The Design and Manufacture of A VTOL UAV

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ABSTRACT

This thesis looks at the practicability of creating a fully electric UAV capable of VTOL. Aircraft that are capable of VTOL is one of the current most popular inventions in the drone world. The capabilities of having properties of different types of drones are what drove this thesis project's making. The UAV is designed using SolidWorks software, and simulations and FEA are also done using the same software. UAV designed has a mass of not more than 5.5 kg without battery, and travel at least 5 km and flight time endurance of 1 hour and speed of 75 km/hr.

The Electronic components consist of; five propellers (One13-inch propeller for horizontal flight mode and four 15-inch propellers for vertical flight mode) with two batteries of 6S 5000mAh connected in series, with a discharge rate of 80C and voltage of 22.2V weighing less than 800g each. The corresponding motors, each with a spec of 400-500KV able to handle a 5-8 S battery and weight of less than 400g. The corresponding ESCs with BEC (Battery Elimination Circuit) of 5.5V/6A can handle input voltage from a 2-6S battery with a maximum continuous current of 150A and maximum burst current of 170A for 10 seconds less than 100g.

The UAV takes off in vertical motion just like a multirotor, and then when it reaches an altitude of 60m, it switches to horizontal flight mode. The UAV uses RC (Remote Control), which requires direct contact with the pilot, and flight control software that the pilot will not see for long distances for specific automated routes taken by UAV via satellite maps. That is why it is equipped with sensors such as gyroscopes, ammeter, GPS, LiDAR, thermal and optical camera necessary for autonomous flight control when following a path created by the Flight control software.

Keywords: UAV: Unmanned Aerial Vehicle**,** FEA: Finite Elemental Analysis**,** CFD: Computation Fluid Dynamics**,** VTOL: Vertical Take-Off and Landing

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Chapter 1 Introduction

1.1 Research Background and Development Trend

UAV, also known as a drone, is an aircraft without a human pilot on board. UAV is part of the Unmanned Aircraft System (UAS), including UAV, ground-based controller, and communication system between the two. Although drones were initially made for military applications, they are now used in different fields such as security, agriculture, entertainment, Surveillance, Transport. Not to be confused with RC aircraft, which only use radio controllers and have to be in direct contact with the drone operator. The UAV may use RC or flight control software for autonomous flights that may not directly contact the drone operator, primarily for very distant flights. The flight control software such as the STIL adds a route the UAV will take and send the instructions to the drone, which follows the route and avoids the obstacles that may be available using sensors installed such as Lidar. Other features such as the GPS, Ammeter, Barometer, Anemometer are also a necessity to help the flight go smoothly.

In 1915 during World War 1 saw the first used aircraft, and in 1939 the US produced the first remote-controlled aircraft. In 1973 after the Yom Kippur War, Israel developed the first modern military drone called Tadiran Mastiff UAV. In the early 1990s, the CIA bought two Gnat 750 drones initially developed by Abraham Karem for surveillance during the Bosnia War, as seen in **Figure 1-1**.

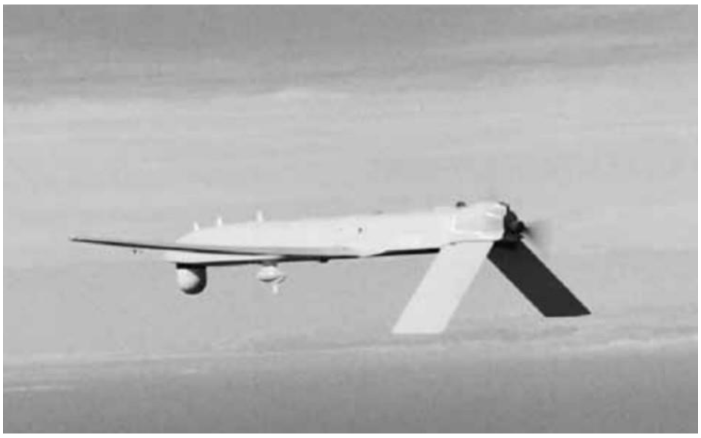


Figure 1-1 The General Atomics Aeronautical Systems Gnat 750.

In 1994 the first models of the Predator drones were introduced, which were deadlier versions of the Gnat 750 that were bigger, steadier, and quieter and allowed to be equipped with missiles in 2000. The use of drones has shifted from military to other applications. There has been controversy on the collateral damage caused by the predator drones, which took many civilian lives in the Middle East. In 2014, Amazon proposed using drones that were simpler than military drones to deliver their packages to households. Since then, many other applications of drones other than the military have been introduced.

UAVs have different levels of autonomy, mainly categorized into two main ones: those under remote control by a human operator or onboard computers. UAV is comprised of two types: Rotary-winged and Fixed-winged drones, as seen in **Figure 1-2**.

(a)

(b)

Figure 1-2 Types of UAVs. (a) Multi-rotor; (b) Fixed-wing.

Rotary-winged drones such as a Quadcopter rely on the vertical thrust of their propellers to keep them in the air, while Fixed winged drones are more conventional like regular airplanes and rely on the lift of wings to keep them afloat. Unlike Rotary winged drones that can hover locally, Fixed wings cannot hover, but their wings increase the efficiency during the flight, which increases flight time.

1.2 The Basic and Significance of the Topic

Research has shown that about 30% of annual crop produce amounting to 450 million $ is lost to weeds. About 21% of field projects are delayed because of the land survey that takes too much time, and 58% of these surveys are risky wherein the US according to DOT, it is estimated that around 3 million inspections of bridges per year are made in dangerous environments. Research shows drones will have a Net Impact of 42 billion Euros, 628000 new jobs, representing nearly 2% of GDP in the UK economy by 2030. The Association for Unmanned Vehicle Systems International (AUVSI) predicts that by 2025 the US drone industry will have more than 100,000 jobs available and add $82 billion to the economy.

UAV has had a significant impact in the world as of late, not only in the military but in other fields as well. These are some of the popular applications of drones:

1.2.1 Agriculture

UAV has been used in agriculture for mapping farm areas and making 3Dmodels of the farm quickly and efficiently, which gives the ability to see the change in terrain over time. UAV can use it for irrigation management as well. Some drones are also used to monitor plant health by showing the field section that has problems. Using UAVs, one can save money on pesticides since they can apply them to only one part of the affected area. Furthermore, effectively use it for distributing seeds in the field and pollination where the drone's wings can cause the plants to pollinate using that wind effect created by the drone. Suppose one has many animals on a farm. In that case, they can use drones to herd animals by replicating the dog's bark. UAV can use a thermal camera on the drone to monitor the animals at night to see all the animals and their location and see no predators and other safety factors.

1.2.2 Conservation

Field-based surveys are expensive and can only measure a small part of the landscape. UAVs can be used to reduce expenses and measure a larger landscape without leaving a footprint. Fixed-winged drones that fly a long distance and stay in the air for a long time are used in mapping large areas such as wetlands, offshore islands, sea birds and turtle habitats, Antarctica system, wildlife behavior even geothermal hotspots.

1.2.3 Construction

UAV can be used in mapping bridges, construction sites, pipelines, power grids.

1.2.4 Delivery

UAVs can be used to transport goods from one place to another instead of using expensive means such as airplanes or helicopters. The area to deliver the load may be hard to reach by road, time-consuming or dangerous. Currently, Rwanda is using drones in Health care by delivering blood banks from one district to the other using fixed-wing UAVs with the help of a company called Zipline. Amazon is also developing a program of delivering packages via drones.

1.2.5 Security

UAVs are used in border patrol units for inspections of dangerous objects. Military UAVs equipped with firearms are used in attacking a dangerous object identified.

1.2.6 Photography and Entertainment

UAVs are used in Hollywood to take images and videos with camera angles normally would not be possible. Music video and documentary producers use drones to captures images and videos. Photographers in events such as weddings, sports, and so on all rely on drones to take nice views. Commercials also use drones. Racing drones are a big thing in the drone industry. Drone formation displays are also an application of drones.

Summary

All in All, the primary significance of UAVs is that they are Timesaving as Convectional Surveying can take days, they can take hours, and processing the results can be done on the same day.

UAV is cost-effective compared to surveys done by Satellites or human-crewed aircraft, and its maintenance is simple, hence reducing the cost of data acquisition.

UAVs offer accessibility to locations that might be hard to access, such as high altitudes or dangerous terrains like active volcanoes.

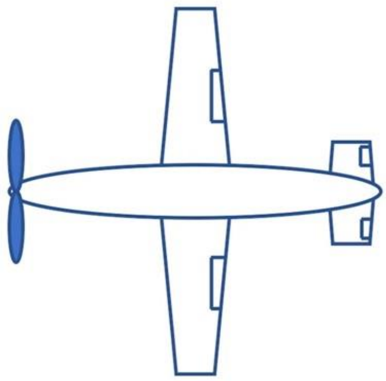
UAVs are more accurate because of their high-resolution cameras, allowing them to capture the smallest detail and accurately map 3D models of the landscape. Land Surveying can be a risky job; that is why UAVs are used to eliminate the need for surveyors to explore unknown terrains.

1.3 Research Contents

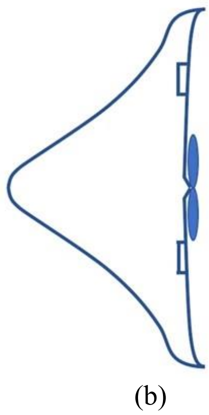
1.3.1 The basic knowledge and principles of UAV flight mechanics and its components

UAVs come in different designs. Studying how each design works and what it can do more effectively than the other can help make it easier to make a reliable drone that is more efficient and cost-effective. One example is fixed-winged drones; they are better suited for long-distance flying, such as mapping a particular terrain. Rotary-winged drones are more of a short time flying and for areas inaccessible because of their ability to hover. Various forces involved, such as Drag and Torque, are studied and command a quadcopter's four propellers in particular ways that allow the drone to roll independently, pitch, yaw, and thrust. We will talk about the two types of drones, which are Rotary winged and Fixed winged drones;

Fixed-wing drones come in different designs and shapes; some come with a propeller at the front, a fuselage, two wings on the side, a tail at the back with horizontal and vertical flaps. On the other hand, blended wing body drones look very futuristic with the wings, and the fuselage morphed into one piece without a tail at all, as seen in **Figure 1-3**.



(a)



(b)

Figure 1-3 Types of fixed-wing UAV (a) conventional body type; (b) blended-wing body.

Whichever design one chooses to make a fixed-winged drone, one must consider which airfoil to decide to generate the required lift. This airfoil, as shown in **Figure 1-4**, which is part of the wing section, can change shape and size along the width of the wing. When selecting an airfoil, one must take into account the purpose of the UAV. Drones used for terrain mapping need an airfoil with low drag and 0^0 angle of attack while racing drones need to change directions more often than an airfoil with higher performance, and a broader lift curve is required.

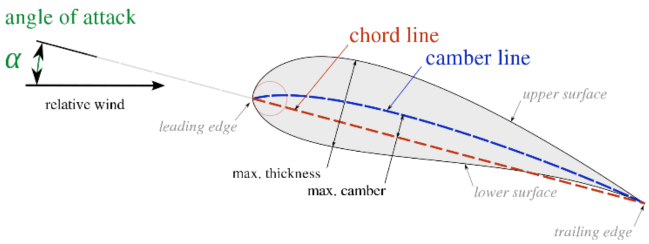


Figure 1-4 Components of an airfoil of a fixed-wing drone.

The most common one is the quadcopter with four propellers used to create thrust and lift for Rotary wings. A quadcopter produces torque from its propellers; that is why for the quadcopter, two propellers rotate in a clockwise direction while the other two rotate in an anti-clockwise direction, as seen in **Figure 1-5**.

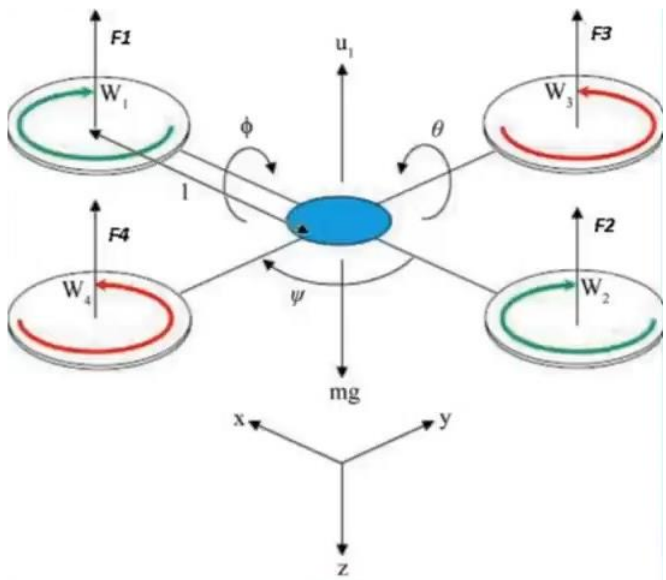


Figure 1-5 The direction of thrust of the propellers of a multirotor.

The propellers are connected to the motors, which ESC drives. By changing the speed of each rotor, the drone can achieve desired torque and thrust.

1.3.2 Electronic and Mechanical relations of a UAV in a UAS

UAV involves both the Hardware/mechanical part, as shown in **Figure 1-6**, which includes assembling different parts of a drone. The software part consists of the code and simulations needed to remote control the drone. Quadcopter consists of a microcontroller connected to various features such as an accelerometer and gyroscope, which provide orientation data. The receiver is connected to a microcontroller, which transfers instructions from the remote controller to the microcontroller. All of these things are powered by a battery. Other components of a Quadcopter include Power Distribution Board, Flight Controller, Camera, Video Transmitter, and Sensors.

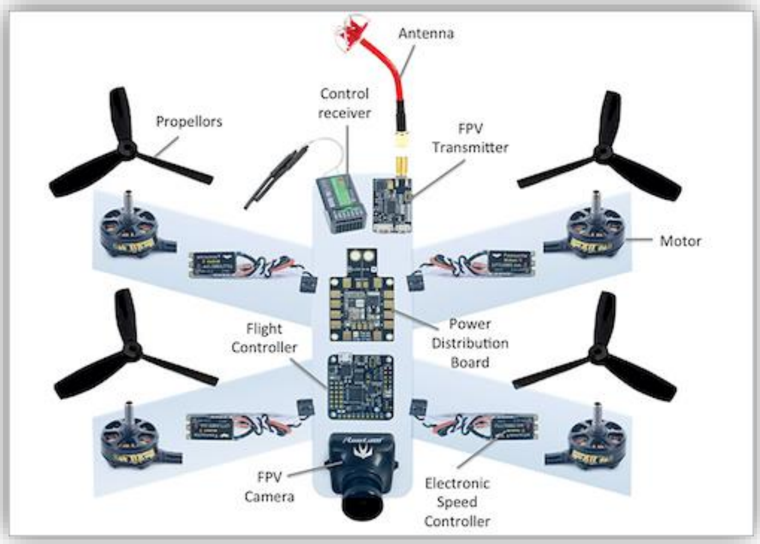


Figure 1-6 Components of a drone.

As a mechatronics student, a drone is the best example of applying this knowledge. For example, the mechanical part can begin with the frame as there are many considerations such as weight, cost strength and size, and material.

We consider the correct size motors, speed controllers, battery size, and electromagnetic interference protection (GPS and Radio communication) for the Electrical part.

Since Quadcopters are inherently unstable, they require control engineering to keep balanced. Hence, a control system measures constant measuring of angle and position and a control algorithm to change motor speed and adjust quickly. Software engineering is essential to ensure everything can communicate with each other, from gyroscope accelerometer processors and speed controllers.

For a Mechatronics System to function correctly, each of these disciplines must be considered to one another.

1.3.3 Challenges facing the Drone Industry

The drone industry is growing rapidly but has a lot more challenges along the way. The most challenging one is the air traffic management system, which is still very far from the desired results. There are many aviation approvals needed for drones to be integrated into the airspace. There are also concerns among the public about their privacy, security, safety, and reliability of the power source of drones to do a given task without failing due to battery issues. Many other challenges are inevitable such as weather, the environment, theft, insurance and costs, communication interference like hacking, unskilled drone pilots. Some areas are banned from drones, Large corporations unwilling to adapt to drone technology and opting to use other conventional means.

Summary

UAV Technology is a very interesting diverse technology involving many engineering fields. It has very high investment opportunities that will have an impact on the economy of many countries. Companies that will develop even more advanced drones are likely to be the topmost wanted and profitable in the years to come as we head into the AI (Artificial Intelligence) and Autonomous vehicle Era.

Chapter 2 Design Principles and Methods

This chapter looks at the procedures took to make the design of the UAV. It includes three parts which are; **Section 2.1** discusses the source idea of choosing the design, **Section 2.2** looks at the process by which the design was made and the assembly, **Section 2.3** shows the process of choosing the electronic components of the UAV. **Section 2.4** shows the communication between the UAV and the remote controller or the flight control software and how they work together.

2.1 Design overview

As seen in Chapter One, which focuses on how different types of UAVs function. This section looks at how to design the UAV in this thesis, which is a hybrid between a multi-rotor(quadcopter) and a fixed-wing UAV.

The first use of VTOL technology was in helicopters, although in the 1960s, with thrust or power vectoring of Harrier Jump Jet came a new era of VTOL. As more research was done on helicopters, many engineers and scientists experimented with helicopters, including the famous Thomas Edison. The French inventor Paul Cornu known as the inventor of the first VTOL brought about that new era that would result in what is known today as VTOL. The helicopter he called Cornu Helicopter lifted him for 20 seconds in the air at about 1 foot in height. In the 1950s with the rise in helicopter technology was the groundwork for the modern VTOL aircraft. In the years that followed, many companies such as Ford Motor Company, Chrysler wanted to make flying cars and made different concepts for which most of them either failed or never reached mass production levels. The 2000s saw the mass production of VTOL aircrafts such as PAL-V. With the rise of the UAV era, as discussed in Chapter One, VTOL technology was also applied to unmanned aircraft.

2.1.1 Idea Creation

Before making the design of the preferred UAV, research was done on different aircraft that are capable of VTOL ranging from Fan-in-wing (Augusta Westland project zero, Tiltrotor (Bell Boeing V-22 Osprey), Tilt-wing (GL-10 Greased Lightning), and vector thrust (Harrier Jump jet) and other VTOL UAV that are developed. Fan-in-wing

VTOL aircraft uses the concept of inserting the propellers inside the wings to reduce drag and lift loss, although it still works more like a helicopter hence not that effective in horizontal flight. Tilt-wing aircraft uses the concept of vertically lifting with its wings (rotors attached) in a vertical direction, and then after a certain altitude, it tilts the wings in the forward horizontal direction for horizontal flight mode. Vector Thrust aircraft uses a method of using the jet engine thrust to vertically lift off then changes the direction of the nozzle for the forward horizontal direction. Vector Thrust aircraft need much power to operate, mainly fuel, so it is not part of the UAV design since the UAV mainly focuses on VTOL aircraft with a battery as source power. Tiltrotor aircraft, of which the designated UAV of this thesis is similarly based, uses the concept of vertical lift-off by rotors then tilting in the forward direction for horizontal flight after reaching a certain altitude.

All of the aircraft have their advantage and disadvantages, as seen in **Table 2-1** below;

Table 2-1 Property of different VTOL aircraft

Aircraft	*Advantages*	*Disadvantages*
Fan-in-wing	-Less drag -Excellent Vertical take-off	-Complex Design -Poor horizontal flight mode -Still in the testing phase
Tilt-wing	-Offers certain advantages in vertical flight relative to a tiltrotor. -Can begin the transition from helicopter to the airplane at zero forward airspeeds.	-Less stable during the vertical flight. -Lower hover efficiency compared to Tiltrotor.
Vector Thrust	-Good vertical Take-off -It does not need rudder and ailerons as much as the other aircrafts	-Difficult in Vertical Landing -Complex flight control
Tiltrotor	Realistic Simpler flight control Faster vertical take-off The superior angle of attack	Takes time and speed before shifting to horizontal flight mode. Loses about 10% of its thrust to interference from the wings

Tiltrotor is the most used, stable, and effective aircraft capable of VTOL among the aircraft mentioned above. With that came an idea of the best effective design that was simple yet effective. Hence, the UAV design was a VTOL that could vertically take off using four rotors in vertical directions and then switched to conventional means of flying like a sailplane using the motor in the horizontal direction, thereby removing the need for a large runway. As shown in **Figure 2-1** below, The UAV is a hybrid between a fixed-wing drone and a quadcopter having properties of both respective UAVs. Since the horizontal flight mode uses mostly wings as a lift force by gliding, the motor power needed is less hence only one motor. For vertical take-off, the thrust needed must be greater than the whole weight of the UAV for it to be capable of hovering; hence four motors are used, which offer a more stable frame for V/STOL(Vertical/Short take-off and Landing).

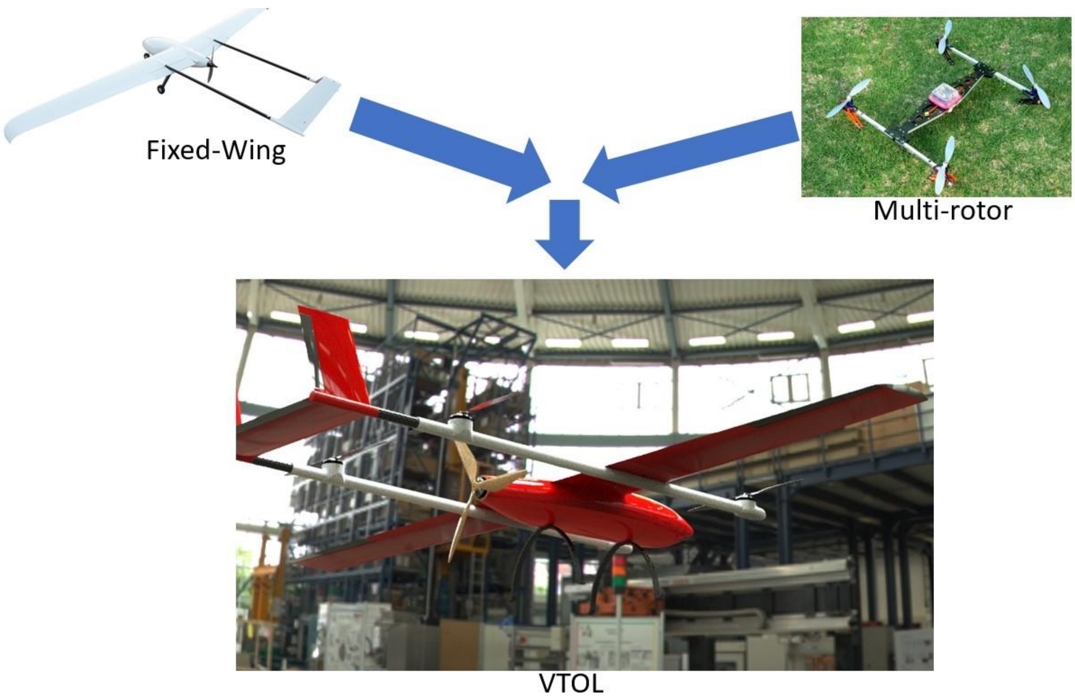


Figure 2-1 Combination of Fixed-wing and Multi-rotor to give a VTOL.

2.1.2 Requirements

It is an outdoor UAV suitable for mapping and surveillance and also delivery. Hence it must have high battery life and endurance to fly over a long distance for a long time, close to what a normal fixed-wing of the exact dimensions would fly. As shown below, these are the design requirements in mind when designing the UAV;

1. It must be capable of flying and hovering like a multirotor during Vertical flight.

2. It must be able to fly like a fixed-wing UAV during horizontal flight.
3. It must be able to Vertically take-off and Land.
4. A battery must power it.

2.2 Airframe

This section discusses the parts of the UAV, excluding the electronic parts, i.e., the drone's shell. We discuss the mass properties of each part, the dimensions, and the given material needed that is not costly, readily available, and not heavy. The UAV is designed to use a battery, but batteries have a low energy density than fuel gases. That is why it is crucial to use materials as light as possible that can withstand mechanical (drop, shock) and environmental (waterproof, salt spray compliant, altitude /low pressure, oil/chemical contamination/corrosion) challenges. Hence, the drone was made from aluminum, carbon fiber, PE (Polyethene), Depron also known as Polystyrene foam, and mostly Balsa wood.

2.2.1 Mechanical Design

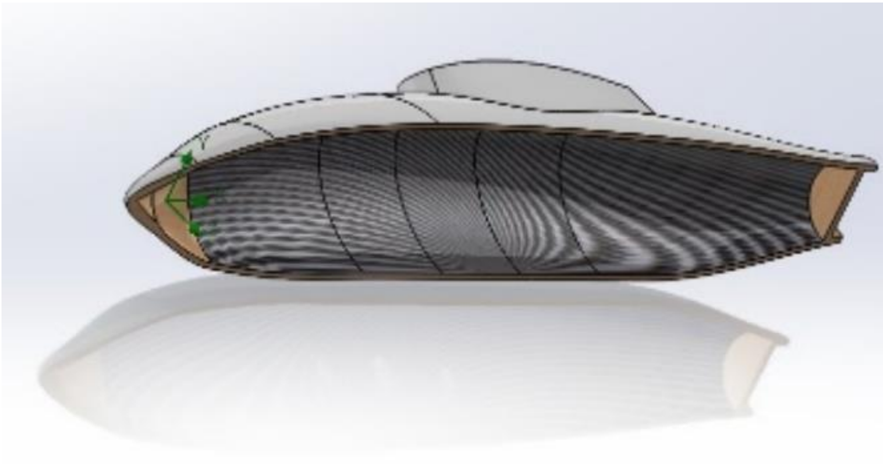
Using SolidWorks, the preferred UAV was designed, which was not an easy task. Still, with many trials and errors, the final design was created while also learning more skills in SolidWorks. **Figure 2-2** shown below is a rendered version of the SolidWorks model using the SolidWorks Add-in feature called Visualize. It shows the fuselage, wings, and frames. Designing the UAV before making a real-life prototype makes it easier to visualize how it will function; for example, the rods of the frame supporting the drone may be closer to each other, and since the vertical propellers are 15 inches, they might intertwine with each other or even be closer to the fuselage, which would be impossible to move. Hence, we get to see all those flaws with the design and correct them to make a more effective design. The design illustrated in **Figure 2-2** excludes the electronic components since those components are just purchased and installed in the UAV and are not fabricated in this project thesis.

Figure 2-2 Mechanical design of the UAV.

2.2.2 Fuselage

A design similar to a conventional airplane for practical aerodynamics was made for the fuselage (**Figure 2-3 (a))**. It was wider in the middle for more space to store the electronics components. The material chosen for the fuselage is Balsa wood covered with a composite of Carbon fiber sheets on the inside (for protection against the overly heated electronic component) then Depron foam on the outside (**Figure 2-3 (b)**). Since the software design, we used balsa wood material; it has a length of 633mm, a mass of (164.22g), a Surface area (0.45m^2), and a volume of the fuselage, as shown in **Table 2-1**. The fuselage has a top and bottom opening for installing electronic parts such as batteries, wires, distribution boards, cameras, or other parts such as sensors according to different applications of the drone (**Figure 2-3 (c);(d)**). The fuselage design also includes the screw holes where the Landing gear is attached firmly to the fuselage and the backspace where the horizontal motor is attached with screws.

(a)



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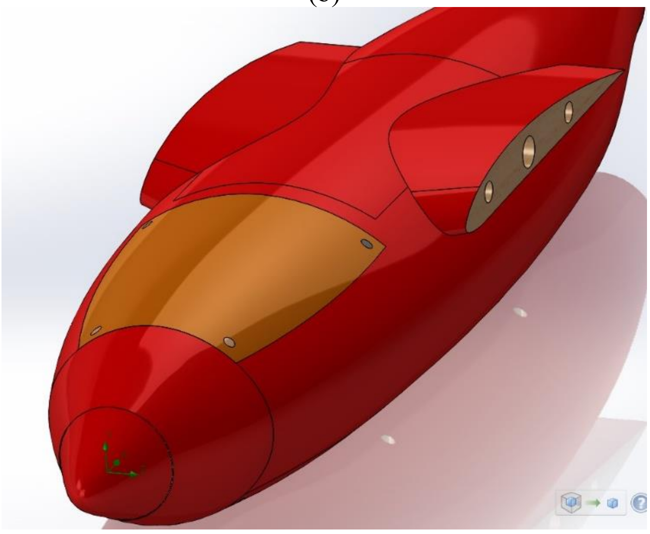
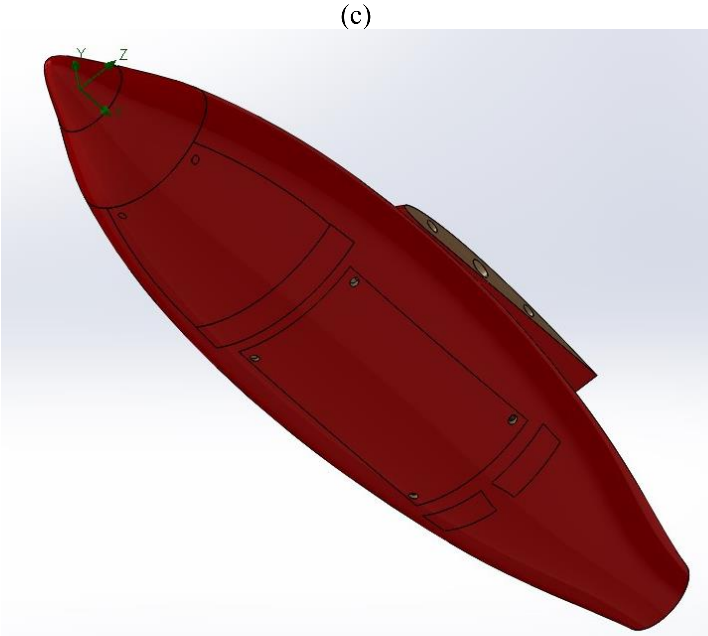


(c)



(d)

Figure 2-3 Fuselage Design. (a) Fuselage; (b) Cross section view; (c) Top Opening; (d) Bottom Opening.

Table 2-1 Mass Properties of Fuselage

Mass = 164.22 grams

Volume = 1026410.37 cubic millimeters

Surface area = 451554.95 square millimeters

Center of mass: (millimeters)
X = 298.19
Y = 4.11
Z = -0.02

Principal axes of inertia and principal moments of inertia: (grams * square millimeters)
Taken at the center of mass.

Ix = (1.00, 0.00, 0.00)	Px = 611730.91
Iy = (0.00, 0.00, -1.00)	Py = 4027349.08
Iz = (0.00, 1.00, 0.00)	Pz = 4213757.01

Moments of inertia: (grams * square millimeters)
Taken at the center of mass and aligned with the output coordinate system.

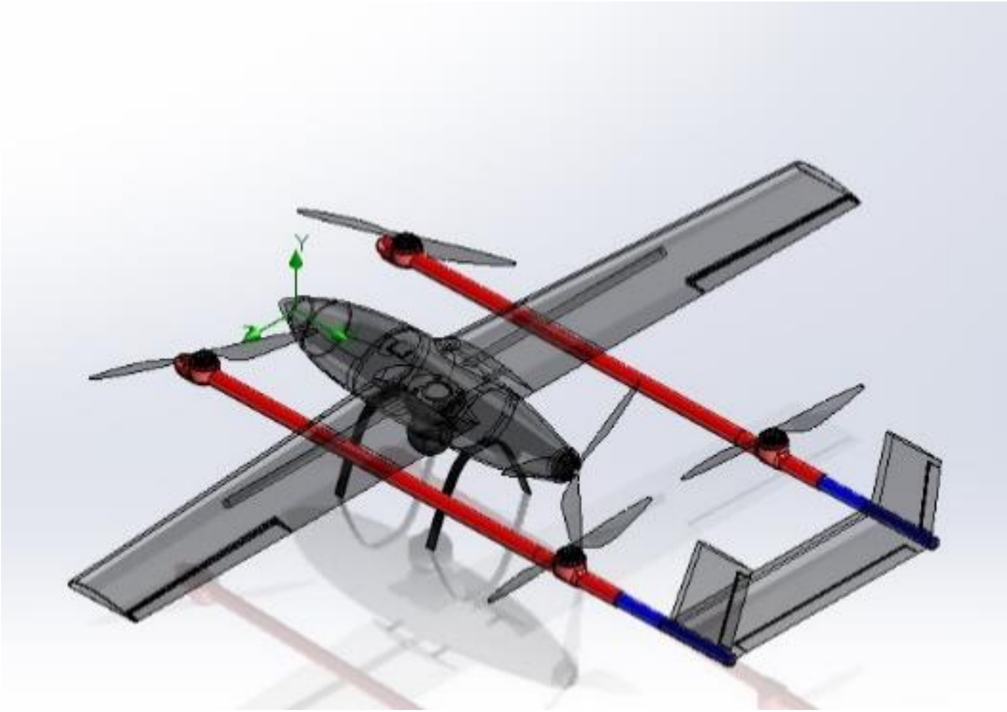
Lxx = 611769.46	Lxy = 11779.68	Lxz = 313.98
Lyx = 11779.68	Lyy = 4213718.33	Lyz = 168.91
Lzx = 313.98	Lzy = 168.91	Lzz = 4027349.21

Moments of inertia: (grams * square millimeters)
Taken at the output coordinate system.

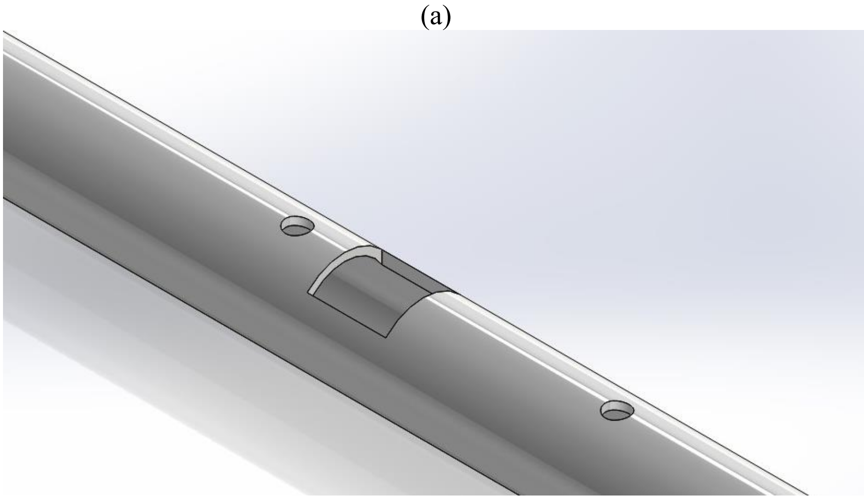
Ixx = 614541.95	Ixy = 212977.72	Ixz = -819.41
Iyx = 212977.72	Iyy = 18814986.62	Iyz = 153.29
Izx = -819.41	Izy = 153.29	Izz = 18631389.81

2.2.3 Frame

The frame comprises two rods and the two motor mounters shown in blue and red color, respectively, in **Figure 2-4 (a).** The frame holds the motors, tail wing, and wings. It is a pathway for the wires to reach the ailerons and the motors and fuselage, as shown in **Figure 2-4 (b)**. The rods have a length of 1147mm and a diameter of 22mm and 16mm for the inside part. The wings are connected to the fuselage by the rods shown in **Figure 2-4 (c)**The material chosen for the frame was the Depron form for the motor mounters and carbon fiber for the rods; hence has a mass of 880g, as shown in **Table 2-2**.



(a)



(b)

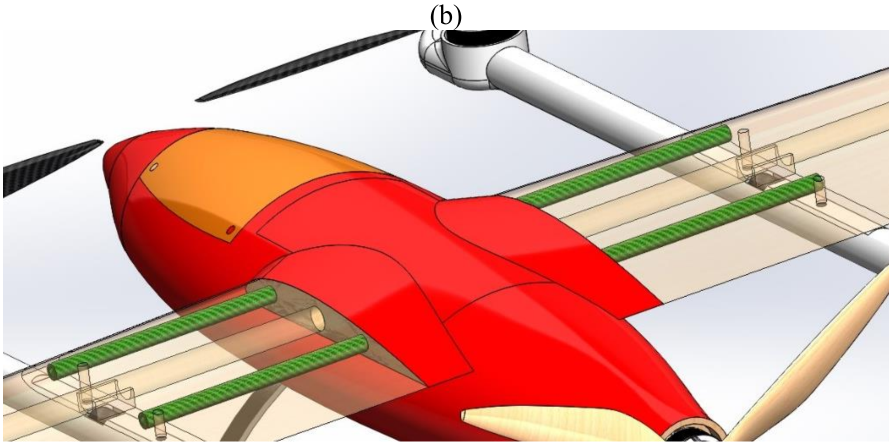


Figure 2-4 (a) Frame holding the UAV; (b) The holes where the wires pass through to reach other different parts of the UAV; (c) Rods inserted inside the fuselage

Table 2-2 Mass Properties of Frame

Coordinate system: -- default –

The center of mass and the moments of inertia are output in the coordinate system of Final
Mass = 879.27 grams

Volume = 710685.25 cubic millimeters

Surface area = 643277.92 square millimeters

Center of mass: (millimeters)
X = 476.53
Y = 18.69
Z = 0.00

Principal axes of inertia and principal moments of inertia: (grams * square millimeters)
Taken at the center of mass.

Ix = (1.00, 0.03, 0.00)	Px = 41952753.90
Iy = (0.00, 0.00, -1.00)	Py = 100186180.80
Iz = (-0.03, 1.00, 0.00)	Pz = 141964058.19

Moments of inertia: (grams * square millimeters)
Taken at the center of mass and aligned with the output coordinate system.

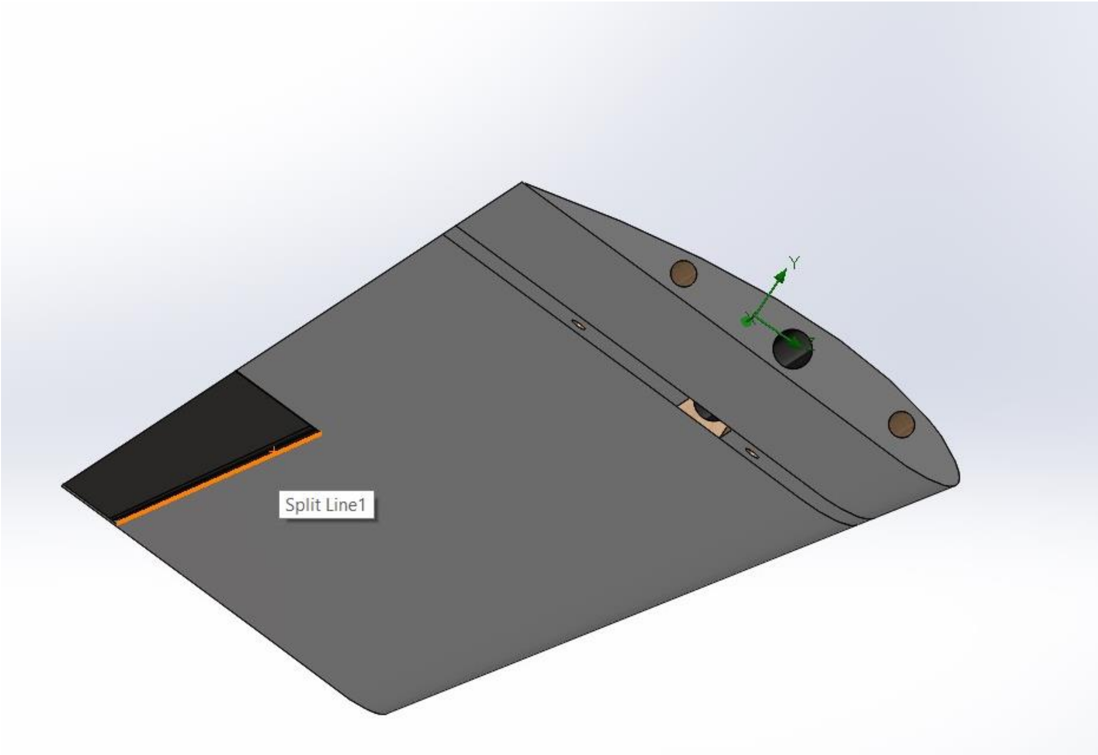
Lxx = 42022508.86	Lxy = 2640344.51	Lxz = -33.34
Lyx = 2640344.51	Lyy = 141894303.23	Lyz = -0.28
Lzx = -33.34	Lzy = -0.28	Lzz = 100186180.80

Moments of inertia: (grams * square millimeters)
Taken at the output coordinate system.

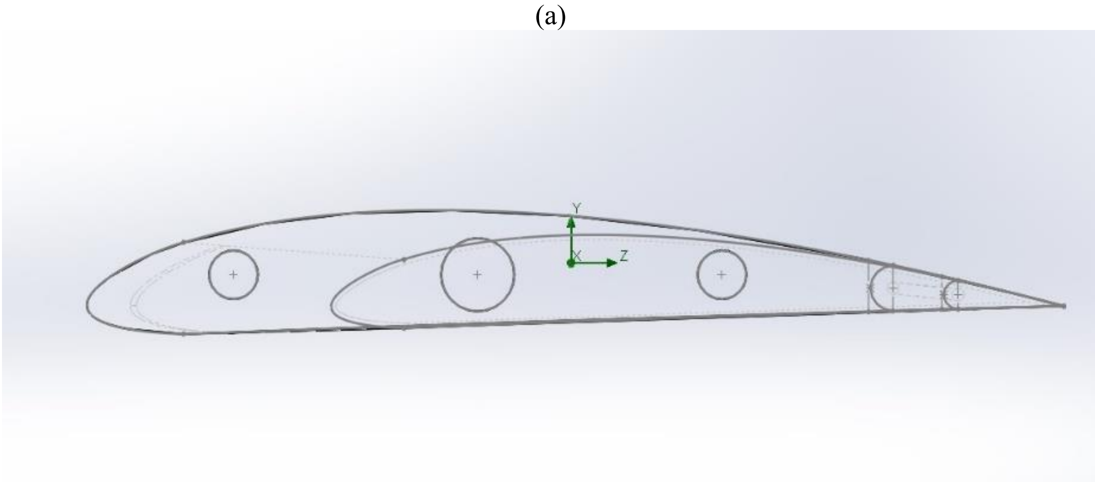
Ixx = 42329698.83	Ixy = 10471943.25	Ixz = 21.79
Iyx = 10471943.25	Iyy = 341555569.60	Iyz = 1.88
Izx = 21.79	Izy = 1.88	Izz = 300154637.15

2.2.4 Wings

The wings, just like the fuselage, are made of balsa wood and covered by a layer of Depron foam. The wings are inserted via the two rods attached firmly inside the fuselage, as seen in **Figure 2-10 (c)**. The airfoil shape was custom designed with the size, weight, and speed range of the UAV in mind. **Figure 2-5 (b)** demonstrates the shapes of the airfoils for one of the wings, which shows they are of different sizes but the same shape, hence the wing's profile when the airfoils are joined via lofting. The wings also include the ailerons shown in **Figure 2-6** with different angles of attack. Ailerons are control surfaces in charge of flight controls during horizontal flight mode. For the software design, the chosen material for the wings was balsa wood, which has a mass of about 354 g, a volume of 1757960 mm^3, and a surface area of 0.29 m^2, as shown in **Table 2-3**. The wings each have a length of 920 mm and a chord line of 200mm and 150mm for both airfoils making up the ends of the wing. The ailerons are 600 mm in length, with the chord line at 40mm and 25mm on both ends. At the bottom includes a hole where the wires' path to reach the fuselage via the center hole shown in **Figure 2-5** and two other smaller holes where the wing is connected to the fuselage via rods.



(a)



(b)

Figure 2-5 Wing of UAV (a) Left-wing; (b) Airfoil Shape.

The wing ailerons are mainly used during the roll motion. When the wing ailerons change the angle of attacks of opposite magnitudes, such as in **Figure 2-6** which shows the wing at 25^0 and -25^0 angle of attack, they tilt the plane, causing it to move to the left or right direction in the vertical axis. They are also used for lifting or descending when they change the angle of attacks simultaneously in the same angles of attack, this is known as pitch motion. This phenomenon is further explained in **Section 2.2.8**

Table 2-3 Mass properties of the wing

Mass = 353.78 grams

Volume = 2211284.84 cubic millimeters

Surface area = 370560.77 square millimeters

Center of mass: (millimeters)
X = 426.89
Y = -3.12
Z = 0.95

Principal axes of inertia and principal moments of inertia: (grams * square millimeters)
Taken at the center of mass.

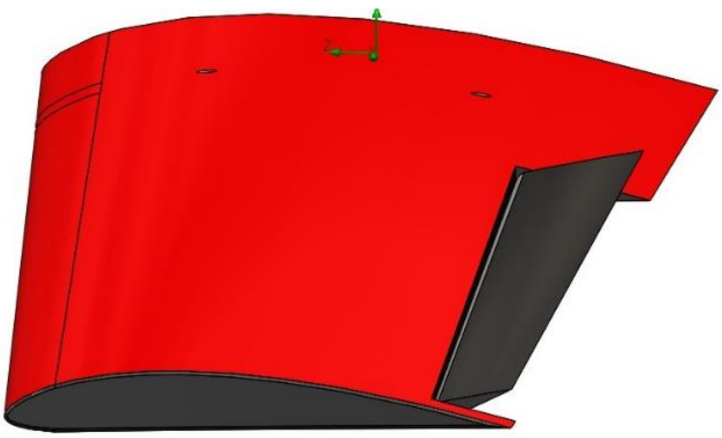
Ix = (1.00, 0.00, -0.03)	Px = 634350.29
Iy = (-0.03, 0.00, -1.00)	Py = 24291770.25
Iz = (0.00, 1.00, 0.00)	Pz = 24905283.20

Moments of inertia: (grams * square millimeters)
Taken at the center of mass and aligned with the output coordinate system.

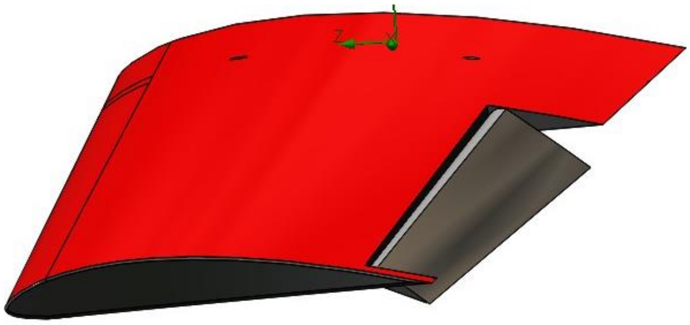
Lxx = 655960.60	Lxy = -40357.68	Lxz = -713577.52
Lyx = -40357.68	Lyy = 24905213.13	Lyz = -147.90
Lzx = -713577.52	Lzy = -147.90	Lzz = 24270230.01

Moments of inertia: (grams * square millimeters)
Taken at the output coordinate system.

Ixx = 659719.72	Ixy = -511071.53	Ixz = -569421.98
Iyx = -511071.53	Iyy = 89375905.75	Iyz = -1200.41
Izx = -569421.98	Izy = -1200.41	Izz = 88744037.09



(a)

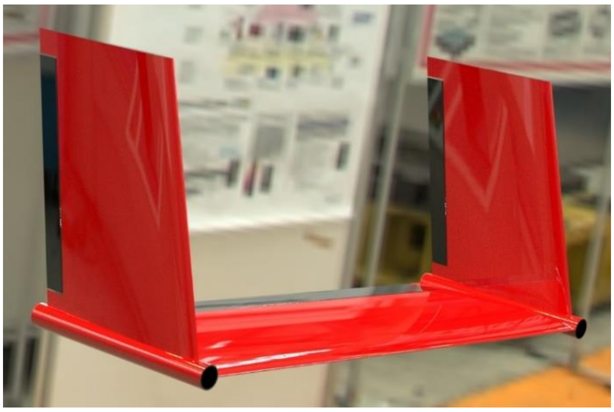


(b)

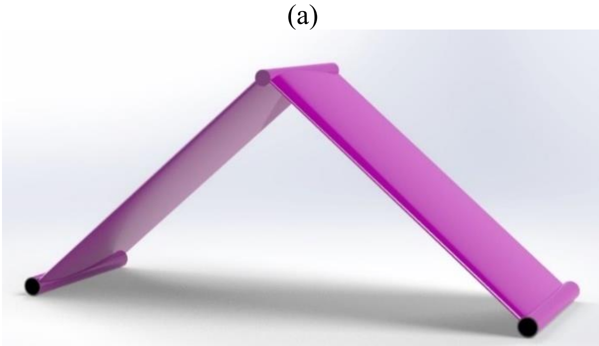
Figure 2-6 Ailerons of the UAV (a) at 25^0 angle of attacks; (b) at -25^0 angle of attacks.

2.2.5 Tail Wing

The tail wing serves the purpose of stability and control of the UAV via the control surfaces. There are two types of tail wings designed for the UAV, The Twin-Boom tail and the V-shaped tail wing, as seen in **Figure 2-7**. The preferred design was the Twin-boom tail wing since it has a more incredible and effective design because it produces a higher lift and more straightforward pitch and yaw motion controlled by its elevator, although the V-shaped tail wing is more stable compared to the Twin boom.



(a)



(b)

Figure 2-7 Tail wing Designs. (a) Twin-boom wing; (b) V-shaped wing.

The Twin-boom tail wing is made from the same material as the fuselage, and the wings are balsa wood covered in a Depron foam layer, and the round edges are made of glass fiber for a smooth movement to avoid being stuck when trying to move at different angles of attack. It has a mass of 102.47g and a surface area of 25.88 m^2, as shown in **Table 2-4** below. It has a dimension of 450mm X 150 mm and 191 mm. It has three control surfaces, two on the vertical wings called the rudders and an elevator on the horizontal wing connecting the booms. The horizontal wing acts as the stability wing.

Table 2-4 Mass properties of tail wing

Mass = 102.47 grams

Volume = 640472.19 cubic millimeters

Surface area = 258816.68 square millimeters

Center of mass: (millimeters)
X = -0.02
Y = 32.31
Z = 77.02

Principal axes of inertia and principal moments of inertia: (grams * square millimeters)
Taken at the center of mass.

Ix = (1.00, 0.00, 0.00)	Px = 422372.75
Iy = (0.00, 0.91, -0.41)	Py = 2933669.75
Iz = (0.00, 0.41, 0.91)	Pz = 3151806.48

Moments of inertia: (grams * square millimeters)
Taken at the center of mass and aligned with the output coordinate system.

Lxx = 422372.76	Lxy = -8.85	Lxz = 116.55
Lyx = -8.85	Lyy = 2970021.23	Lyz = -81290.61
Lzx = 116.55	Lzy = -81290.61	Lzz = 3115455.00

Moments of inertia: (grams * square millimeters)
Taken at the output coordinate system.

Ixx = 1137156.85	Ixy = -69.84	Ixz = -28.85
Iyx = -69.84	Iyy = 3577844.95	Iyz = 173686.00
Izx = -28.85	Izy = 173686.00	Izz = 3222415.44

The elevator provides the lift force for the UAV while in horizontal flight mode by tilting to a certain angle of attack, as shown in **Figure 2-8**. When it tilts at an angle of attack of 15^0, it creates a lift that tilts the plane in the transverse axis in the upward direction. When the angle of attack is -15, then the UAV tilts in the downward direction in the transverse axis. This process is further explained in **Section 2.2.8.**

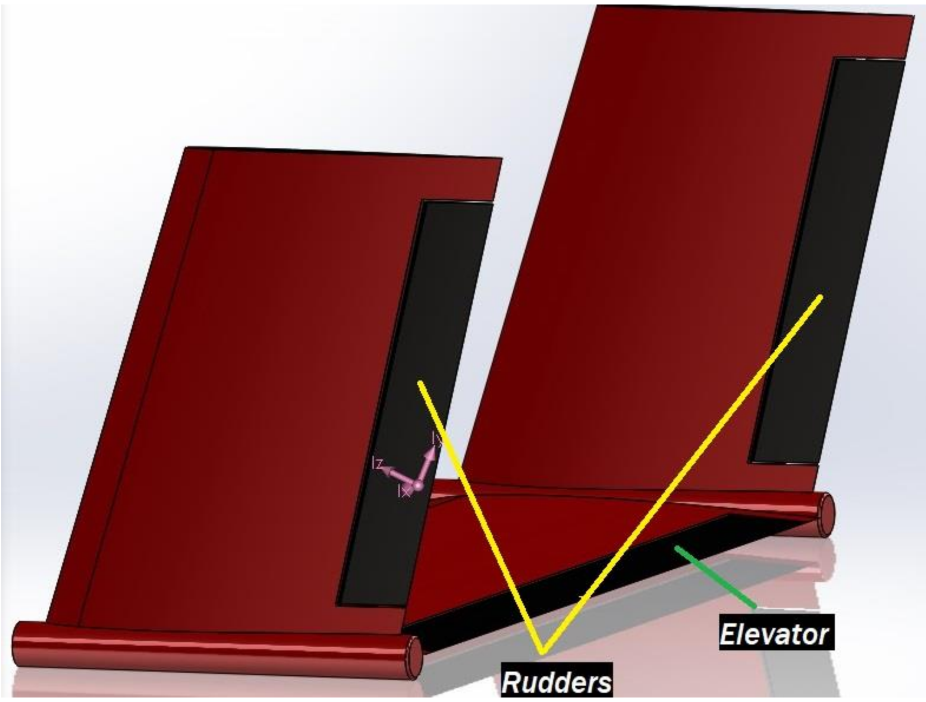


Figure 2-8 Control surfaces of the tail wing.

2.2.6 Landing Gear

Landing Gear was a simple aluminum U-shaped metal with two 5mm holes. Each landing gear is placed at designated areas where they are screwed firmly on the fuselage. The Aluminum material is 356.06-T6 with a mass density of 2680 kg/m^3. Each one has a mass of 44.37 g, as shown below. The landing gear can also be made of carbon fiber material, which is another option that would be less weight (33 g).

Figure 2-9 Landing Gear.

Table 2-2 Mass properties of Landing gear

The center of mass and the moments of inertia are output in the coordinate system of assembly.
Mass = 135.65 grams

Volume = 50614.59 cubic millimeters

Surface area = 32659.45 square millimeters

Center of mass: (millimeters)
X = 304.52
Y = -122.25
Z = 0.00

Principal axes of inertia and principal moments of inertia: (grams * square millimeters)
Taken at the center of mass.

Ix = (1.00, 0.00, 0.00)	Px = 1237856.86
Iy = (0.00, 0.00, -1.00)	Py = 1711189.40
Iz = (0.00, 1.00, 0.00)	Pz = 2317030.98

Moments of inertia: (grams * square millimeters)
Taken at the center of mass and aligned with the output coordinate system.

Lxx = 1237856.86	Lxy = 0.00	Lxz = 0.00
Lyx = 0.00	Lyy = 2317030.98	Lyz = 0.00
Lzx = 0.00	Lzy = 0.00	Lzz = 1711189.40

Moments of inertia: (grams * square millimeters)
Taken at the output coordinate system.

Ixx = 3265101.58	Ixy = -5049821.42	Ixz = 0.00
Iyx = -5049821.42	Iyy = 14896023.58	Iyz = 0.00
Izx = 0.00	Izy = 0.00	Izz = 16317426.72

Table 2-3 Properties of Carbon Fiber and Aluminum Alloy

Material	*Density ($Kg/m^{3)}$*	*Elastic Modulus*	*Tensile strength*	*Cost*
Aluminum Alloy	2680	720GPa	228MPa	Medium
Carbon Fiber	2000	1700GPa	1400MPa	High

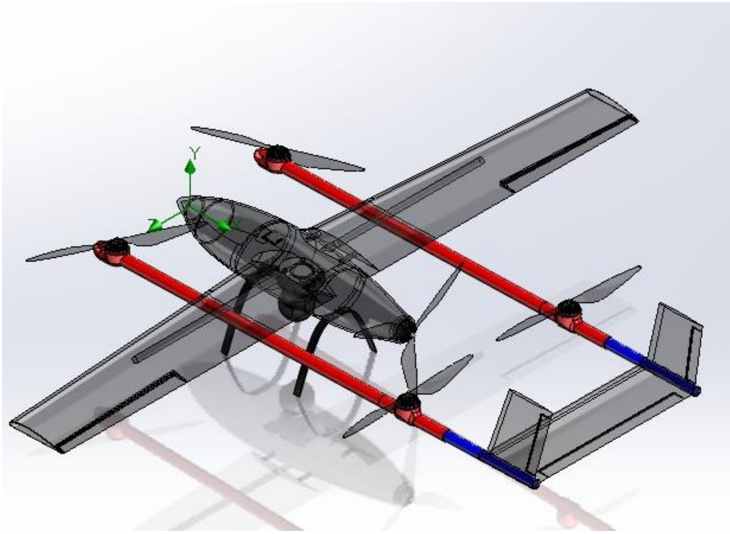
2.2.7 Assembling Process

Step 1: The Assembling starts with the rods, as shown in blue inserted into the motor mounters in red, as seen in **Figure 2-10 (a)**. **Figure 2-10 (b)** shows the hole in which the wires pass through to reach the motors and tail wing.

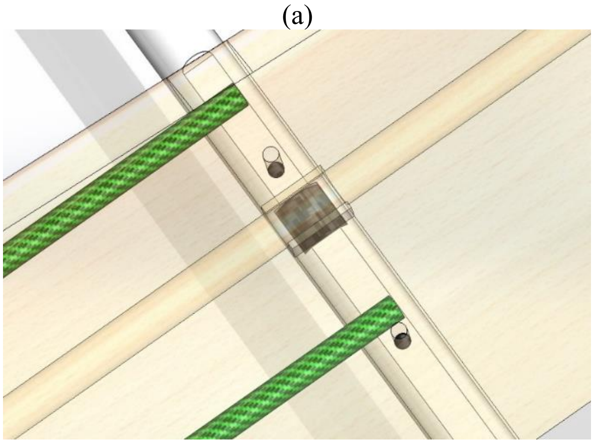
Step 2: The side rods (shown in green) are then connected fuselage and screwed together to attach firmly inside the fuselage, as shown in **Figure 2-10 (c)**.

Step 3: The wings are then connected to the fuselage, and then the tail wing is inserted on the frame through the rods and screws attached to attach firmly, as shown in **Figure 2-10 (d)**.

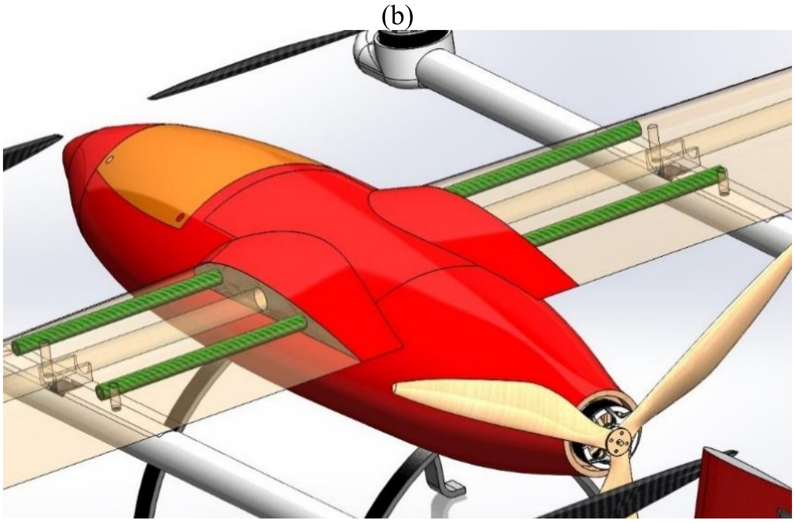
Step 4: The motors, propellers, and other electronic equipment are installed at last, as shown in **Figure 2-10 (e)**.



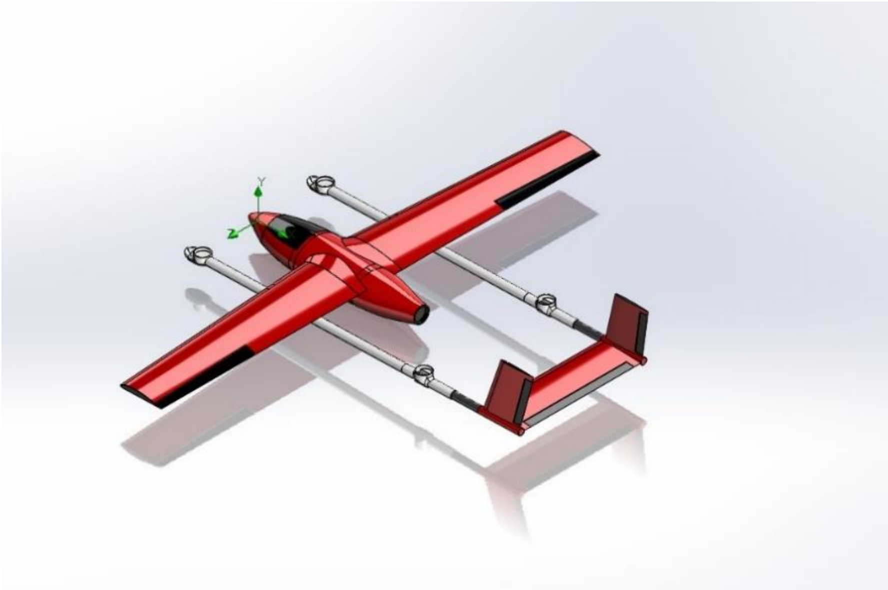
(a)



(b)



(c)



(d)

(e)

Figure 2-10 Assembly Process.

2.2.8 Flight Mechanism

There are two types of Flight mechanisms for the UAV since it is a hybrid of two UAVs with different flight mechanisms. There is the fixed-wing flight mechanism and the quadcopter flight mechanism. Some of the flight mechanisms have been discussed in chapter 1, so this is more about discussing the different flight mechanisms in one VTOL UAV.

2.2.8.1 Quadcopter Flight Mechanism

During vertical take-off, the VTOL UAV is in a multirotor state. The four propellers start rotating at the same speed, but two of the propellers move in the opposite direction of the other two, as shown in **Figure 2-11**

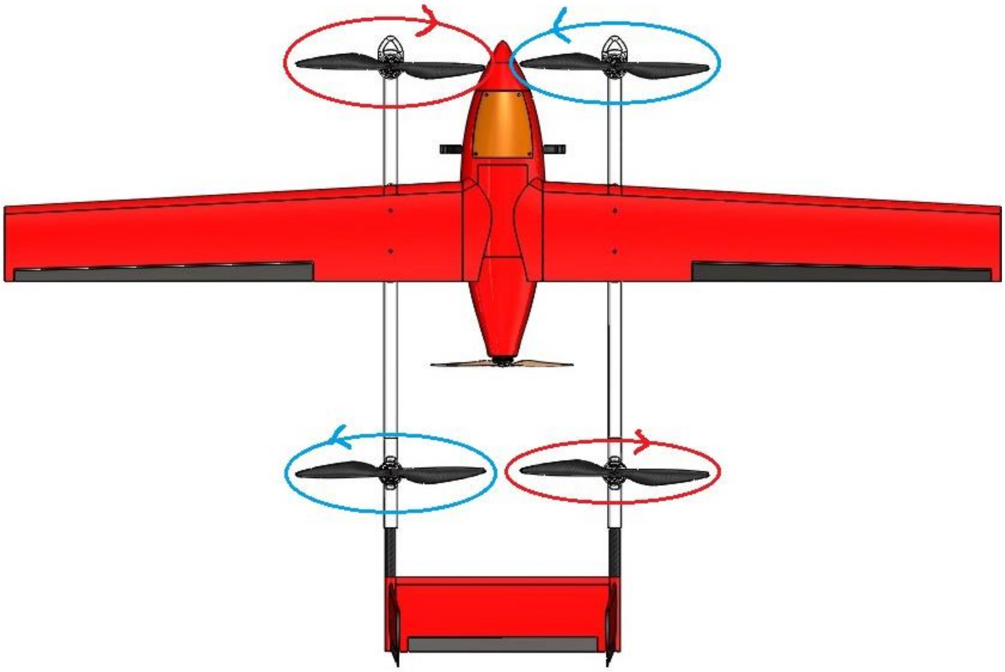


Figure 2-11 Anti-clockwise and clockwise rotational directions of the propeller.

For the UAV to hover in the air, all propellers will have to give a thrust equal to the weight of the UAV at the same proportions. The propellers must give a thrust higher than the UAV's weight to ascend without the UAV moving in any other direction besides the upward direction, at the same proportions for each of the four propellers. This phenomenon is called throttle. To descend, we use the same method, but this time, the thrust must be less than the weight of the UAV. For pitch motion, the front rotors have less thrust than the back rotors, which causes the back to lift, hence moving the UAV forward. The same theory applies to move UAV backward, but this time, the front motors have more thrust than rear rotors. Since our design is a UAV capable of VTOL, the pitch motion that does not consume power is a fixed-wing flight mechanism. For the Roll motion, if the UAV moves in the left direction, the propellers on the left reduce their thrust or lift while the right propellers increase in thrust, making the UAV move in the left direction. The same process is applied to move to the right, but this time, the right propellers reduce lift while the left propellers increase thrust. For the Yaw motion of the UAV in multirotor mode, the two propellers spinning in an anti-clockwise direction reduce the thrust, and the propellers spinning in clockwise direction increase thrust to create left yaw motion, as seen in **Figure 2-12**.

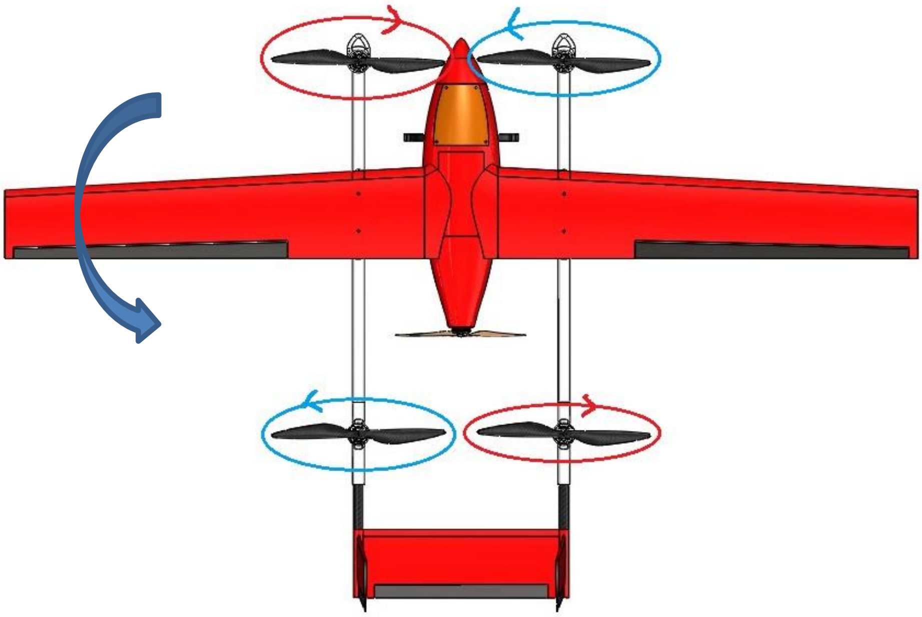


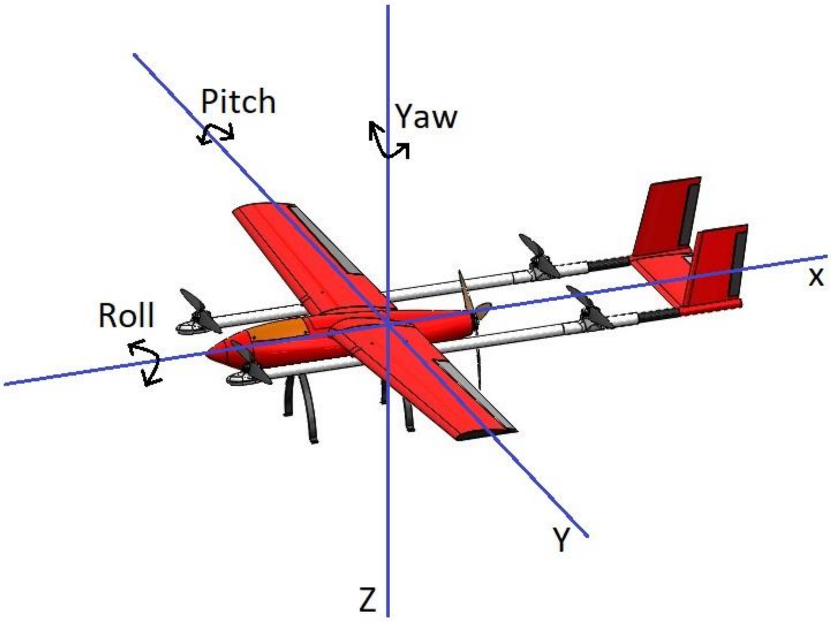
Figure 2-12 Yaw Motion.

2.2.8.2 Fixed-wing flight mechanism

As seen **Figure 2-13** shows how the different ailerons work together to control the flight of the UAV in horizontal mode. The control surfaces are necessary for the steering of the UAV while in the air; their efficiency changes based on speed. The ailerons and elevator are responsible for the pitch and roll motion. As shown in **Figure 2-14** The elevator works by raising or lowering the UAV in its transverse axis, while the airlerons work by tilting the wings of the UAV from the left or the right direction in longtitudunal axis. The rudders are used for yaw motion to move the UAV to left or right in its vertical axis. The ailerons on the UAV also act as flaps and air breakers since most radio-controlled UAVs do not use flaps or air breakers as it is not necessary. Big commercials aircrafts such as the Boeing or jetfighter are the ones that commonly require the use of specified ailerons, flaps, and air breakers.

(a)

(b)

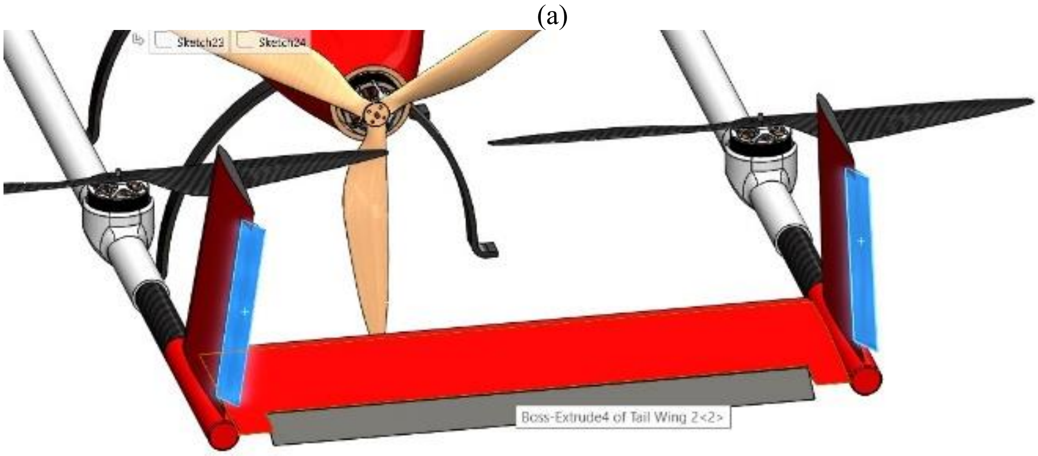


(c)

Figure 2-13 Flight mechanism in Horizontal mode. (a) Three axes in which the motions are applied; (b) The forces applied during flight; (c) The three motions involved.

Once the UAV takes off vertically at a certain altitude, it transitions to horizontal flight mode, where the horizontal motor starts running and pushes the propeller forward. In horizontal flight mode, the vertical propellers do not use the same amount of power as when hovering since the lift force from wings and the thrust from the horizontal motor will be more active. The UAV can do the three types of motion when in horizontal flight mode, just like a fixed-wing UAV. These include the Pitch, Yaw, and Roll motions, as discussed in chapter one. For the gliding in the air, the ailerons are all normally at a 0^0 angle of attack. When the UAV wants to reduce or increase the altitude at which it is flying in the transverse axis, the ailerons and elevator change the angle of attack. This phenomenon is known as pitch motion. **Figure 2-14 (a)** shows the ailerons at an angle of -25^0, meaning it is in a descending pitch motion together with the elevator on the tail wing, as shown in the blue highlight. When the UAV wants to turn left or right (Yaw) in its vertical axis, it turns the rudders at a certain angle of attack. This phenomenon is known as the yaw motion. **Figure 2-14 (b)** shows the rudders on the tail wing, put to an angle of attack of 25^0 to the right for a right direction yaw motion. Since the yaw and roll motion go hand in hand for a safer turning, the roll motion works by tilting the wings from one side to the other using wing ailerons at opposite angles of attacks, as shown in **Figure 2-14 (c)**. When the right aileron goes up at an angle of attack of 25^0 and the left aileron goes down at an angle of attack of -25^0, the UAV tilts in the right direction.

(a)



(b)

(c)

Figure 2-14 Control Surfaces. (a) Pitch Motion; (b) Yaw Motion; (c) Roll Motion.

The ailerons are connected by cables, hydraulic systems, or advanced electronically controlled motors. An example showing aileron servos is shown in **Figure 2-15** below;

Figure 2.15 Aileron Servo.

The servos are part of the flight control system as they will control the movement of the ailerons based on the instructions given to it by the remote control via the source codes through a link of communications. The remote controller or Flight control software is set up to allow transition from multi-rotor to fixed-wing and vice versa.

2.3 Power System

This section discusses the different parts that make up the power system necessary to lift the UAV and fly the UAV. Section 2.3.1 discusses the propellers used their pitch dimension, screw holes, and weight, Section 2.3.2 discusses the type of battery to choose, its dimensions, weight cells and volts, and C-rate, and how much power it gives off. Section 2.3.3 discusses the ESC needed to drive the motors, including the brands on the market, the types of ESC needed for the UAV, and other different specs to look at before choosing a brushless ESC and then finally section 2.3.4 discusses the process of choosing the motors to be used how much thrust they give off and how they are connected to all the other electronic parts.

The most important part of the selection is knowing the application we have to fit the power system. Since this thesis looks at a remote-controlled UAV, the first element we select is the battery pack, knowing how much voltage is needed to operate the UAV.

The UAV is medium-sized; hence fairly high voltage of the battery is needed. The motor must be operating in the correct total RPM (Revolutions Per Minute) output for the application. For example, a 6S radio-controlled UAV would require a smaller RPM in the range of 10,000-15,000 RPM. By calculating, one can determine the correct KV of the motor. The power output needed for the motor is also influenced by the size of the motor needed; a larger motor can dissipate a larger amount of total power. When the size of the motor is found, the battery pack's capacity needs to be determined. The battery pack capacity and discharge rate or C rate will help calculate the total continuous power output the battery can deliver. Based on the power output to get from the brushless motor, we can determine the battery pack specs accordingly. The final part of the power system is the speed controller, which is based on the brushless motor specifically. The ESC output has to be the same or higher than the maximum brushless motor input in terms of the voltage and the current. If a brushless motor was to deliver 50 amps and 6s 22.2 V, then the ESC has to have input voltage to accept the 22.2V mark and have a continuous discharge rating of at least 50 A, but for safety measures, a 75A ESC is needed in this case. The load of the power system is the propellers, which is the final piece of the puzzle. The propeller chosen needs to align with the goal output of the power system; that is, if the output is 50 A and 22.2V, then after determining the required diameter and pitch of the propellers, it is added to the motor. After adding the propellers, the power system is powered up to determine if the propellers are effective. It is to be noted that when the propeller capacity is beyond the required amount, then the load is to be reduced to the precise one. Below are the components of the power system;

2.3.1 Propellers

Propellers are responsible for converting the rotary motion of the motors into thrust, and they do that by spinning and creating an airflow that results in a pressure difference between the bottom and top surfaces of the propeller. The smaller racing drones usually have less than 8-inch propellers, while UAVs such as the one designed in this thesis that carry heavier load use propellers of 8-inch diameter and above. The numbers on the propeller product example 9X6 represent the diameter and pitch of the propeller. The propeller’s pitch means the distance it would have moved forward after one rotation, while the diameter is the diameter of the circle formed when the propeller makes one rotation. That means the 9X6 propeller has a diameter of 9 inches and a pitch of 6 inches.

The bigger the diameter and lower the pitch, the higher the power but less speed.

There are two types of propellers for the design, as seen in **Figure 2-16**. The first one (**Figure 2-16 (a)**) is a 15-inch two-blade propeller for the vertical motors with a pitch of 5 inches and shaft of 6mm; since there are four motors for the vertical flight, four of these propellers are needed. The second (**Figure 2-16 (b)**) is a 13-inch three-blade pusher propeller for the horizontal motor with a pitch of 5 inches and a shaft diameter of 6mm. There is a method to get the diameter of the three-blade propeller, according to **Formula 2-1**;

Formula 2-1 Conversion from two to three-blade propeller

$$\boldsymbol{D \times D \times D \times P\sqrt{N-1}} \qquad \text{-------------------------------(2-1)}$$

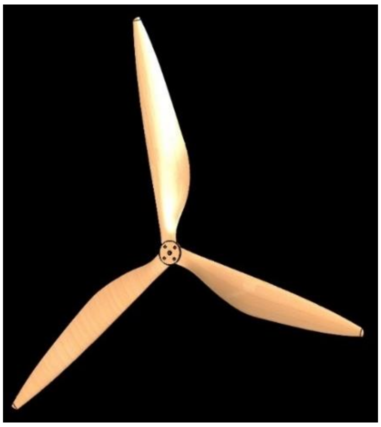
$$\boldsymbol{D^a \times D^a \times D^a \times P^a\sqrt{N^a-1} = D^b \times D^b \times D^b \times P^b\sqrt{N^b-1}} \qquad \text{---------------(2-2)}$$

Where **D**= Diameter of propeller **P**=Pitch of propeller **N**= number of blades of the propeller **a** =Two-blade **b**=Three-blade

If the pitch of the three-blade propeller is the same as the two-blade propeller, they cancel out and remain with the diameter and number of blades for each propeller. By substituting the corresponding Diameter and the number of blades for each propeller in equation (ii), you get a D of approximately 13.36, which means a three-blade propeller would be 13 inches in diameter and a pitch of 6 inches.

The horizontal motor is located at the back of the fuselage requires one propeller. The three-blade was chosen for the horizontal motor because it produces a smaller pulse per revolution for the same magnitude of thrust, smoother, and less noisy than a two-blade propeller. The carbon fiber material for the two-blade propeller was considered, while a wood material of Beech was considered for the three-blade propeller. The mass chosen for both types is 20 g for two-blade and 40 g for the three-blade. Both of these propellers were chosen because they are commercially available on the market and are made of light material. Hence, the propellers make up about 120 g, including four for the vertical motors and one for the horizontal motor. The two-blade propellers include three holes, two for screws and one for the motor shaft with 3mm and 6mm dimensions, respectively. The three-blade propeller includes four holes for screws and the middle one for the shaft with 3mm and 4mm, dimensions respectively.

(a)



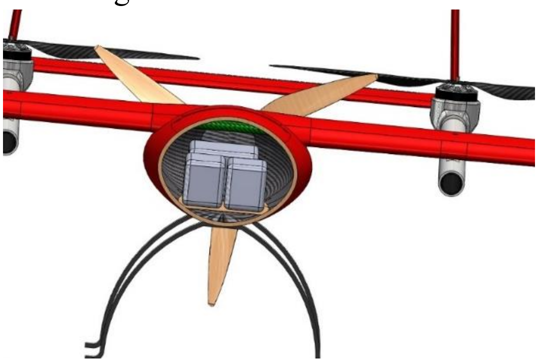
(b)

Figure 2-16 Propellers of the UAV. (a) Two-blade propeller; (b) Three-blade Propeller.

2.3.2 Battery

The battery is the source of power for almost all electronics on the UAV. The battery must be made of LiPo (Lithium Polymer) battery beforehand. Its battery cells have almost four times higher energy density and offer a steadier voltage as the battery is discharged compared to other batteries made of nickel-cadmium or nickel-metal hydride; hence have a higher power to weight ratio. They are lightweight and do not easily explode when pressure is applied to them, although if overheated can explode, safety measures must be put in place.

One rule about a LiPo battery is that it is must never be drained to less than three volts per cell. The voltage of the battery should not below, or else the UAV will not function and cannot be very high as there will be a risk of burning. The increasing size of the battery would increase its capacity, which would influence how long it could go for but would not be increasing its power cell count, making it easier by combining cells. If a 1S battery would produce 3.7V, then a 4S battery would produce 14.8 V. smaller UAVs use 1S or 2S, and the medium size, like the drone designed for this, takes in about 4S to 6S battery. The mA rating on the battery can determine the capacity of the battery. The LiPo battery can handle around 222mAh to 12000mAh, which means if the battery has 3000mAh, it can provide 3A per hour until it can become fully discharged. The discharge rating or C-rate can determine the quality of the battery. It represents how much current we can safely pump into the drone without degrading the battery. Choosing a battery with a higher discharge rate will allow us to push batteries harder and use them longer. The discharge rate on the battery should be as high as possible when increasing the throttle to give a better balance between the motors and the throttle to lift as soon as we throttle it up. Suppose the battery provides 30C, then multiplying with the 3000mAH provided by the same battery gives 90000mA or 90A. Hence, the battery can discharge up to 90A without damaging the battery or UAV in general. **Figure 2-17** demonstrates how one battery with dimensions of 160X70x50 (mm) and two batteries of dimension 140x40x46 (mm) would fit inside the fuselage.



(a)

(b)

Figure 2-17 Cross-section view of batteries inside the fuselage. (a) Front cut; (b) side cut.

2.3.4. ESC

ESC is an electronic device that adjusts and controls the speed of the motor. It gives the motor's power in the form of voltage, and depending on the situation; it can lower or increase it. ESC has to have a 10%-20% higher amp rating than the motor's maximum. If the motor is 50A, then the ESC has to be at least 55A-60A. It is not highly advised to use an overly higher current for ESC than motors as that may cause the motor to get ruined if it exceeds its maximum current. The ESC must also be able to handle the same number of cells as the motors can handle. Most motor products have specs showing the cells they can handle; hence the ESC should handle the same. ESC with a built-in BEC is also recommended to reduce the need for more space or wiring. BEC is what powers the receivers, servos, or flight controller without needed extra batteries. Since our UAV mainly uses a LiPo battery, LCV (Low Cut-off Voltage) is a must-have. LCV is the voltage at which the battery is fully discharged. Most electronic devices automatically shut down when fully discharged, but for safety measures to not risk the battery dying, LCV is necessary. LCV for a LiPo battery is around 3V per cell; hence the ESC must not go below that or risk draining the battery pack, thereby damaging it.

When choosing ESC, the different specifications are current rating, input voltage, different protocols, dimensions, whether individual or 4-in-1, and finally, the different processors that come with an ESC.

2.3.4.1 Current Rating

ESC has to handle the current pulled through it; the higher current, the more the ESC has more headroom; hence safer the ESC will not blow up due to pulling too much power. Most ESC manufacturers grade the current rating as higher than they are; hence, most will automatically think it will give more power. It is more about how the ESC can handle the flow of current through it without blowing up.

2.3.4.2 Input Voltage

The battery must work with the ESC; most ESC manufacturers list the type of battery the ESC will work with, usually in a range.

2.3.4.3 Dimensions and Weight

ESCs are generally not very differentiable, so the weight and dimensions are not an important factor to look at, although the lighter one is better since we want the UAV to be as light as possible.

2.3.4.4 Protocols

Protocols are how the ESC and flight controller communicate with each other, that is the signal flow between the two. The flight controller and ESC work in a cycle by determining if they have to speed up to about the motors or slow them and repeat the process repeatedly. A faster protocol paired up with a faster processor on the flight controller makes it easier to have a smooth flight.

The most common types of protocols are Oneshot and Dshot, which also have different models, such as OneShot 1.25 or Dshot 150. The lower the number means a shorter pulse width hence a faster refresh rate. The Oneshot is now a bit outdated, and the current ESC commonly used is Dshot. It has a faster refresh rate and a digital protocol, meaning there are more commands we can send from the flight controller to ESC, such as sending a signal to the motor to be a beeper. The beeper can act like a lost model beeper if we have lost the UAV so that when it crashes, it can beep, and we can tell where it is. The difference in price between Oneshot and Dshot is not that far; hence Dshot is the chosen protocol. The processor available for the Dshot is commonly the 32-bit processor with more features such as collecting telemetry information from ESC, RPM of the motor, and future proof.

2.3.4.5 Individual or 4-in-1

Depending on which size of the UAV we intend to build. The smallest one available is better but can also handle the current and input voltage of what we are building around it. 4-in-1ESC is four ESC's integrated into one single board of the same size as the flight controller. 4-in-1 brushless ESC enables us to move ESCs from the arms of the UAV into the center stack with a flight controller. It is better since it has less space, more compact, and less wiring hence less weight, while individual ESC requires more wires for each ESC and time-consuming soldering many wires on each ESC. With a 4-in-1 ESC, there is no need for a PDB (Power Distribution Board) and a separate BEC in some cases. The advantage of the individual ESC to 4-in-1 is that one of the spoilt ESC can be replaced, while for the 4-in-1 ESC, damaging one means retirement of the whole board. The 4-in1 ESC is cheaper than four individual ESC, but replacing the whole thing when damaged, can mean buying another one, while the individual ESC buying one spoilt is cheaper.

The common ESC ecosystems on the Market are KISS ESC, BIHEL ESC, and

Flightone ESC. KISS ESC has its ecosystem, which means it has its own ESC and flight control software with very high quality. The downside to KISS ESC is that they are expensive compare to Flightone or BIHEL ESC.

2.3.5. Motors

Motors are the backbone of a UAV, the driving force of the power system. They are used to spin the propellers at high speed, enabling the UAV to lift off and fly. The motors very common for multi-rotor are brushless, and since the design for the project is a VTOL with multi-rotor capabilities, we choose a brushless motor. A brushless motor operates in the same mechanism of magnetic attraction and repulsion as brushed motors. However, instead of mechanical commutators and brushes, the stator's magnetic field is rotated using an electronic commutator, which requires active control electronics. Brushless motor lasts longer than brushed motors; they have more speed and acceleration, more efficient, and less electrical and acoustic noise. The only disadvantage is the Higher cost due to added electronics but not by a very wide margin. When choosing a motor, some specs have to be kept in mind; KV, stator size, cost, and propeller.

2.3.5.1 KV

KV is the speed at which the motors are going to rotate. If the motor has 2450 KV and provides a voltage of 1 V, it will spin about 2450 RPM. That means that KV is the Number of RPM per 1 V. If for a 3S battery, each cell has 3.7V, then 3 Cells is 11.1V multiplying that by the 2450KV, we get 27,195 RPM.

2.3.5.2 Stator Size

Motor products have dimensions such as 22O7, 14O8. These are the size of the stator and not the whole motor. 22O7 means the stator is 22mm wide and 7 mm thick.

2.3.5.3 Cost

The cost of motors may vary depending on different features it used such as; the materials used may be of low quality hence not durable, the bearing used may have rough edges hence not smooth, the quality control for the motor is also a factor as the one that has passed the quality control is considered higher quality and more costly. A cheaper motor may break a lot due to the low durability, which means that it may be more costly than expensive ones over time. Therefore, it depends on the application of the motor.

Other specs that affect the cost include; windings (types, materials used), Airgap (the closer magnet is to stator the better performance hence more cost), Magnet (Amount of power influences the cost), and lastly, the balance of the motor (minimal vibrations are crucial hence the better lower vibration, the higher the cost)

The power each motor gives varies because even when the dimensions and KV are the same, other components that make up the motor might have a hand in a power difference between motors of the same dimensions and KV. The brand of the motor is also crucial in choosing the motor since most big motor brands have a better support system and quality for the motors.

2.3.5.4 Propeller

The propeller used is also necessary when choosing the motors. A 6-inch propeller needs a motor of 2206 and above for easier flight. The bigger the propeller, the bigger the motor and the lower the KV and vice-versa. A smaller motor may be efficient because of less weight but may have lower torque and power; hence may struggle to spin the propeller. Choosing the motor is about finding the balance between the motor and the propeller to get the most optimal setup. The motor with a big motor and higher KV is recommended with a lightweight, thin propeller.

When choosing the motor, calculating AUW (the total weight of the UAV with the Electronic equipment, sensors) is the first step, followed by the thrust.

The rule for the motor is that the thrust produced by the motor and propeller must be 2-3 times the AUW. If the AUW is 1 kg, the thrust needed is just a bit more, but when the UAV hovers, then the thrust needed must be 2times. For maximum safety margins, the thrust must be three times in real life. If the AUW is 1 kg, there will be a thrust of 3kg; since a quadcopter has four vertical motors, then each motor would have to give 750 g motor thrust.

2.4 Control System

This section discusses how the UAV communicates with the flight controller or flight control software to perform the given instructions and send information to the drone pilot.

2.4.1 UAS

This section discusses how all the different sensors, electronic components of the UAV work together to deliver a smooth flight operation, as shown in **Figure 2-18**. The first part is the brain of the UAV, which is the Flight controller. The Flight controller is where all the commands are received and sent to different features of the UAV. The radio controller or Flight control software will send the commands to the receiver, and the receiver will send the instructions to the flight controller. The ESC takes the signal from the flight controller and tells the motor how fast it will spin. Since our UAV has five motors, the flight controller sends a signal to five ESC. The 4-in1 ESC would mean sending a signal to two ESC, one for the horizontal motor and the 4-ni-1 ESC for the quadcopter system. GPS sends location information to the flight controller. FPV camera takes images from UAV and sends them to the flight controller, which has built them into the onscreen display. The onscreen display takes flight data and overlays it on video so we can read it in real-time. The overlayed information is sent to the video transmitter, then transmitted to the video receiver on the digital video recorder. The battery provides the power to the flight controller and all other features inside the UAV. There are also capacitors for cleaning dirty power signals to prevent interference, and the flight controller also acts as the PDB, meaning the flight controller has more places for soldering the features on it. The PDB also controls how much voltage each feature is going to get.

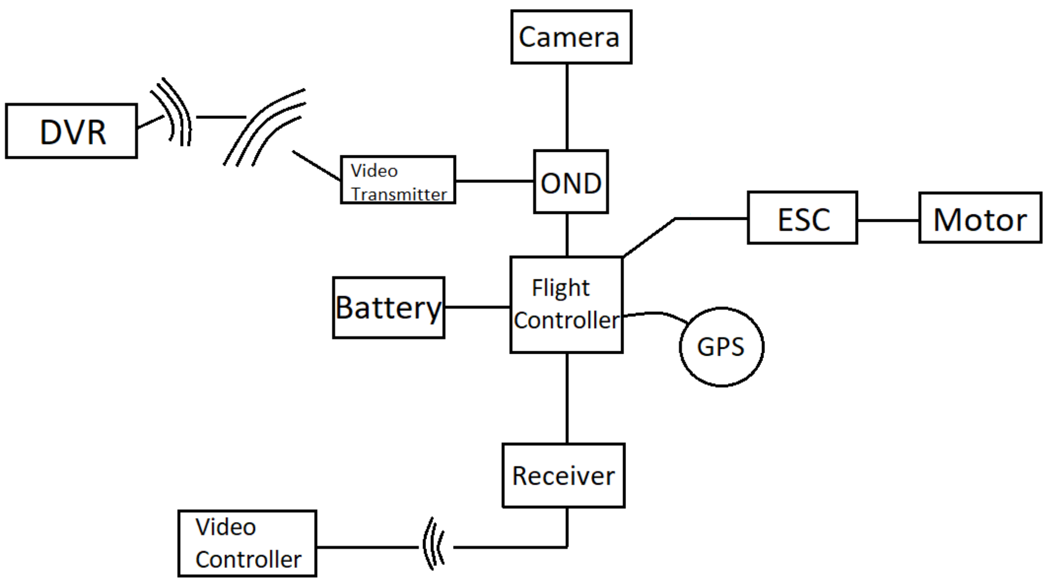


Figure 2-18 Components of a UAS.

2.4.2 Mission Planner

Most UAVs use Mission Planner as the preferred flight control software. Mission planner software is used to set up the flight controller unit. The software uploads the correct firmware to the flight controller to match the prototype's aircraft type, a VTOL UAV. The software is also used to tune the PID (Proportional, Integral, Derivative) control gains to achieve the best stability. The tuning can be obtained during actual flight tests where the gains are changed accordingly by the drone operator or set before flight tests, and the Trial-and-Error method is used to obtain the best outcome. **Figure 2-19** shows a screen snap of the flight control software known as Mission Planner.

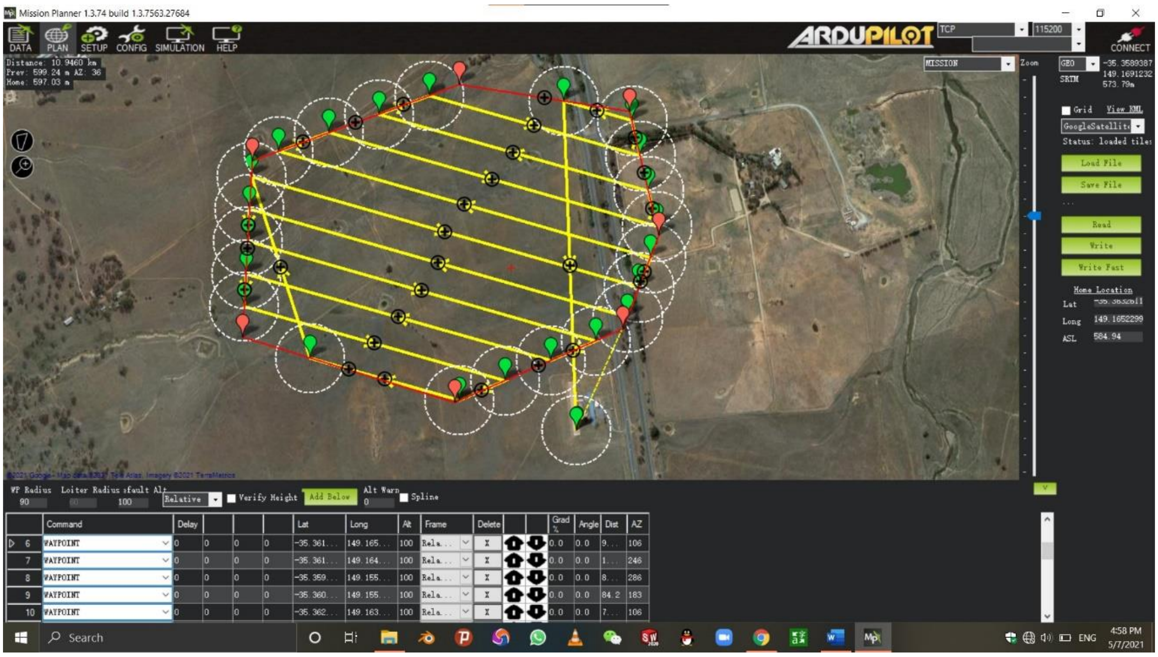


Figure 2-19 Pathway in Mission Planner.

2.4.3 Sensors and other features

A UAV needs sensors for autonomous purposes and sends the information to the drone operator to know how the UAV is functioning. The primary sensors in a UAV are the IMU (Inertial Measurement Unit). The IMU has two sensors, which are the accelerometer and gyroscope. The accelerometer is used to calculate the force exerted on the UAV, while the gyroscope measures the rotation motion of the UAV. Other sensors include a Barometer which tells the altitude, a Voltmeter for measuring battery voltage, Ammeter for measuring current. Voltmeter and Ammeter measure the power used from the formula $\boldsymbol{P} = \boldsymbol{IV}$ where P stands for Power, I for Current, V for Voltage. This gives the display of power used over time, which is expressed in Wh or mAh. The compass tells us the heading of the UAV. GNSS (Global Navigation Satellite Systems), which includes the GPS(US) and GLONASS(Russia) measures the position speed and altitude of the UAV

UAV also includes features necessary for autonomous landing and taking off or finding a way back home autonomously. These features include Lidar, Thermal, and others. LiDAR (Light Detection and Ranging) sensors, which measure the reflection time of a pulsed laser beam, have many uses in unmanned systems. They may be used for navigation and collision avoidance by UAVs and autonomous driving systems, and mapping, and other imaging applications such as agricultural and forestry surveying. LiDAR offers an alternative to conventional photogrammetry methods for when the mapped area contains many obstructions. Thermal imaging is also another sensor for building inspection, search & rescue, security, and other electro-optical (EO) sensors that operate in the visible spectrum. Hyperspectral remote sensing for precision agriculture UAV sensors measure reflected light to provide data on the health of crops, allowing farmers to optimize the application of pesticides and fertilizers and maximize crop yields.

Summary

Designing a UAV, especially one that is capable of VTOL, requires the knowledge of the functionality of both the fixed-wing and multi-rotor drones. This means that every aspect of the design is to make sure that the properties of both types of drones are fulfilled, or else it will not be called a true hybrid of both drones. The UAV is a V/STOL; hence it will hover for a short period for landing and taking off to avoid draining the battery quickly. The process of choosing the lightest and the tolerant material, the size of the fuselage to fit the required battery for the required performance, and other factors that are considered make up a large part before putting the actual design in effect. With 3D modeling software, it has become easy to understand how the UAV will look before making a real-life prototype. The design also focuses on the alignment of dimensions to have the actual blueprint of the UAV since most tools such as CNC (Computer Numerical Control) cut objects into place based on the dimensions given to them.

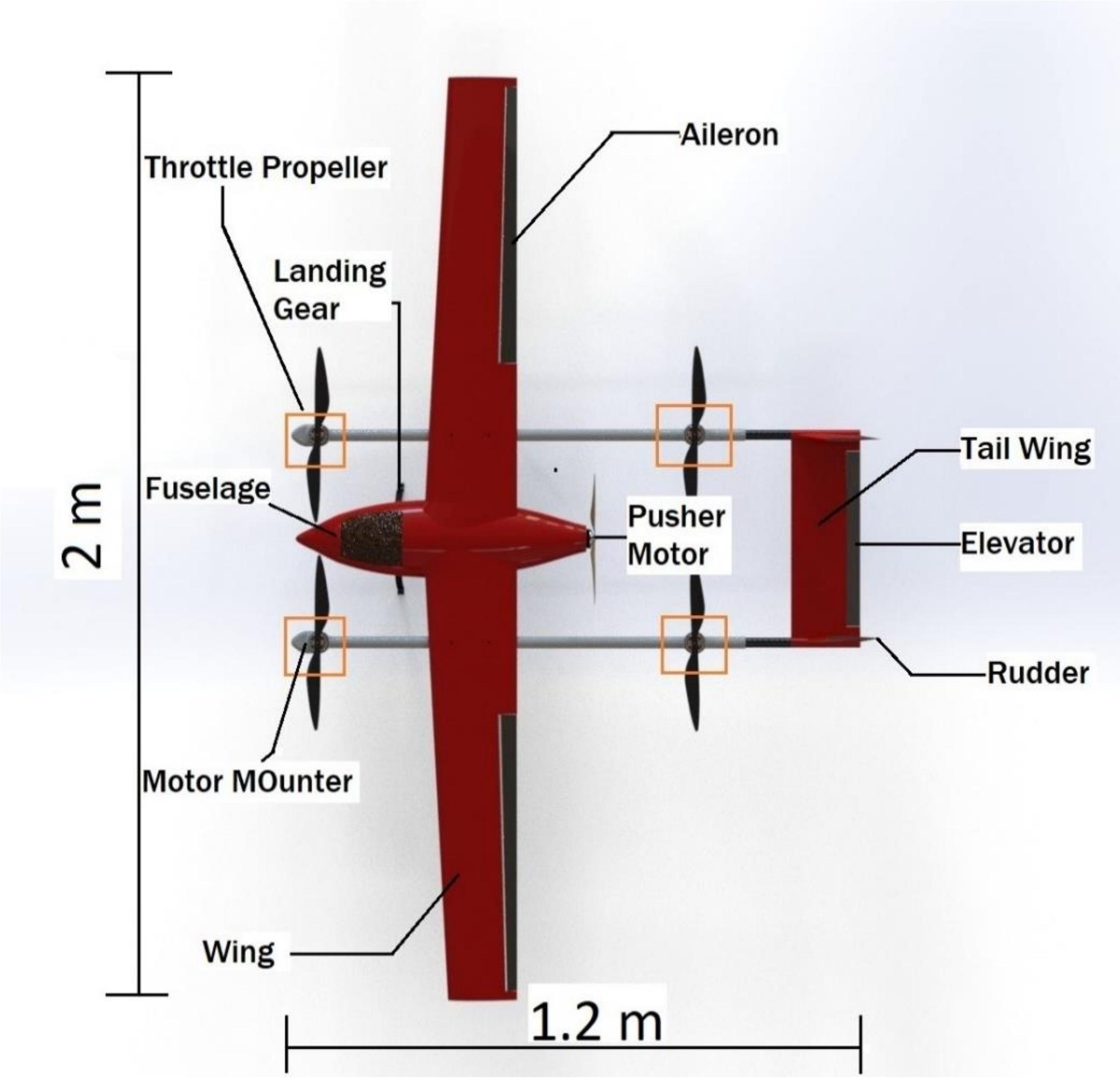
Chapter 3 Results and Simulations

This chapter looks at the final design of the project, the UAV applications, the electronic components are chosen to calculate the amount of thrust needed by the motors to lift and fly the UAV. It also discusses the motor system schematics, block diagram of UAS, and different simulations such as FEA done on different parts of the design to see how the UAV behaves in different environments and obtain the idea of how it would be operational in the real world. The simulations done are aerodynamics, pressure, the calculation of lift, the propellers thrust, stress/strain on different parts of the mechanical design such as wings and frame, and finally the Thermal analysis of the motor mounter to see how much they can withstand the motors.

3.1 Rendered Version

The rendered version of the final design, including the propellers and motor, is shown in **Figure 3-1** below. It is a more realistic look at how it would look in the real world. It has a wingspan of 2m and a length of 1.2m from the fuselage tip to the tip of the tail wing.

(a)



(b)
Figure 3-1 Rendered version of the UAV. (a) Angled view; (b) Top view.

3.2 Electronics

The electronic components chosen for this thesis were based on the total weight of the shell of the UAV, which is the mass of the mechanical design shown in **Table 3-2.** The process of choosing the motors, is shown below;

If the mass of mechanical design is 1990g, then we assume approximately 2100g. The battery chosen is for this project was the LiPo battery, of course, with less or equal to 800 g in weight. The 15-inch propeller is made of carbon fiber of 20g each, which is 80 g for four two-blade propellers plus one wooden three-blade propeller of 40g making it 120g in total. Each ESC has 95g. Each motor is also less than 400g. We assume other parts make up 300g.

Table 3-1 Calculation for AUW

Component	Description	*Dimensions(mm)*	*Quantity*	*Mass(g)*
Shell	Custom	2000x1200	1	2100
Battery	5000mAh 80C 22.2V 6S LiPo Battery - No Connector	325 x 52 x 49	2	800
ESC	100A-150A, 5.5/6A, 8-16 HZ	PCB size 50x30mm	5	100
Propeller	Carbon fiber two-blade and wooden three-blade	15" and 13" diameter with a 5-inch pitch and 6mm shaft diameter	1	120
Motor	Brushless motor with 400-500KV 70A	5050-5060	5	400
Others (wires, servos, Sensors, PDB, Flight controller)	N/A	N/A	1	300
Total				6620

Since the total weight is 6620 g means each throttle motor will have a thrust of more than 1655g. Using the method described in **Section 2.3.5.4**, the thrust of the motors will be anywhere between 4000-5000 g each for safety measures to avoid overheating. The takeoff weight without the Batteries is approximately 5 kg.

Table 3-2 Mass properties of Shell

Coordinate system: -- default --

The center of mass and the moments of inertia are output in the coordinate system of assembly.
Mass = 1990.52 grams

Volume = 6859177.05 cubic millimeters

Surface area = 2188020.16 square millimeters

Center of mass: (millimeters)
X = 436.78
Y = 15.79
Z = 0.20

Principal axes of inertia and principal moments of inertia: (grams * square millimeters)
Taken at the center of mass.

Ix = (0.00, 0.00, 1.00)	Px = 171082269.85
Iy = (1.00, 0.05, 0.00)	Py = 279932714.40
Iz = (-0.05, 1.00, 0.00)	Pz = 443560293.27

Moments of inertia: (grams * square millimeters)
Taken at the center of mass and aligned with the output coordinate system.

Lxx = 280323811.05	Lxy = 7990092.43	Lxz = -15762.90
Lyx = 7990092.43	Lyy = 443169193.48	Lyz = 16341.52
Lzx = -15762.90	Lzy = 16341.52	Lzz = 171082272.97

Moments of inertia: (grams * square millimeters)
Taken at the output coordinate system.

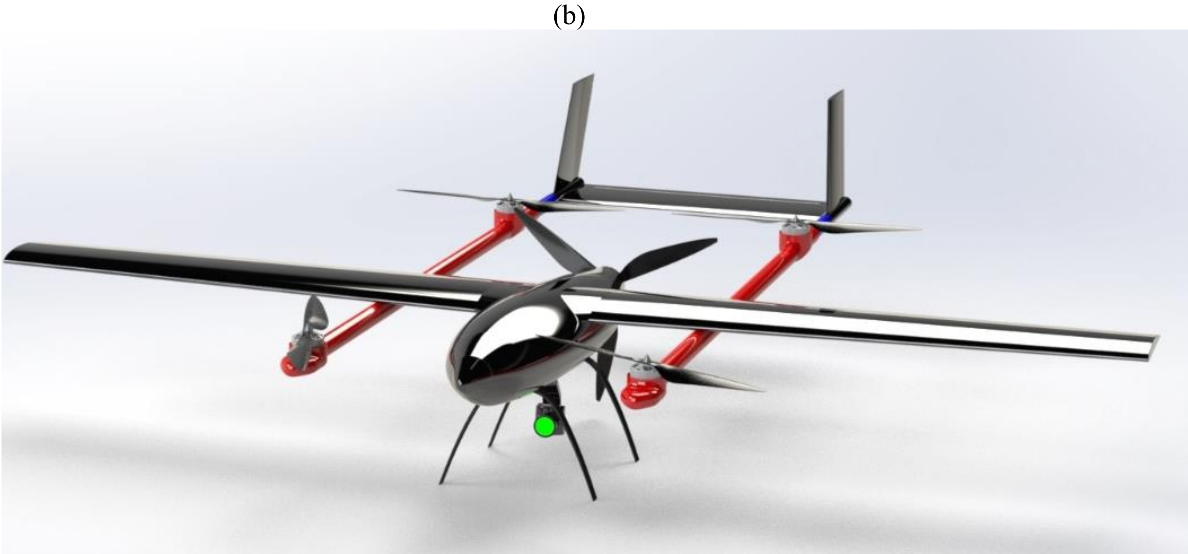
Ixx = 280820177.77	Ixy = 21718058.92	Ixz = 161746.74
Iyx = 21718058.92	Iyy = 822905806.00	Iyz = 22758.73
Izx = 161746.74	Izy = 22758.73	Izz = 551315086.25

3.3 Applications

The UAV in this thesis was designed for outdoor flight and uses the forward flight mode for less power consumption; hence its applications are more on the fixed-wing side than the multi-rotor side. The applications include border security, agricultural inspections, search and rescue, fire-fighting, and wildlife monitoring. There are three types of designs made according to different applications. **Figure 3-2 (a)** shows the UAV with a delivery box at the bottom, hence used for the payload. The next is the one with a high-tech camera, **Figure 3-2 (b)**, which is military-grade used for thermal vision and better sight for border patrol and mapping applications. As seen in **Figure 3-2 (c)**, the last one is a simple, low-cost camera used for navigation and similar but not the same level as the high-tech camera, hence applications that do not require much detailed imaging.

(a)

(b)



(c)

Figure 3-2 UAV design according to applications. (a) Delivery; (b) Mapping; (c) Navigation.

3.4 Simulations

The simulations done for this thesis include the Aircraft Design Aerodynamics

Analysis, Aircraft Landing Gear FEM Analysis, Optimization of a wing with CFD Simulations.

3.4.1 Aerodynamics

Aerodynamics includes the flow simulation of the UAV which are the airflow trajectories, as seen in **Figure 3-3,** where the lines in yellow and orange signify the velocities of 54-73 m/s. The cut plot shown in **Figure 3-4** illustrates the pressure effect on different sides of the UAV based on different velocities shown in red, green, orange, and yellow. The surface plot is showing the different areas affected by the air pushing on the UAV in **Figure 3-5** with round edges on the wings showing the highest pressure applied since they are in the yellow range. The velocity was 75 m/s in the horizontal opposite direction relative to the UAV. The simulations were done for the external parts, as shown in **Table 3-3.** The temperature and velocity applied are shown in **Table 3-4.** The gas medium is Air, and we assume no friction and no gravity effect set. **Table 3-5** shows the friction force in X-direction and lift force in the Y-direction of the UAV in the air.

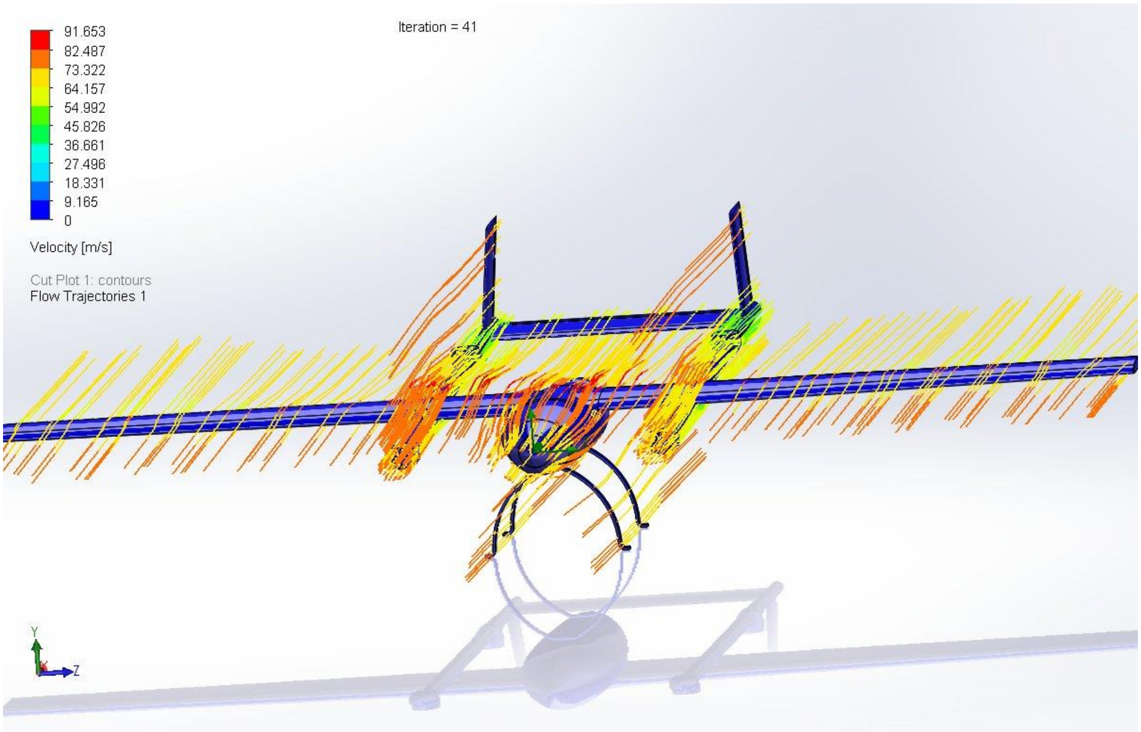


Figure 3-3 Airflow trajectories on the mechanical design.

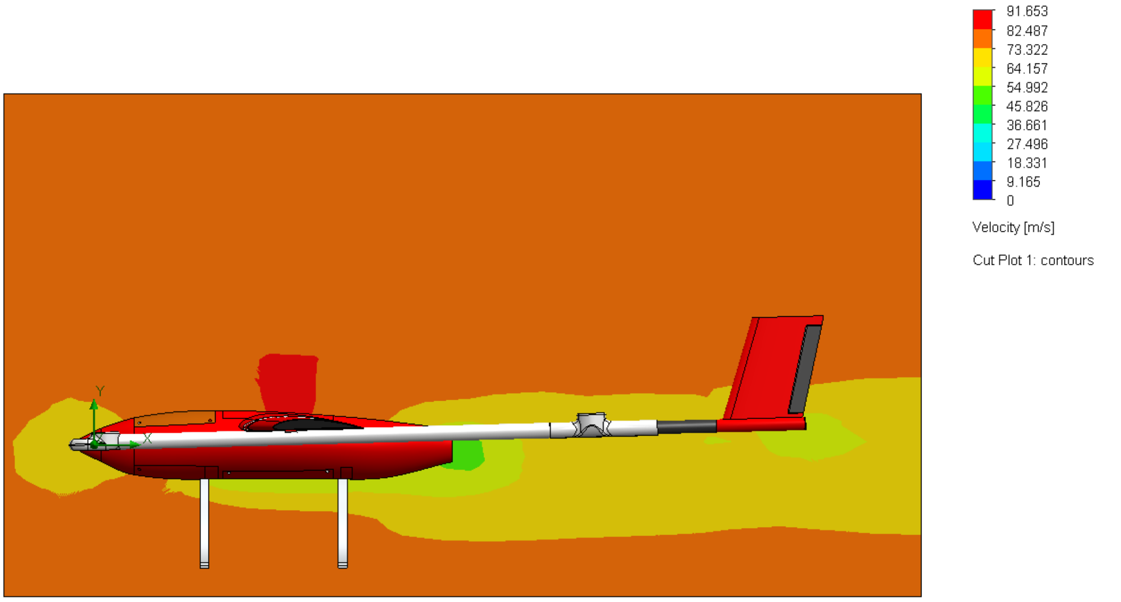


Figure 3-4 Cut plot of the UAV.

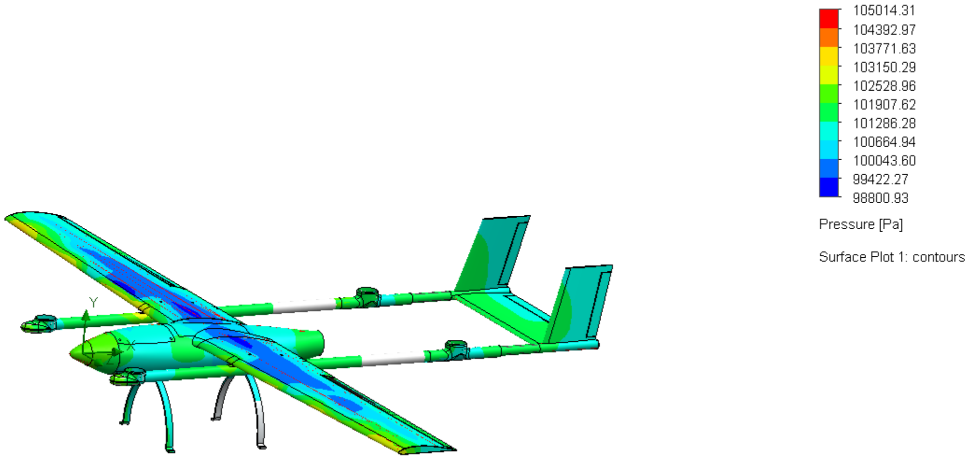


Figure 3-5 Surface Plot the UAV.

Physical Features

Heat conduction in solids: Off

Time-dependent: Off

Gravitational effects: Off

Rotation: Off

Flow type: Laminar and turbulent

High Mach number flow: Off

Humidity: Off

Free surface: Off

Default roughness: 0 micrometer

Default wall conditions: Adiabatic wall

Table 3-3 Ambient Conditions

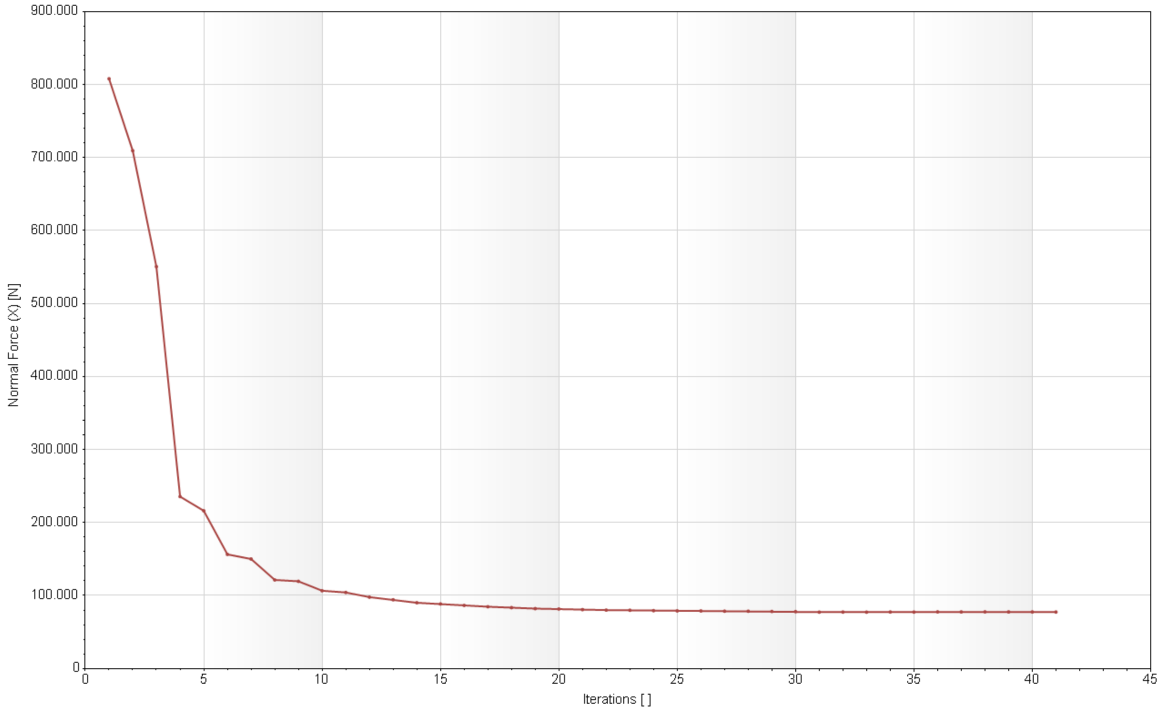
Thermodynamic parameters	Static Pressure: 101325.00 *Pa* Temperature: 293.20 *K*
Velocity parameters	Velocity vector Velocity in X direction: -75.000 *m/s* Velocity in Y direction: 0 *m/s* Velocity in Z direction: 0 *m/s*
Turbulence parameters	Turbulence intensity and length Intensity: 0.10 % Length: 0.004 *m*

Table 3-4 Friction and Lift Force

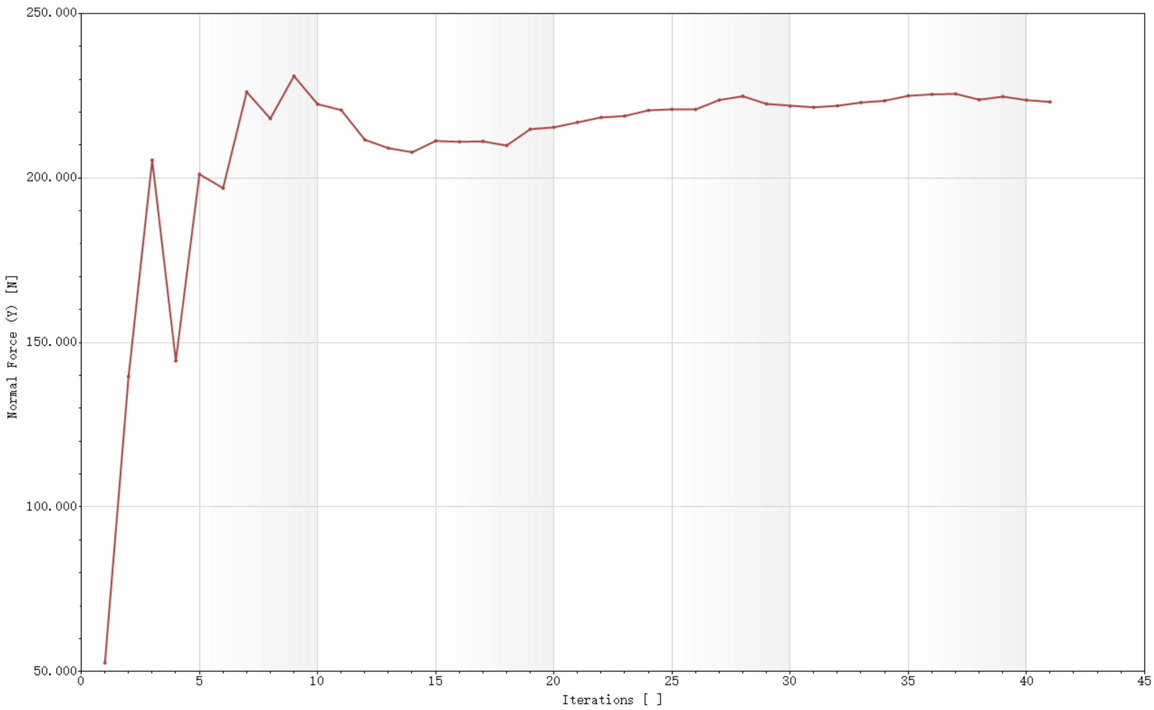
Name	*Unit*	*Value*	*Progress*	*Criteria*	*Delta*	*Use in convergence*
GG Normal Force (X) 1	*N*	77.443	100	51.1673967	3.45230242	On
GG Normal Force (Y) 2	*N*	223.125	100	9.35889159	8.6576064	On

Table 3-5 Min/Max Table

Name	Minimum	Maximum
Density (Fluid) [kg/m^3]	1.17	1.25
Pressure [Pa]	98800.93	105014.31
Temperature [K]	291.77	296.02
Temperature (Fluid) [K]	291.77	296.02
Velocity [m/s]	0	91.653
Velocity (X) [m/s]	-13.091	91.599
Velocity (Y) [m/s]	-18.559	41.688
Velocity (Z) [m/s]	-26.468	26.983
Mach Number [ ]	0	0.27
Velocity RRF [m/s]	0	91.653
Velocity RRF (X) [m/s]	-13.091	91.599
Velocity RRF (Y) [m/s]	-18.559	41.688
Velocity RRF (Z) [m/s]	-26.468	26.983
Vorticity [1/s]	0.10	3259.92
Relative Pressure [Pa]	-2524.07	3689.31
Shear Stress [Pa]	0	25.50
Bottleneck Number [ ]	7.4380798e-11	1.0000000
Heat Transfer Coefficient [W/m^2/K]	0	0
ShortCut Number [ ]	3.8477647e-11	1.0000000
Surface Heat Flux [W/m^2]	0	0
Surface Heat Flux (Convective) [W/m^2]	0	0
Acoustic Power [W/m^3]	0	0.002
Acoustic Power Level [dB]	0	92.51



(a)



(b)

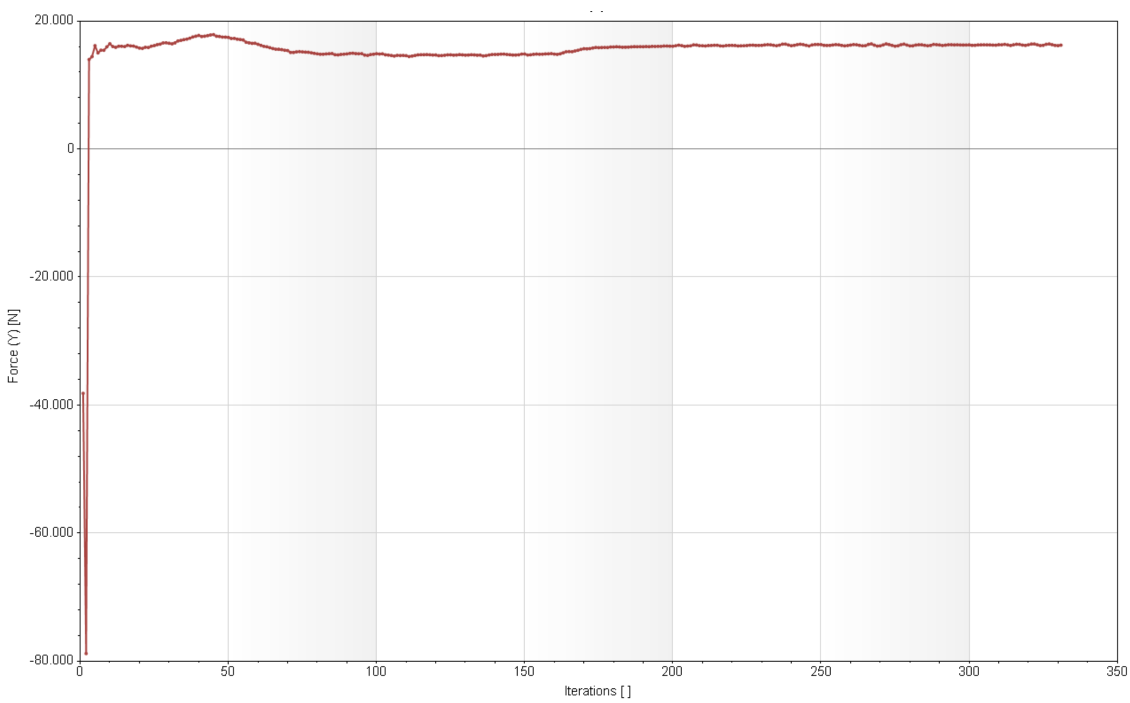
Figure 3-6 Graph showing maximum and minimum values of the force acting on UAV in (a) Horizontal axis and; (b) Vertical axis.

3.4.2 Wings CFD

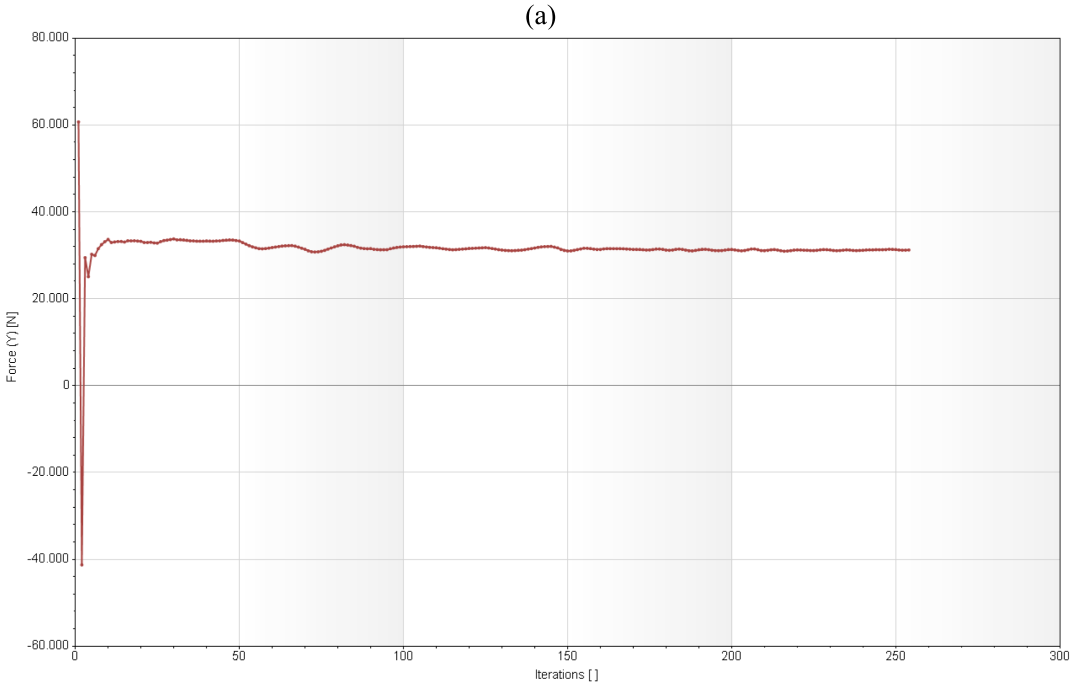
Simulations done for the wings include the calculations of the lift force and the pressure effects on the surface of the wings and the flow trajectories of how the air hit the wings at different angles of attack and which areas are more affected than the others. The velocity of air on the wing was 35 m/s in the horizontal direction.

Table 3-6 CFD of the angle of attacks of left-wing aileron for calculation of lift

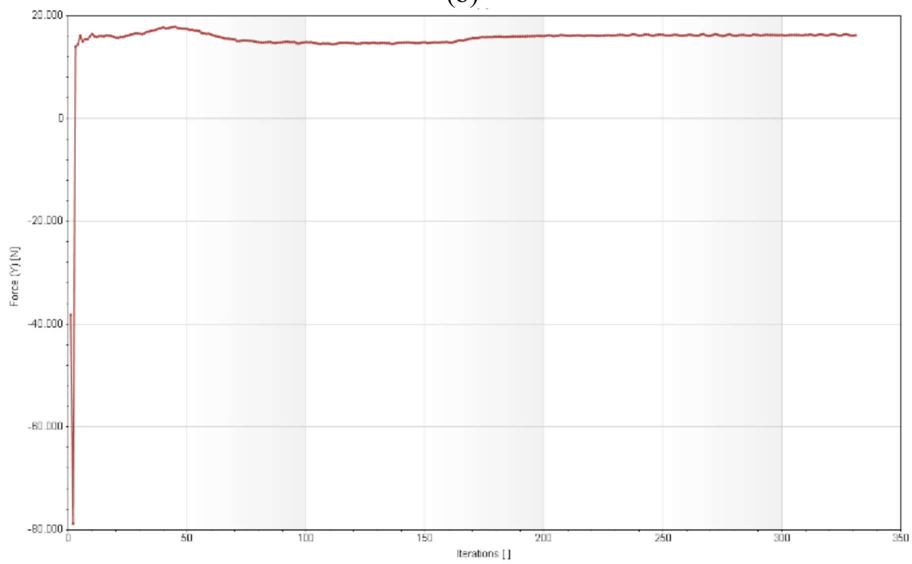
Goal Name	Unit	Value	Averaged Value	Minimum Value	Maximum Value	Progress [%]	Use in Convergence	Delta	Criteria
LF (0^0)	[N]	16.22	16.25	16.06	16.43	100	Yes	0.115	0.116
LF (-15^0)	[N]	-0.311	-0.30	-0.54	0.17	100	Yes	0.23	0.25
LF (15^0)	[N]	31.23	31.20	30.94	31.45	100	Yes	0.25	0.26



(a)



(b)



(c)

Figure 3-7 Graph of Maximum and minimum values Lift force. (a) 0^0 angle of attack; (b) 15^0 angle of attack; (c) -15^0 angle of attack.

Physical Features

Heat conduction in solids: Off

Time-dependent: Off

Gravitational effects: Off

Rotation: Off

Flow type: Laminar and turbulent

High Mach number flow: Off

Humidity: Off

Free surface: Off

Default roughness: 0 micrometer

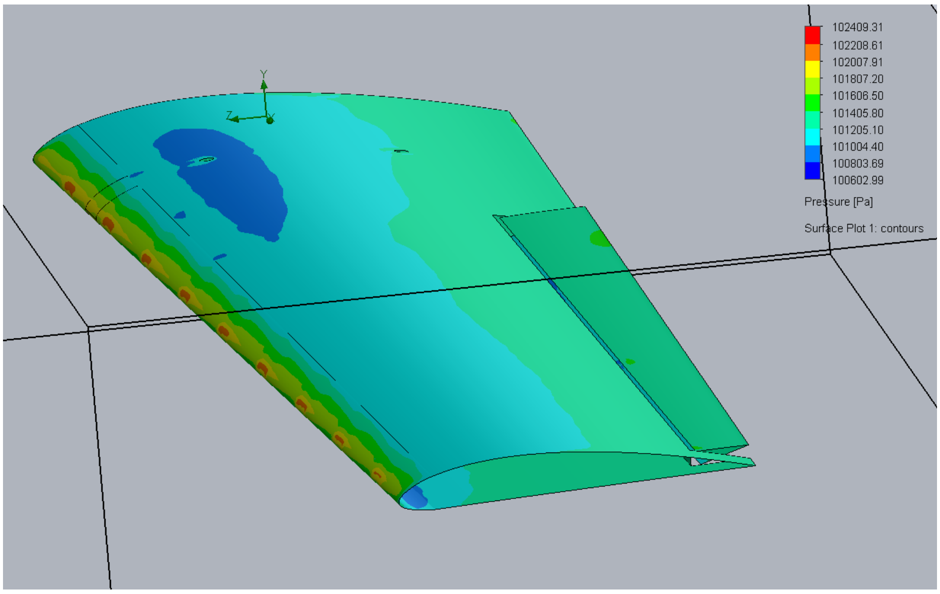
Default wall conditions: Adiabatic wall

Fluids: Air

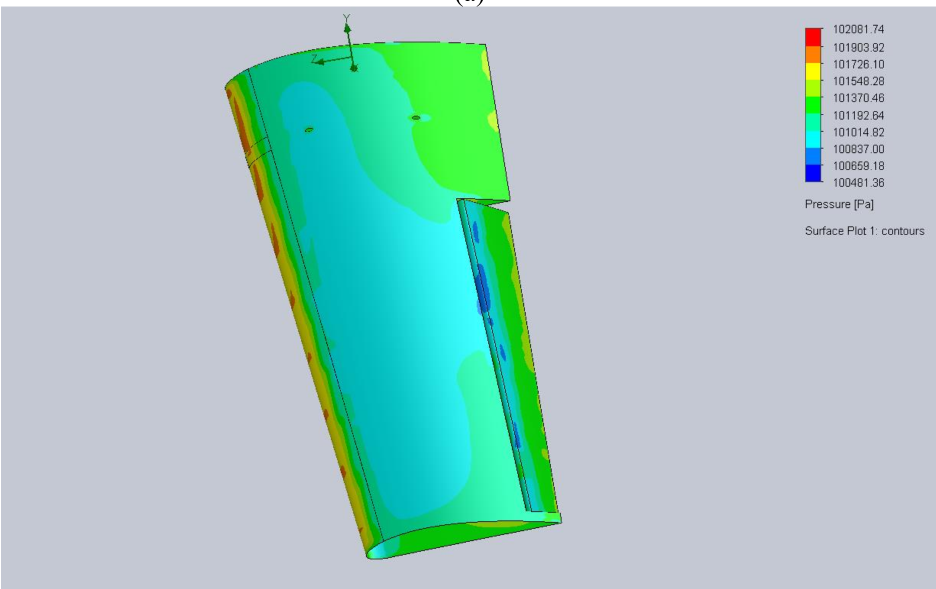
Table 3-7 Ambient Conditions

Thermodynamic parameters	Static Pressure: 101325.00 Pa Temperature: 293.20 K
Velocity parameters	Velocity vector Velocity in X direction: 0 m/s Velocity in Y direction: 0 m/s Velocity in Z direction: -35.000 m/s
Turbulence parameters	Turbulence intensity and length Intensity: 0.10 % Length: 3.021e-04 m

Figure 3-8 shows the pressure differences on the wings as it flies at a speed of 35m/s. The 15^{0} angle of attack shows a lower pressure region than the -15^{0} angle of attack, which means there is a lift.



(a)



(b)

Figure 3-8 Surface plot of pressure on the wing. (a) 15^{0} angle of attack; -15^{0} angle of attack.

Figure 3-9 illustrates a 100N force applied to the wing in which shows the areas where the most stress is high are the middle and the ends of the wing.

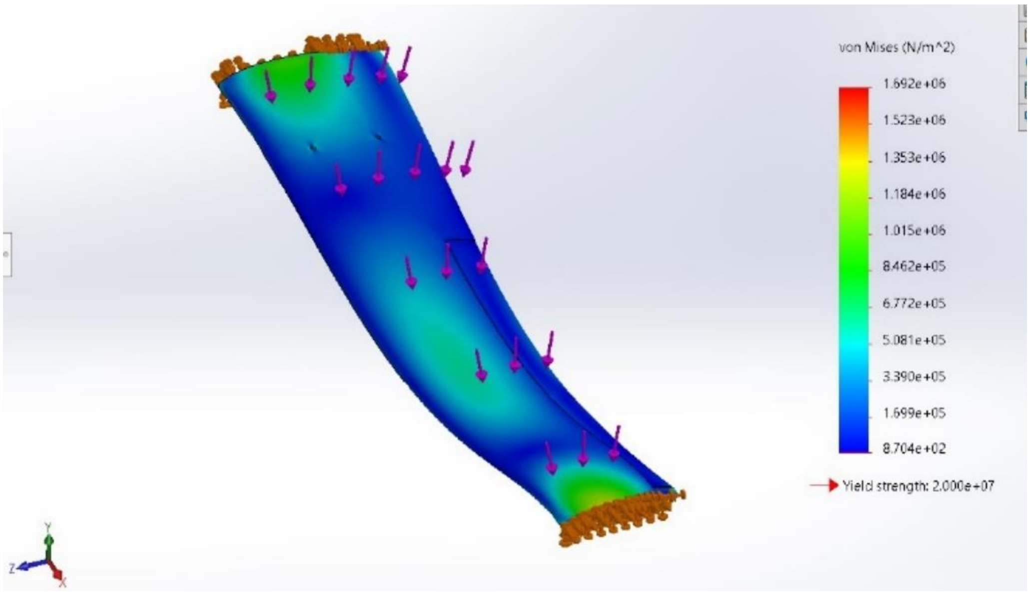
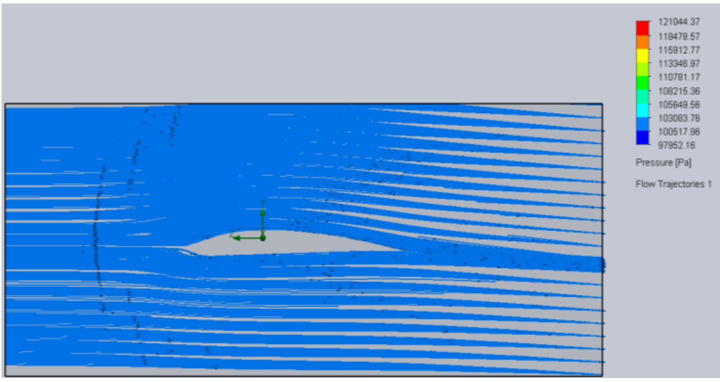
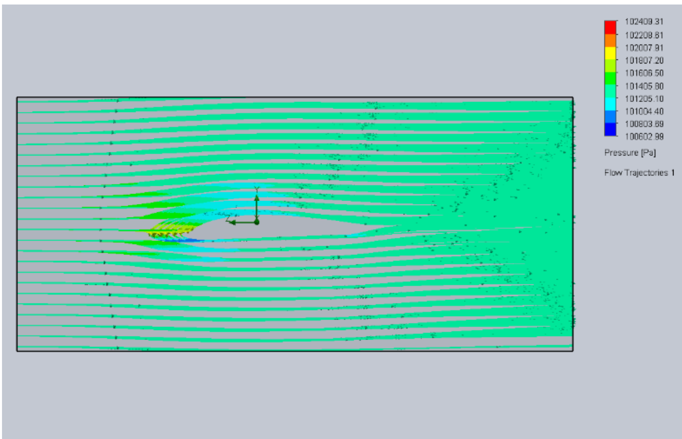


Figure 3-9 FEA applied to the wing for stress testing.

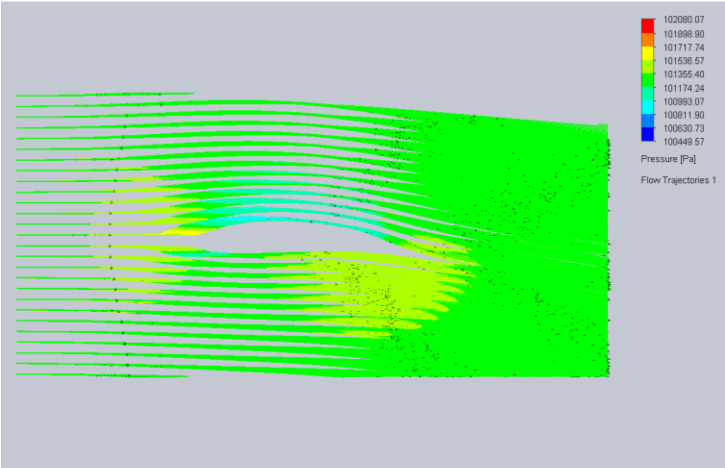
Figure 3-10 illustrates the flow trajectory of air reacting to the wing at a velocity of 35 m/s. It shows different flow trajectories from different angles of attack.



(a)



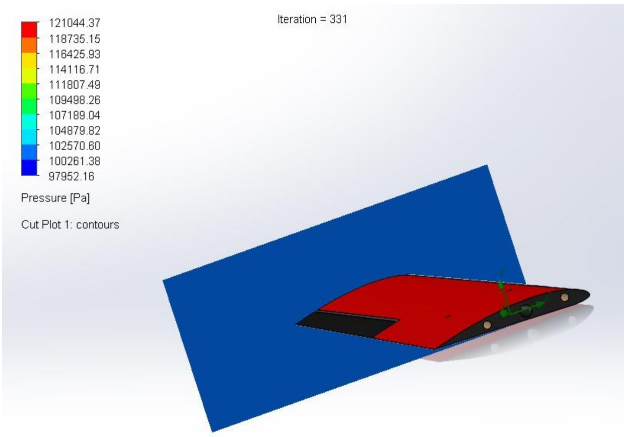
(b)



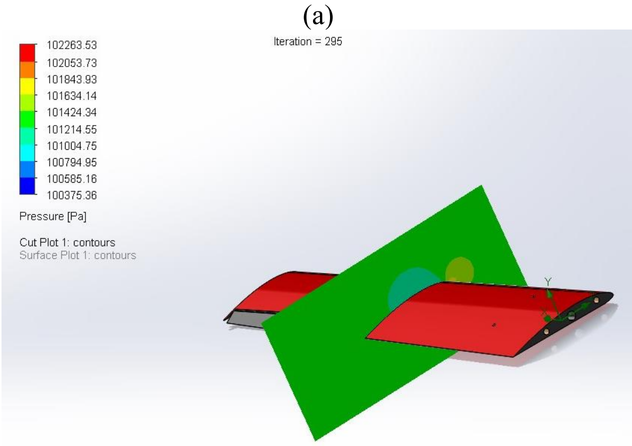
(c)

Figure 3-10 Airflow trajectory of the Airfoil. (a) 0^0 angle of attack; (b) 15^0 angle of attack; (c) -15^0 angle of attack.

As seen in **Figure 3-11**, the 15^0 angle of attack has a larger pressure differential above and below the wing and a larger stagnation zone shown in the blue and orange areas, respectively, giving a lift force.



(a)



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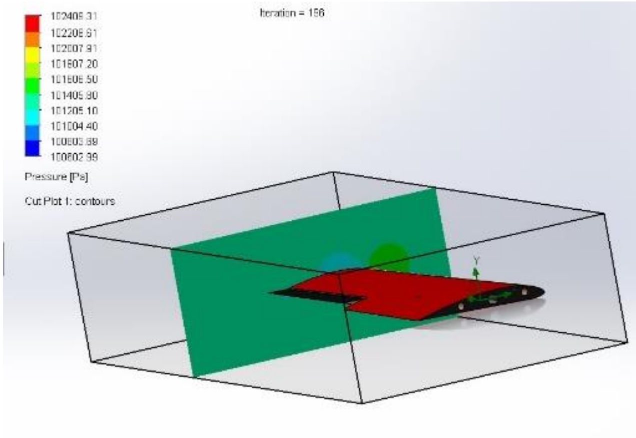


(c)
Figure 3-11 Cut plot of the wing (a) 0^0 angle of attack; (b) -15^0 angle of attack; (c) 15^0 angle of attack.

3.4.3 Landing Gear

FEA was performed on landing gear, as shown in **Figure 3-12**. The most affected areas are the curved areas at the foot and where the landing gear is screwed to the fuselage. 100N of force was applied to the landing gear.

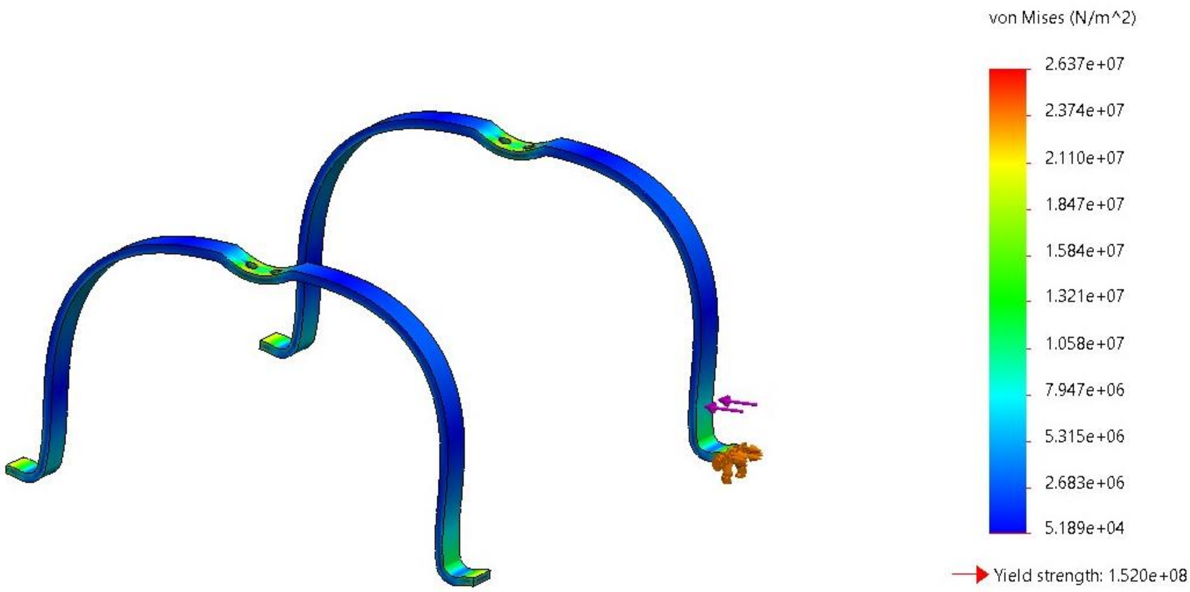
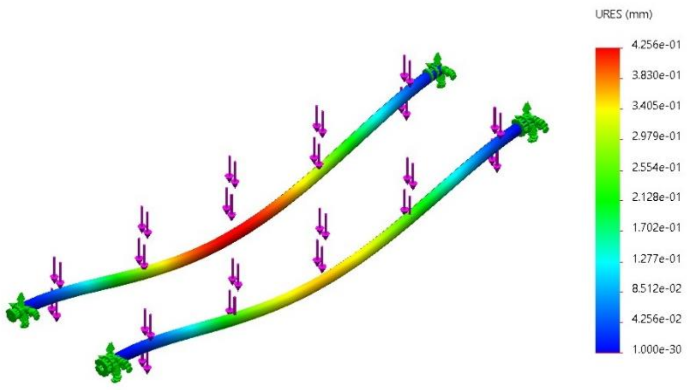


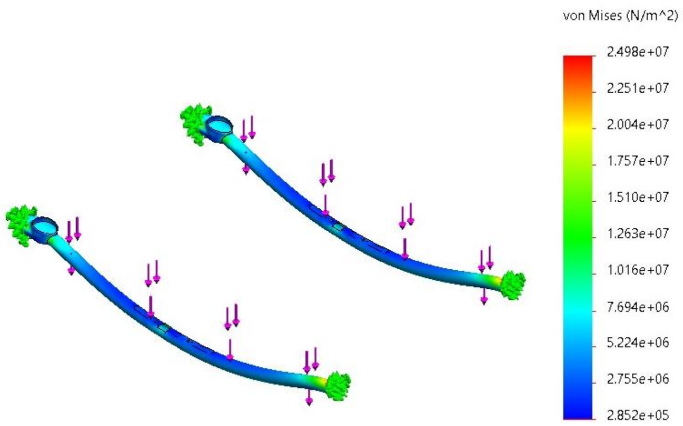
Figure 3-12 FEA on Landing gear.

3.4.4 Frame

The frame of the UAV consists of the rods supporting the fuselage, rods supporting the wings including the tail wing, and the motor mounters. Hence, the FEA was done on each separate part, as seen in **Figure 3-13**, where a force of 100 N was applied to each of the rods and the amount of thermal heat from motors the motor mounter would take. A temperature of 60^0 was applied on the motor mounter to see the most affected areas around the edges.



(a)



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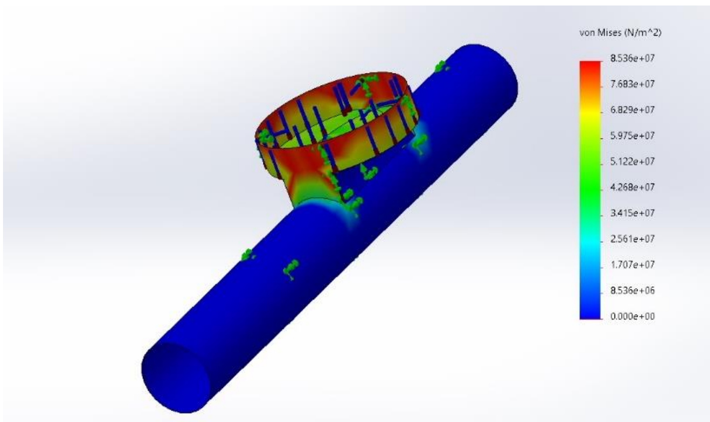
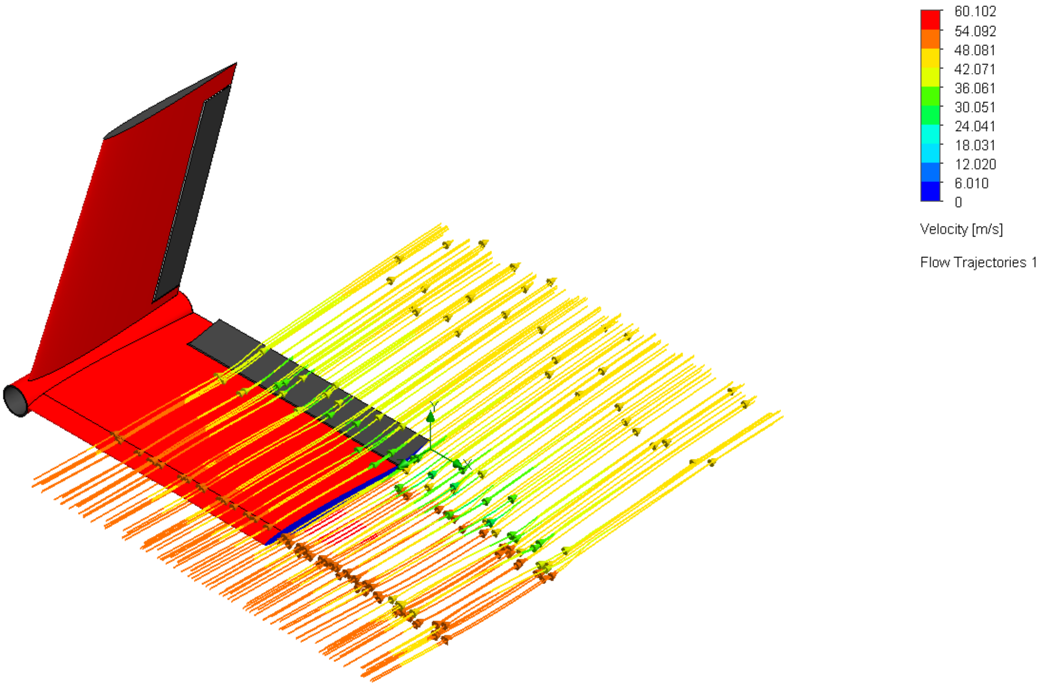


(c)

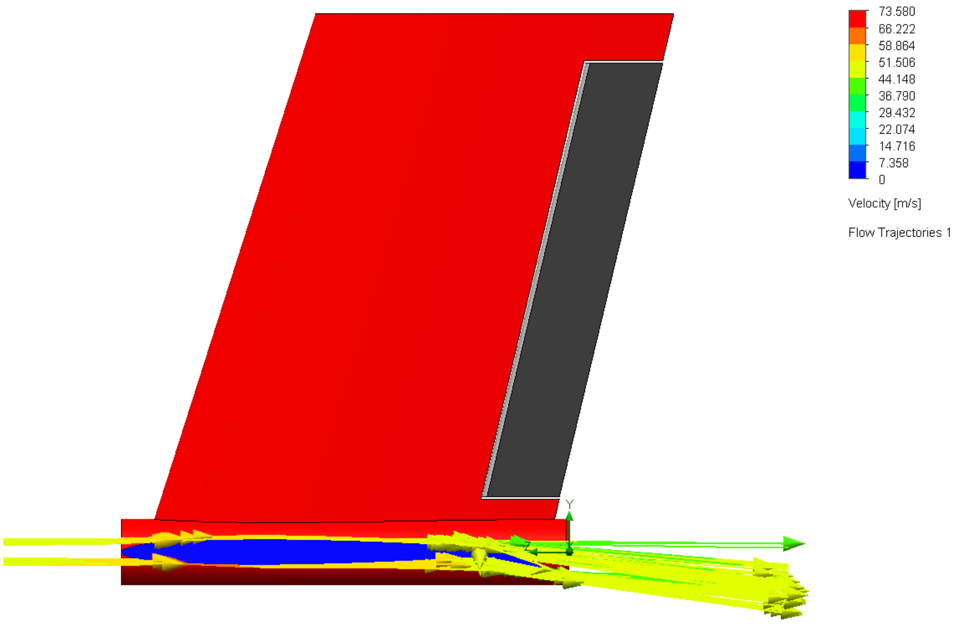
Figure 3-13 FEA on Frame and motor mounters. (a) Rods inside fuselage; (b) Rods holding the wings; (c) Motor mounter.

3.4.5 Tail Wing

For the tail wing, CFD was done on the elevator to calculate the lift force. The elevator was put on two different angles of attacks to calculate the results each gives. Other factors included in the simulations are listed below;

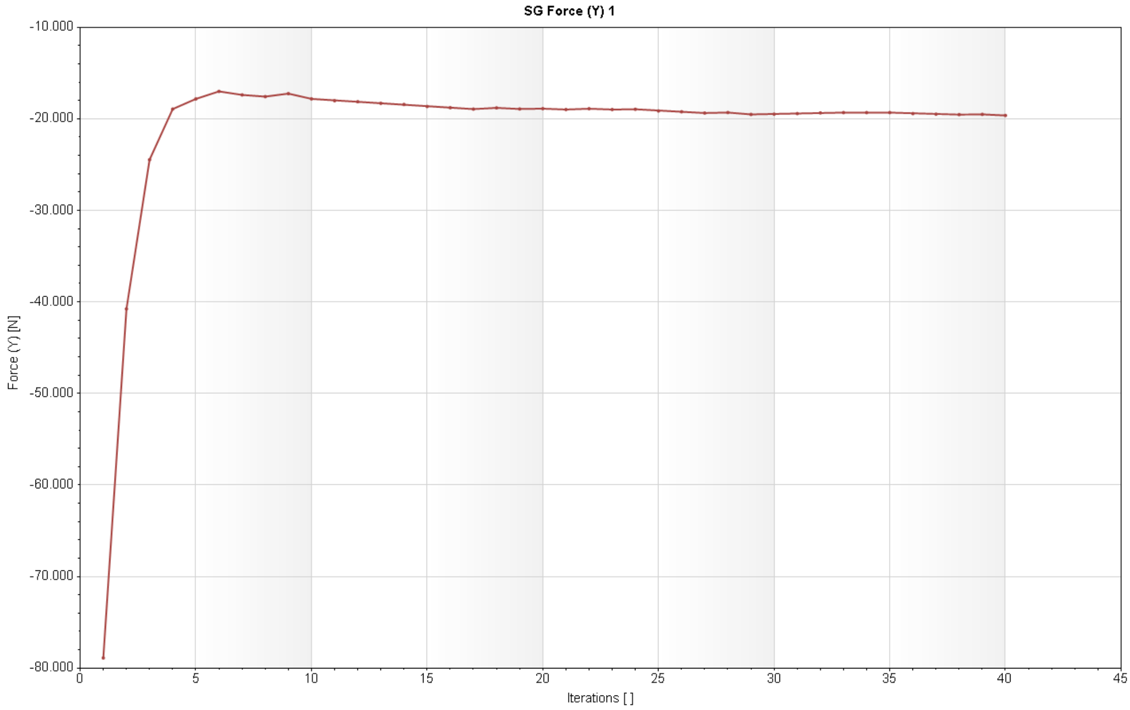


(a)

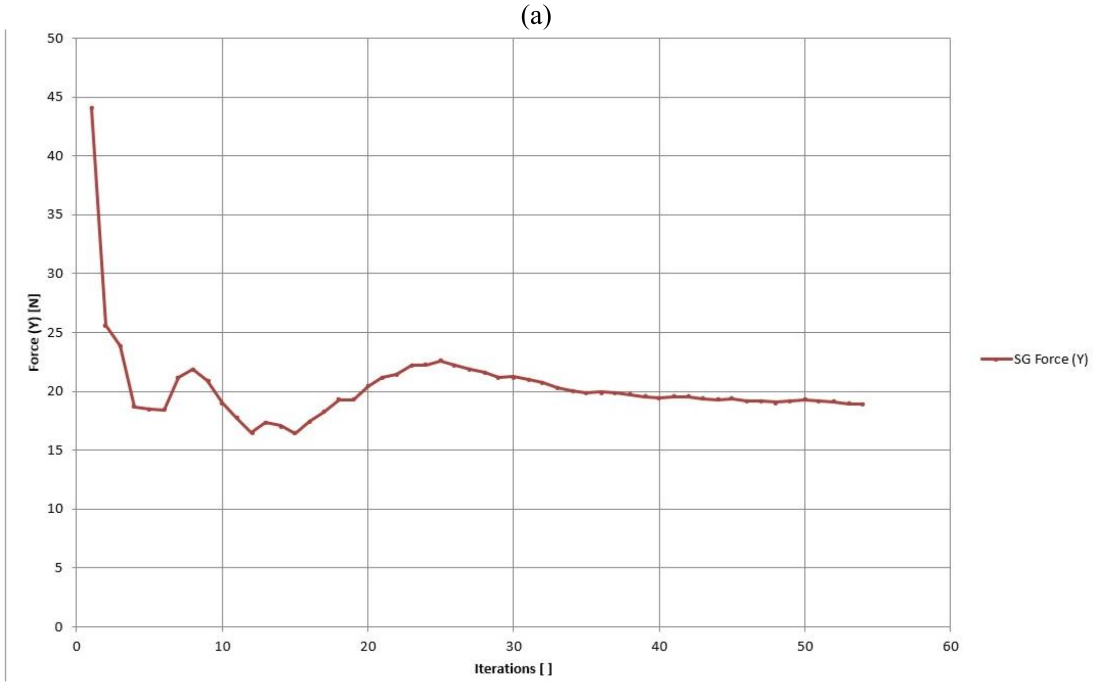


(b)

Figure 3-14 Airflow trajectory on the elevator. (a) 15^0 angle of attack; (b) -15^0 angle of attack.



(a)



(b)

Figure 3-15 Graph Maximum and minimum values of Lift force. (a) -15^0 angle of attack; (b) 15^0 angle of attack.

<u>Physical Features</u>

Heat conduction in solids: Off

Time-dependent: Off

Gravitational effects: Off

Rotation: Off

Flow type: Laminar and turbulent

High Mach number flow: Off

Humidity: Off

Free surface: Off

Default roughness: 0 micrometer

Default wall conditions: Adiabatic wall

Table 3-8 Ambient Conditions

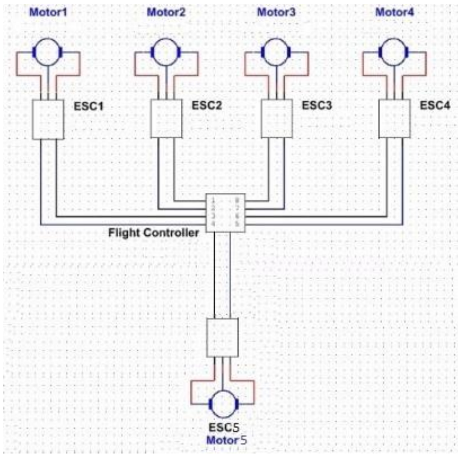
Thermodynamic parameters	Static Pressure: 101325.00 Pa Temperature: 293.20 K
Velocity parameters	Velocity vector Velocity in X direction: 0 m/s Velocity in Y direction: 0 m/s Velocity in Z direction: -50.000 m/s
Turbulence parameters	Turbulence intensity and length Intensity: 0.10 % Length: 0.002 m

Table 3-9 CFD results of the lift force

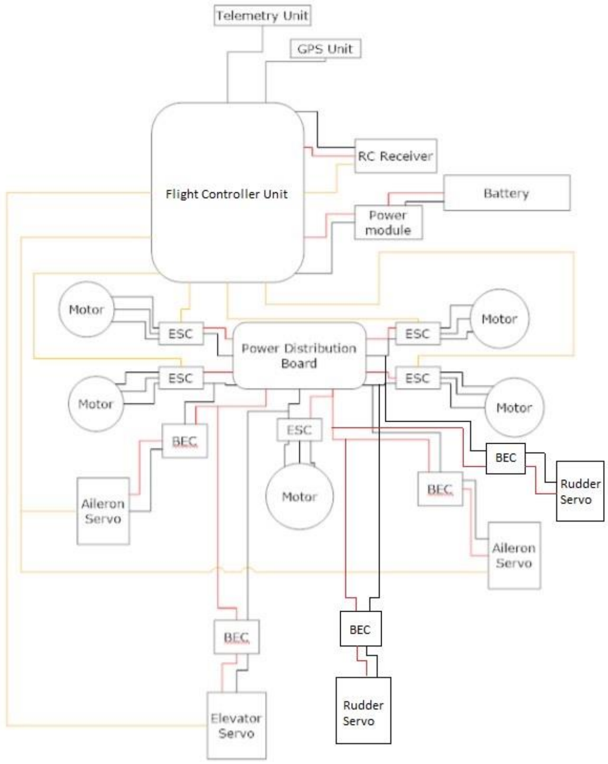
Name	Unit	Value	Progress	Criteria	Delta	Use in convergence
Lift Force (-15^0)	N	-19.633	100	1.11940973	0.737125087	On
Lift Force (15^0)	N	18.922	100	1.0109	1.091	On

3.5 Electrical Schematics

Figure 3-16 illustrates the proposed electrical schematics showing how all the wires and components are connected. More explanation on how it functions can be seen in **Section 2.4.1**



(a)



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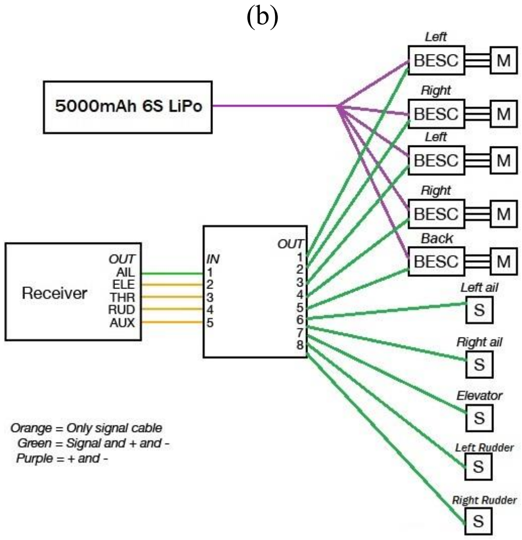

(c)

Figure 3-16 Proposed Electronic Schematics Diagrams.

Summary

The Simulations of the UAV are important to know how much lift force the UAV can give and how much pressure it can experience before breaking. It is part of the reliability testing before making a real-life prototype to save the resources and time required to perform all the tests on the initial prototype.

Chapter 4 Conclusions

4.1 Concluding Remarks

In conclusion, the goal of this thesis was to design a UAV capable of VTOL. The VTOL UAV is a fast-growing technology that has been primarily used in military aviation. Many companies are starting to tap into the VTOL drones as they can perform both the horizontal and vertical flight modes. VTOL UAVs do not need a runway and can take off and land from anywhere. There are many challenges involved, especially since the UAV in this thesis uses a battery as its power source, which has a very low energy density compared to fuel gases. This means the flight time and speed will be limited because of the power-to-weight ratio.

For this reason, The UAV does not need to be the same size or fly very long distances as a conventional manned aircraft. A battery-powered UAV is more eco-friendly than fuel gases since it has fewer emissions compared to the fuel gases, and also comes from a renewable source of energy. With more advancements, eVTOL (electronic VTOL) will be more effective as batteries that store more power in a smaller size are created.

4.2 Future Work

In the future, the plan is for the design of this VTOL UAV to go from just a concept to a real-life manufactured product. The time for the thesis was limited; hence making a prototype for the UAV would require time and resources which were not available. The change from battery to fuel gas is also an idea for future design, although eco-friendly sources are more encouraged in today’s world. Hence adding solar panels on the wings as sources of energy would also be something to work on in the future. The tilting of rotors from vertical to a horizontal direction at a certain altitude to transition in the horizontal flight mode and landing gear capable of landing in water is also an idea in future works.

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