School of Engineering and Digital Sciences

Bachelor of Engineering in Mechanical and Aerospace Engineering

Design and analysis of a small cargo UAV

Capstone Project Report

by

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Declaration

We, Ainur Yessenova, Rustem Khamze, Zhandos Bakytov, and Zhanggir Irgaliyev, hereby declare that this report, entitled "Design and analysis of a small cargo UAV" is the result of our own project work except for quotations and citations which have been duly acknowledged. We also declare that it has not been previously or concurrently submitted for any other degree at Nazarbayev University or elsewhere.

Signature:

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Name:

Date: April 28th, 2024

Abstract

This Capstone Project focuses on taking an engineering approach to designing a small cargo (2 kg payload) all-electric UAV that has the purpose of solving the problem of inaccessibility of medical aid in distant, hard-to-reach areas of Kazakhstan. Having set up exact parameter requirements for an UAV according to the mission, it is possible to define required dimensions and configurations of an UAV. It is decided to use a launcher to enable the UAV to take-off and the landing is to be done by belly landing. Analysis includes calculations, statistical data analysis, computer aided modeling and simulations.

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Introduction

Kazakhstan is a country of vast territories, mostly consisting of steppes that divide towns by large distances. Taking into account the poor transportation infrastructure and harsh weather conditions, this creates a problem of accessibility to remote villages and settlements. If an emergency strikes, the inability to provide any kind of support from nearby cities in time can lead to disastrous consequences. This also applies to medical emergencies, when a person is in urgent need of certain medical aid, most commonly, insulin and blood packs. As ground transportation can be dependent on road conditions, as well as traffic inside the city from where the transport is leaving, an electric cargo unmanned aerial vehicle-s (UAV) are often proposed as a possible solution. Electric UAV offers fast transportation of small cargo, and often does not require large take-off runways and pre-flight maintenance as other air transports might. For this Capstone Project, it was decided to set a mission of 100 km total distance, with an 1 hour requirement to reach the drop destination of a 2 kg payload.

Theory

General application of UAVs

In recent years, industry players, investors, and governments have turned special attention to the implementation of UAVs in different fields. UAVs are vital in precision agriculture for tracking crop health, identifying diseases, perfecting irrigation, and dispensing targeted treatments such as pesticides and fertilizers. Mapping tools, LIDAR systems and photogrammetry allow UAVs to build detailed maps and to make urban planning and building constructions more effective by surveying lands. Drone cameras that have high resolution and stabilization technology can be used to capture panoramic shots which could be very useful in films, documentaries, advertisements and photography with unique perspectives that once were very expensive or hard to get. There are also examples of UAVs being widely used in infrastructure inspection, environmental monitoring and delivering packages. Today, the complete range of machines is referred to as advanced air mobility (AAM).

Why should we use UAV in delivery?

Several significant reasons make UAVs an attractive approach for cargo transportation. Swift delivery services especially for an urgent or time-sensitive cargo can be achieved through UAVs. They bypass traffic and go directly to the destination, which significantly cuts down delivery time as compared to the traditional ground transport. Drones can navigate into areas that are isolated from conventional modes of transport. The ability to do this is especially important when delivering essential supplies, medical aid, or emergency items to remote areas, or a disaster-struck region. UAVs can potentially reduce delivery costs by decreasing the amount of human labor required in the transport process. Modern technology and automation advancements may reduce operational costs for UAVs even more than those of conventional delivery methods. Moreover, emissions of electric-powered drones are significantly less than that of traditionally powered delivery vehicles, ultimately leading to less carbon footprint and a sustainable way of transport. Drones utilize air space to deliver goods. This helps to relieve roads from increased pressure thus alleviating traffic congestion and smoothing transportation operations in urban areas. The evolution of UAVs in terms of their technology will make the cargo transport sector more innovative. The potential for research and development in payload capacity, flight range, battery life and other factors could completely change the drone delivery system [1].

Main obstacles in using UAV as cargo transport

Tech enthusiasts have long been captivated by the potential of drone technology. According to CBS News, back in 2013, Jeff Bezos, CEO of Amazon, revealed an ambitious plan to introduce a groundbreaking drone delivery service named Prime Air [2]. This innovative service aimed to revolutionize the way packages were delivered, promising swift doorstep delivery within a mere half-hour of placing an order. A wave of anticipation swept through the masses when news of this proclamation emerged, igniting a fervor for the potential transformation of logistics and the delivery landscape. However, a full decade has elapsed since that announcement, and the realization of drone delivery continues to elude the world.

Over the last decade, an array of drone delivery enterprises has been caught up in the arduous process of testing and rolling out their services across various regions. While a handful of companies have managed to achieve notable advancements, with a few even carrying out restricted deliveries, the likes of Amazon's Prime Air, Google's Wing Aviation, UPS's Flight

Forward, and other similar ventures are diligently undergoing trials to perfect their drone delivery mechanisms for seamless transportation of products from sellers to customers.

Regulatory challenges have posed the greatest obstacle to the advancement of drone delivery.

The primary challenge encountered by Amazon's Prime Air and other companies has been navigating the intricate web of regulations. In the United States, the Federal Aviation Administration (FAA) assumes the responsibility of establishing rules and regulations concerning commercial drone usage. Following Amazon Prime Air's groundbreaking announcement, the FAA imposed strict limitations on drones' operational scope. For a considerable period, drones were prohibited from operating beyond the operator's line of sight, carrying payloads, or conducting flights during nighttime. It wasn't until the year 2020 that the FAA began to loosen its grip on these regulations. Additionally, Amazon had to exercise patience until August 2020 in order to attain the coveted Part 135 certification from the FAA, which would grant them the status of an "air carrier" as per the regulations. As a result, the progress and implementation of Prime Air have been severely hindered by these prolonged delays [3].

Technology presents yet another formidable obstacle. Despite the rapid strides made in drone technology, there remain considerable hurdles to surmount. A paramount apprehension revolves around guaranteeing the safety of both drones and the general public, particularly in densely populated regions. Autonomous drones must deftly navigate through obstacles, contend with capricious weather conditions, and flawlessly transport payloads. The range constraint significantly impacts a drone's lifting capacity, relative to its battery power. As the drone's batteries increase in size, so too does the drone's weight, ultimately diminishing its payload-carrying capability.

Also, The Electronic Frontier Foundation has highlighted the concerns raised by privacy advocates regarding the presence of drones hovering above residential regions [3].

Recent view on the UAV delivery

From 2021 onwards, Walmart has been on a remarkable expedition to transform the realm of customer convenience through the implementation of drone delivery services. Throughout this period, they have witnessed exponential growth, extending delivery to encompass seven states and an impressive network of 36 stores. Over this time they conducted over 10,000 secure deliveries [4].

There are also several outstanding cases of helping with medical emergencies by delivering needed medicines. For example, in December 2021 in Trollhättan, Sweden, a UAV cargo helped save the life of a 71-year-old man when an Everdrone autonomous drone carried a defibrillator to him [5].

Zipline is one of the biggest drone delivery companies. The company has established distribution centers across various countries such as Rwanda, Ghana, Japan, the United States, Nigeria, Cote d'Ivoire, and Kenya. Impressively, by now, their drones have successfully completed almost one million commercial deliveries and covered a staggering distance of more than 60 million miles autonomously. These remarkable drones play a crucial role in delivering essential medical supplies. Their deliveries encompass a wide range of products, including whole blood, platelets, frozen plasma, and cryoprecipitate. Additionally, they are also responsible for transporting medical items such as vaccines, infusions, and various common medical commodities. Notably, as of September 2021, Zipline drones have been utilized for more than 75 percent of blood deliveries outside of Kigali in Rwanda [6].

What UAV should be used to complete our mission?

UAV can generally be classified in two: fixed wing and rotary wing. A fixed-wing drone has a singular inflexible wing, fashioned to mimic an airplane, thereby generating lift without the assistance of vertical lift rotors. Consequently, this particular drone solely necessitates energy for propelling forward, rather than spending it to remain airborne. On the other hand, rotary-wing drones utilize a central mast that orchestrates the rotation of their rotor-blades, generating a downward flow of air that generates vertical lift necessary for their take-off.

The main advantages of fixed wing UAV is its ability to fly to a longer distance than the rotary-wing without the need of refueling. Due to its aerodynamic design, the fixed wing has higher flight speed compared to the rotary-wing. It is also more stable in unsuitable weather conditions. However, the take-off and landing of such UAV is more complicated as the aircraft needs to be accelerated to fly and should land smoothly to prevent damage. Rotary-wing UAV can easily take-off and land as it is done vertically. It has the ability to maneuver easier than that of a fixed wing and can hover, which makes it suitable for applications that need precision.

It was decided to use fixed wing UAV, as in medical emergencies, the time and distance are a crucial factor. To help deliver the medical supplies faster to a distant area, high speed and long range fixed wing is an ideal choice.

How do fixed wing UAV operate?

The primary force that guarantees the continuous flight of UAV is known as lift. Lift occurs as a result of the varying air pressure between the upper and lower surfaces of the UAV's airfoil. When air flows over the wings, it generates higher pressure beneath the wings and lower pressure above them, hence creating a pressure difference effectively causing the drone to ascend. This suction pressure above the wings is considerably larger, especially near the leading-edge compared to the pressure under the wings. However, the force of gravity persistently pulls the UAV downwards. Hence, in order to remain airborne, the lift generated by the wings must counterbalance the weight of the UAV. Another crucial force to consider is thrust, which propels the UAV forward. This force is produced by a propulsion system, typically comprising an electric setup encompassing a battery pack, motor, propeller, and control system. The motor transforms electrical energy, sourced from a battery, into mechanical energy to drive the propeller. When the motor sets the propeller in motion, it generates thrust by accelerating a stream of air in the opposite direction. According to Newton's third law of motion, this expulsion of air backward creates an equal and opposing reactionary force (thrust) that propels the UAV forward. Once the drone is in motion, its momentum naturally desires to maintain its current path. This momentum provides stability and makes it more challenging to swiftly alter the UAV's trajectory. Conversely, altering the UAV's momentum enables it to execute maneuvers.

What are the regulations?

EU Regulations 2019/947 and 2019/945 have been put in place to establish a comprehensive framework for ensuring the safe operation of civil drones within European airspace. These regulations take a risk-based approach, meaning that they do not differentiate between leisure or commercial drone activities. Instead, they take into account factors such as the weight and specifications of the drone, as well as the nature of the intended operation. As of 31 December 2020, Regulation (EU) 2019/947 is in effect in all EU Member States, including Norway and Liechtenstein. It is anticipated that Switzerland and Iceland will also soon adopt this regulation.

This particular regulation covers a wide range of civil drone operations and categorizes them into three distinct categories: 'open', 'specific', and 'certified'. Each category corresponds to different levels of risk associated with the operation [7].

In the USA, the UAVs are regulated by the national aviation authority, the U.S. Federal Aviation Authority (FAA) that state [8]:

- UAV must weigh less than 55 pounds, including payload, at takeoff.
- Should fly in Class G airspace.*
- It should be within visual line-of-sight.*
- UAV should fly at or below 400 feet.*
- It must fly at or under 100 mph.*

There are no working official regulations about drones in Kazakhstan. The lack of drone rules does not always imply that you can fly wherever and however you want in Kazakhstan—in fact, authorities may be generally hostile to the usage of drones, particularly by tourists.

Literature review

UAVs are already widely used all around the world both in civil and military medical purposes, with the blood packs being one of the most common payloads. For example, Christopher et al. analyzed the efficiency and logistic infrastructure of using autonomous UAV for blood delivery in military conditions [9]. Research proved that battery-powered UAVs are very efficient in connecting different medical facilities with each other should a sudden spike in need for blood in one place appear. Dantas et al. looked into the financial aspect of such operations and logistics, in order to come up with the cheapest set of tools and approaches in hard times of COVID-19 [10]. By this research, it was proven that even by using the simplest set of tools - open source software, cheap frame and cheap flight controller board - the UAVs can fully operate highly efficiently. Saponi et al. investigated the solutions on how the cargo can be embedded within the UAV, compatibility of UAV with medical cargo, and the usability aspects of such approach [11]. Additionally, Lammers et al. provided research on 27 different cases of using UAV for medical logistics, concluding that “UAVs may offer a novel solution for the transport of medical supplies and blood products in a safe and timely manner for the forward-deployed setting [12].” All of these studies show that the usage of UAV for small cargo transportation of such vulnerable yet crucial payload as medicine is a solution with high potential.

Design

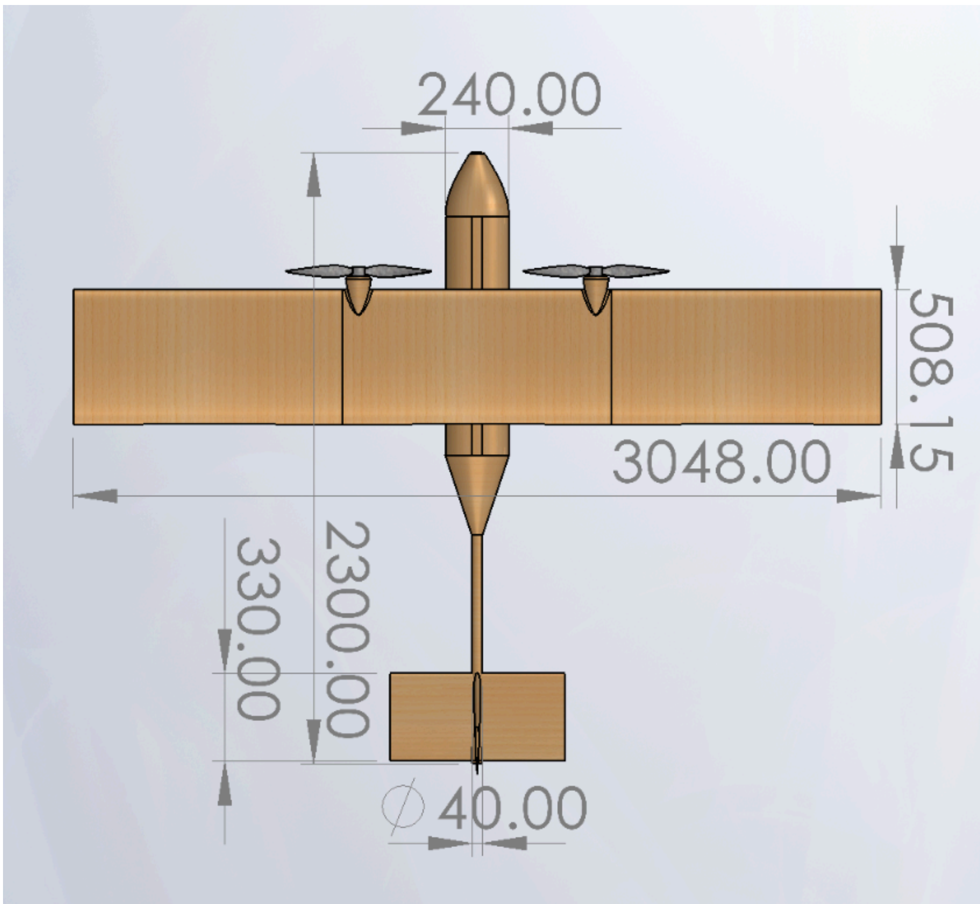


Figure 1. The drawing of the final UAV design.

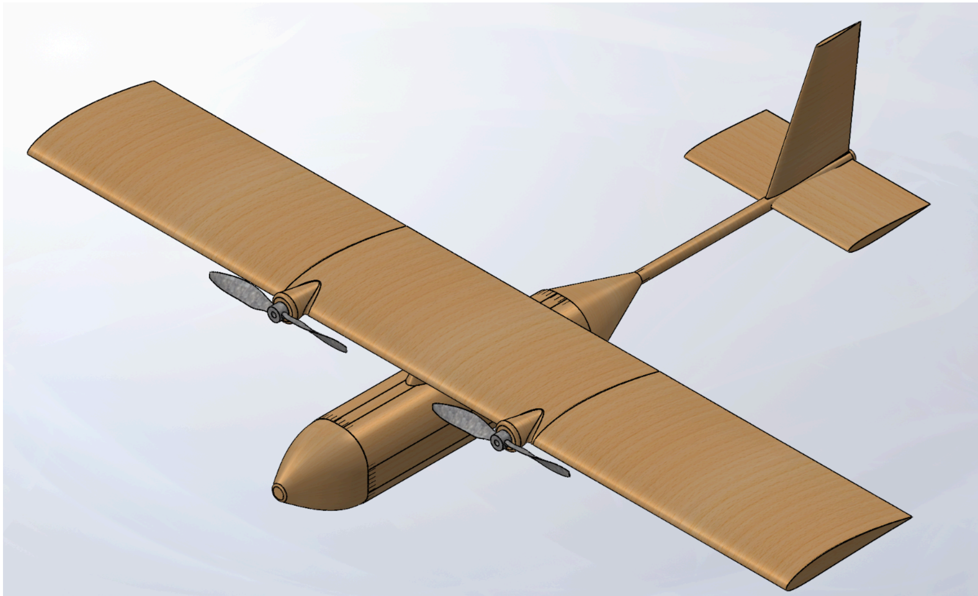


Figure 2. The final design of UAV.

Airfoil

Choosing airfoil is the next critical step in the design of aircraft. For our UAV, there is an incredibly wide variety of available airfoil that can suit the design. To find the best one, an airfoil with the most efficiency should be found. For our mission, there is a short list of requirements, however each one of them is crucial.

- High lift during low speeds up to 50 km/h max
- Low stall speed for takeoff and landing procedures
- Overall efficiency at low speeds
- Stability

Since the aircraft is not going to accelerate to speeds higher than 50 km/h, it is taken as the maximal speed that is required for the airfoil to perform. For the aircraft to not crash during and right after take off launch, the airfoil needs to be efficient at low speeds as well, and therefore have good stall characteristics without flaps. The flaps could be used, but will

1. add weight to aircraft
2. make the design and structure more complicated
3. add load to the wing and accompanying flap actuators
4. greatly complicate takeoff and landing dynamics and control since changed lift, drag, weigh and pressure parameters will require new control algorithms.

So, these are the reasons why cost efficiency is best reached without the use of flaps. Now it means that the airfoil should perform well at critical angles of attack, and generate the highest lift at around 50 km/h, or 14 m/s.

We need to find the Reynolds number of the airstream. At 14 m/s by using the following formula

$$\mathrm{Re} = \frac{\rho u L}{\mu} = \frac{uL}{\nu} \qquad (1)$$

The chord length L at this stage of work is estimated to be 0.5 meter.

$$Re = \frac{1.204 \times 14 \times 0.5}{1.825 \times 10^{-5}} = 462\ 000 \qquad (2)$$

This is the Reynolds number that will be used in further analysis.

Considering the experience of other commercially successful small UAV-s, eight airfoils were chosen to be analyzed for main wings. XFLR5 software is used in further examinations.

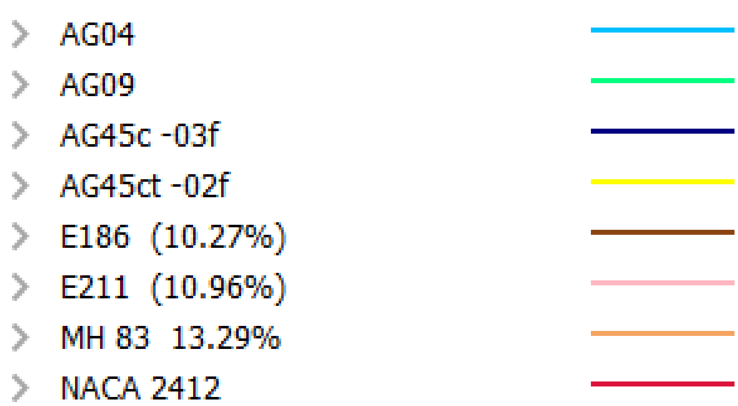


Figure 3. Considered airfoils. Main wings.

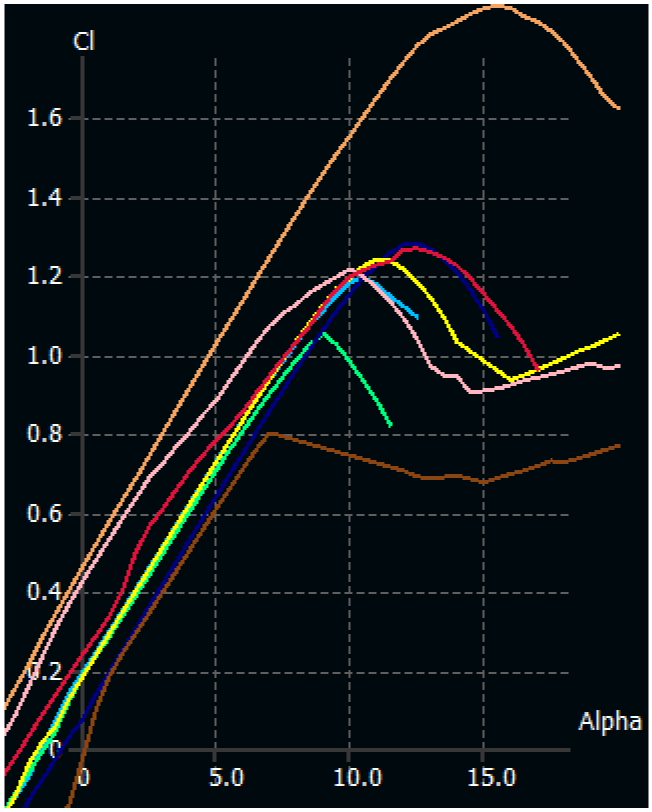


Figure 4. C_l vs. α. Main wings.

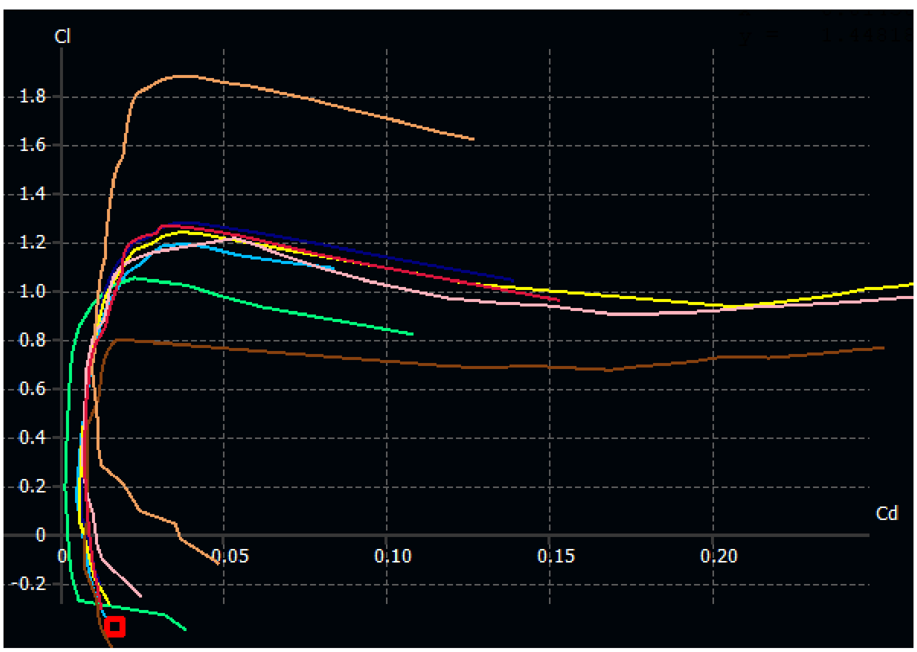


Figure 5. C_l vs. C_d. Main wings.

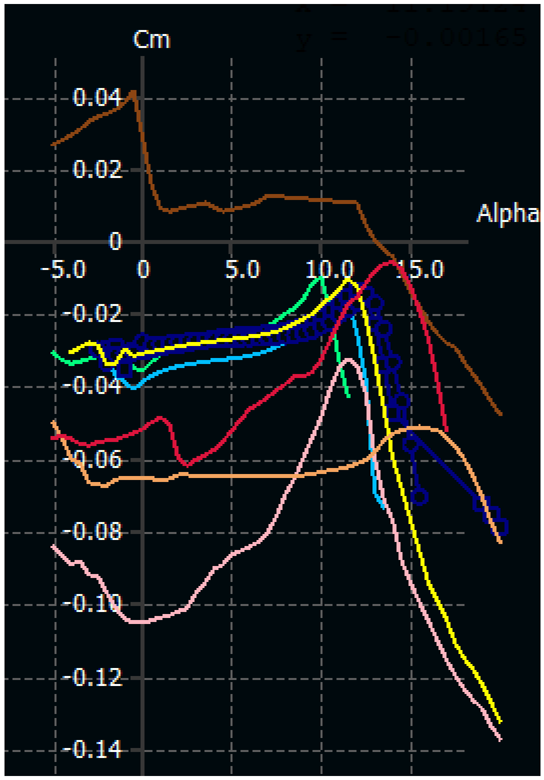


Figure 6. C_m vs. α. Main wings.

At first glance, MH 83 is a very decent airfoil, which can provide high lift coefficients throughout the whole operating angles of attack, while also granting very late stall. However, by looking at C_m vs. α graph, it can be noted that MH 83 will provide poor stability, which is not a good choice for an unmanned aircraft. As a result, NACA 2412 was chosen, as it is the closest contestant in terms of lift coefficient with a fairly good static stability.

Stabilizers:

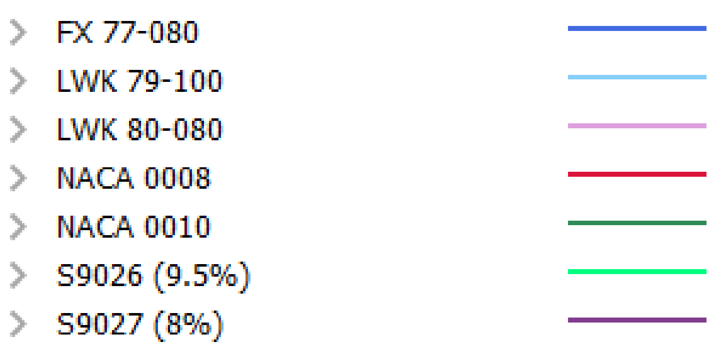


Figure 7. Considered airfoils. Stabilizers.

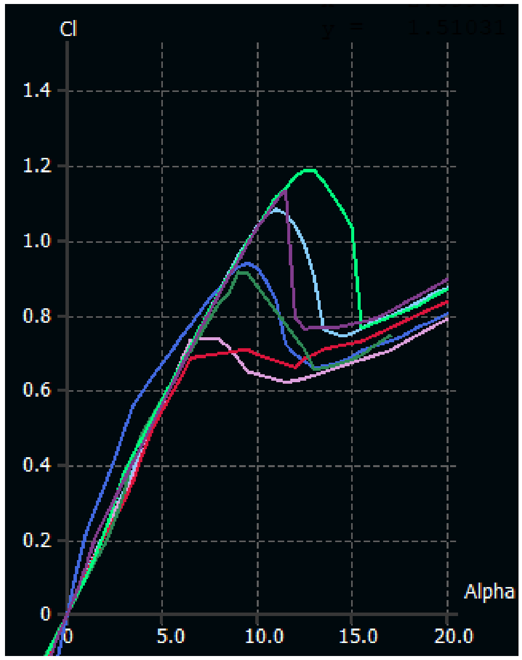


Figure 8. C_l vs. α. Stabilizers.

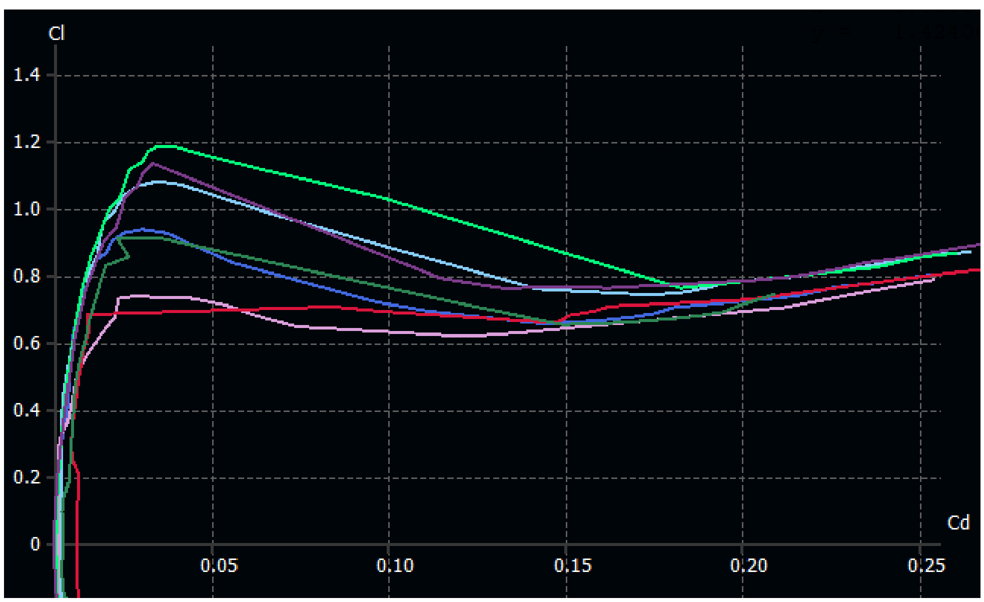


Figure 9. C_l vs. C_d. Main wings.

For stabilizers, data for the C_m vs. α graph is not needed as stabilizers are symmetric and do not produce any pitching moment at zero angle of attack. S9026 was chosen as horizontal stabilizer and S9027 was chosen as vertical stabilizer, because they both provide high lift coefficients.

S9026 was chosen as a horizontal stabilizer because its lift coefficient is slightly higher, which is more important for a horizontal stabilizer than for a vertical one.
Simultaneously it needs minimal drag. It is minimal at the point where induced drag and parasite drag meet.

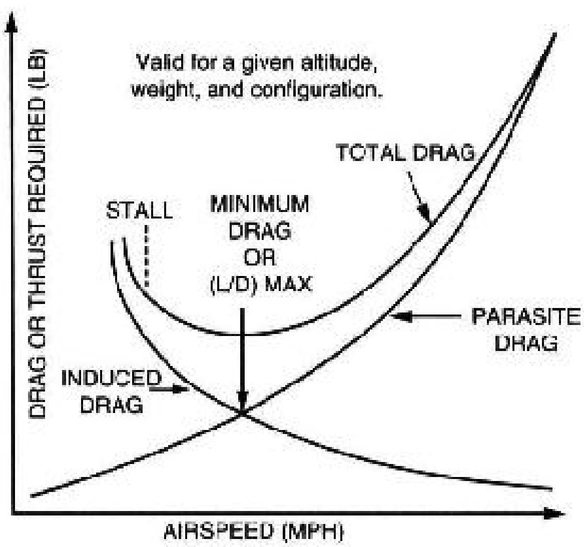


Figure 10 Drags vs Speed graph.

The process of choosing airfoil is a highly complicated operation due to considerations of angle of attack, Cl and Reynolds number, which, in turn, can not be calculated without knowing the airfoil type. In other words, creating a wing is a practical process with an iterative approach where initial guess is followed by an experimental procedure. So for the initial guess, we decided to choose an airfoil that was already widely used on previously built aircrafts.. And therefore, as an initial airfoil the NACA 2412 was chosen for a number of reasons.

1. It is a simple standard airfoil, which is taken as a reference in many other airfoil designs that were developed later.
2. The lift and drag characteristics are known to be good at various speed ranges, including low speeds.
3. It is easy to manufacture and test.

Then, chosen airfoils were analyzed on ANSYS software.
First, we went to http://airfoiltools.com/plotter/index to plot the airfoil profile used for the initial 2D simulation in ANSYS software.

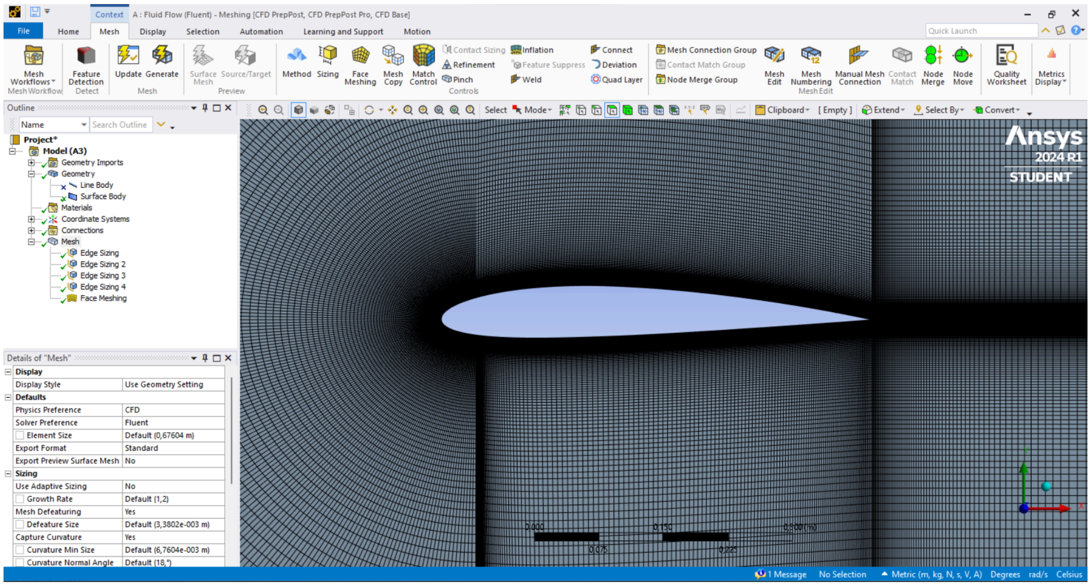


Figure 11. The 2D mesh of the NACA 2412 airfoil created in ANSYS.

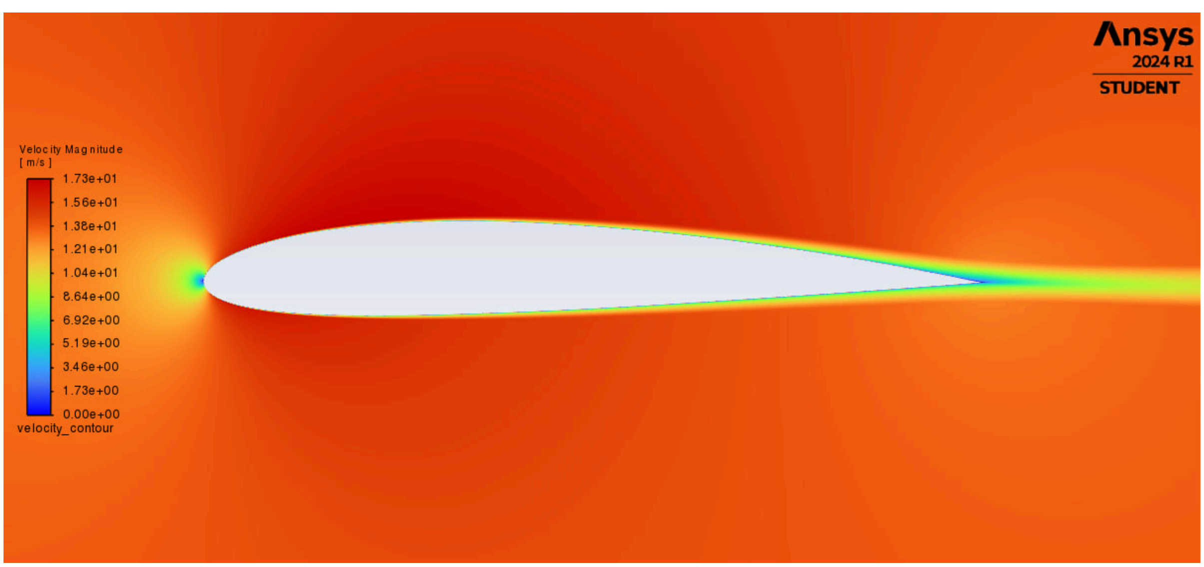


Figure 12 . Velocity Magnitude Simulation.

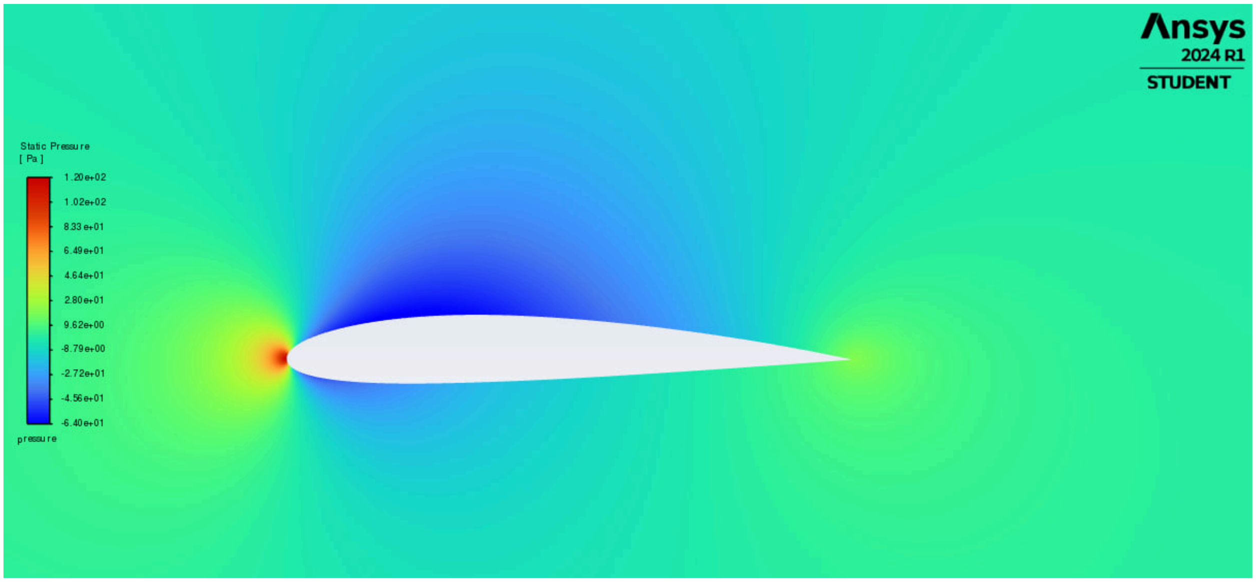


Figure 13. Static Pressure simulation.

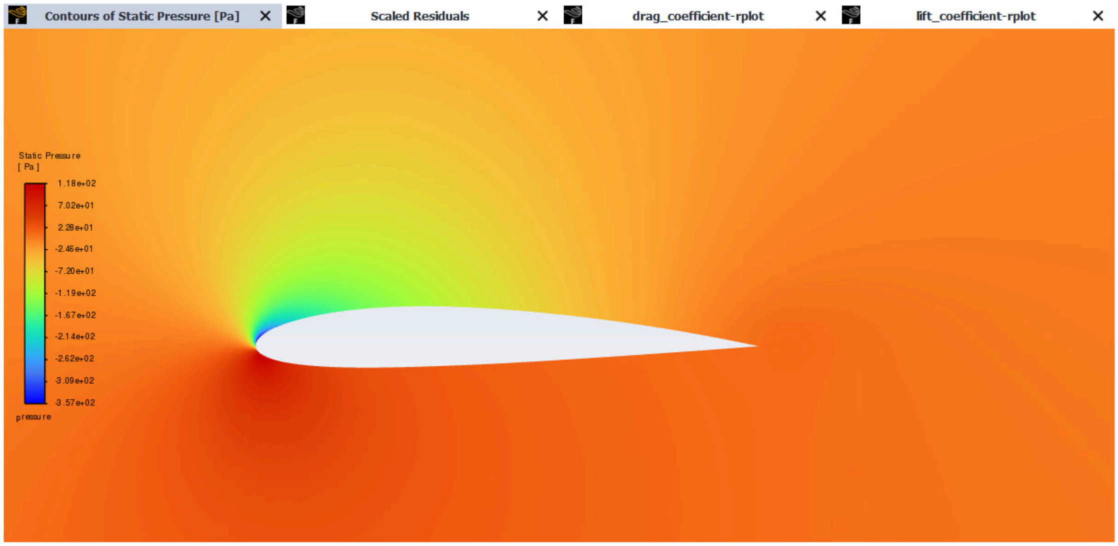


Figure 14. Static pressure values for airfoil at 8 degrees.

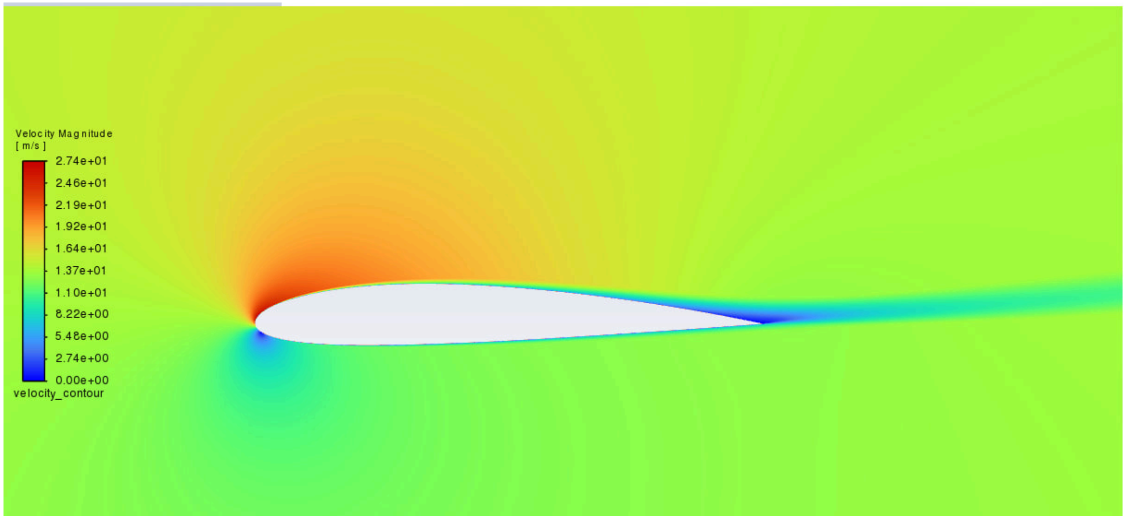


Figure 15. Velocity magnitude values for 8 degree.

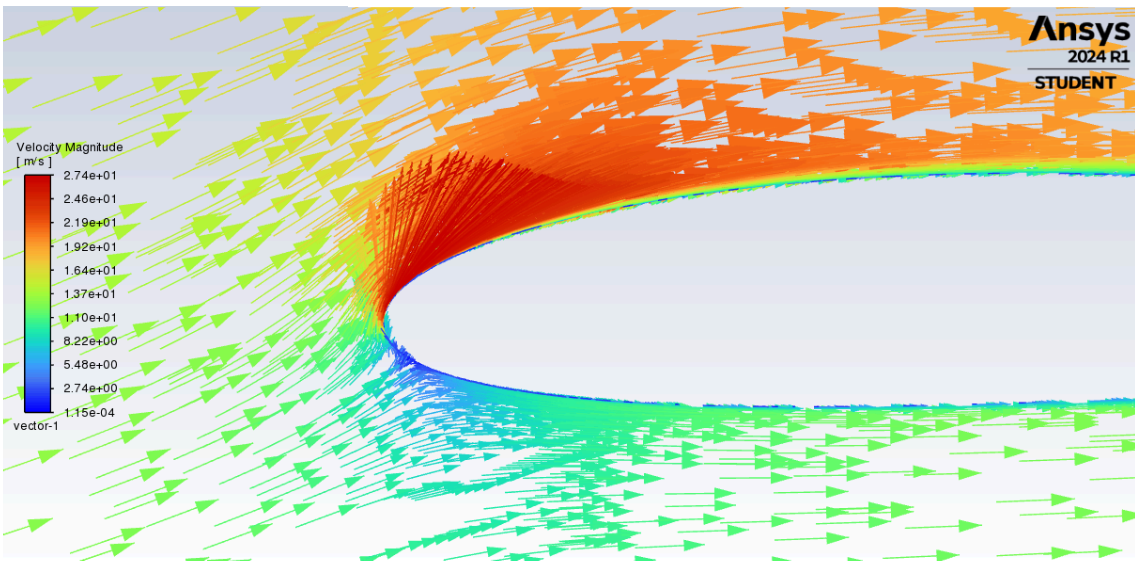


Figure 16. Closer view with magnitude vectors.

Wing load

Next significant factor in the design of aircraft wings is the wing load. It is a measurement of how much load is applied per unit area of the wing surface. The wing load affects the speed at which the aircraft can take off and land, considerably increasing its versatility and improving operational efficiency. The wing loading is calculated by

$$Wing\ loading\ =\ \frac{Total\ mass}{Wing\ area} = \frac{10}{1.72} = 5.81\ kg/m^2 \qquad (3)$$

Dimensions

To estimate the wingspan of UAV, the dataset of different commercially used UAV was gathered with their maximum payload and wingspan parameters.

Table 1. Commercially used UAVs and their parameters.

UAV	Wingspan (m)	Max. payload (kg)
Aeronautics Defence Systems Orbiter II link	3	1.8
Alpi Aviation Strix-DF	1.5	1.5
Applied Aeronautics Albatross	3	4.4
Rolta India Limited Rolta Mini UAV	2.8	1.5
Skyeton UAV Raybird-3	2.9	5
JOUAV CW-15	3.54	3
Rainbow CH-803 link	3.1	3.5
EOS Technologie Strix 400 link	4.25	2.5
MavTech AGRI 1900 link	1.9	2.6
DeltaQuad Pro #CARGO link	2.35	1.2

Then, a plot was constructed to assess the relationship between two given parameters. However, the dataset of Alpi Aviation Strix-DF was removed from the dataset as it was an outlier with a completely different wing configuration. The plot obtained gave an estimate of 3 m wingspan for 2 kg payload.

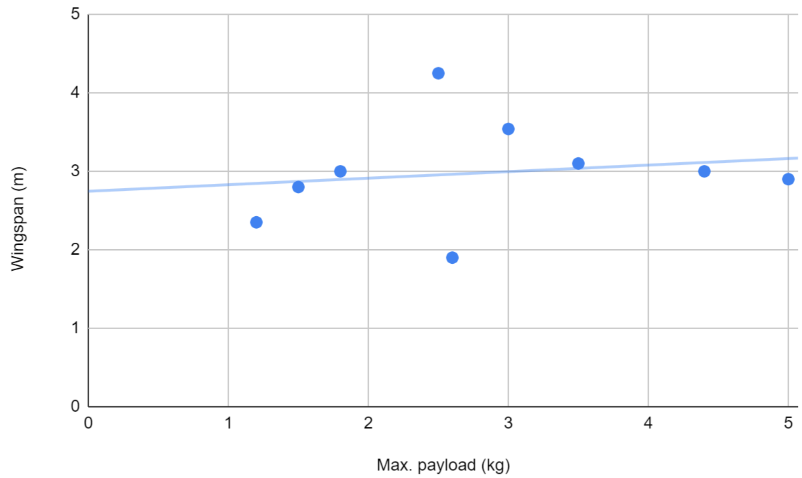


Figure 17: Max payload vs. wingspan of commercial UAVs

Using the correlation of wingspan to fuselage length [13]:

$$\frac{b}{l_{fus}} = 1.30 \tag{4}$$

We have an estimated fuselage length of 2.3 meters.

One of the fundamental factors that determine the dimensions of the aerial vehicle is the load that it is required to carry. Since our maximum payload is currently set to be 2 kg, this was taken as the first major requirement. Secondly, the general size of the aircraft depends on its overall wing area, which in turn depends on the speed of the vehicle during the flight. For this project, the speed requirement currently is 50 km/h, which allows it to deliver the useful load relatively quickly, compared to other types of goods transportation.

$$L = \frac{1}{2}\rho V_{\infty}^{2} \times S \times Cl \tag{5}$$

This is the simplified formula that allows to calculate the preliminary dimensions of needed wing area that will provide enough lifting force for the aircraft. The lift is assumed as the weight of the aircraft. By doing some statistical analysis, an average aircraft with 2 kg payload will have a total maximum weight of 10 kg. The biggest assumption is the wing dimensions that we will use in our very first prototype. They are 3 m wing span and 0.5 m wing chord length.

$$S \times C_l = \frac{10\times9.81\times2}{1.2\times14^2} \tag{6}$$

$$S \times C_l = 0.83418 \tag{7}$$

$$C_l = \frac{0.83418}{1.5+0.22} = 0.485 \quad (8)$$

Now to find the Drag we need to calculate the induced drag and add parasitic drag which is equal to 0.02 for average standard aircraft

$$C_{Di} = \frac{C_L^2}{\pi\, e\, AR} = 0.015 \quad (9)$$

$$C_D = C_{D0} + C_{Di} = 0.035 \quad (10)$$

$$D = \frac{1}{2} \times \rho \times V^2 \times S \times C_D \quad (11)$$

$$D = \frac{1}{2} \times \rho \times 196 \times 1.5 \times 0.035 = 6.3\, N \quad (12)$$

Thrust required to maintain level flight for our aircraft is at least 6.3 N.

The propeller is chosen to be NACA 4412. Since NACA 4412 is a popular choice for UAV propellers for its effective combination of lift, drag and blade efficiency, we decided to use it as our primary choice. Next, the thrust T generated by a propeller can be estimated from the following formula where:

$$T = C_T \rho n^2 D^4 \quad (13)$$

- C_T is the thrust coefficient, which depends on the propeller design and operating conditions (normally 0.03).
- ϱ is the air density (in kg/m³).
- n is the propeller speed in revolutions per second (RPS, not RPM).
- D is the propeller diameter in meters (0.55 m).

And by that

$$RPM = \sqrt{\frac{6.3}{0.03 \times 1.225 \times 0.55^4}} \div 60 = 2600 \quad (14)$$

Power required:

The power required can be estimated from the thrust and the efficiency of the propeller, which is expressed by:

$$P = (T \cdot V) / \eta = \sim 190 \text{ Watts.} \quad (15)$$

The torque is found by

$$\tau = \frac{P}{\omega} \quad (16)$$

Rounding this up to 200 watts, we get the motor requirements: 200 watt, 3000 RPM, 0.7 Nm Torque.

Figure 18. The HANPOSE 895-200W motor.

The motor we chose is Hanpose 895-200W 3000 RPM 0.98 Nm 500 g Motor. Since there will be two propellers, we will use two of these motors which will result in total motor mass of 1.0 kg.

Take-off

When delivering medical supplies to remote locations, there are a number of take-off inconveniences that must be taken into account, including the need for infrastructure for traditional runways, as well as the rapid acquisition of altitude. To overcome these obstacles and ensure that the UAV reaches the required speed to take off, it was decided to use a UAV launcher. Catapulting method is significantly advantageous when the short take-off distance is needed. Because the launcher gives the required momentum, there is no need for large space for UAV to accelerate.

Moreover, the launch trajectory is precisely controlled by the catapult mechanisms, ensuring that the UAV takes off at the best angle and direction, which is important for maneuvering in difficult terrain. Taking off into the wind is preferred because it increases airspeed over the wings, providing more lift for a quicker and safer takeoff which is possible by controlling the direction.

Which of the UAV launchers are most suitable?

The majority of small and medium-sized UAVs' catapulting systems require the mobility of the system, so that they can be easily loaded to a vehicle. Such mobile catapults can be arranged in the following categories:

- Pneumatic launchers;
- Hydraulic launchers;
- Fixed rail launchers;
- Zero Length Rocket Assisted (Rato) launchers [14].

Among them, the fixed rail bungee catapults and pneumatic launchers are used most commonly. However, pneumatic launchers are more suitable for larger UAVs as they produce more power. The UAV that is being designed by us is relatively light, making up for approximately 10 kg, which means that bungee launchers fit our situation better.

Designing the bungee launcher

The design of the system should consider different factors such as the weight of the launcher, the ability to quickly reassemble it and the number of people that control this system. As our UAV should be able to be used by a small number of people in the emergency and be handled by not only engineers but also other people such as doctors in the hospital, it was decided to design a very simple model.

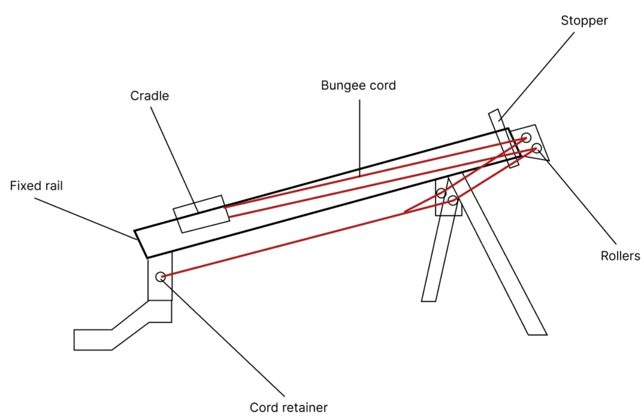


Figure 19. Preliminary design of the bungee launcher.

The system consists of the following components: fixed rail, cradle, bungee cord, stopper, cord retainer and the rollers. The UAV is attached to the cradle that is connected to the bungee cord and is restricted in the initial position. Then the bungee cord is stretched by the cord retainer. The cord will be experiencing the maximum tension when the cradle is still tied. After releasing the cradle strap, the elastic energy accumulated in the cord will convert to the kinetic energy, making the cradle and the UAV move alongside the rail. At the end of the launcher, there is the stopper that prevents the cradle from moving further. Then the UAV continues to fly with the propellers.

Mathematical model of the launcher

To find out the forces that act on the launcher the following model was used:

$$m\overline{a} = \overline{F_e} + m\overline{g} + \overline{F_\mu} + \overline{R_x} + \overline{R_z} + \overline{T} + \overline{N} \tag{17}$$

In which:

m - the mass of UAV + cradle;

a - acceleration;

$\overline{F_e}$ - force of the cord;

$\overline{F_\mu}$ - friction force;

$\overline{R_x}$ - lift;

$\overline{R_z}$ - drag;

$\overline{T}$ - propulsive force;

$\overline{N}$ - normal force.

To simplify the model, several assumptions were made, such as:

- The lift and drag are very small, so they can be neglected;
- The masses the the cord system are relatively small compared to the mass of the UAV and cradle, so they can also be neglected;
- The friction of the cord is also neglected;
- The pulling force of the cord is directly and linearly proportional to the elongation of the cord;
- The propulsive force is always the same;

With all the assumptions, these formulas were obtained:

The length of the cord vs. time:

$$x(t) = [x_0 + \frac{T+n_r}{q_r} - \frac{mg}{q_r}(\mu cos\alpha + sin\alpha) - b]cos\sqrt{\frac{q_r}{m}}t + \frac{mg}{q_r}(\mu cos\alpha + sin\alpha) + b - \frac{T+n_r}{q_r} \quad (18)$$

The velocity of the UAV vs. time:

$$x'(t) = -[x_0 + \frac{T+n_r}{q_r} - \frac{mg}{q_r}(\mu cos\alpha + sin\alpha) - b]\sqrt{\frac{q_r}{m}}sin\sqrt{\frac{q_r}{m}} \quad (19)$$

In which,

x_0 - cord length;

b - initial cord length without stretching;

T - thrust of the engine;

n_r - cord offset;

q_r - cord stiffness;

μ - friction coefficient;

α - launching angle.

Launcher parameters

To find out the length parameters of the launcher, the research was conducted. Comparing different launchers, it was found out that the length of the track of the launcher varies independently on the weight of the UAV and the desired launch speed. However, the angles of inclination of the majority of launchers varied between 12-15 degrees. That is why, the track length was taken from one of the most popular launchers on the market ElevonX's Scorpion that launches UAVs up to 20 kg. And the degree was decided to be 15 degrees.

Track Length	2.4 m
Weight	< 20 kg
Launch Energy	Up to 2kJ

Figure 20. The characteristics of the ElevonX's Scorpion.

From the track length and the degree of inclination, other parameters were found using the sine and cosine laws.

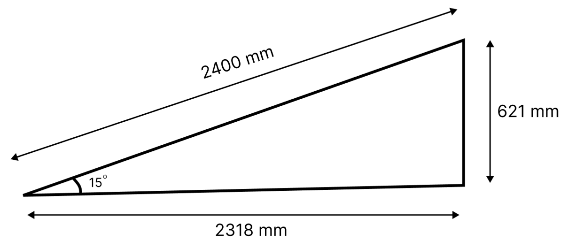


Figure 21. The parameters of the launcher.

The CAD model was drawn in Solidworks with these parameters, as well as other estimated parameters.

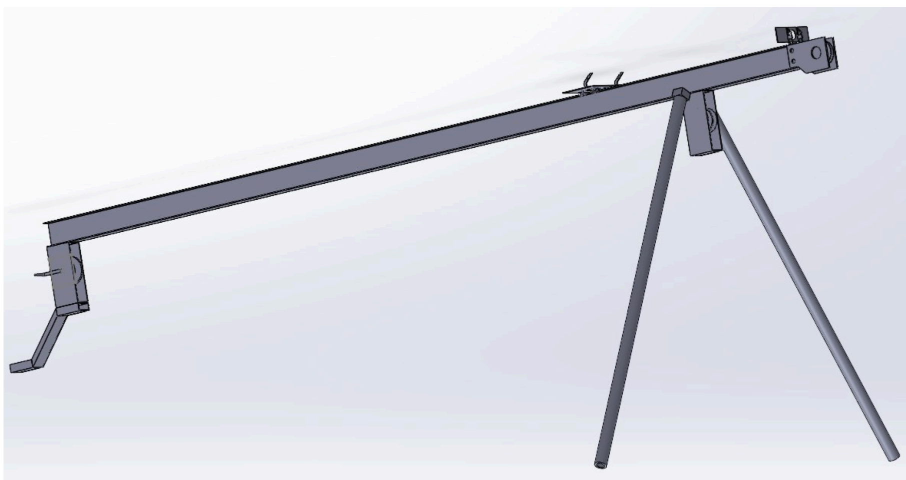


Figure 22. the 3D model of the launcher

Velocity calculations

There are other parameters that are yet unknown such as the cord stiffness, cord length etc. They are typically obtained by practical analysis. The cord is stretched by 0.5 m elongations and the tensile force of the cord is measured. However, as this research is entirely theoretical, there was no opportunity to do the tests. That is why the values were taken from the papers that already have conducted the relevant experiments.

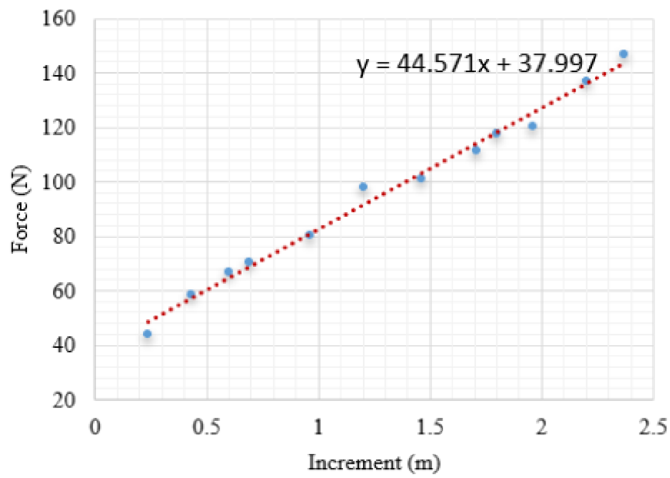


Figure 23. The linear regression of the cord stiffness [15].

The values are arranged in the table below:

Table 2. The values for the calculation

Parameter	Value
m, kg	11
$q_r, N/m$	535
n_r, N	456
x_o, m	10
b, m	5
μ	0.096
T, N	6.3
α, $degree$	15

Using the formula for the velocity, it was estimated that the launcher will be able to give 19.3 m/s for the UAV.

Landing

Landing will be done by belly landing.

Battery

When selecting a battery for a fixed-wing Unmanned Aerial Vehicle (UAV) designed to carry a 2 kg payload at a cruise speed of 50 km/h over a range of 100 km, several critical factors must be considered to ensure optimal performance. Firstly, the energy density of the battery must be high enough to provide sufficient power over the required distance without significantly adding to the aircraft's weight. Lithium-polymer (LiPo) batteries are often favored in UAV applications for their favorable energy-to-weight ratios. The capacity of the battery, measured in ampere-hours (Ah), must align with the UAV's power consumption, including the propulsion system and onboard electronics, to achieve the 100 km range. This necessitates precise calculations of the UAV's energy expenditure at the targeted cruise speed, accounting for aerodynamic efficiency, propulsion system efficiency, and the additional energy required for take-off, landing, and any in-flight maneuvers. Furthermore, the battery's discharge rate, indicated as C-rating, needs to be compatible with the peak power demands of the UAV to prevent voltage sag and maintain consistent performance. The battery should also have a robust Battery Management System (BMS) to ensure safe operation, including features for overcharge protection, temperature monitoring, and cell balancing to prolong the battery life and maintain reliability. Moreover, the physical dimensions and weight of the battery pack must be compatible with the UAV's design constraints, ensuring that it can be securely housed without adversely affecting the aircraft's center of gravity and flight dynamics. Lastly, considerations for recharge times, lifecycle costs, environmental operating conditions, and the availability of charging infrastructure should influence the final selection to ensure the UAV's operational readiness and cost-effectiveness for the intended application. For our project, the chosen battery is Fullymax 12s Lipo Battery Pack High Voltage 32000mAh 23.52V 6 cell. The dimensions are 66.5 x 99 x 222 mm, weight is 3120 g and Wh is 752.64.

Figure 24. The Fullymax LiPo battery pack.

Endurance calculations

The battery that we chose is stated to output 752 Wh, which in combination with 200W motors will give according to following formula:

$$Duration = \frac{Battery\ Capacity\ (Wh)}{Motor\ Power\ (W)} \tag{20}$$

$$Duration = \frac{752.64}{2 \times 200} = 1.88\ Hours \tag{21}$$

For our mission, which is 50 km to the destination and 50 km back to starting position on constant speed of 50 km/h it takes 2 hours flight time total. 1.88 hours equals to 113 minutes of full-throttle performance which is considering that motors are slightly more powerful than we exactly need, is enough to safely complete the mission. Additionally, it is important to remember that at the end of the mission, motor power can be decreased and that even with fully discharged batteries, the aircraft can glide until fully landing on its belly, which makes the last 7 minutes covered.

Full Scale Simulation (XFLR5)

The full scale simulation of the UAV was performed in XFLR5 software.

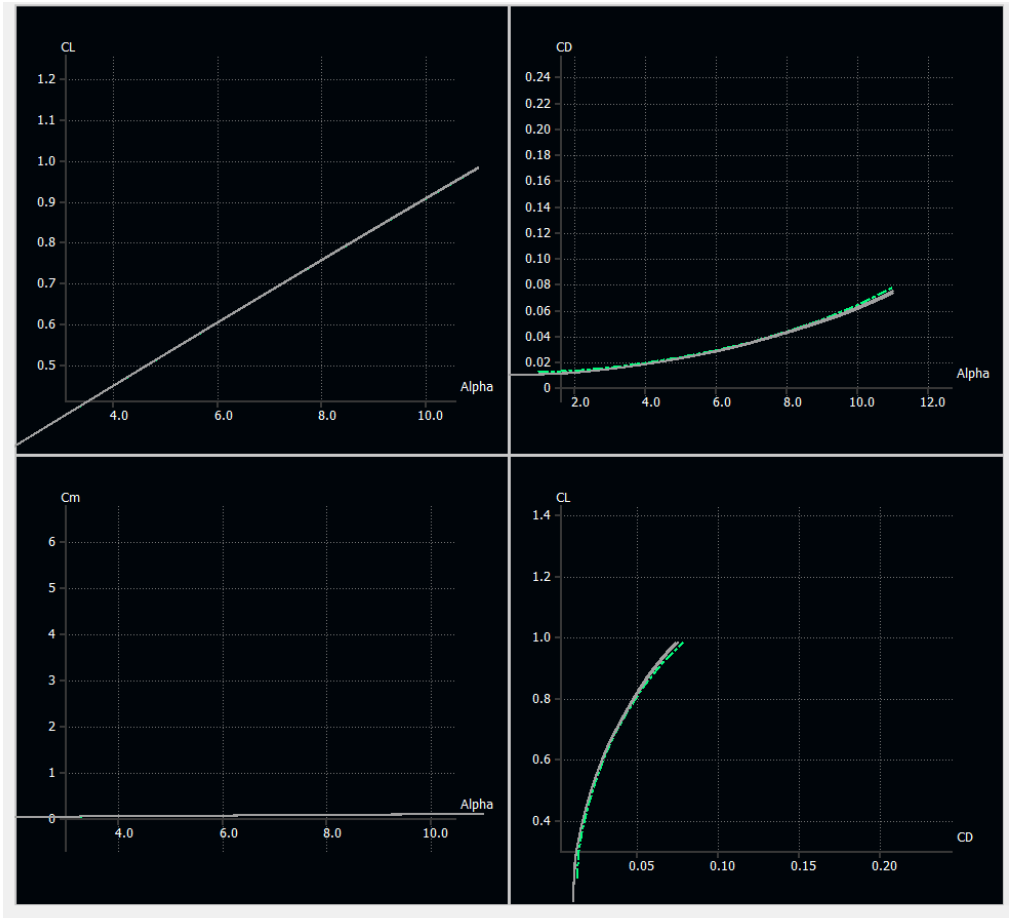


Figure 25. XFLR5 Simulation setup graphs.

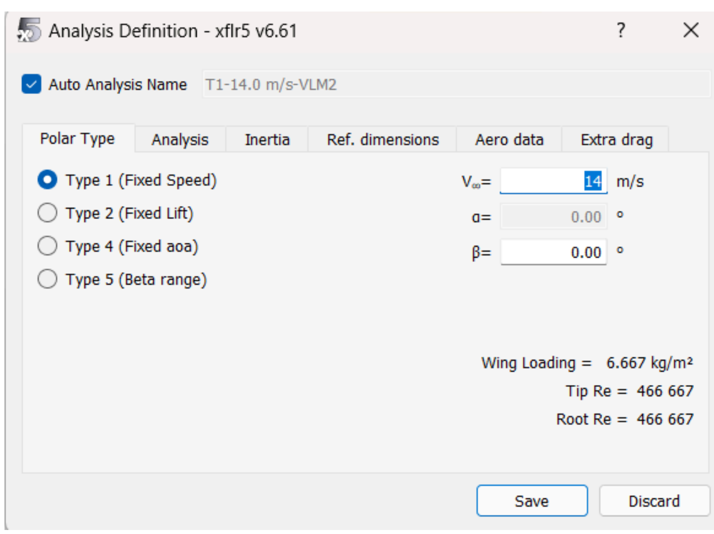


Figure 26. The XFLR5 simulation setup - Polar type choice.

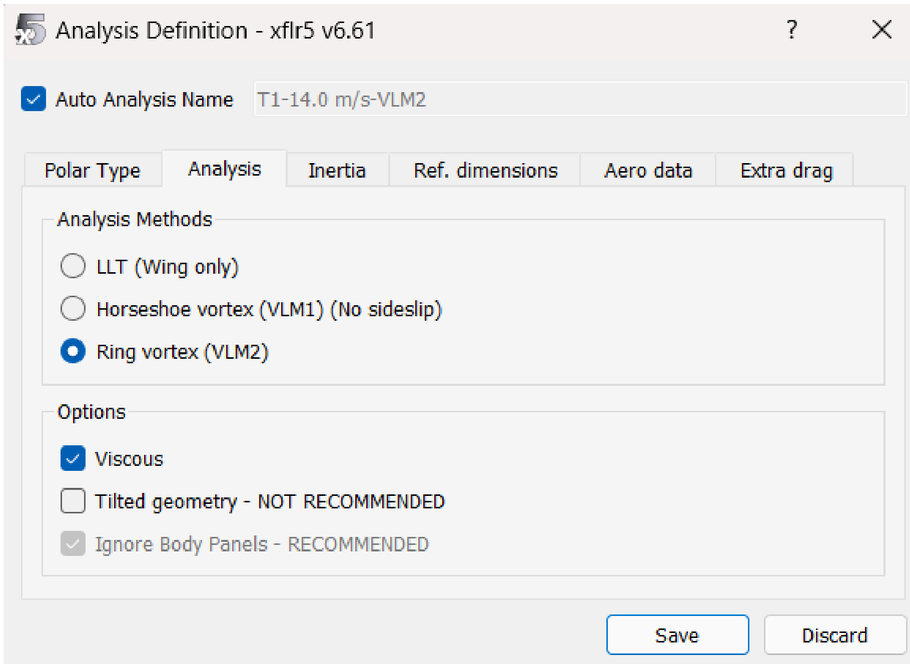


Figure 27. The XFLR5 simulation method.

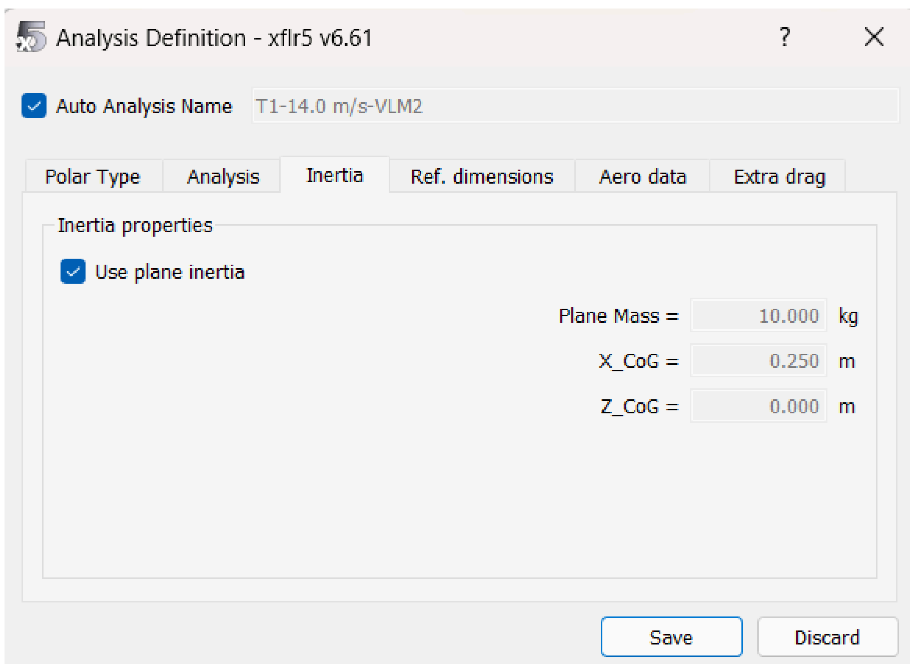


Figure 28. The Inertia parameters.

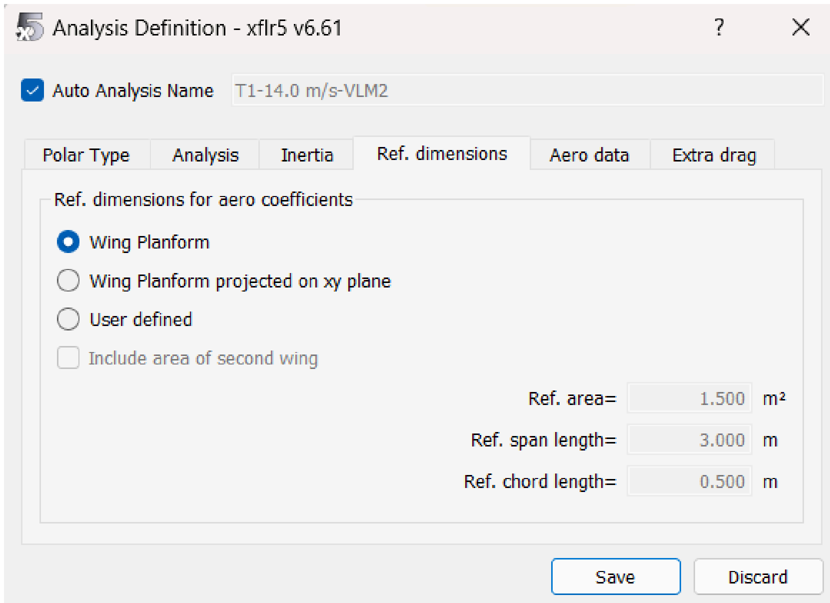


Figure 29. The reference dimensions parameters.

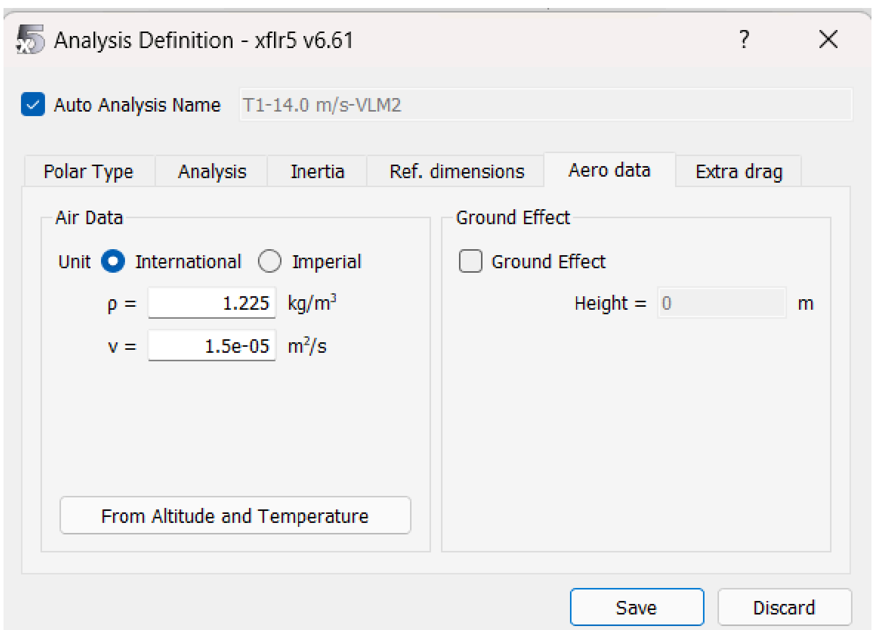


Figure 30. The aero data parameters.

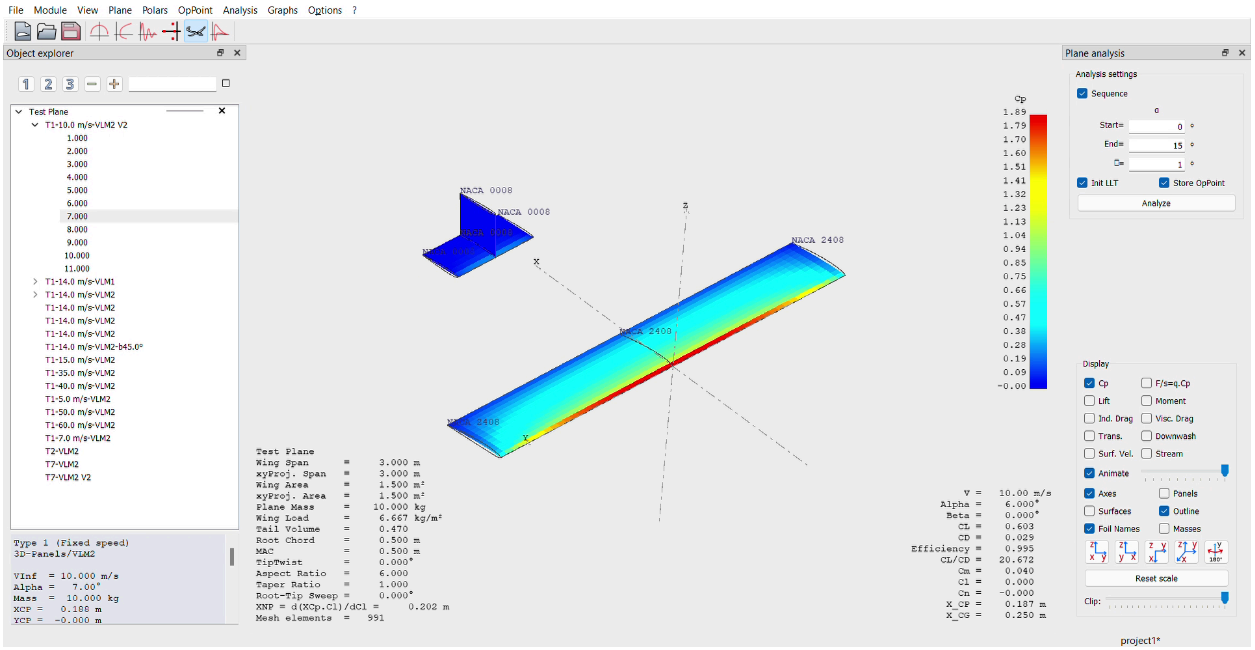


Figure 31. The Cp simulation.

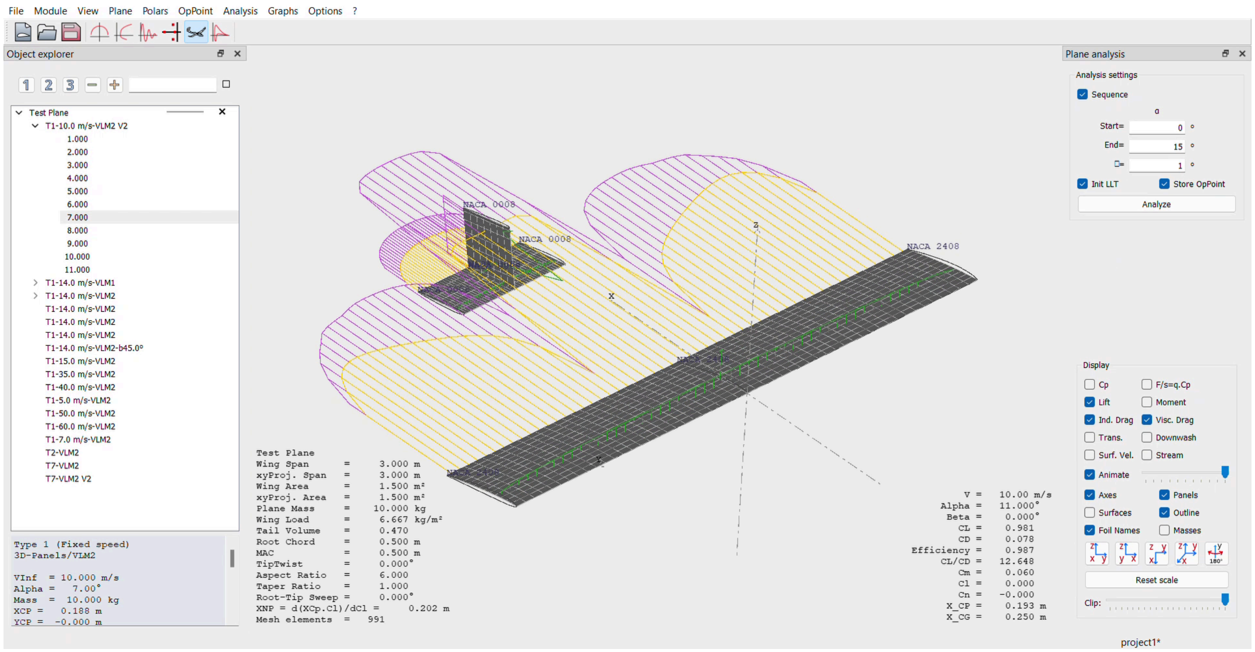


Figure 32. The Lift, Induced Drag and Viscous Drag simulation.

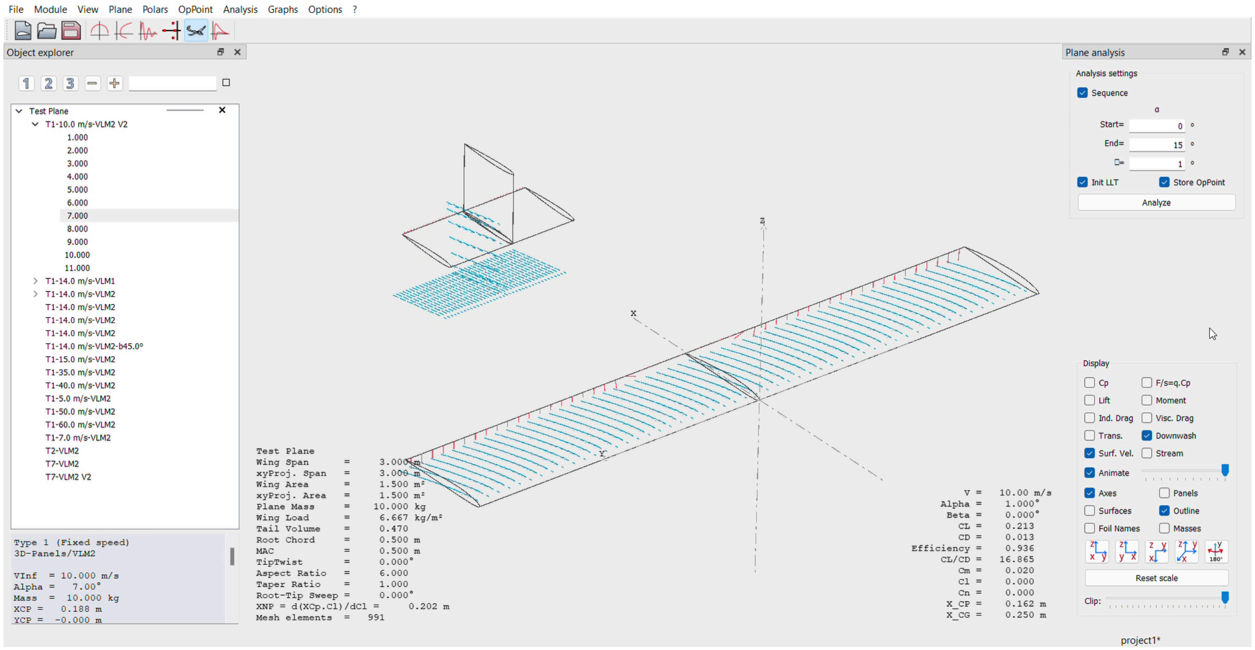


Figure 33. Downwash and Surface velocity simulation.

Control System

Raspberry Pi 4 will be used as an on-board computer with Navio2 autopilot HAT. While Raspberry Pi provides powerful and fast computational capabilities in a very small space, Navio2 will supply the system with a tool that can track both GPS and GLONASS satellites. Navio2 also has inertial sensors which are needed for UAV stabilization: accelerometers, gyroscopes and magnetometers.

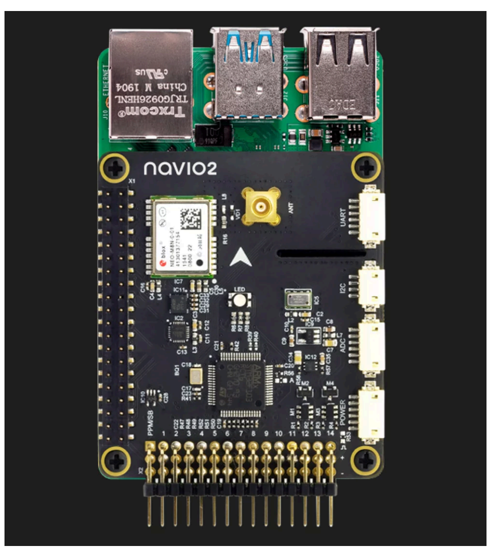


Figure 34. Navio2 mounted on a Raspberry Pi.

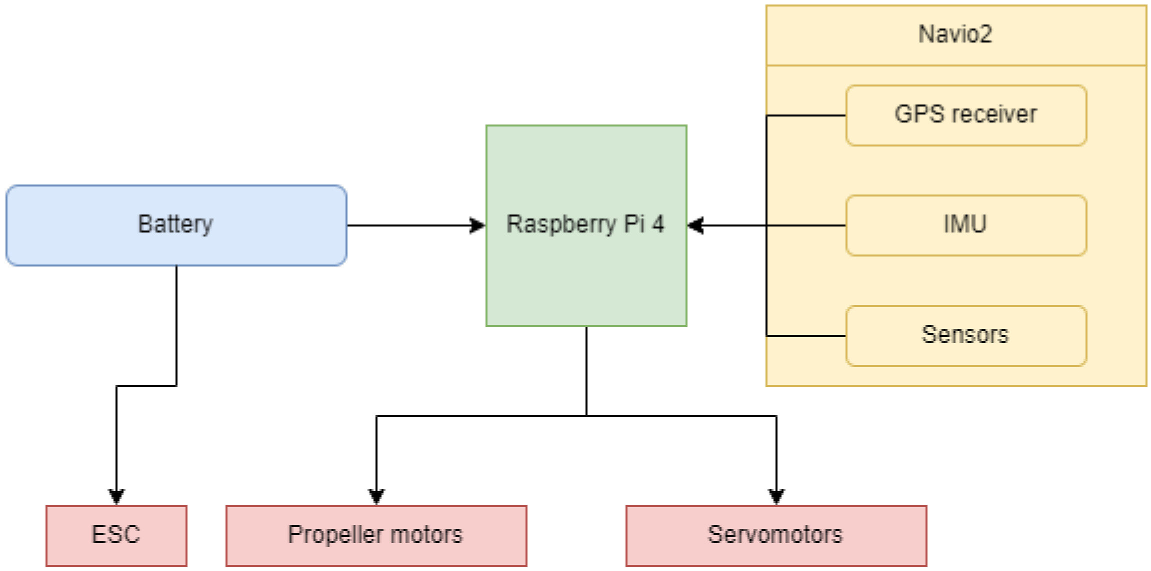


Figure 35. Hardware Block Diagram.

Battery will power the Electronics Speed Control Unit and the on-board computer. Inertial sensors, along with the help of GPS (or GLONASS) navigation, from the Navio2, will collect information which is then sent to the computer.

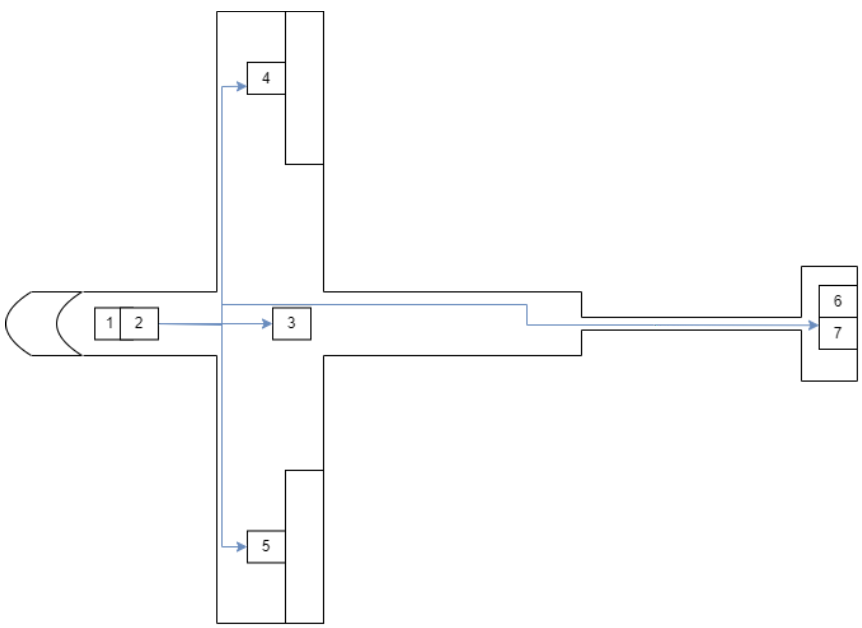


Figure 36. Avionics Schematics.

The schematics shows where the board computer and servomotors are located. The table with the components list is below:

Table 3. Avionics components.

1	Raspberry Pi 4 on-board computer
2	Navio2 Autopilot HAT
3	Payload dropping system servo
4	Right wing aileron servo
5	Left wing aileron servo
6	Horizontal stab servo
7	Vertical stab servo

Material selection

In the large amount of material type one of the most common from the beginning of aircraft development is wood. There are primary characteristics that wood contains, such as availability, lightness, and simpleness in forming. To achieve the lowest possible mass of UAV is used Balsa wood. Balsa wood has many advantages like a uniquely high strength to weight ratio, providing strong structure and also minimizing the weight of aircraft. Due to relatively high Elastic modulus, Balsa wood has suitable resistance deformation against the applied stress. Although one of the virtues of this material is acceptable flexibility, which improves stability and durability.

Balsa Wood Properties:

- Mass Density = 159.9 kg/m^3
- Elastic Modulus = 2.99 GPa
- Poisson's Ratio = 0.29 N/A
- Shear Modulus = 0.29 GPa

Table 4.Weights of parts of UAV made of Balsa wood.

Part	Mass
Wing	1950.92 grams
Fuselage	1018.32 grams
Horizontal stabilizer	715.03 grams
Vertical stabilizer	243.16 grams
Propellers	63.88 grams

Payload dropping system

The principle of operation of cargo dropping is based on the coupling of the cargo and the holding shaft on four hooks. A small motor turns the torque from a smaller shaft to a large one, and hooks mounted on that shaft cling to the eye closures of the payload block.

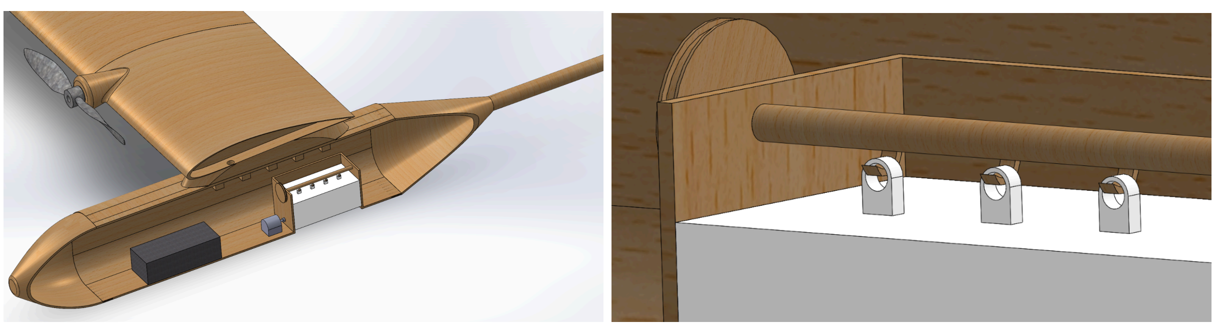


Figure 37. Illustration of cargo drop system

Manufacturing and Assembly

The designed UAV elements manufacturing process contains several shaping and forming methods to create interconnecting joints between parts. Dowel based joints are the most simple type to fasten wooden elements together and also easy in production. Drilling and milling machines provide precise shapes and dimensions to assembly. Gluing is a complementary method to achieve a much stronger connection. The mating surfaces by covering with high-grade butyl adhesive, such as resin or resin glue, which is then clamping until the glue reinforces. It basically makes a single object.

Generally assembling begins around the wing. First step is integrating two motors into their housings, and its wires go inside of the wing and middle fuselage part to the controlling system block. Then the middle fuselage part connects the wing by butt joint method and stuffing with the battery pack. Then the fuselage is closed on both sides by the nose and tail of the aircraft. Vertical and Horizontal stabilizers joints with tail and fixes in the back with cap. Propellers and motors connect with coupling and lastly cargo loading to be fully finished.

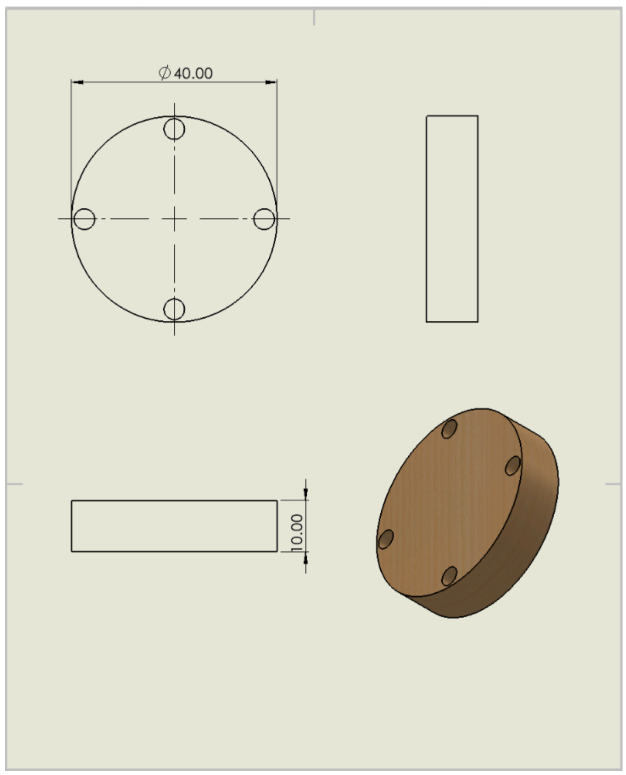


Figure 38. Back cap drawing

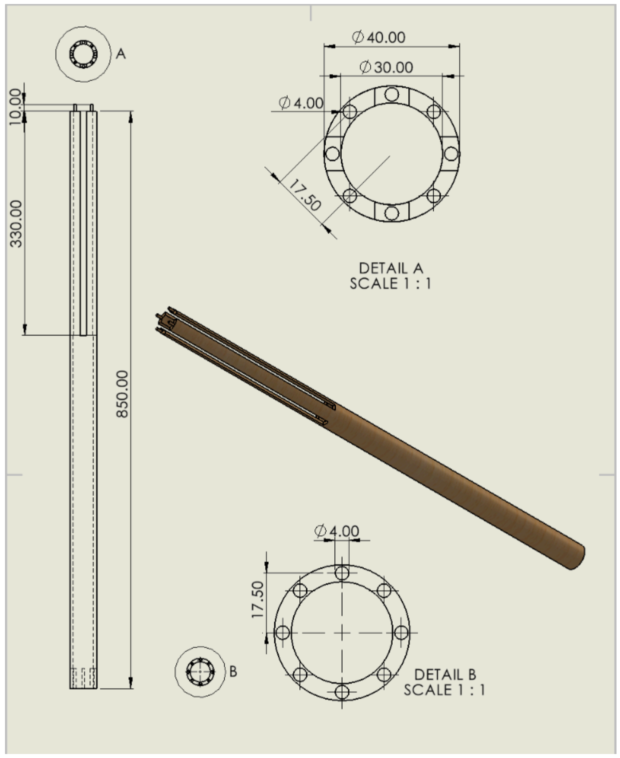


Figure 39. End-Tail drawing

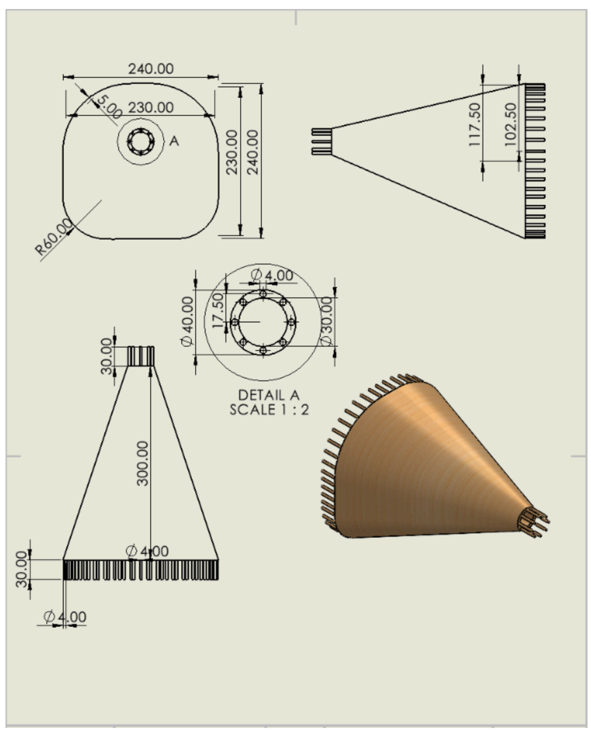


Figure 40. Tail drawing

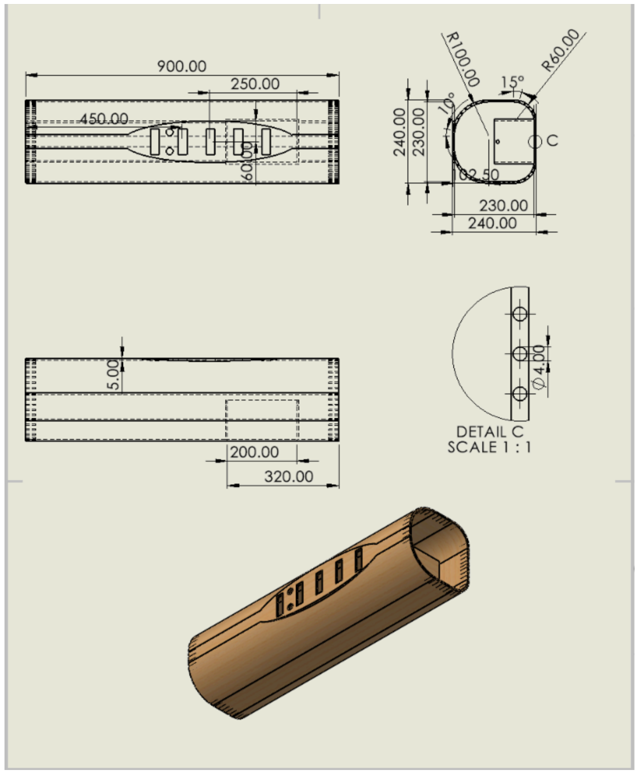


Figure 41. Middle fuselage drawing

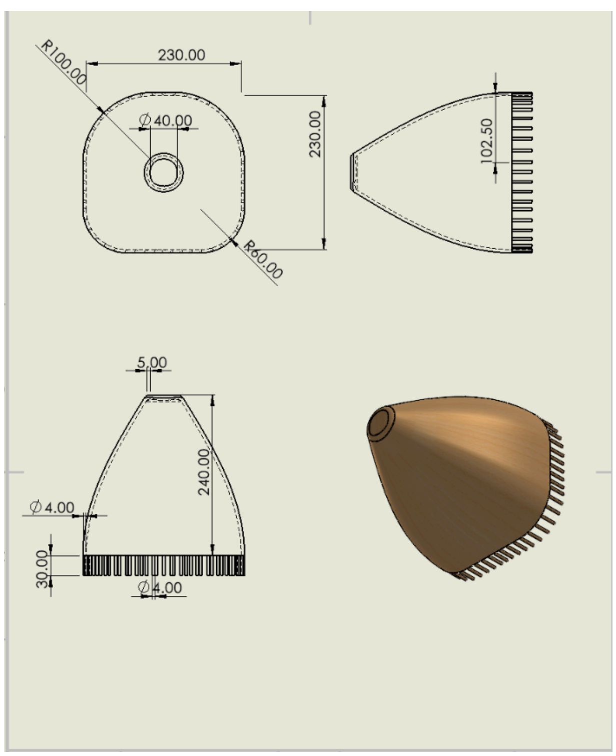


Figure 42. Nose drawing

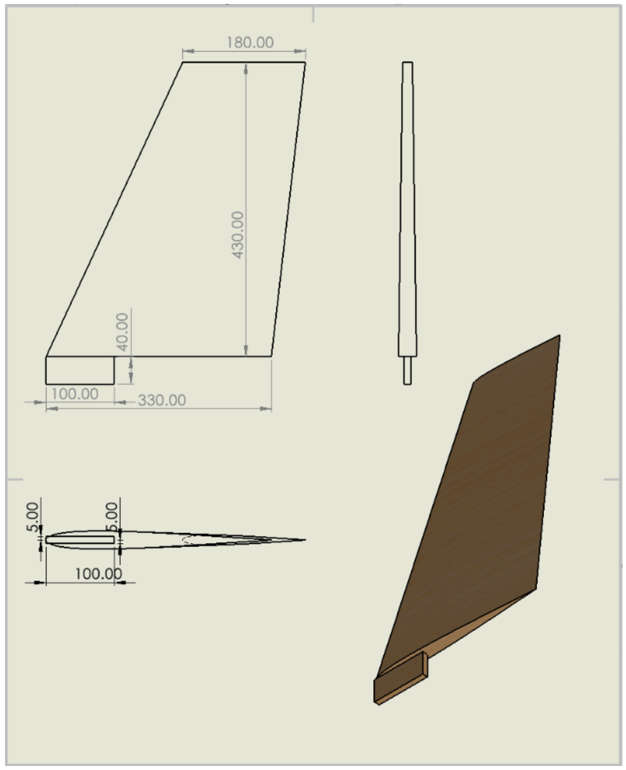


Figure 43. Vertical stabilizer drawing

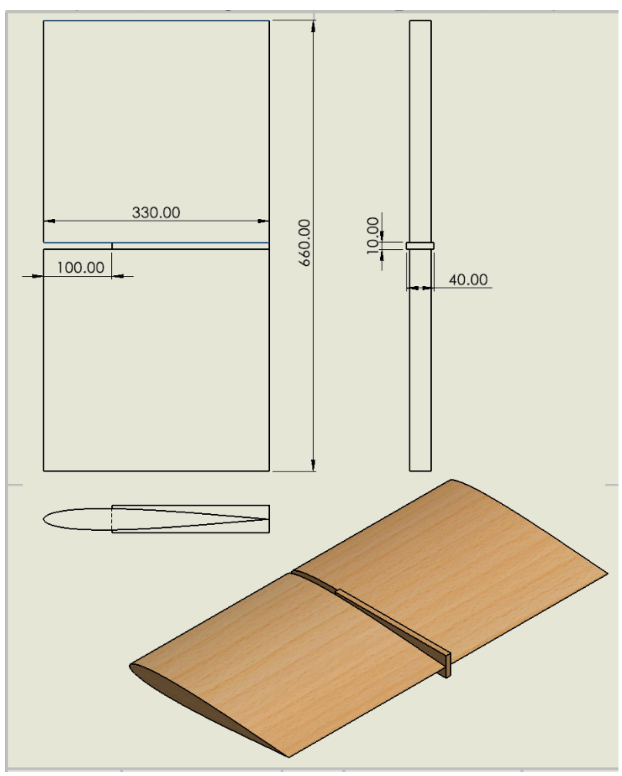


Figure 44. Horizontal stabilizer drawing

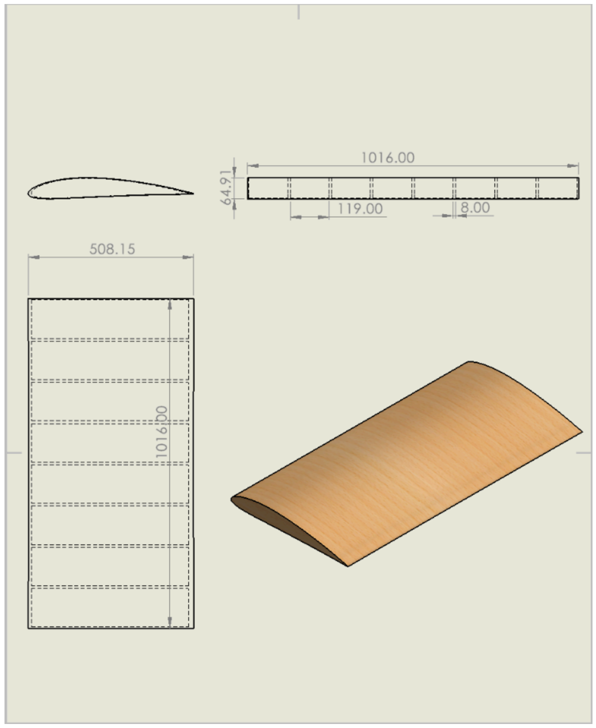


Figure 45. Side fragment of the wing drawing

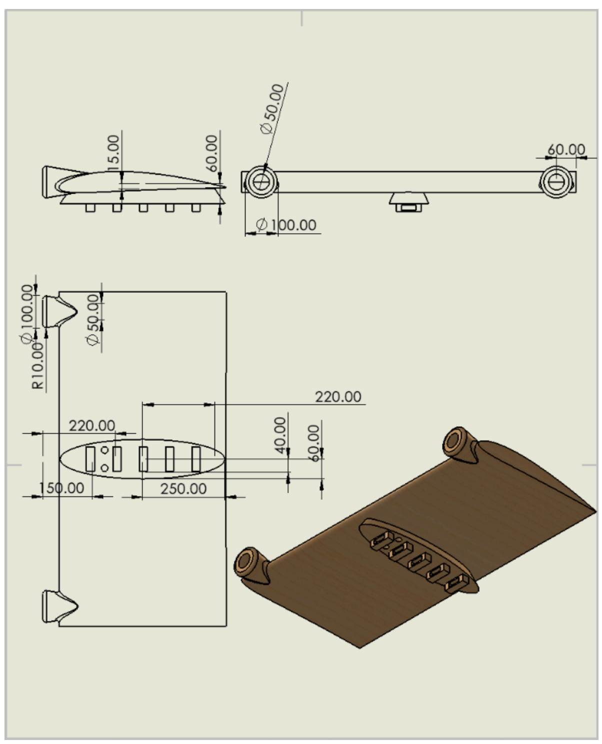


Figure 46. Middle fragment of the wing drawing

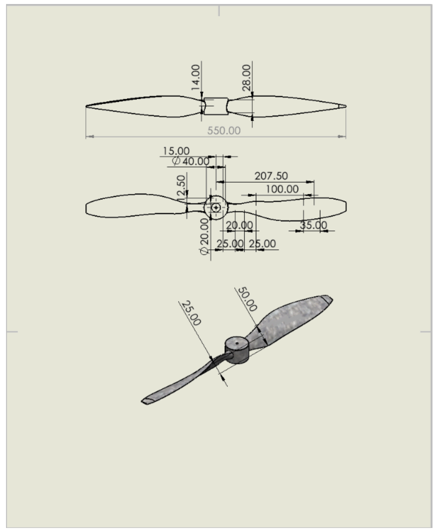


Figure 47. Propeller drawing

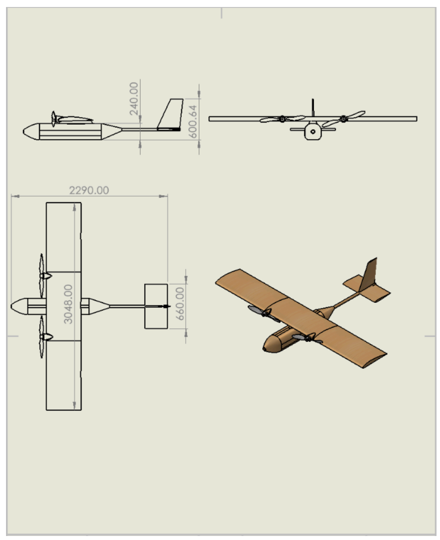
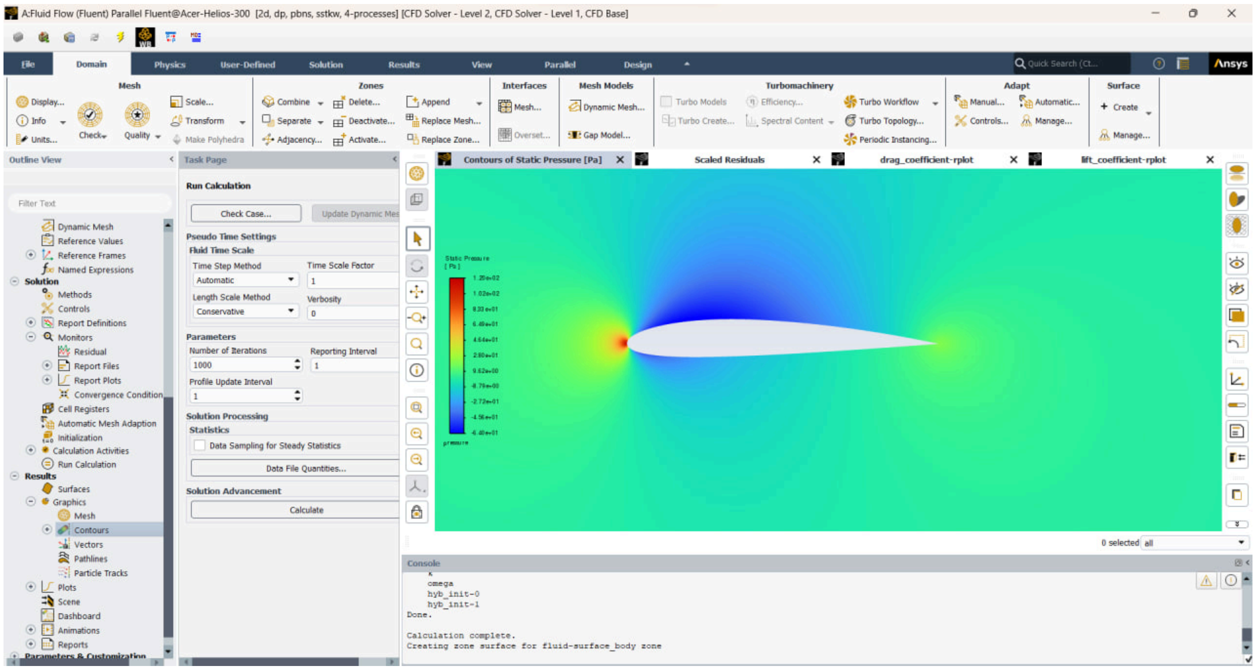
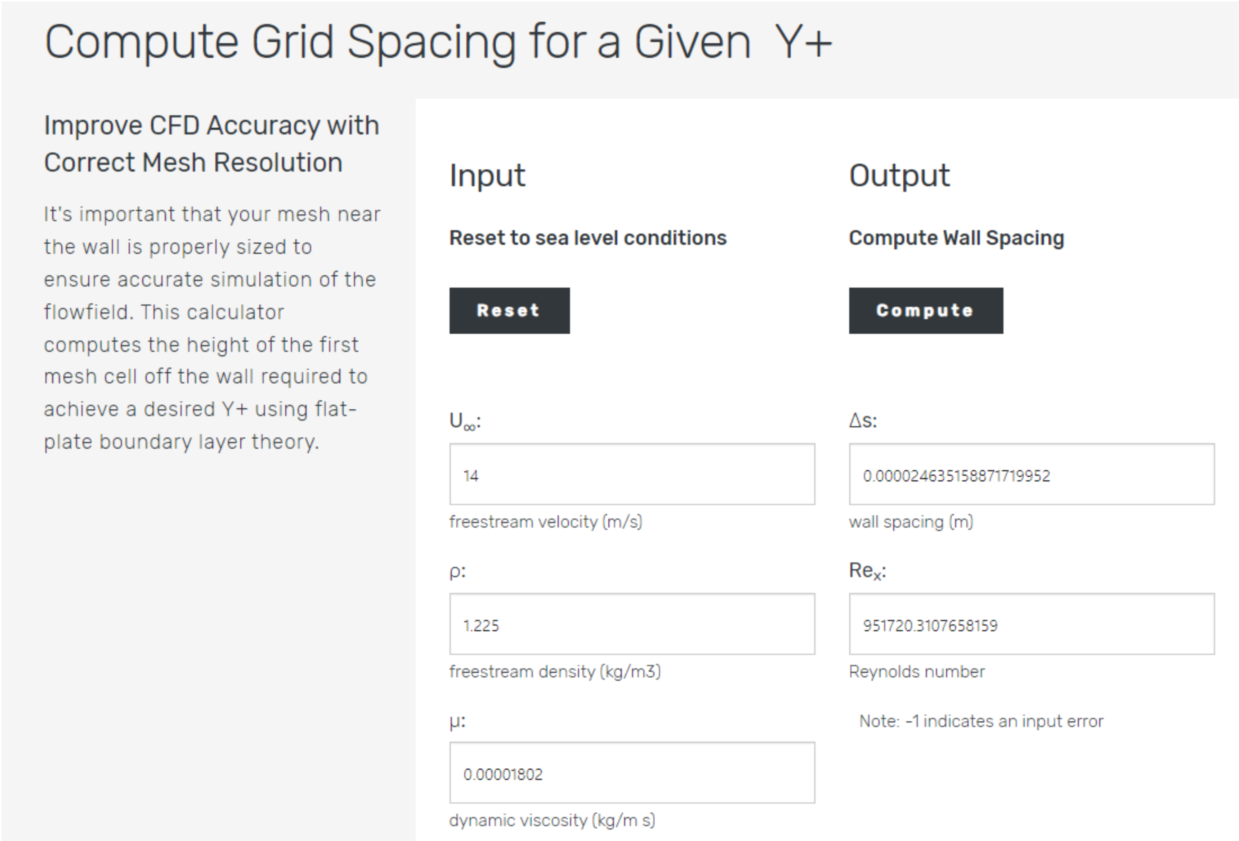


Figure 48. Model drawing

Appendix

Appendix A. Simulation details in ANSYS





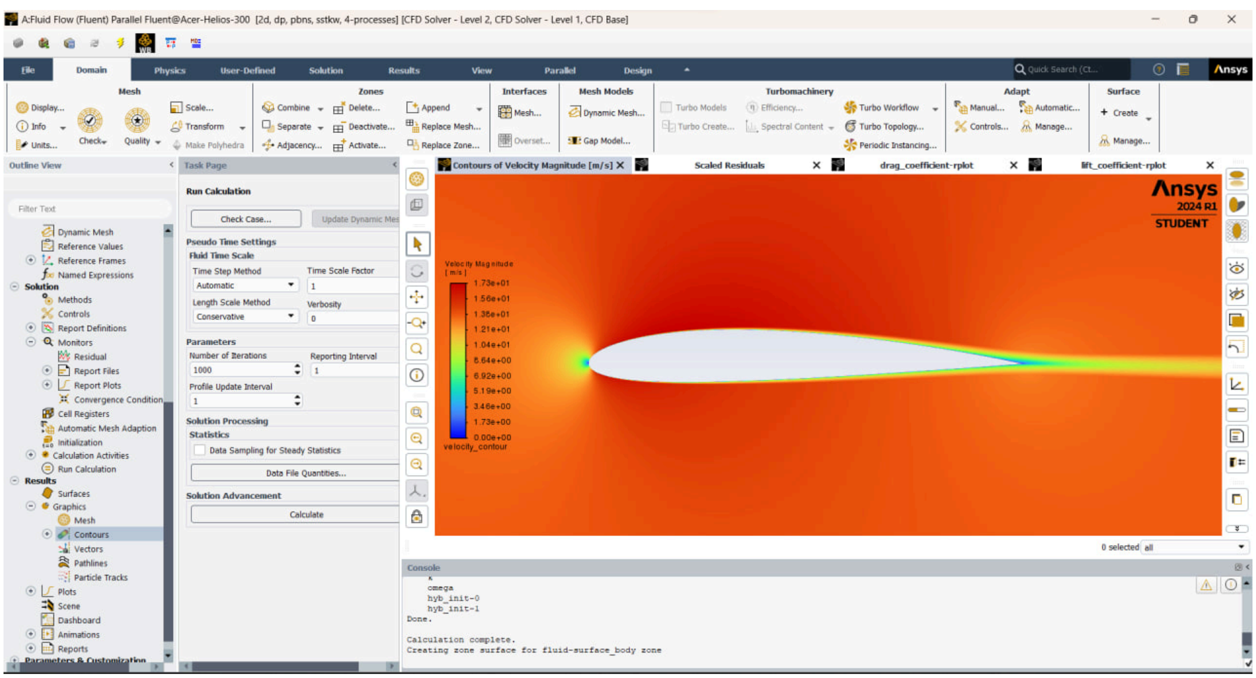


Figure . Ansys 2D simulation of the velocity magnitude with airfoil at 0 degrees.

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