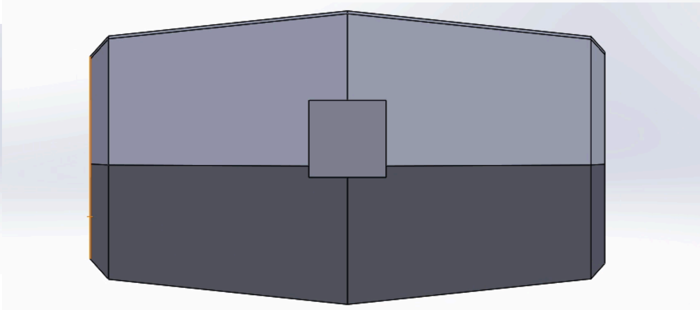


Figure - CAD Fuselage Mrk.1 (Rear View)

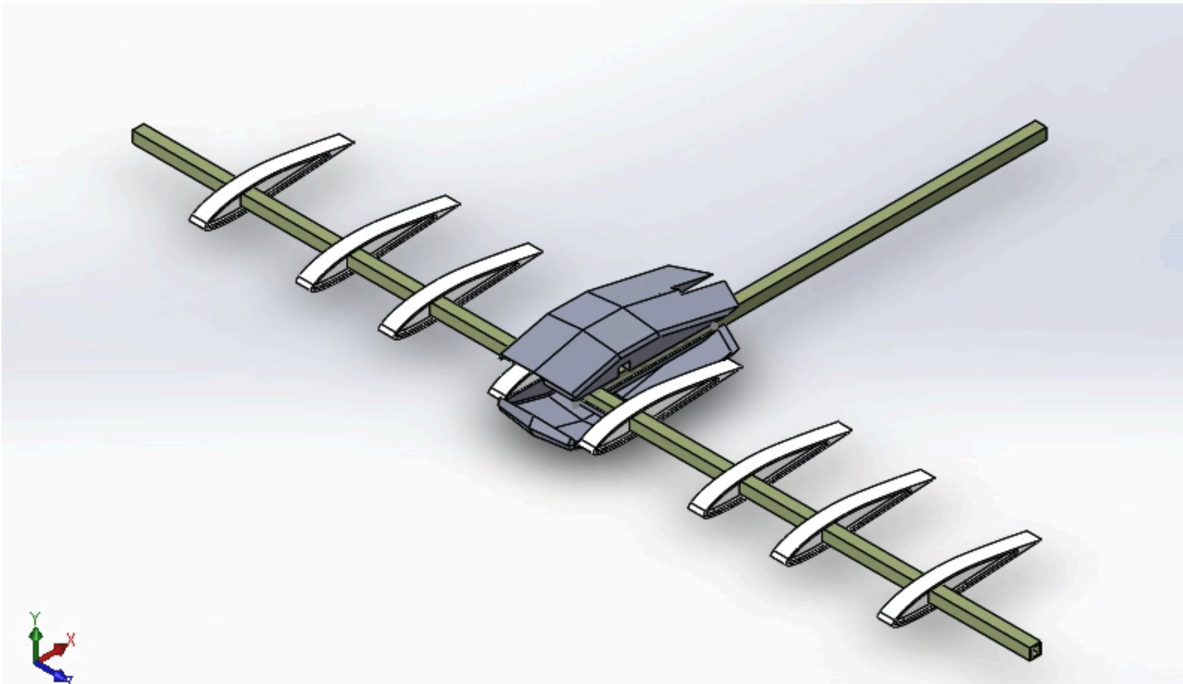


Figure - CAD Fuselage Mrk.1 Full Assembly

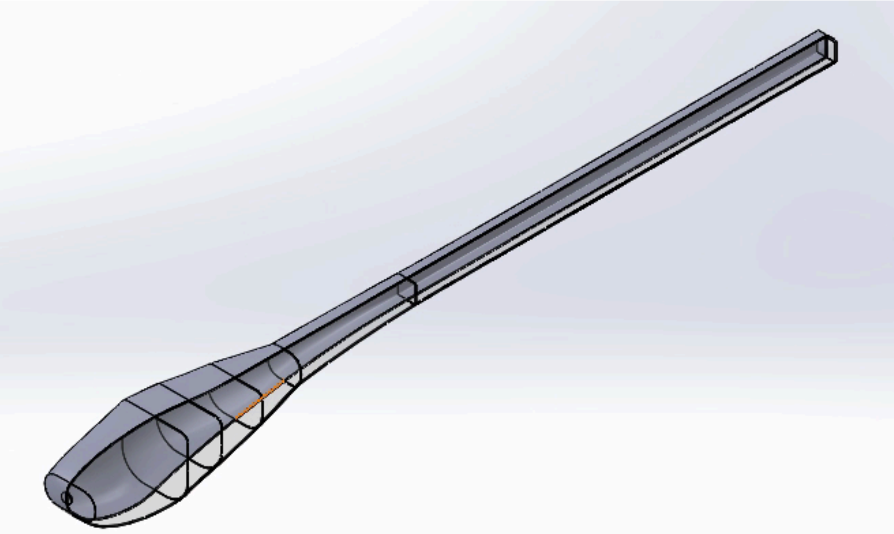


Figure - CAD Fuselage Mrk.2 (Isometric View w/ hidden lines)

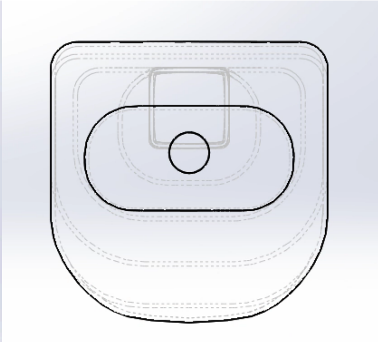


Figure - CAD Fuselage Mrk.2 (Front View)

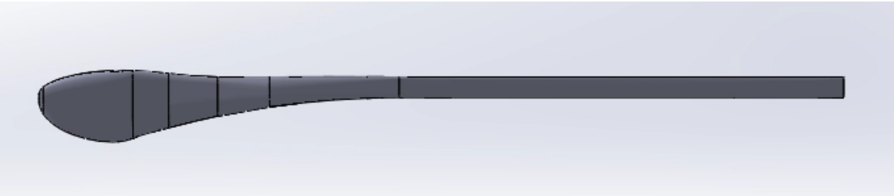


Figure - CAD Fuselage Mrk.2 (Side View)

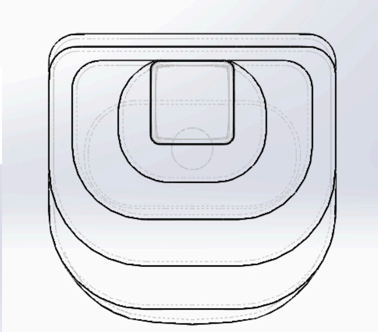


Figure - CAD Fuselage Mrk.2 (Rear View)

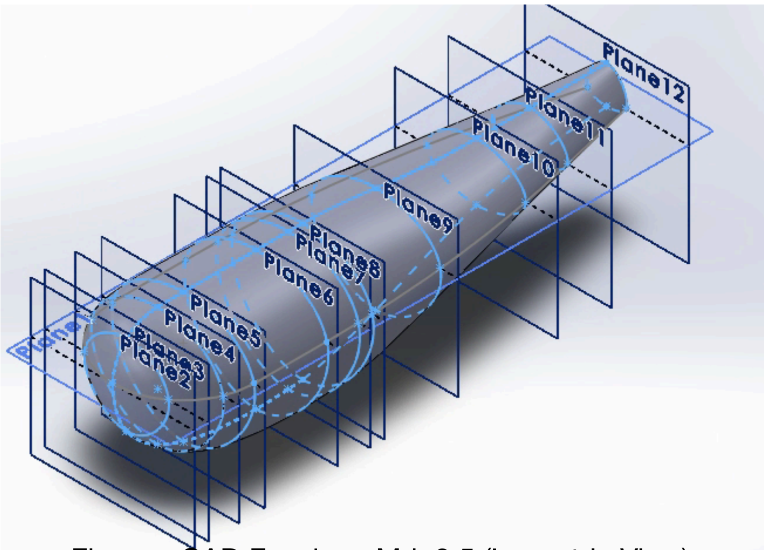


Figure - CAD Fuselage Mrk.2.5 (Isometric View)
Updated with more organic lines and geometry

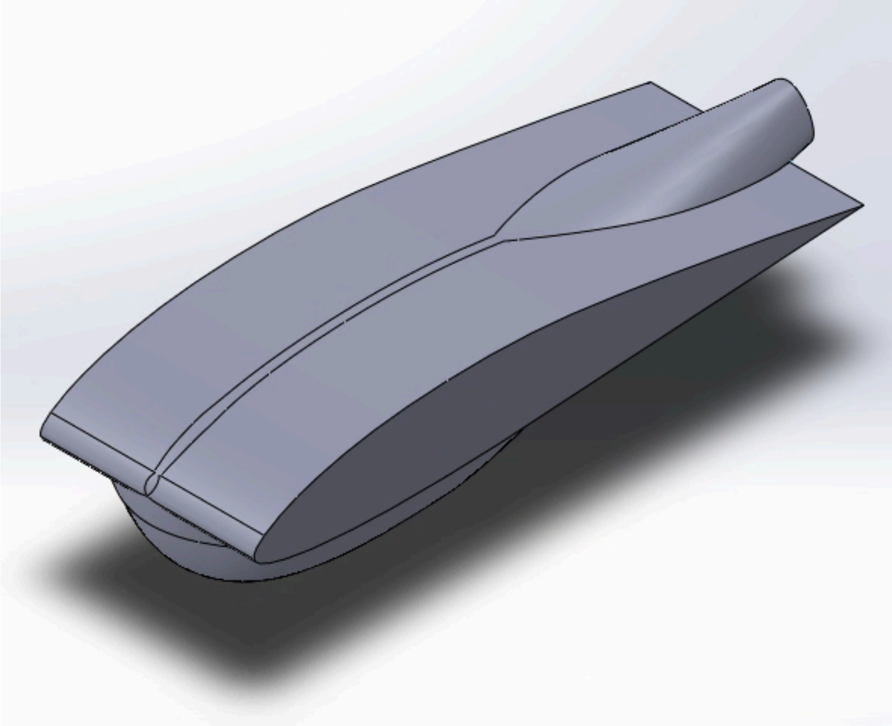


Figure - Tail Tilt Mechanism

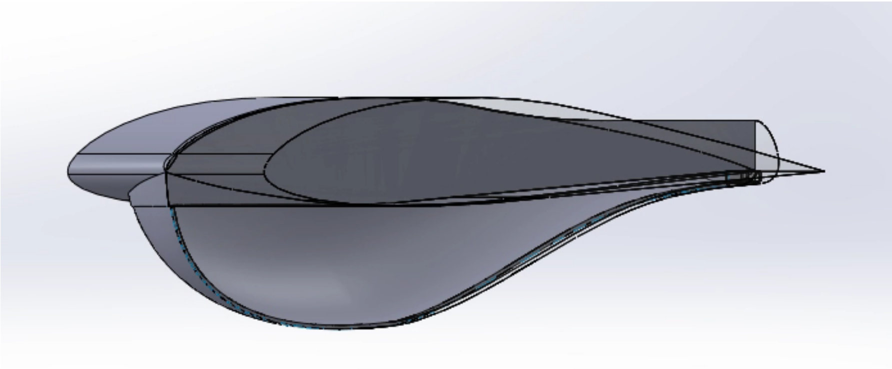


Figure - CAD Fuselage Mrk.3 (Side View w/ hidden lines)

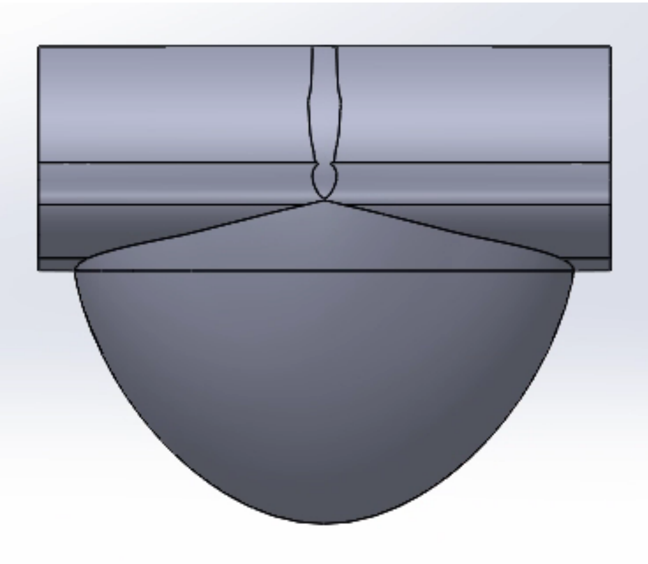


Figure - CAD Fuselage Mrk.3 (Front View)

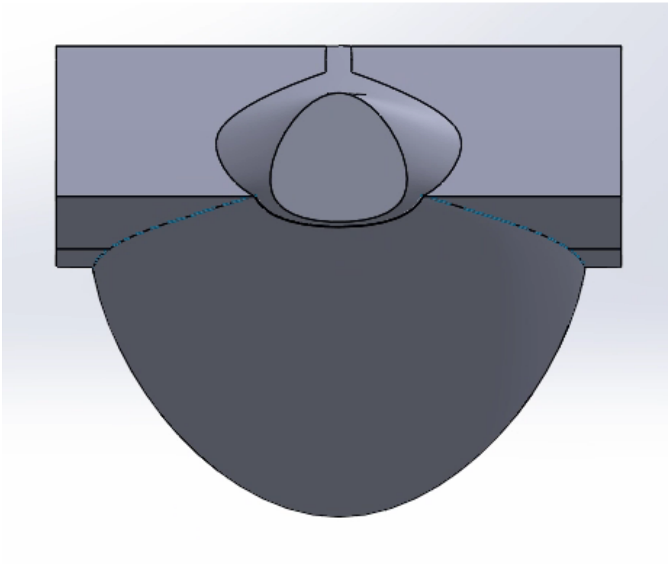


Figure - CAD Fuselage Mrk.3 (Rear View)

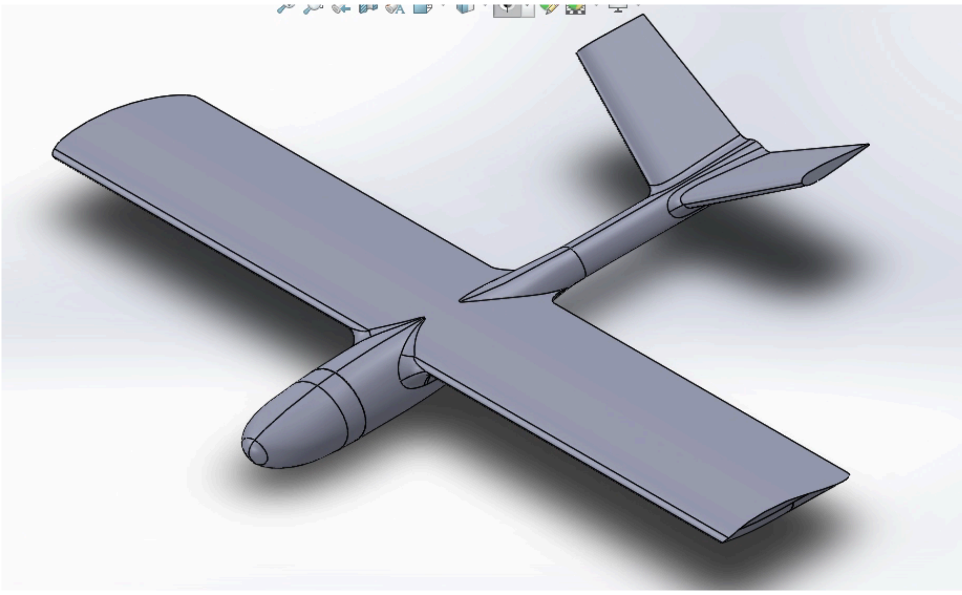


Figure - Final CAD Model (Isometric View)

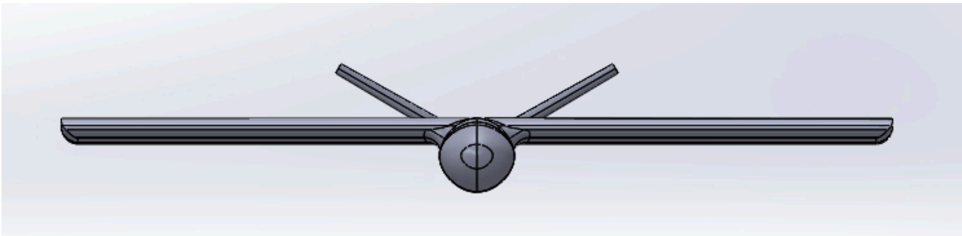


Figure - Final CAD Model (Front View)

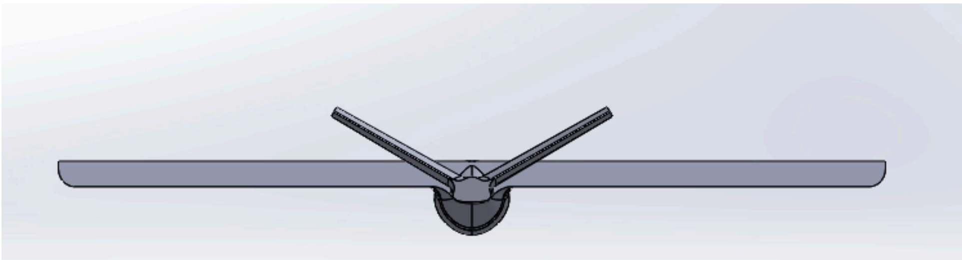


Figure - Final CAD Model (Rear View)

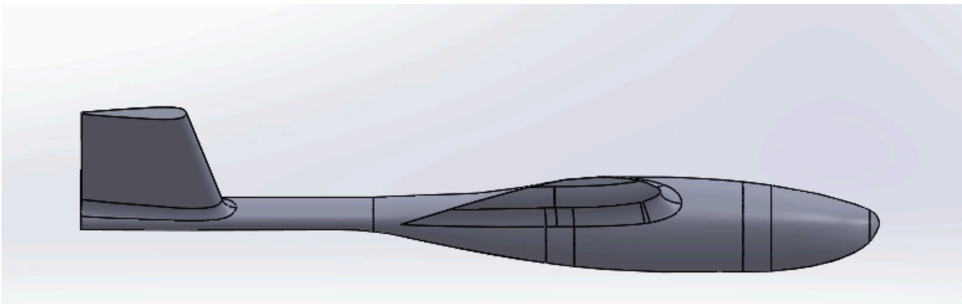


Figure - Wing Tilt Mechanism

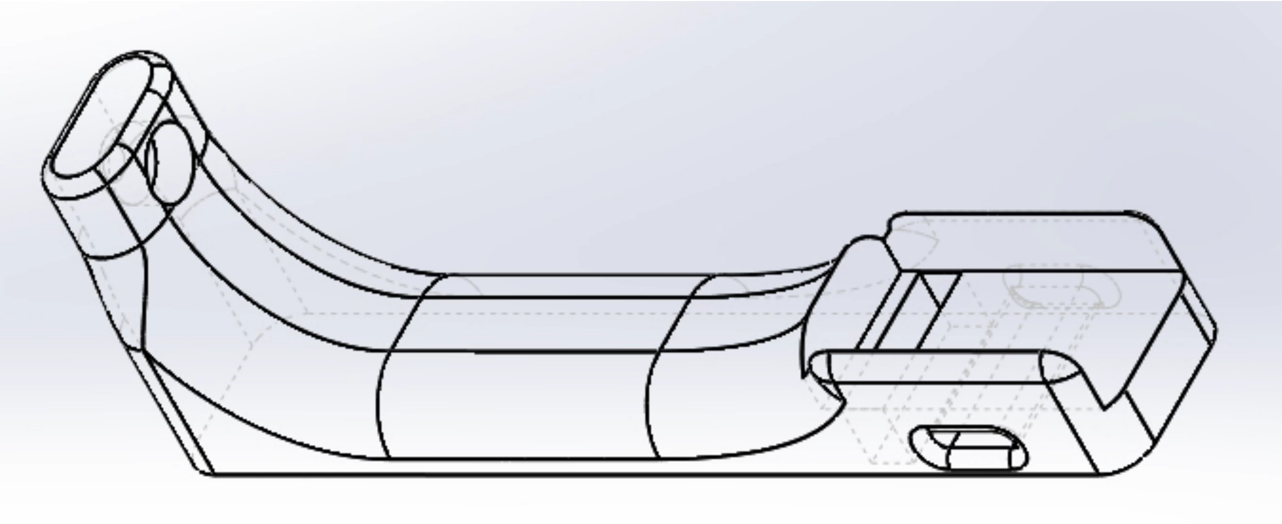


Figure - Tail Tilt Mechanism

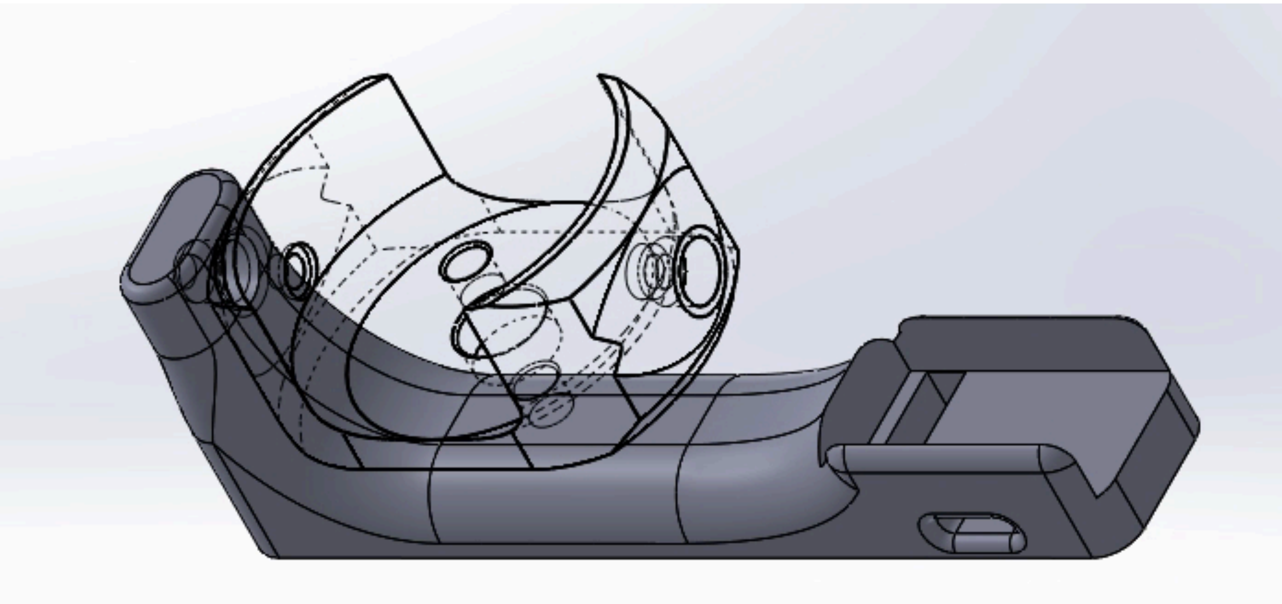


Figure - Tail Tilt Mechanism with Motor Mount

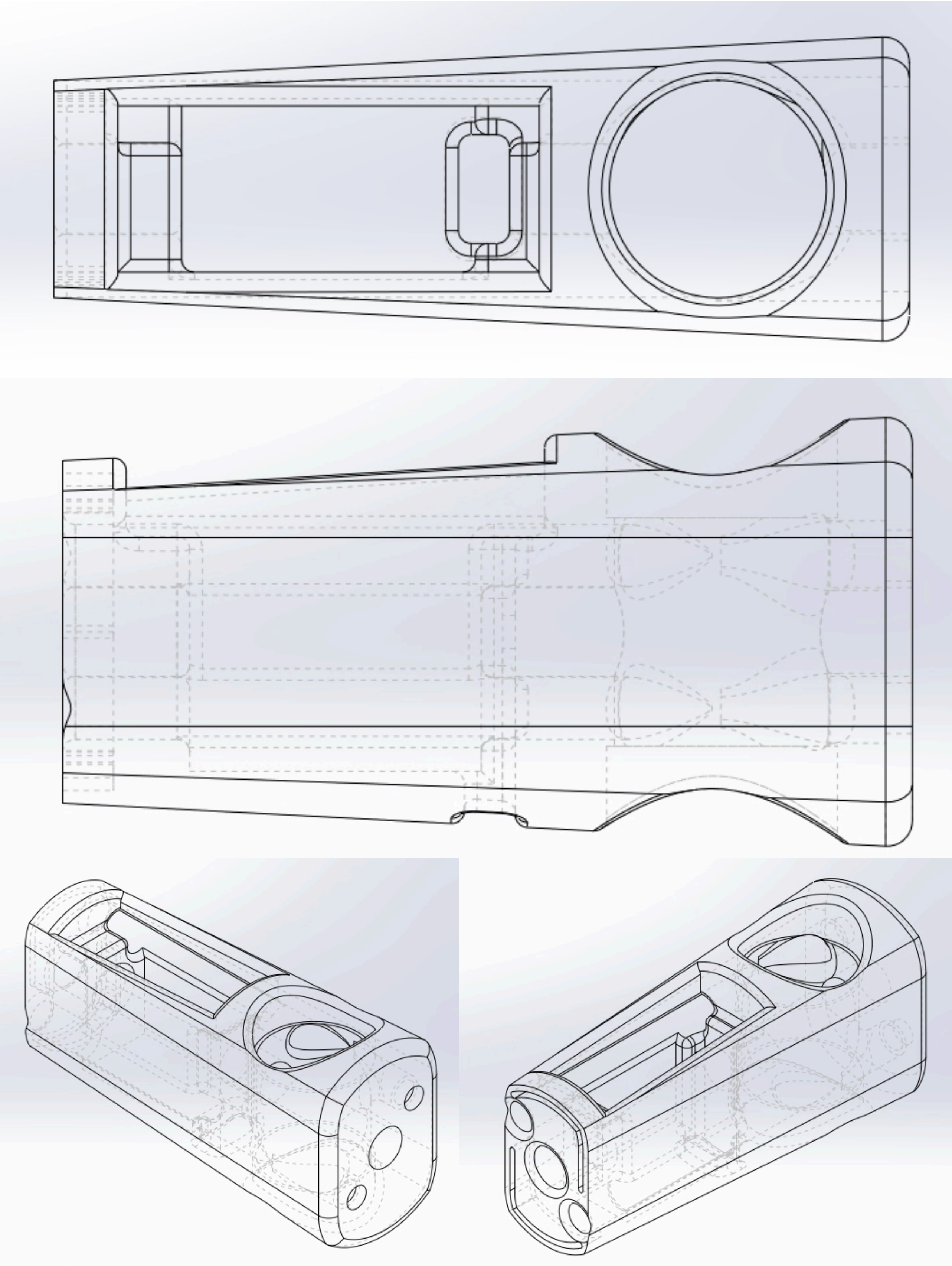


Figure - Wing Tilt Mechanism

Chapter 5 CFD Analysis

Computational Fluid Dynamics is the method of simulating and predicting fluid flow through computer processing. [17]

CFD is important in engineering as it allows testing of fluid flows without costing too much or needing to fabricate a model for use in a wind tunnel.

CAD prototype can be put through CFD testing, optimised and subsequently retested within a short amount of time. Changes can be quickly made in order to verify, for example, the aircraft's ability to generate enough aerodynamic lift to sustain flight at various flight speeds.

In order to predict the flow of a fluid a number of key parameters must be known, some of these are;

- Flow Pressure (P)
- Flow Velocity (u, v, w)
- Flow Temperature (T)
- Fluid Density (ρ)
- Vorticity (ω)
- Turbulence Intensity
- Fluid Composition
- Chemical reaction/ Energy release

CFD calculates governing equations for a fluid in a domain in order to predict the flow over an object. The governing equations are known as Navier-Stokes equations. They consist of;

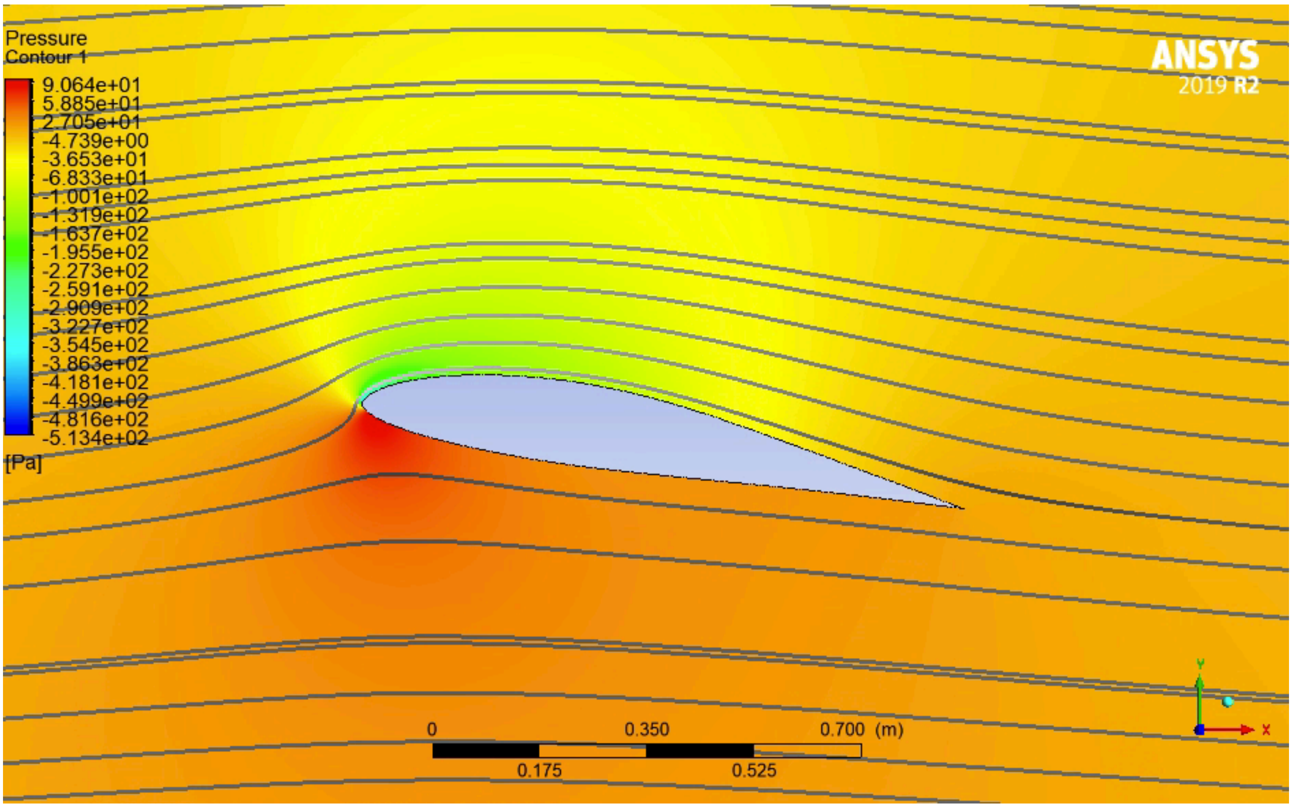
- Mass Conservation Equation (Continuity Equation)
- Momentum Conservation Equation
- Energy Conservation Equation
- Chemical Species Conservation Equation

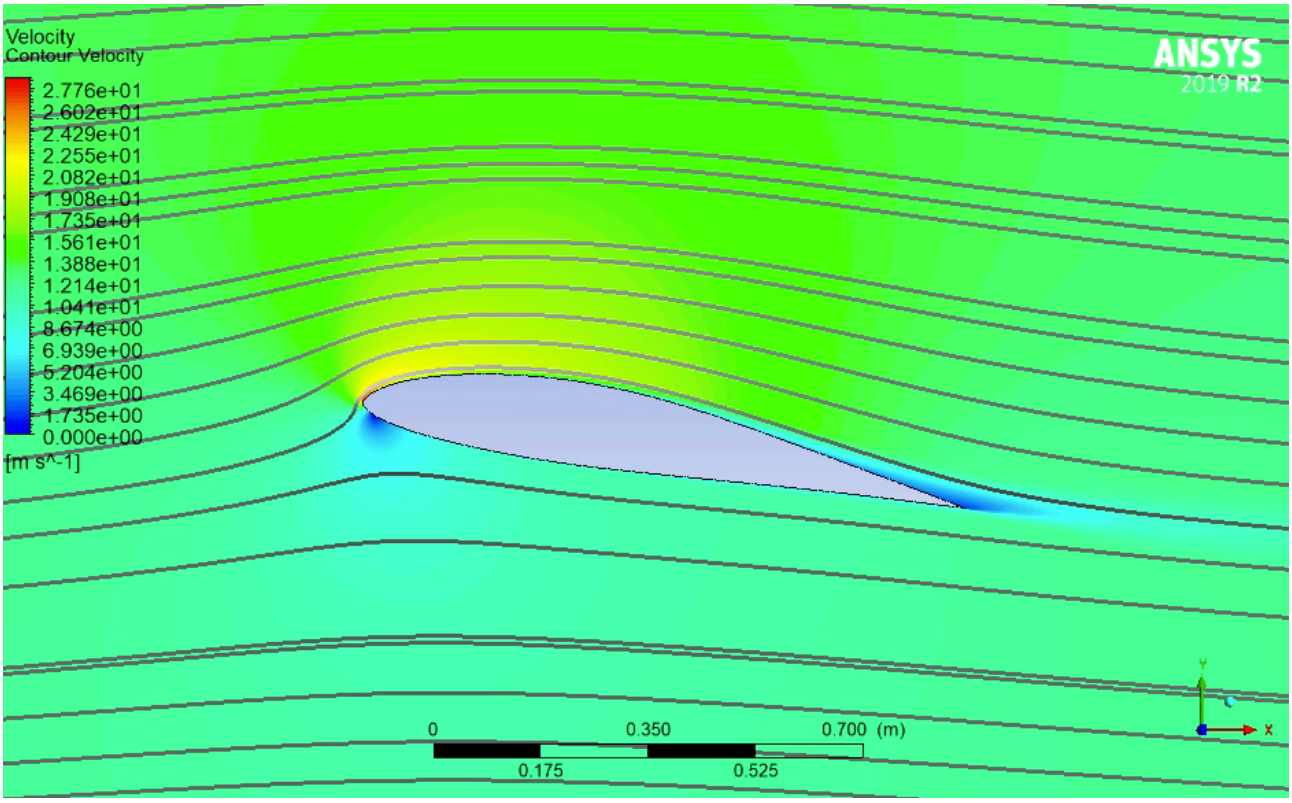
CFD begins with Pre-Processing in which the physics are analysed and select an appropriate simulation model.

Fluid properties

- ρ Density
- μ & υ Dynamic and Kinematic Viscosities
- R Gas constant
- Cp Heat capacity
- k Thermal conductivity
- h Convective Heat transfer Coefficient

2D Fluent CFD on E197 Airfoil





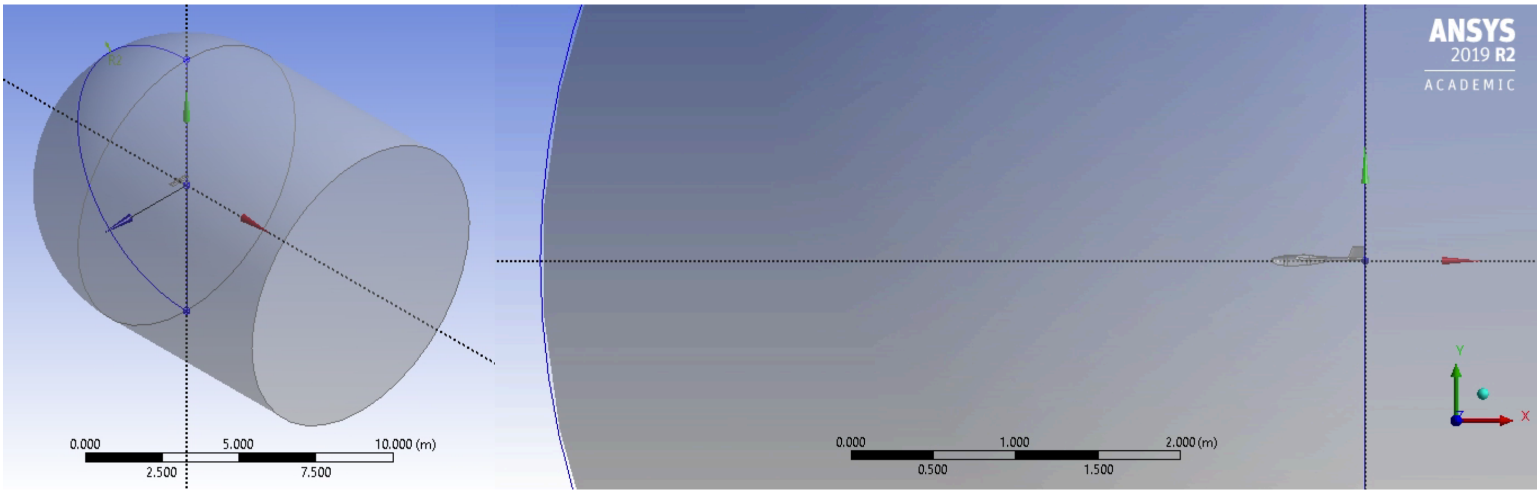


Figure X: Domain creation and fluid region isolation

A cylindrical domain is created around the UAV model. The radius of the front arc is 5m and the region behind the aircraft is extruded to a length of 8m. Having the region behind the aircraft longer than the front region is advisable as it will show more of how the airflow is affected by the aircraft.

Initially both the aircraft and domain were generated as solids. A boolean subtraction is used to remove the aircraft from the domain leaving a cavity in its place. This way, during the the Fluent analysis, the 'void' where the aircraft is will act as the solid, and the domain will act as a fluid region.

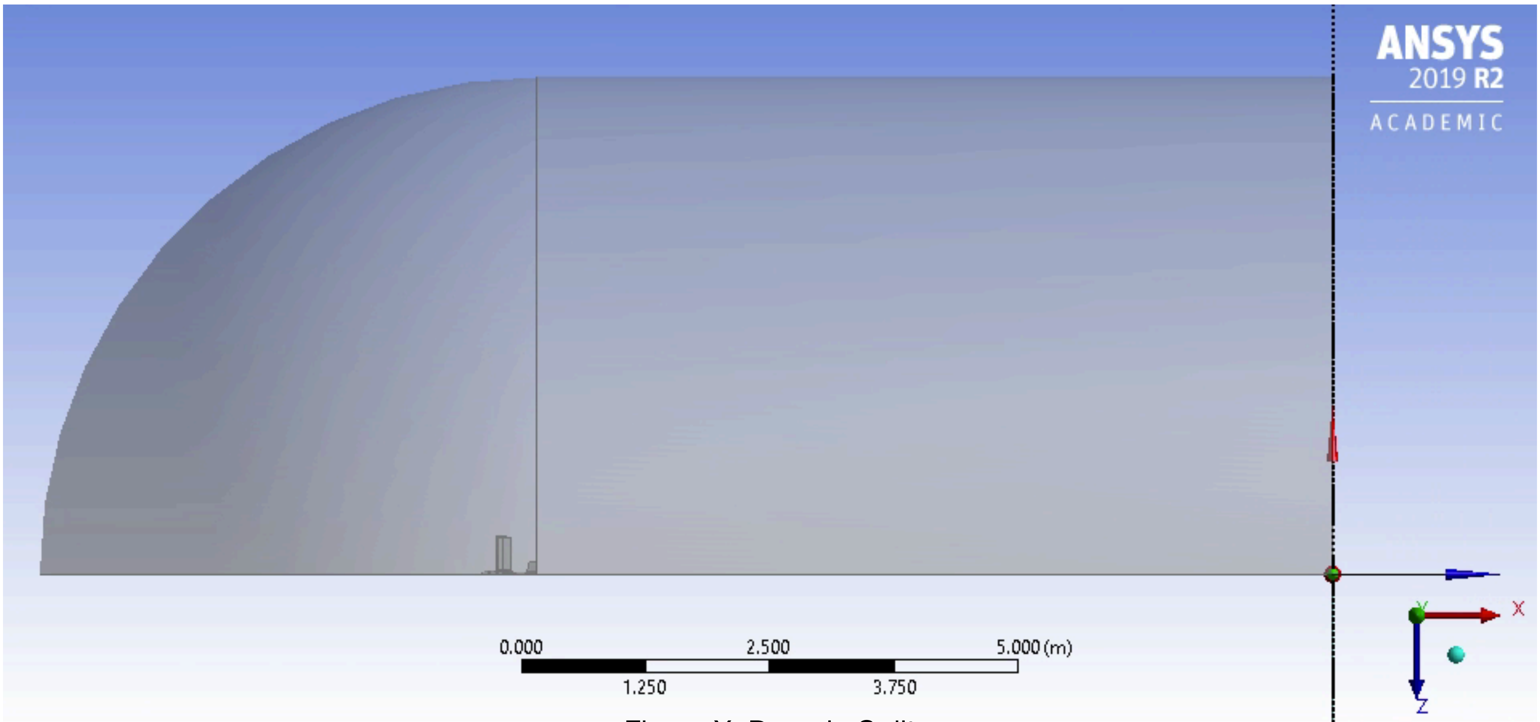


Figure X: Domain Split

As the model of the UAV is symmetrical, it is possible to split the domain in half. Doing so will reduce the amount time needed to generate a suitable mesh and compute the solutions of the airflow.

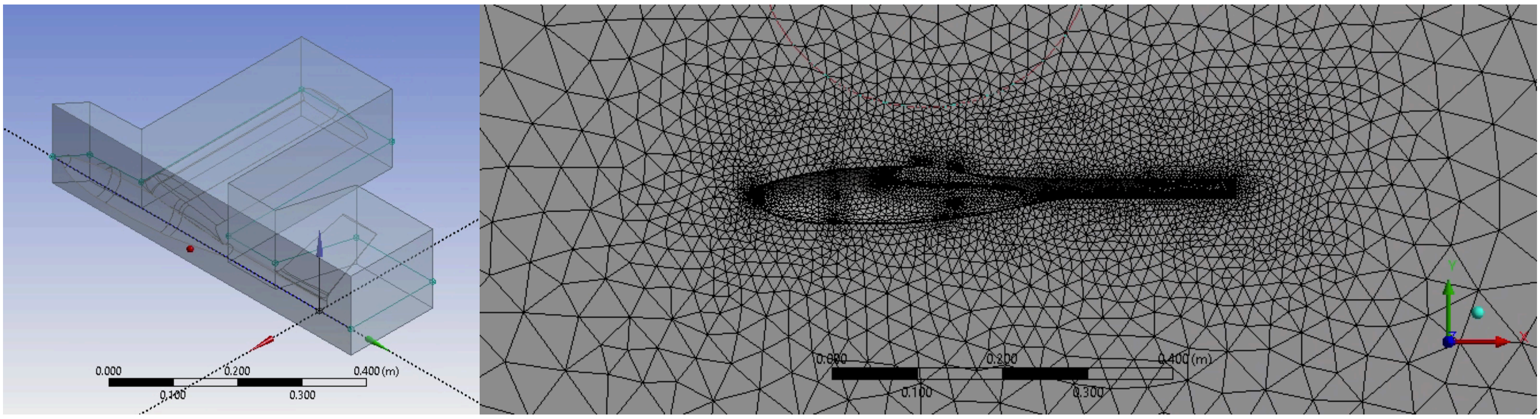


Figure X: Close Proximity Body Sizing of Mesh in Fluid Region

When generating the mesh for the fluid domain it is best to create one with a high resolution. However doing so for large fluid domains, such as the one that i have created, will yield unnecessarily long processing time as it is computing fine detail in regions of the domain where the fluid flow is possible of not great importance, i.e, in regions far from where the fluid is interacting with the model.

By creating another domain with a close proximity to the UAV, I can specify the mesh in this region to be of higher resolution than its surroundings. In doing so I am ensuring that computation time is reduced whist resolution around the model is kept high.

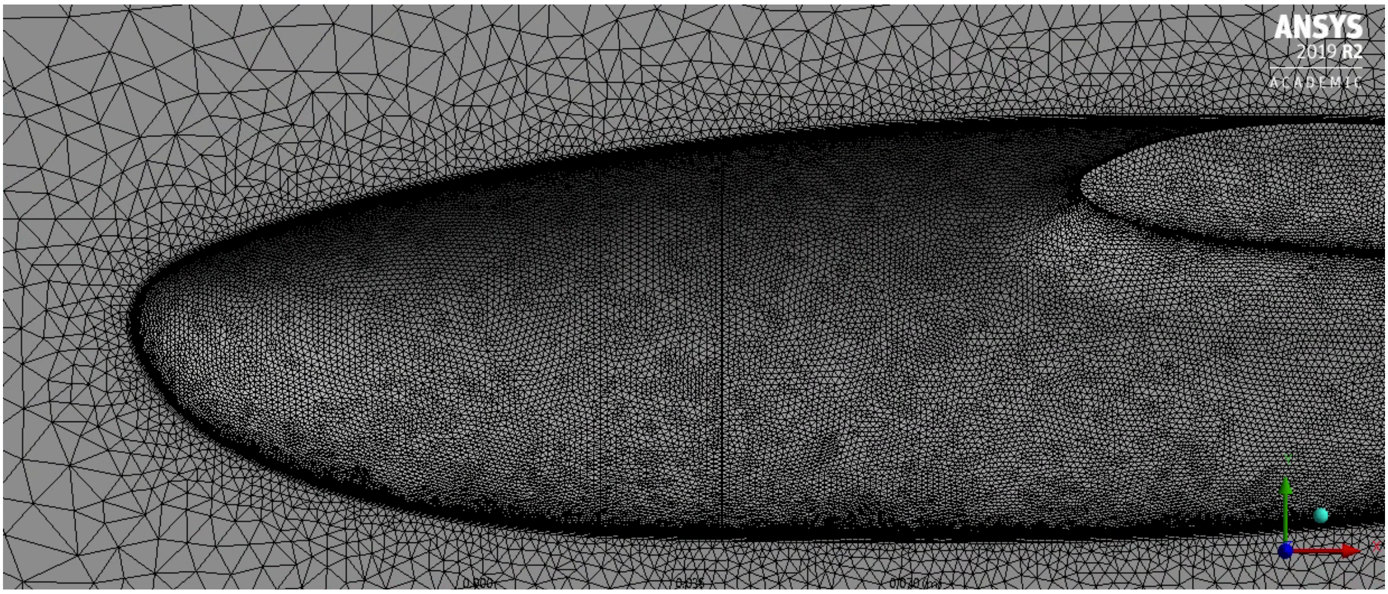


Figure X: Face Sizing of Mesh

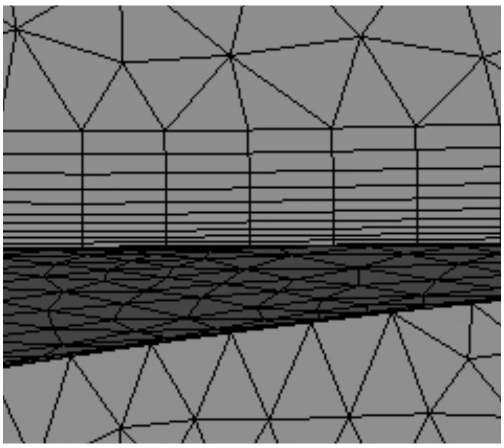


Figure X: Inflation Layers

As I am interested in how the airflow interacts with the UAV's geometry, I created an even finer mesh that covers the entire surface of the UAV. A face sizing mesh parameter was used to select all faces and an element size of 0.001m was set. Additionally I have configured the face sizing parameter to 'capture curvature, doing so ensures that the mesh stays are close to the face especially around areas of high curvature.

Lastly, using inflation layers in the mesh allows an accurate representation of the close interaction in the region where fluid and solid make contact. These regions are vital to observe as it is where different velocities of the inviscid region and viscous region meet, causing shear stresses. As a result fluid particle can move from one layer to another.

CFD Solution Setup

The environment that I will be simulating the UAV within must be set up to adhere to the conditions similar to those found in a real world situation.

The model i will be using is the 2 equation k-epsilon realisable model with standard wall functions. This model is a better choice than the standard model for 2 main reasons; firstly it uses a newer formulation for turbulent viscosity where C_μ is a variable, secondly this model also utilises a more updated equation for the dissipation rate, ε. **[18]**
Other models may yield more accurate results in regards to airflow and its turbulence, however use of this model can be justified by the fact that no a lot of turbulence should be affecting the UAV during flight especially at slow speeds of around 12.5 m/s.

Boundary conditions for this simulation are setup for the inlet and outlet as these are areas where airflow will be entering and leaving the domain from.
The Inlet is given an airflow velocity magnitude of 12.5 m/s with a direction in the X-component. Turbulence is using the specification method of Intensity and Viscosity ratio, where turbulent intensity is set to 5% and turbulent viscosity ratio is 10.
The Outlet is only where the airflow exits from. The pressure profile multiplier is kept at 1 as the exiting airflow is not passing through a nozzle or diffuser which would change the velocity and pressure.

CFD Results

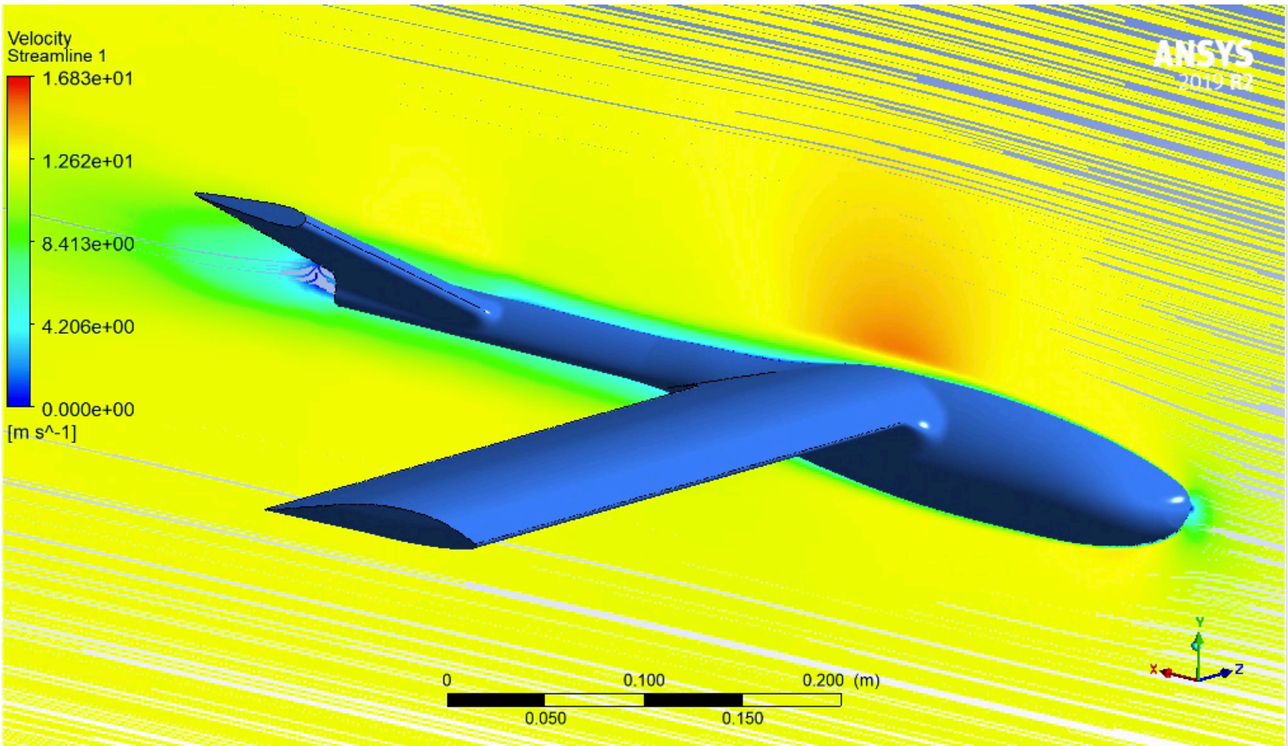


Figure X: Velocity Streamline

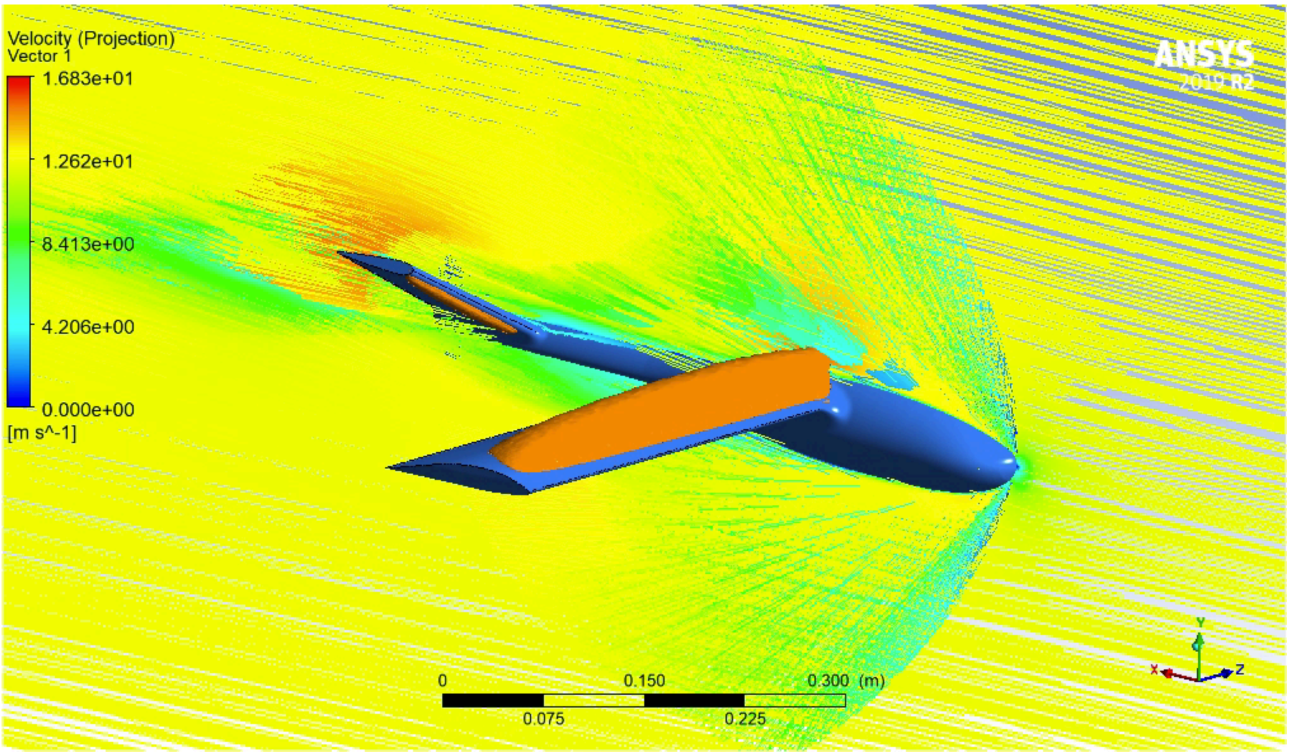


Figure X: Velocity Streamline with Vector Projection and Isosurface

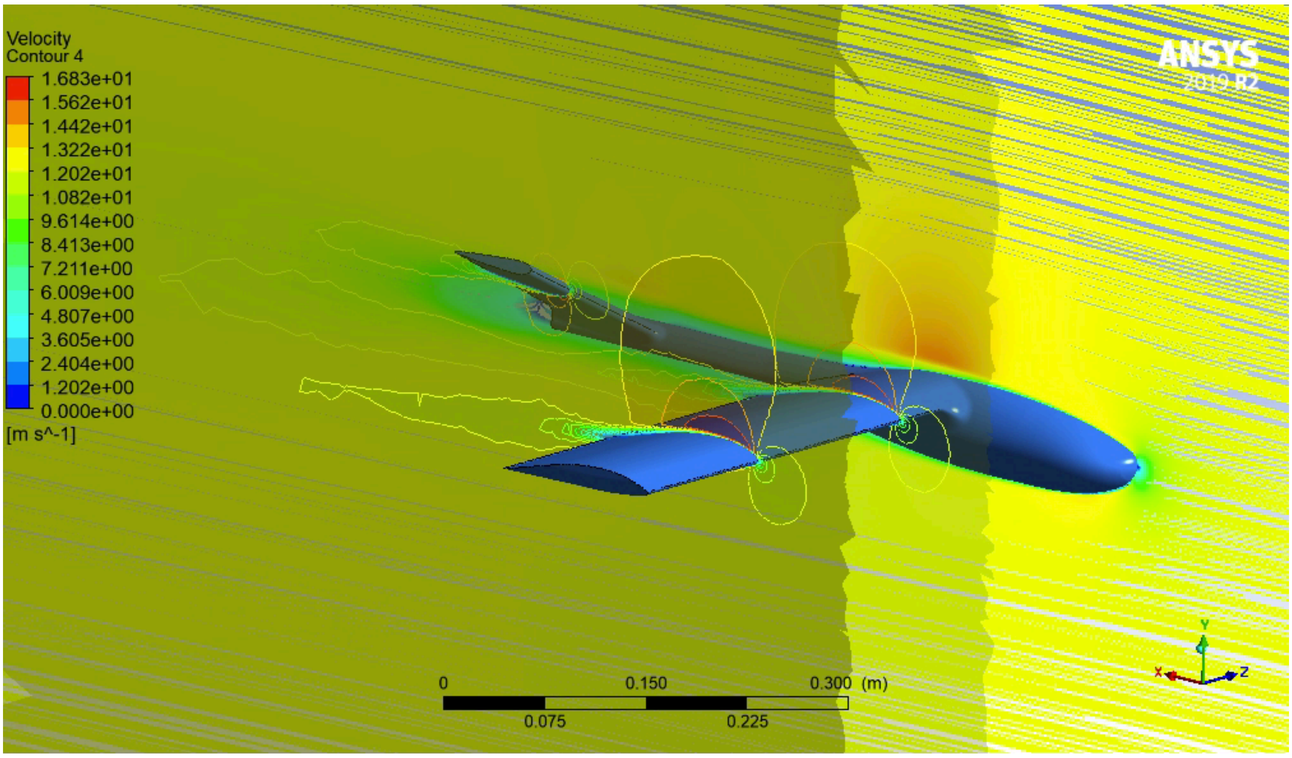


Figure X: Velocity Streamline with Velocity Contours

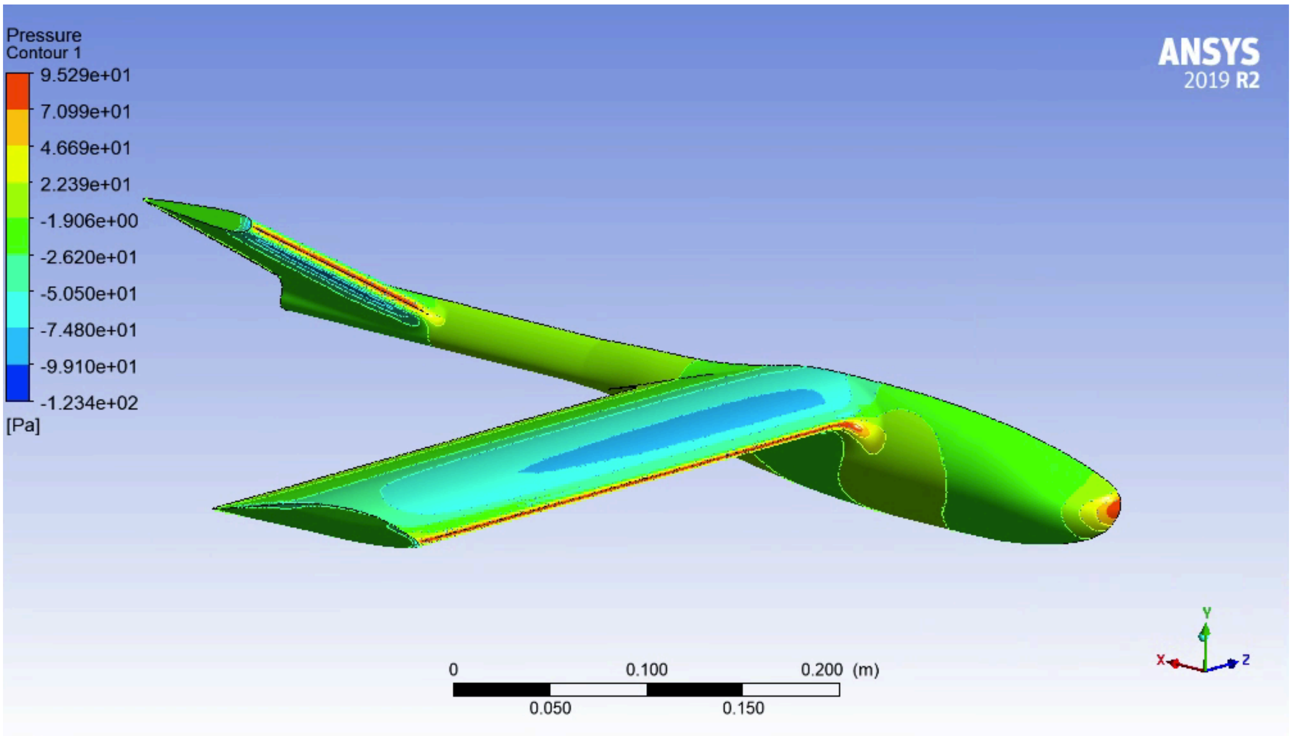


Figure X: Pressure Contours on UAV Surface

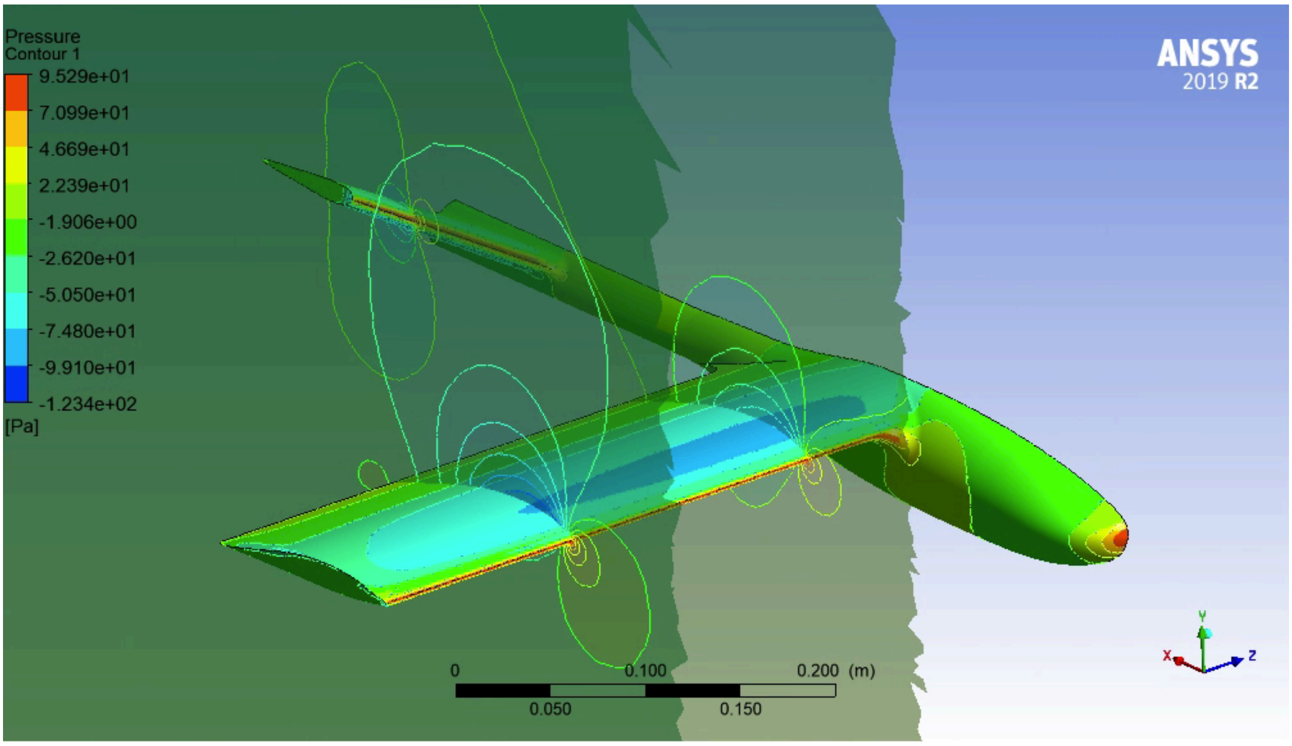
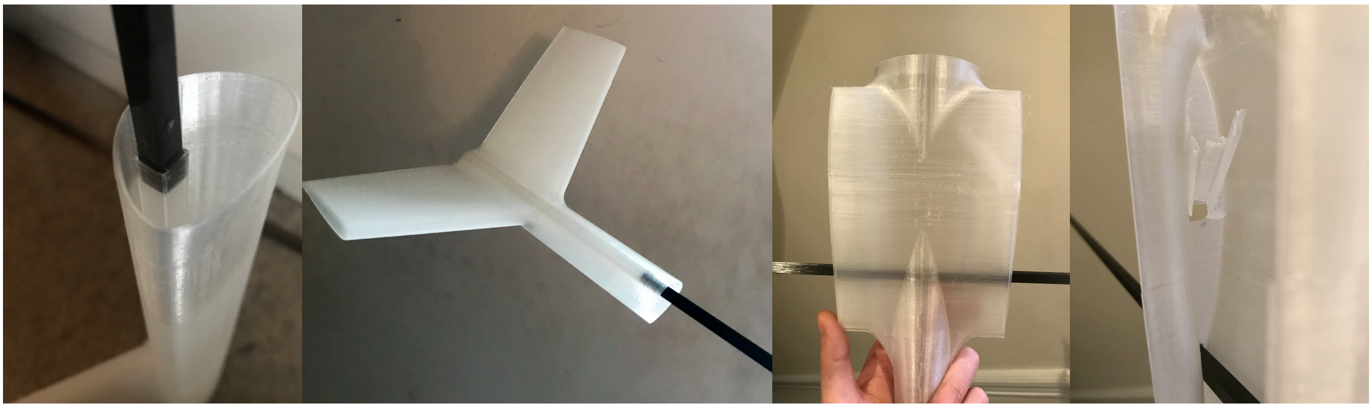


Figure X: Pressure Contours on UAV Surface with Pressure Contours of surrounding Air



These are some of the first 3D printed sections of the UAV. Upon completion they were used to test fit the Carbon Fibre Spars which will connect and align the tail section to the mid-wing section, and the wings to the fuselage. It was apparent that the 6mm thick CF Tube wasn't passing through, as shown in the tail and in the mid section where the plastic broke.
This wasn't due to miscalculation of dimensions in CAD but instead an inherent problem with 3D printing; as the filament is heated and extruded it eventually cools, when the temperature difference between the nozzle and ambient air is large shrinkage with the plastic can occur.
Since the CF tubes were inserted a little, although with great resistance, I made changes in CAD and increased the openings by 1mm to allow for shrinkage.

With shrinkage taken into account, new sections have been printed. Using the CF Tube as a spine, each section was aligned and super glue was used to adhere and fuse the edges together. Additionally, a scrap piece of plastics was glued internally to strengthen the region where the front section meets the mid section.

The fuselage of the UAV is complete, once the glue was given time to fully cure all sections had fused together, this resulted in the fuselage acting as a single uni-body shell increasing its structural rigidity.

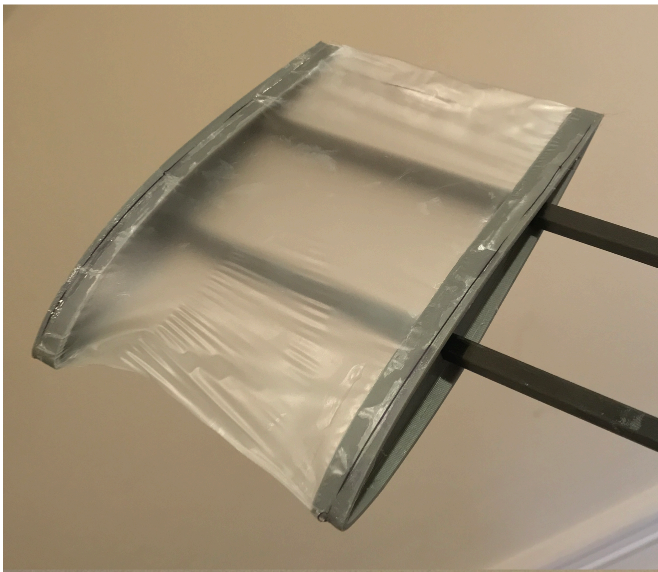
This is the very first wing rib that was designed and printed. I created this prototype before the dimensions for the wings were determined. This rib has a chord length of 200mm and a thickness of 20mm. It was a good prototype to test the capabilities of the 3D printer however the general design of the rib made it very dense and heavy for its size, multiple ribs in the wing with this style would prove to be too heavy.

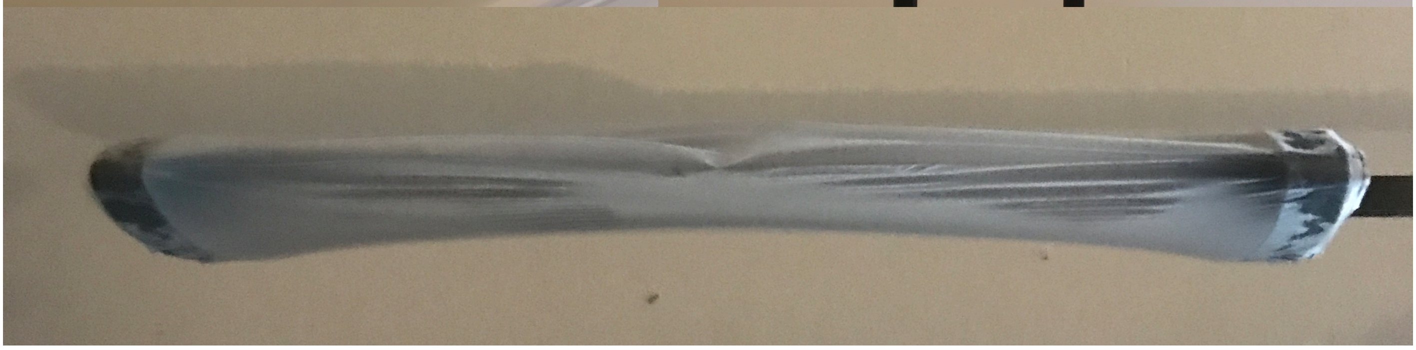
At this stage, dimensional values for the UAV have been figured out, and as so this rib measures a chord length of 150mm.

The shape of the rib is similar to a structural I-Beam.
Weight was reduced by increasing the depth of the flange and decreasing the thickness of the middle section.

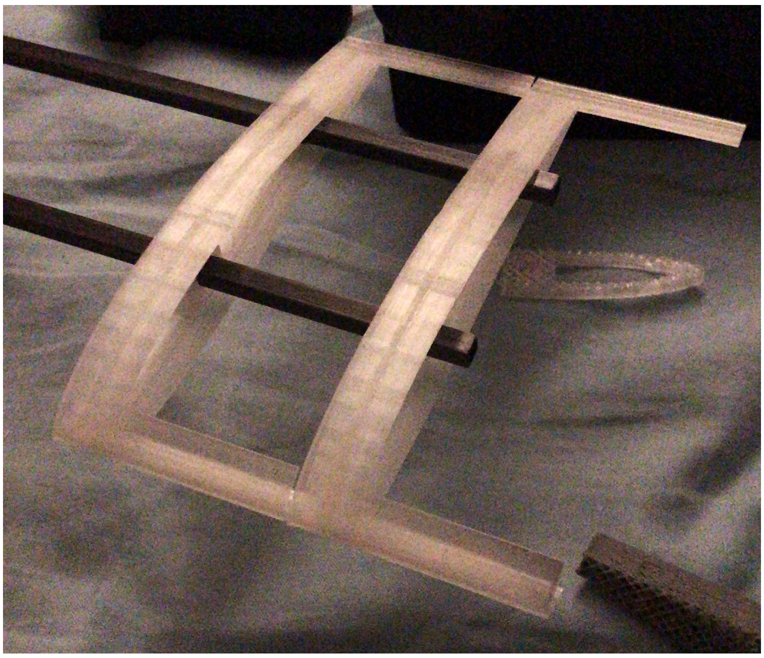
The wing spar holes have been reduced to 6mm to fit over the CF tubes. An additional hole toward the rear was added for the inclusion of a secondary CF tube, I did this to reduce any torsional strain or angular deflection that may be experienced by a single CF tube.

Twisting of the wing could lead to varying Angle of Attack during flight, possibly leading to negative flight characteristics. This prototype, although very light weight, is not rigid. So much so that de-lamination had occurred on the flanges due to shrinkage.

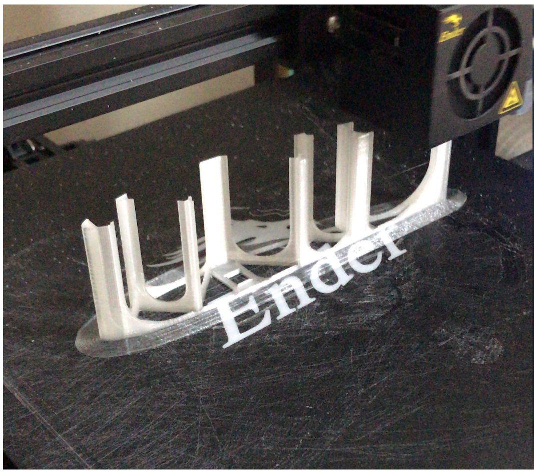


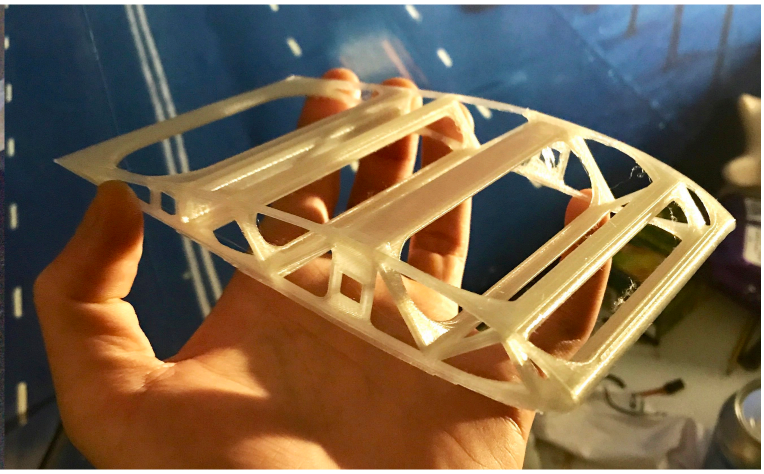


From what I had learnt from the previous rib, I increased the thickness overall on the new rib. This reduced the risk of delimitation during printing. Refinements can still be made to reduce the weight, however for this current period I was interested in testing how large of a gap can be made between the ribs before the Airfoil film don’t follow the require profile anymore. It was determined from this test that the distance is around 100mm before warping occurs. Having the ribs any closer to each other will result in more ribs having to be used in the wings, subsequently increasing weight further.

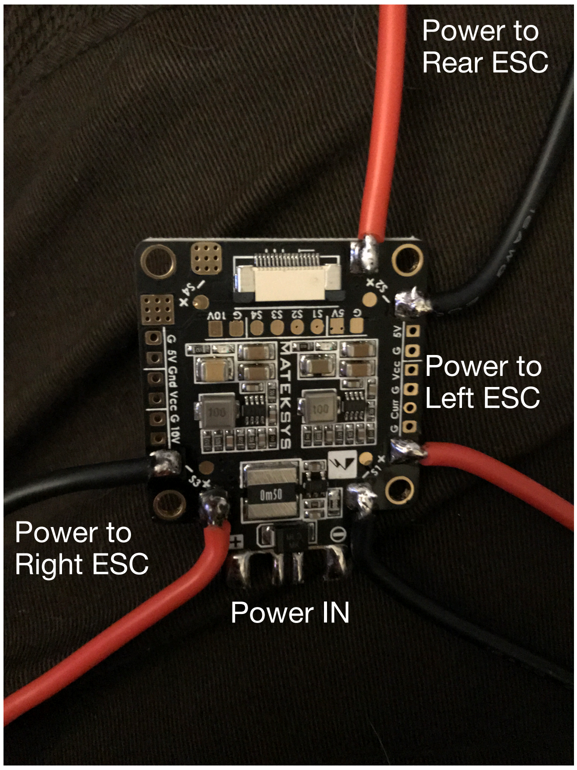


Similar to the previous prototype, this ribs keeps flange and middle section thicknesses the same as it seemed a good compromise for weight and structural rigidity. To over come the issue of foil warping, pillars run from the leading and trailing edge of the airfoil, this give some support for the foil to push against when being tightened. Unfortunately these pillars reduce the distance between subsequent ribs due to the fact that it is difficult to high aspect ratio structures. And so although this design assists in preventing foil warping at the leading and trailing edge, it doesn’t prevent warping anywhere else, and it reintroduces the problem where the closer the ribs are, the higher that quantity of ribs per wing and thus more weight.





The next iteration of wing rib was designed to fix the issues found in the previous prototype. The main issues being the need for further weight reduction and a way to reduce warping of the wing foil. This new design merges two ribs with pillars that connect the two. These pillars allow the 3d printer to use it as support for when printing the top layers, they are also designed to be flush to the profile of the airfoil so when the foil is tightened around the wing, it has something to push against and maintained its shape. Since the pillars can be quite fragile during printing, fillets were made to increase structural rigid at the expense of a little extra weight. Extensive weight reduction was achieved by removing material in areas which didn't need it, mostly seen on the face of each ribs.



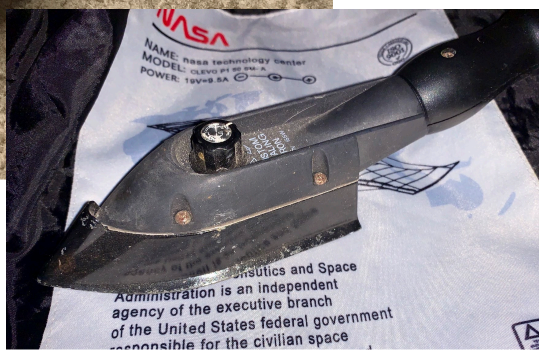
As the PDB will be tucked away within the fuselage it would be difficult to solder connections to it once the airframe had been fully assembled.

And so I begun routing the power leads down the tail of the fuselage and to the ends of the wings to allow the ESC's and motors to be soldered.

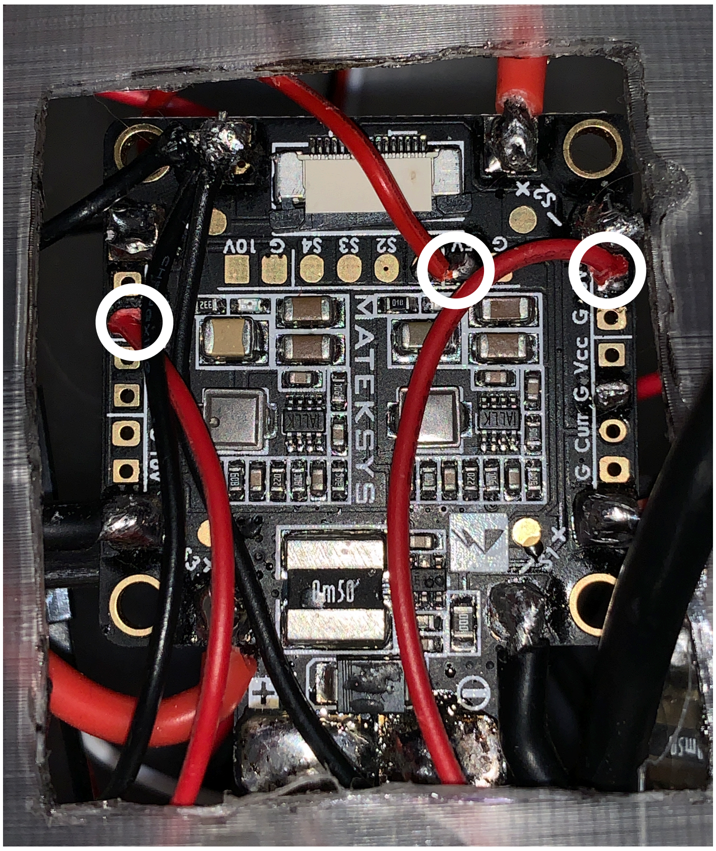
With a final design being chosen for the wing ribs, I begun additional testing of the the foil. The wing ribs were initially connected to the CF Spars to keep them aligned whilst each face was superglued and fused together. The CF spar can then be removed and reinserted later.

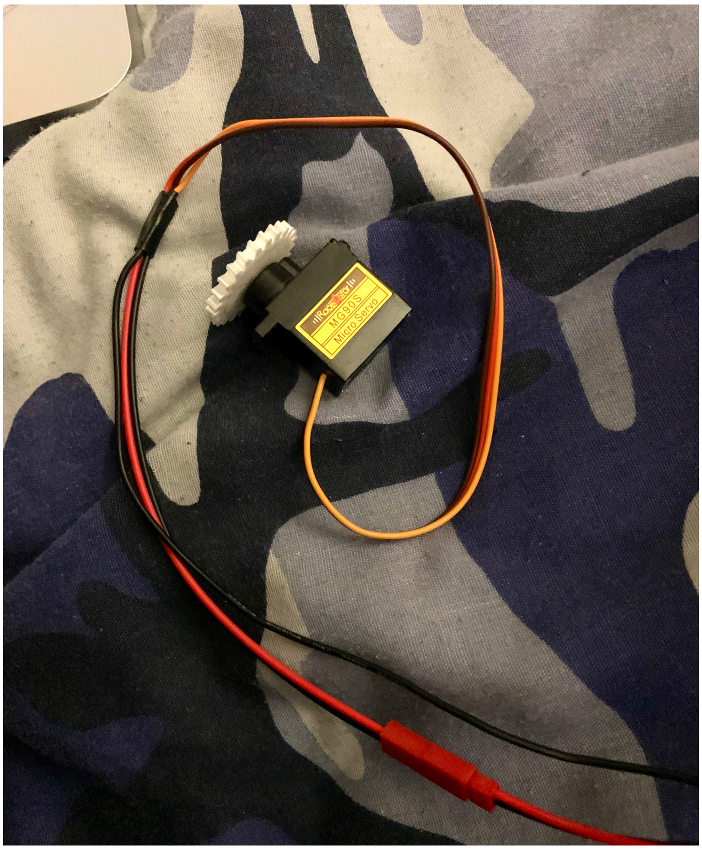
Typically, a small heated iron is used to heat the foil causing it to shrink and conform to whatever shape it is covering. At the time, I didn’t have access to an iron and so used the heat from a soldering iron instead, it worked well enough to show that the rib i had developed was successful for its application.

Once I had acquired a foil iron I was able to strip the foil from the previous attempt and start again. Due to the iron having a large surface area to dissipate the heat I was able to get the the foil much tighter and true to the airfoil profile. This adds additional strength to the wing and ensures that the airflow around is consistent.



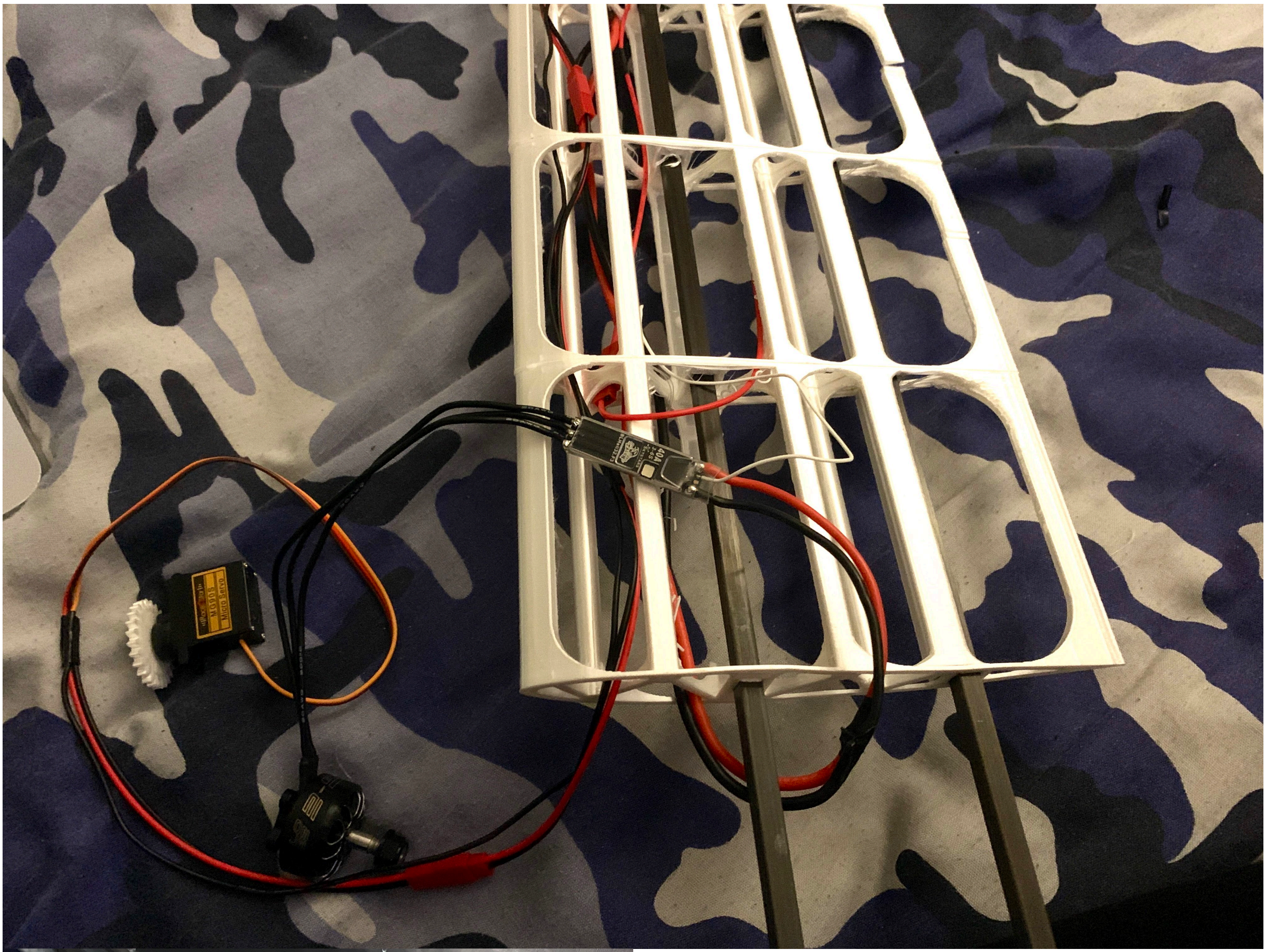
Both wings have had their foils installed, had the CF tubes run through them and attached to the fuselage. Power cables can be seen running out the ends of the wings and out of the the tail. Next in the assembly will be attaching the motor tilt mechanisms, soldering the electronics, and plugging signal outputs into the Pixhawk for actuator control.

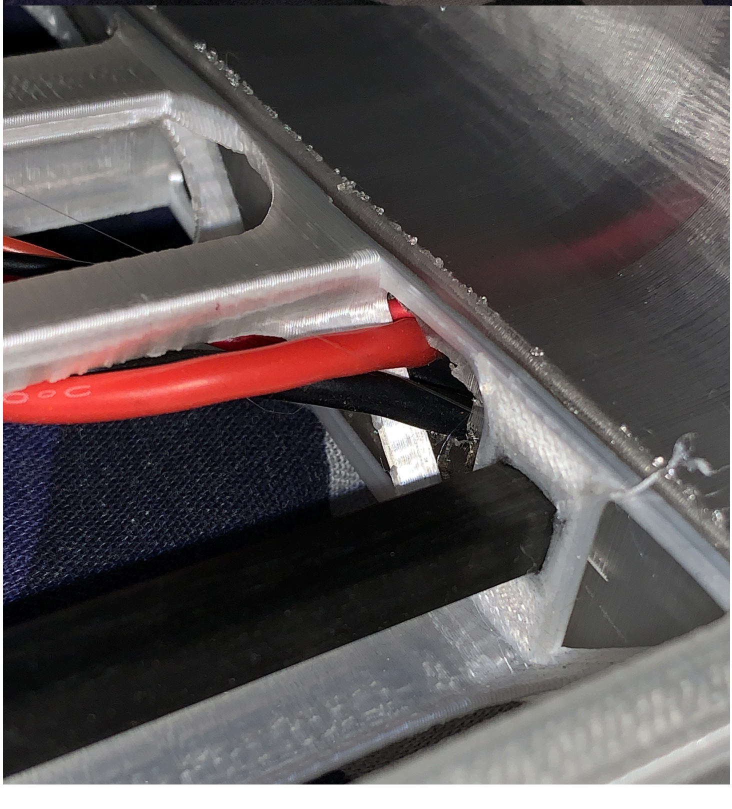




As predicted, it would be difficult to solder new connections to the PDB once installed into the fuselage.
Unfortunately i realised the the servos cannot be directly powered by the Pixhawk FC. Because of this I had to supply each servo with 5volts.

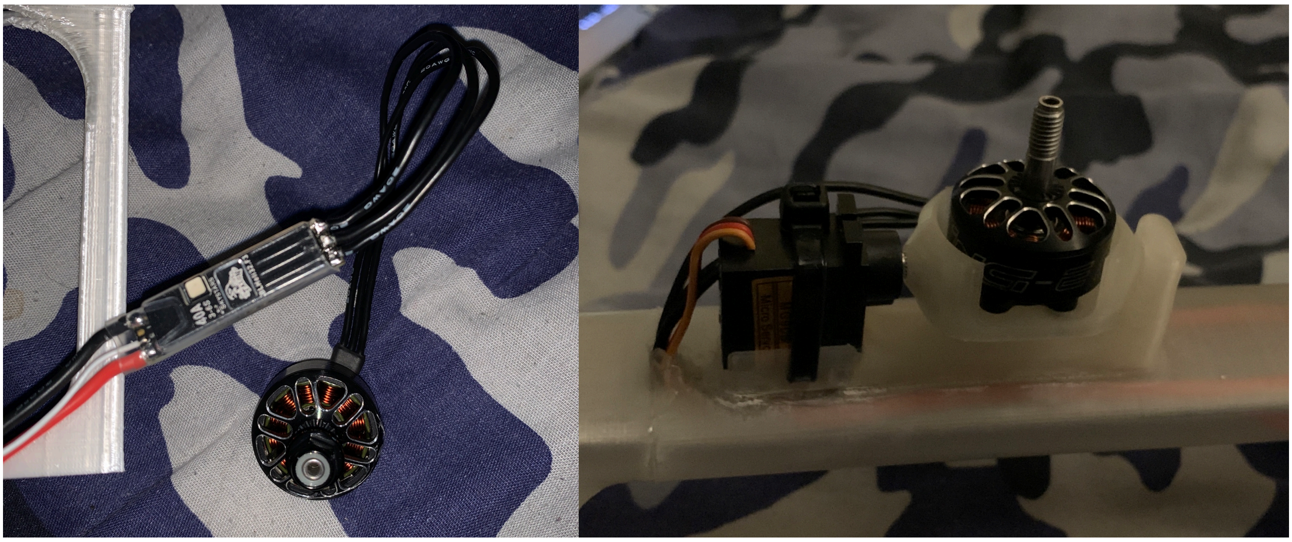
For each of the 3 servos, a new wiring harness had to be made. This harness splits the signal and power cables, the power cables are ‘daisy chained’ with the JST connectors leading to the 5volts on the PDB. A long black wire was used to extend the servo signal wire to connect into the Pixhawk.





All wiring is routed internal through the wing. It would be better to run the power cables and signal wires separately at a distance to reduce the chance of electromagnetic interference which may introduce noise into the system.

A small hole was cut into the fuselage to allow routing of cables into the main airframe.



A zip-tie is used to constrain the servo into the holder. The motor is attached to the motor mount with screws underneath. To prevent the propeller cut the cables from the servo and ESC, have tucked the majority of the wiring and the ESC within the tail boom of the UAV.

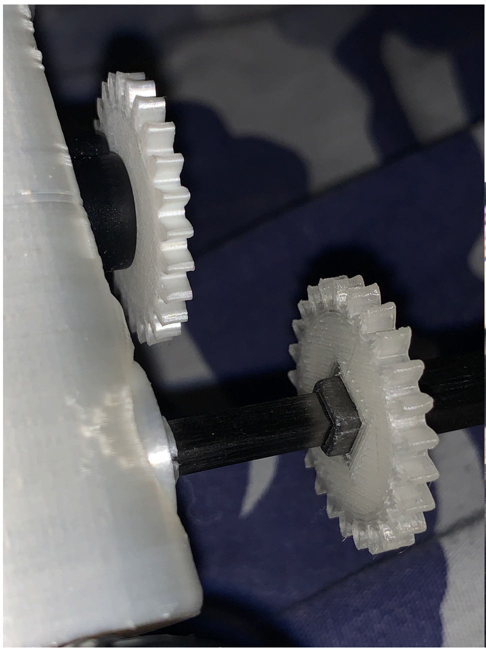
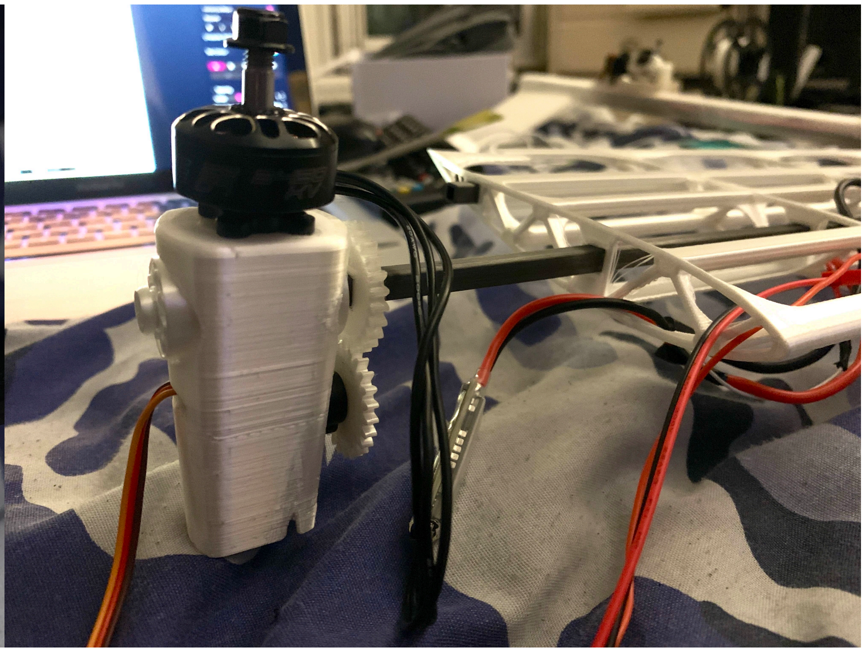
Hot glue was used to tack the mechanism in place and super glue was used around the parameter to fuse the airframe and the tilt mechanism together.

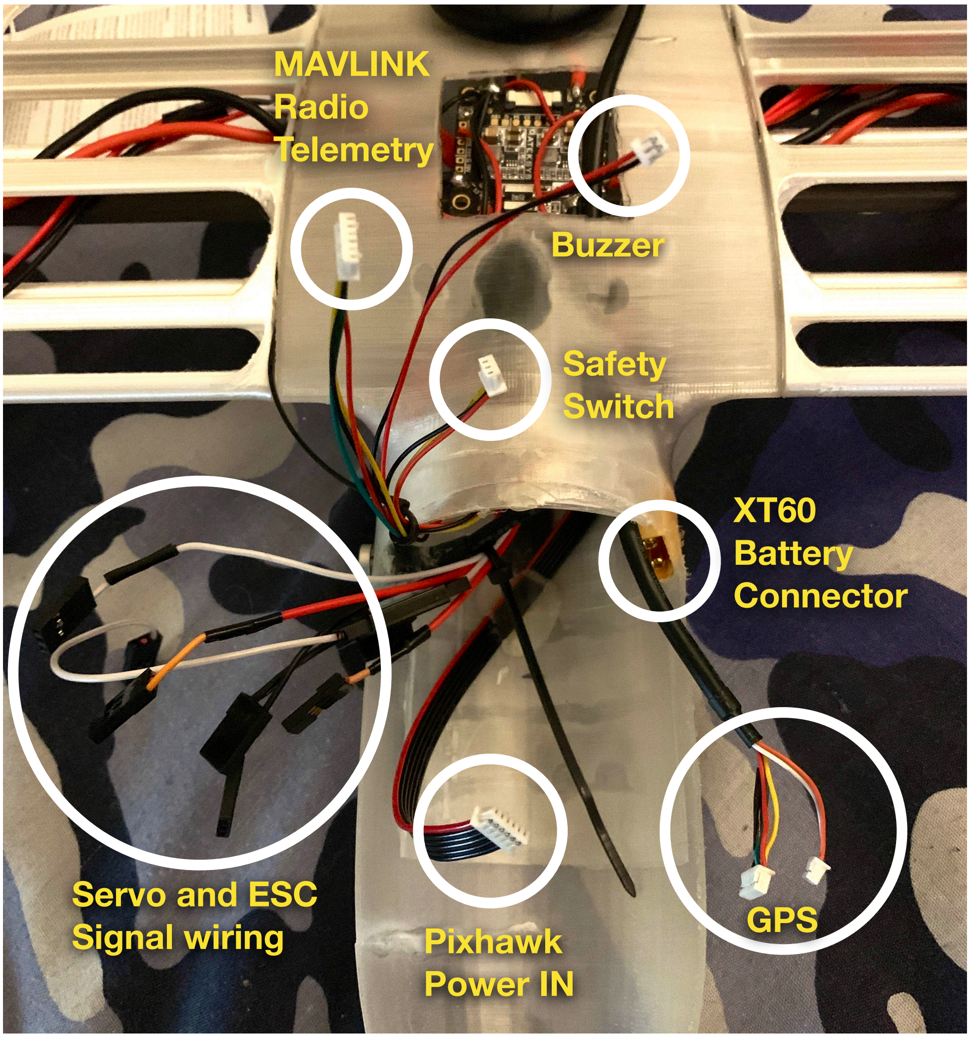
The tilt mechanisms used on the wings for VTOL capabilities use many components to operate. The main body houses the servo, in which the wiring can be passed through, and the motor is screwed to that top.

3D printed bearings were used to reduce the resistance of the shaft when the main body is pivoting around it, and since these bearing won’t be subject to high levels of loading they should function well without breaking. Metal bearings were an option, but was decided against due to their weight and cost to purchase.

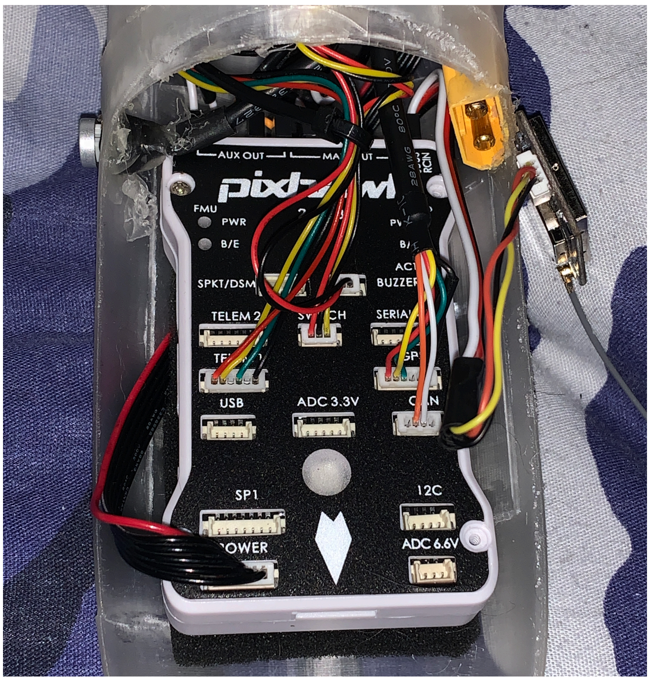
Smaller 4mm CF tubes are used a shaft for the mechanism, a 3D printed adapter make the region of the shaft cylindrical and so will fit tight within the bearings. The 4mm tubes can be fed into the internal opening of the 6mm CF tubes and superglued together.

A cog is pressed onto the servo and a small screw holds it in place. This cog will interlock with another cog fixed to the 6mm CF spar of the wing.



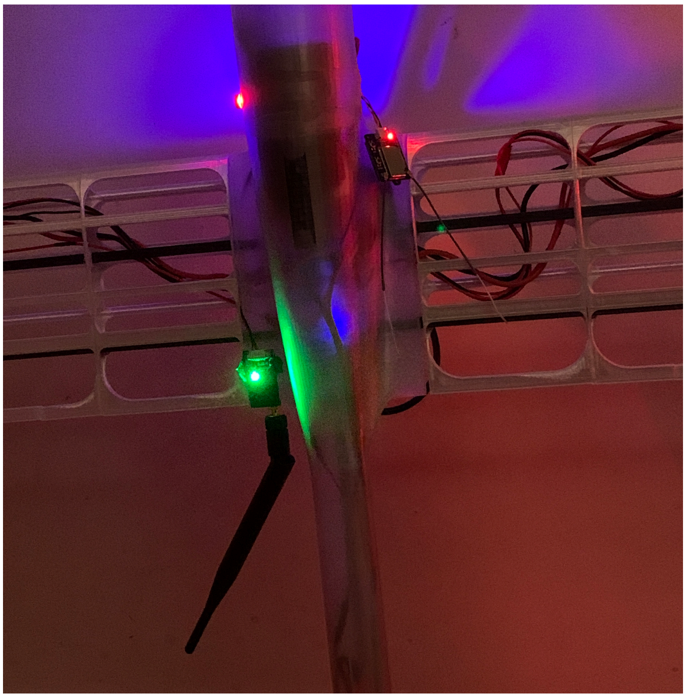
With everything mostly installed, the cables that need to be plugged into the Pixhawk FC are pulled through the airframe and zip tied to keep the wiring tidy.



All signal wires are now plugged into the output ports of the Pixhawk FC.

With a battery plugged in, the FC is able to get power as well as all other electronics.

The safety switch can be seen in red at the side of the UAV, this switch is used to arm the motors.

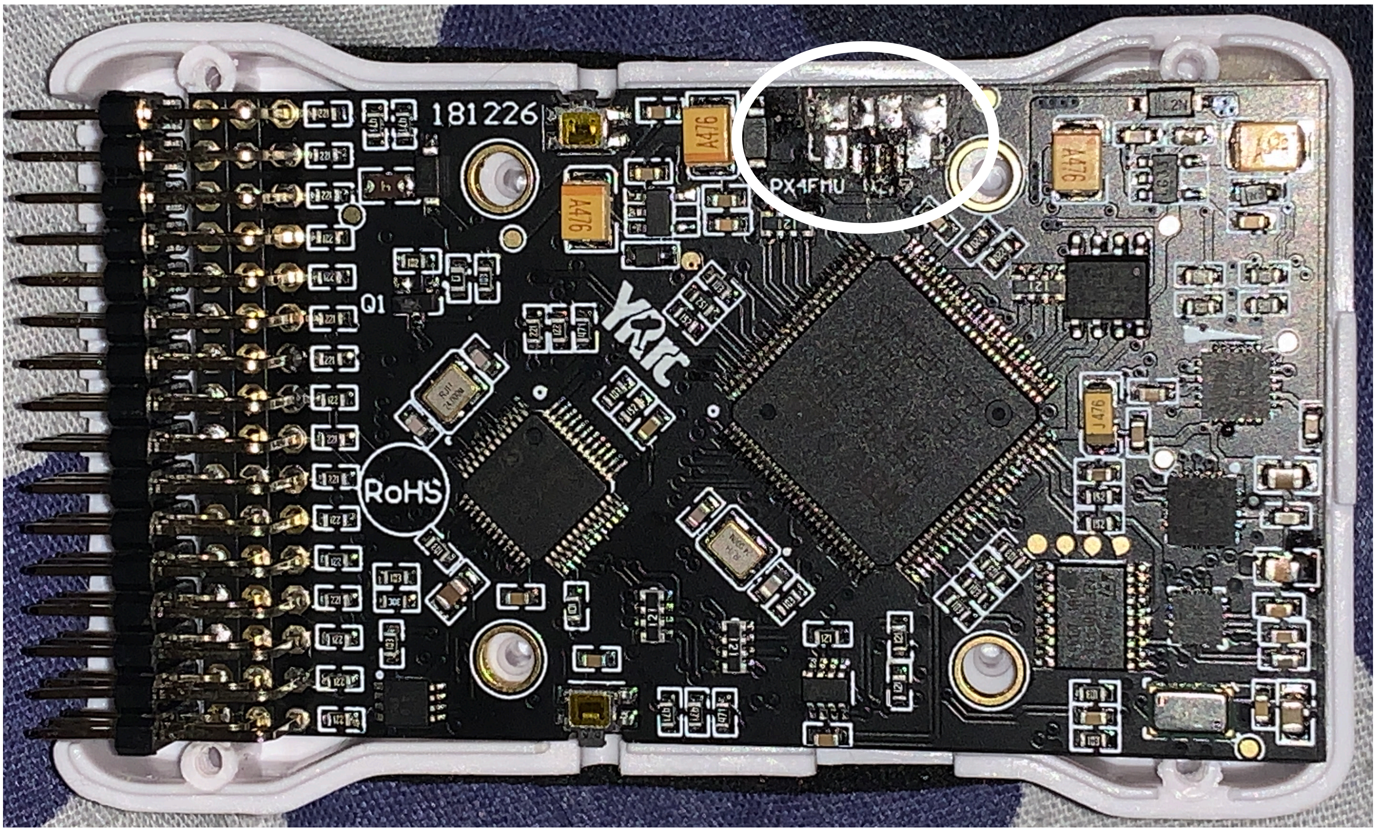


A blue from the FC indicate that the craft is armed and ready for next command.

Red lights are a power indicator for the ESCs and PDB.

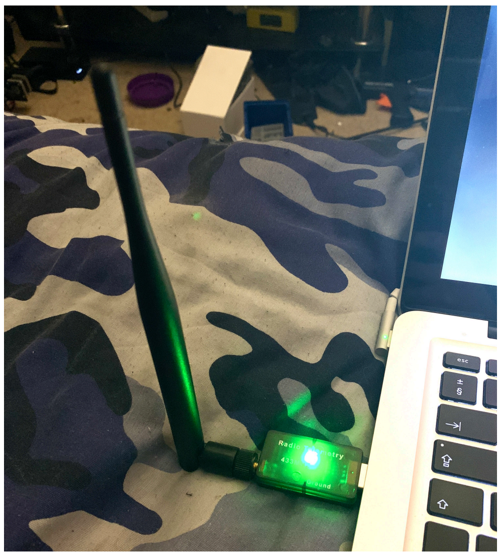
The green light towards the rear indicates that the mavlink telemetry transmitter is powered up and ready to transmit.

In the picture beside, the radio receiver can be seen also with a red power indicator light.



During the process of configuring the Ardupilot software for the Pixhawk FC, the micro-USB port which allowed communication between the FC and the computer had broken off. On inspection of the board it was apparent that the solder joints used were very poor, resulting in the micro-USB port shearing off of the FC and staying connected to the datalink cable.

Although very frustrating I proceeded to attempt to re-solder the port back onto the board. I was able to recreate it however it was too difficult to solder the data connections without specialist equipment. Use of the MAVLINK telemetry was an option to wirelessly communicate between the FC and computer, unfortunately the radio reciever needed a firmware update which was only possible through purchasing a data cable to connect to SERIAL port devices. Given the current state of the country during this pandemic, it would be difficult to the acquire this in time.



MAVLINK Radio Telemetry

Video footage was successfully captured of the UAV responding to pilot commands through a radio transmitter for movement of servos manually as well as autonomous movement of the tilt mechanisms when flight modes were changed.

As a consequence of communication no longer able to the FC, i will be unable in performing a maiden flight of the UAV. Although most of the systems are fully operational, I was in the process of calibrating the ESC to all respond correctly, without this calibration being done, the motors will not run at the correct RPM and the UAV will not be able to fly effectively.

Flight Modes

The Arduplane software allows for use of multiple flight modes. These flight modes can change how the plane operates.

The standard plane flight modes can give fully manual control to the pilot, assisted manual control where the plane can stabilise itself, or by using external sensors like a GPS can perform autonomous flight.

Flight modes are changed from the transmitter and is usually setup as a switch.

As the UAV I am developing will need VTOL capability, the flight modes i will be interested in are Q_ variants of the normal plane flight modes.

Symbol	Definition
-	Full manual control of flight surfaces
+	Manual control with stabilized limits or assistance
s	Stabilized control with limits
A	Automatic control
SPD	Controls speed

Mode	Roll	Pitch	Throttle	GPS	Need TX	Summary
MANUAL	-	-	-		Y	Manual control surface movement, passthrough
FBWA	s	s	-		Y	Roll and pitch follow stick input, up to set limits
FBWB	s	A	SPD	Y	Y	like FBWA, but with automatic height and speed control
CRUISE	A	A	SPD	Y	Y	like FBWB, but with ground course tracking and terrain following
STABILIZE	+	+	-		Y	Wing-leveling on stick release
AUTOTUNE	s	s	-		Y	like FBWA, but learns attitude tuning while flying
TRAINING	+	+	-		Y	Manual control up to roll and pitch limits
ACRO	+	+	-		Y	rate controlled mode with no attitude limits
Q(Copter Modes)	s	s	A	Y	Y	Varies depending on mode. See quadplane documentation
AUTO	A	A	A	Y		Follows Mission
LOITER	A	A	A	Y		Circles point where mode switched
CIRCLE	A	A	A			Gently turns aircraft
GUIDED	A	A	A	Y		Circles user defined point from GCS
Return To Launch (RTL)	A	A	A	Y		Returns to and circles home or rally point
LAND (AUTO)	A	A	A	Y		Final part of automatic mission for touchdown

Figure X: Flight Modes

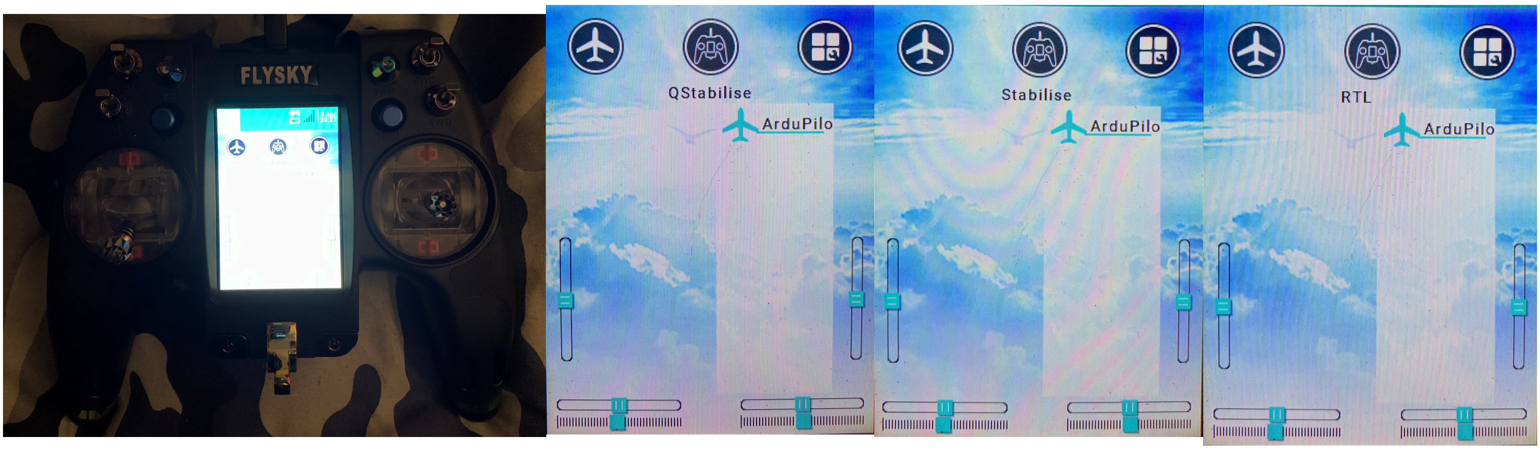


Figure X: Transmitter and Flight Modes

Ardupilot is an open source autopilot software, developed over 5 years, and is currently the only autopilot software able to allow control of most vehicle's. Ranging from cars, tanks airplanes, multi-rotors, helicopters, boats and submarines.

Development and refinement of the software over the years, along with advancements in microprocessors has allowed further support for hybrid vehicles such as quad-planes (planes with 4 motors for use of VTOL).

The open-source code base means that it is rapidly evolving, always at the cutting edge of technology development.

With many peripheral suppliers creating interfaces, users benefit from a broad ecosystem of sensors, companion computers and communication systems.

Due to the software's open-source code, reliability and usability for most applications many OEM UAV companies, such as 3DR, jDrones, PrecisionHawk, AgEagle and Kespry, have the software installed in their aircraft.
Several large institutions also used Ardupilot for testing and development of experimental systems, this includes NASA, Intel and Boeing.

Ardupilot is the software/code that is used flashed onto a flight control. To configure the software parameters another software, Mission Planner, is used.

Figure X: Ardupilot Mission Planner Configurator

What is the PixHawk?

https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=3&cad=rja&uact=8&ved=2ahUKEwjhmPrwrMfoAhW8UhUIHYfQA4gQFjACegQIFRAI&url=https%3A%2F%2Fpixhawk.org%2F&usg=AOvVaw1pXTj9ziL2liEho13Sjt17
https://www.amazon.co.uk/Controller-Integrated-Multicopters-Quadcopter-LITEBEE/dp/B072FKFX3J

Pixhawk is an open hardware flight controller, it is the newest type of flight controller to support Ardupilot, replacing the older legacy APM flight controllers.

Onboard the flight controller are a number of sophisticated components, such as;

- 32 bit STM32F427 Cortex M4 Processor unit
- L3GD20 3 axis digital 16 bit gyroscope
- LSM303D 3 axis 14 bit accelerometer /magnetometer
- MPU6000 6 axis accelerometer / magnetometer
- MS5611 high precision barometer

32 bit processors are able to run newer 32 bit encoded firmware, hence why the PixHawk is a favourable option for this project as VTOL functionality isn't available on legacy Ardupilot software or non-32 bit hardware.

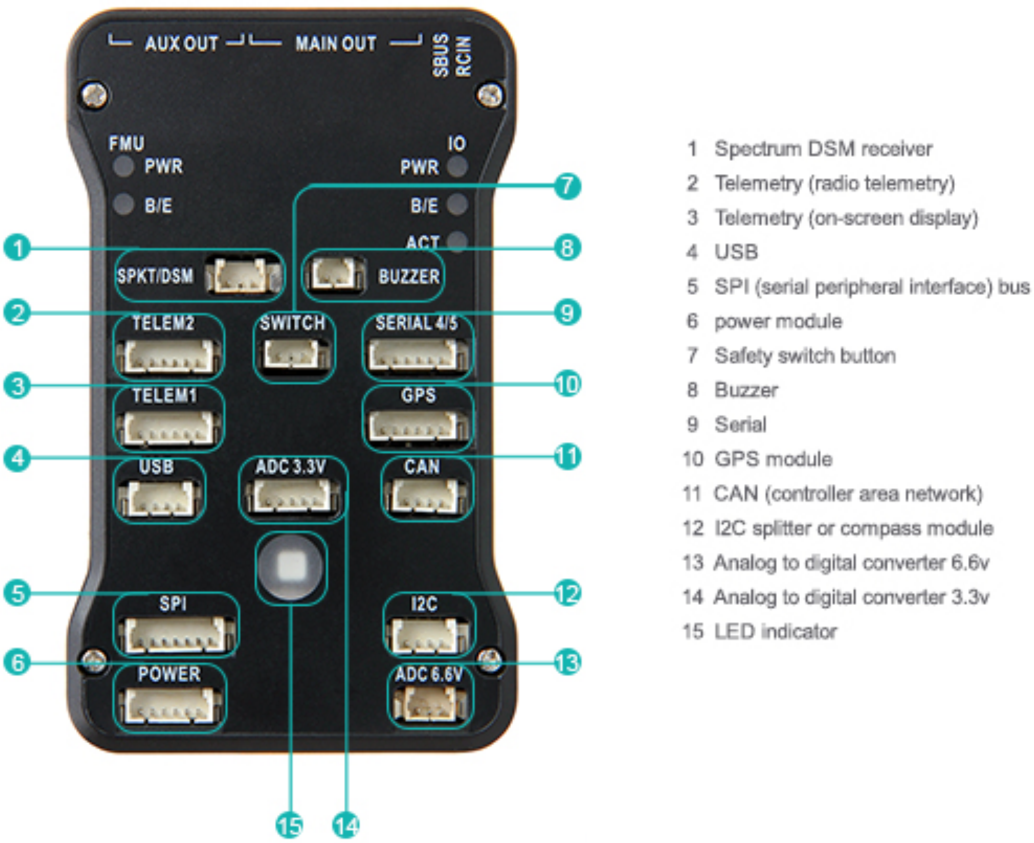


Figure X: PixHawk Flight Controller Connections
https://www.geeetech.com/wiki/images/b/b4/PIXHAWKInterfaceLayout2.jpg

As can be seen in the image above, the PixHawk has the capability to be connected to a large number of external peripheral devices, such as GPS, telemetry recievers, buzzers, and serial ports.

Connecting to the Pixhawk

Once Mission Planner is installed onto the computer, launch it and connect to the Pixhawk via micro USB. Once connected, Windows will detect the Pixhawk and install the appropriate drivers to allow communication.

Figure X: PixHawk USB Connection
https://ardupilot.org/plane/_images/pixhawk_usb_connection.jpg

To begin communication between the Pixhawk and Mission Planner, select the correct COM port and set the baud rate to AUTO. At this initial stage, connecting to the board won't do anything as no firmware has been flashed onto the Pixhawk yet, more specifically Mission Planner will be trying to talk to the code within the Pixhawk but won't get a response.

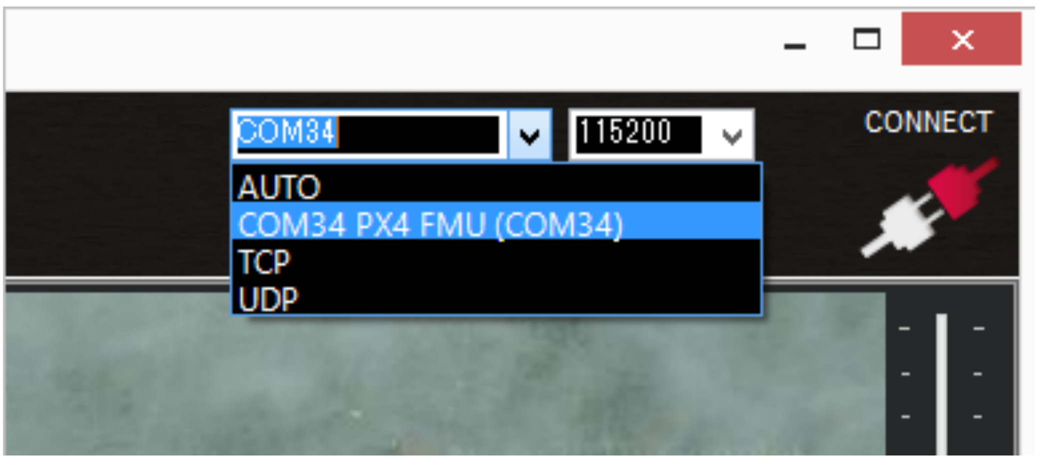


Figure X: Mission Planner COM Port
https://ardupilot.org/plane/_images/Pixhawk_ConnectWithMP.png

Flashing Firmware to the Pixhawk

Flashing the firmware onto the Pixhawk requires locating the Initial Setup tab and Install Firmware screen from Mission Planner. In doing so will display a graphical interface of the different Ardupilot code variations that can be flashed.

These include;

- ArduRover - Used for wheeled vehicles
- ArduPlane - Used for Airplanes
- ArduCopter Quad - Used for quadcoptors
- ArduCopter Hexa - Used for Hexa-copters
- ArduCopter Octa - Used for Octa-copters
- ArduCopter - Used for Helicopters
- ArduCopter Tri - Used for Tri-copters
- ArduCopter Y6 - Used for Tri copter configuration with 6 motors.

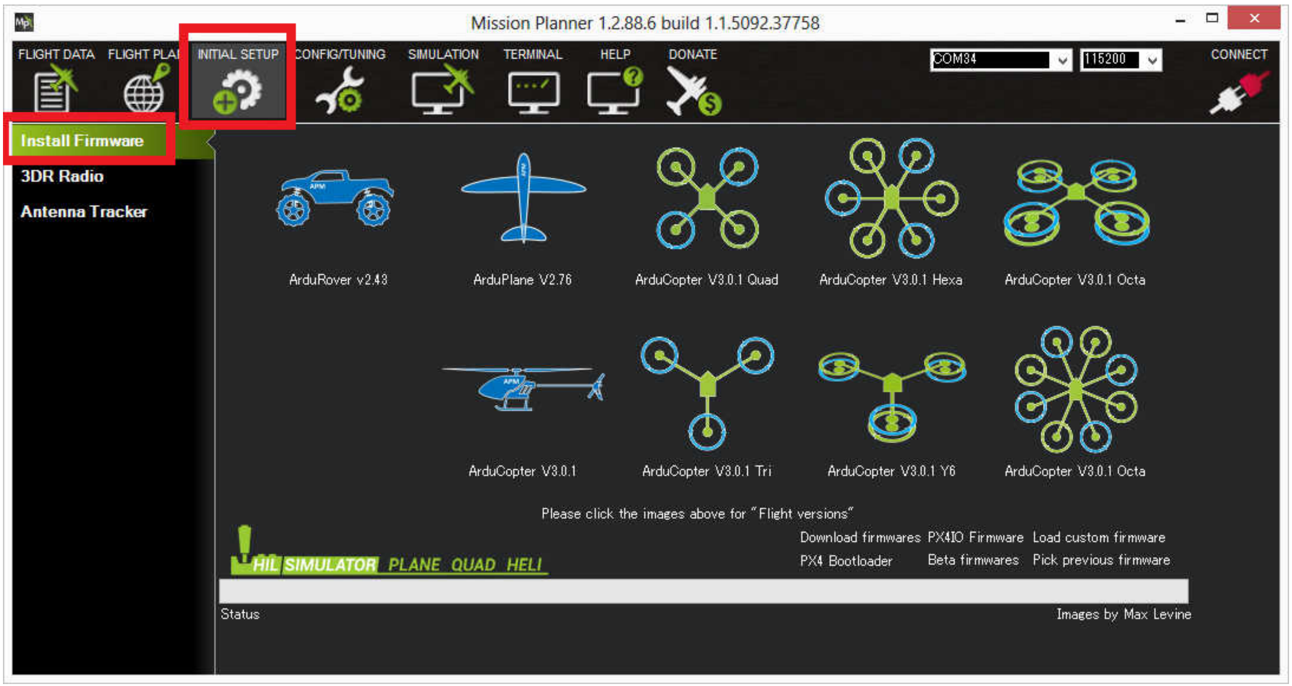


Figure X: Mission Planner Install Firmware Screen
https://ardupilot.org/plane/_images/Pixhawk_InstallFirmware.jpg

Selecting an icon will proceed to initiate the firmware flashing process. For my case I will select the ArduPlane configuration which will be modified to allow QuadPlane features needed for VTOL.

Once ArduPlane is selected, it will download the specific .hex file from the internet. With the .hex file downloaded, Mission Planner will request that the board is unplugged and then plugged in again. Mission Planner does this to detect what flight controller it is flashing to as well as to give the boot-loader on the Pixhawk a brief period to be accept the new firmware to be flashed.

ArduPlane Configuration

For the UAV to be able to fly horizontally, using wings as a main means of vertical lift, ArduPlane parameters will allow this to be possible. However ArduPlane does not support VTOL capability until some parameters are activated.

A plane with VTOL capable is classed as a QuadPlane, this is so it is easier to distinguish the parameters relating to normal Plane flight or parameters for Q-Plane flight characteristics.

Parameters can be found by going to the Flight Plan tab and locating the Full Parameter List. From here specific parameters can be searched for and modified. This screen will give a description about each parameter as well as what the options for modification are.

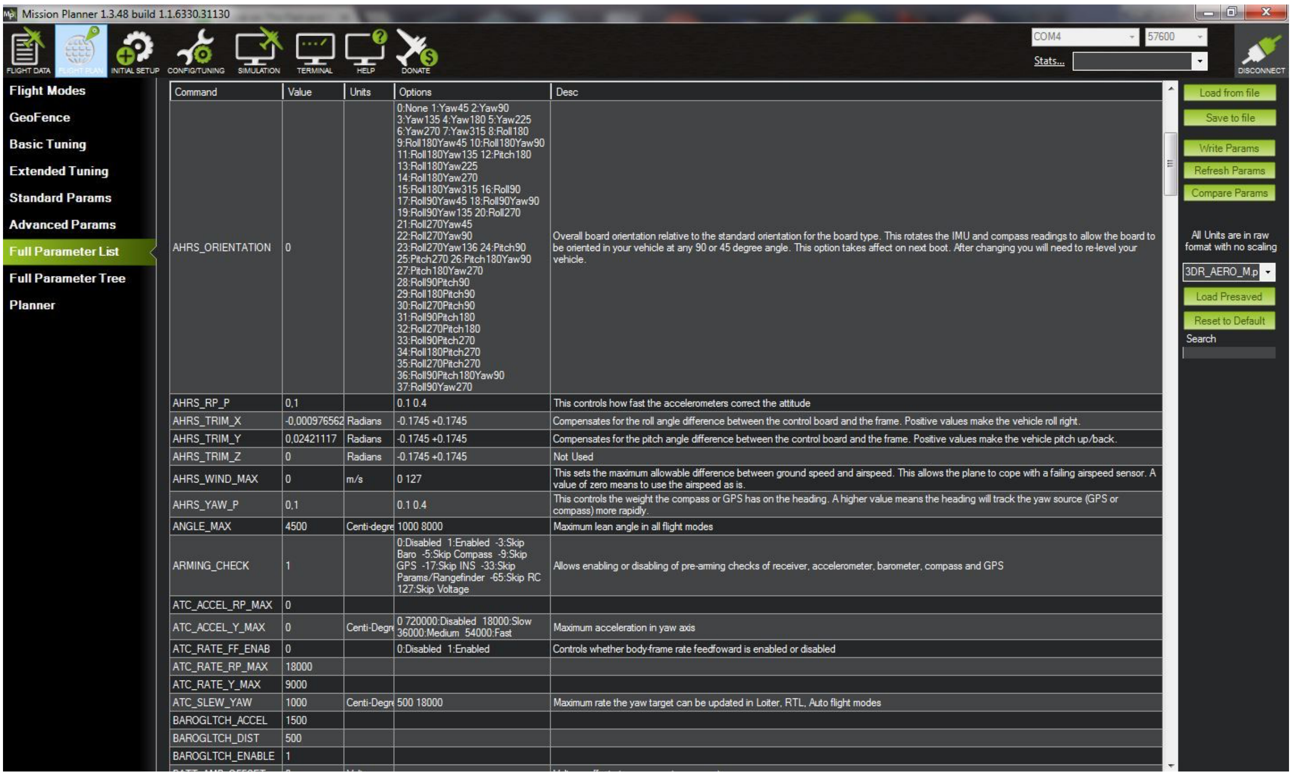


Figure X: Mission Planner Full Parameter List Screen
https://discuss.ardupilot.org/uploads/default/original/2X/1/15384f46005d1919ae4907c045567e61495bbba2.JPG

Before any other parameters are changed, QuadPlane functionality must be enabled to configure VTOL characteristics.

Searching for the Q_ENABLE parameter and changing the value to 1 so that Q_ENABLE = 1 will activated VTOL functions and all other Q_ parameters.
Once Q_ENABLE = 1 a restart on the Pixhawk is required to be able to view the new Q_ parameters.

Ardupilot uses parameters and PID rates which are quite conservative and not too aggressive, this ensures that most airframes in which the Pixhawk placed into will have relatively docile flight characteristics. Tuning and optimisation of these settings can be refined to fit the airframe characteristics. Because the purpose of the UAV is to demonstrate VTOL capability and simple flight, I will not be concerning myself with modifying the stock Plane parameters as the presets are already satisfactory. Emphasis will be put on understanding and developing the Q_Plane parameters for VTOL usage.

Q_FRAME_CLASS = 7

// Frame class refers to what configuration the motors are in during a hover. As the UAV uses 3 motors in a tri configuration the Frame Class is set to 7.

Frame Class	Q_FRAME_CLASS
Quadcopter	1
Hexacopter	2
Octacopter	3
Octaquad	4
Y6	5
Tricopter	7

Figure X: Q_FRAME_CLASS

Q_TILT_MASK = 3

// This parameter is a Bit-mask referring to which motors are able to tilt on the UAV. As the UAV is only tilting the 2 front motors for VTOL transitioning the mask is set to 3, as 1+2 = 3.

Q_TILT_TYPE = 2

// This parameter sets up the tilting method to be continuous servos with vectorised yaw.

Tilt Type	Q_TILT_TYPE
Continuous	0
Binary	1
Vectored	2

Figure X: Q_TILT_TYPE

Q_TILT_MAX = 45 degree

// The angle of tilt used during transitioning from vertical to horizontal flight is controlled by this parameter. Until the UAV has reached the speed of transition, it will stay at this angle. Once past the minimum speed threshold, the motor will complete the full 90 degree tilt.

Q_ASSIST_SPEED = 10 m/s

// If the UAV is moving slower than 10 m/s, the quad motors will assist in providing stability and lift.

Q_ASSIST_ANGLE = 5

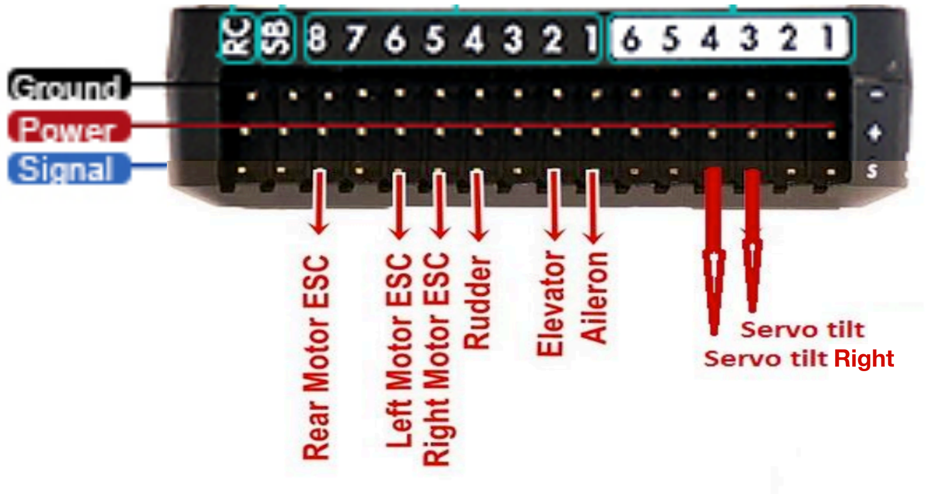
// When Q_ASSIST_SPEED is greater than zero, this is the angle the quad motors will tilt to (from horizontal) to provide assistance at low speeds.

Q_TILT_RATE_DN = 0

// Tilt rate downward when set to 0 will use the same value as Q_TILT_RATE_UP.

Q_TILT_RATE_UP = 15

// This parameter sets up the speed that the motors will tilt during a transition. As **Q_TILT_RATE_DN = 0,** this parameter will be used for both down and upward tilting. Its units are in degree/second. And so with a speed of 15 degree/sec, a complete 90 degree transition will take 6 seconds. A slow transition speed is advised as it increases the aircrafts stability during transition.



SERVO11_FUNCTION =41 // motor tilt
SERVO12_FUNCTION =75 // left motor tilt
SERVO13_FUNCTION =76 // right motor tilt

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