THE AERODYNAMICAL AND STRUCTURAL DESIGN OF UNMANNED AERIAL VEHICLES

A critical Literature Review and a Case Study for the use of UAVs in the Medical Transportation Buisness

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Chapter 1

Introduction

1.1 Motivation and Backround

The fast-growing technological usage of unmanned aerial vehicles (UAV) in commercial areas is driving to a disruption of old business models and civil applications. The fast microcontroller, sensor and propulsion improvement of the last years lead to a deployment of UAVs in numerous business sectors.[10] Examples of the contemporary and future use of UAVs are cargo and human transport, as well as tasks in which a drone can use sensors and actuators to overserve and interact with the environment.[4]This assignment discusses the general design approaches for UAVs with a stronger focus on fixed-wing related topics like the vehicle aerodynamics, airframe structure and materials.

The currently most common types of drones are the rotorcraft and the fixed-wing configurations which both have their advantages and disadvantages in their operations. The rotorcraft vehicle got the benefit to take off in narrow settlement areas but has weaknesses regarding high flight efficiency for long ranges. On the other hand, a fixed-wing configuration is providing excellent power to weight ratio but is not able to take off without a runway. In the past engineers were forced to set requirements in a way that only allows deciding between these both types. In last years a hybrid technology, which brings together the advantages of rotorcraft and fixed-wing, gained in popularity. With that configuration, it is possible to operate in urban areas while using less power and with that being more eco-friendly.[10] One of the disadvantages is the higher weight of the structure because it needs to fit the structural requirements of and multi-copter and a fixed-wing. Another drawback is the complexity of the design and control of those flight vehicles.[15]

1.2 Problem Statement

The problem presented in this assignment is the critical literature review of current approaches for the general unmanned aircraft systems design. This work is mainly focusing on the influences of aerodynamics, structural and material problems in the UAV design. That means that some essential parts of a successful UAV design, like the design of the avionics, control and propulsion systems, are not being presented in this assignment. Furthermore, this work will mainly focus on fixed-wing design approaches since the number of pages is limited and it is possible to talk about all design approaches.

1.3 Aim and objectives

This assignment aims to investigate the current best practice approaches for the UAV design in the scientific literature. Because of the large scope of this topic is this work is mainly focusing on the fixed-wing drone development in which the core of the assignment discusses the construction of UAS under aspects such as aerodynamics, stress analysis and materials selection. This broad aim can be separated into five primary objectives:

- Providing a general overview of the Design process of an unmanned aerial vehicle
- Introducing the requirements definition and relevant law regulations
- Introduction to the conceptual design approach with an introduction to different relevant configurations
- Exhibition of the preliminary design with given methods for the initial sizing
- Presentation of the Detail Design Phase with tools for detailing the aircraft wing construction

Chapter 2

Overview of the UAV Design Process

The design life cycle process is the activity in which a flight vehicle gets developed. That means that the working engineers are detailing an aircraft from scratch and defining aircraft systems such as the avionics, propulsion, structures and control systems. Also, first simulations and prototype tests are made during that time to secure that the outcome of the design process is a flawless aircraft which is suitable for the required operations. The design life cycle process can be split up three parts, which are discussed more detail in this chapter.

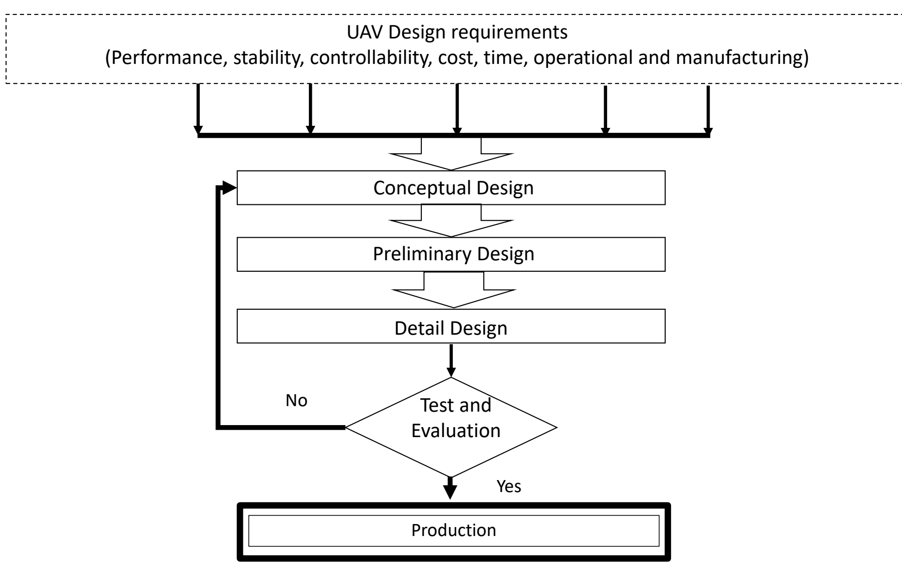

Figure 2.1: Flow Diagramm of the Aircraft Design Process [36]

2.1 The different Design Phases

2.1.1 Conceptual Design

The Conceptual design is the first step of the actual design process. In this phase different configuration getting considered which are technically feasible and best fitting for the defined requirements of the customers and end-users.The engineers are comparing different design approaches and trying to determine parameters such as which wing configuration, propulsion type and landing gear type the future aircraft should have. It is very important that during the process of research all studies about possible options should be considered. At the end of the process, a three view concept sketch of the prospective aircraft should be delivered. [16]

2.1.2 Preliminary Design

In this phase, the prefered configuration will be analysed more. The optimal geometry for the demanded operations will be calculated. That means parameters such as wing area, mass and demanded thrust should be defined. Also, first simulations and prototypes are created. Furthermore, the aerodynamic and stability behaviour of the aircraft gets investigated with wind tunnel tests. Simultaneously the first concepts for the control systems are made and tests.[34]

2.1.3 Detail Design

This step is the last big step. In that level, the aircraft gets analysed in the highest possible resolution. Details of the aircraft structure design and avionics are made. Only small changes can be now made on the design because of the high number of design dependencies. [16]

Little changes woulrd be for example little changes in mass or design details to secure a ease of maufactuiring, which are not changing the general behavior of the whole aircraft and don’t risk the strcutrual integratie of the flight vehilce.[3]

Chapter 3

Design Requirements and Regulations

3.1 Introduction

For the usability of the planned UAV in the approached market area, every design team have to define requirements to secure the successful design of the drone. The goal of the requirements definition phase is to produce requirements which are securing the final mission success in an efficient and economical manner. Oliver de Weck defined in his work [11] followed: “Requirements describes the necessary functions and features of the system we are to conceive, design, implement and operate Performance.“
All requirements should be defined together with all relevant stakeholders and the developers of the project. Good requirements specify what the aircraft should achieve during the operation. The Question of “how to achieve the requirements” is not considered in this early stage. That question is going to be answered in the following development phases. To achieve the best results with the highest cost efficiency all relevant requirements should be defined before the start of the development or in early stages of it.[11] They should be also defined in a way that they helping the developer to use the information in the best way. The NASA defined characteristics to how requirements should be made.[33]
To follow the NASA appraoch all defined Requirements Statements should have following Characteristics :

- Clear and consistent – easily understandable

- Correct – does not include a falsity
- Feasible – can be accomplished within physical laws, state of the art technologies, and other design restrictions
- Flexibility – Not declared as to whereby it is to be satisfied
- Without ambiguity – only one interpretation makes sense
- Singular – One actor verb-object requirement

Table3.1 shows examples for possible design requirements and ways to achieve these goals with different design approaches.

Design requirements	**UAV component that are affected**
Payload (weight) requirements	Maximum take-off weight
Payload (volume) requirements	Fuselage
Performance Requirements (Range and Endurance)	Maximum take-off weight
Performance requirements (maximum speed, Rate of climb, take-off run, stall speed, ceiling, and turn performance)	Engine; landing gear; and wing
Stability requirements	Horizontal tail and vertical tail
Controllability requirements	Control surfaces (elevator, aileron, rudder), Autopilot
Flying quality requirements	Center of gravity, Autopilot
Airworthiness requirements	Minimum requirements, Autopilot
Cost requirements	Materials; Engin; Weight;....
Timing requirements	Configuration optimality
Trajectory requirements	Autopilot

Table 3.1: Design Requirements and possible effects on Major Components of the UAV[36]

3.2 Functional requirements

The functional requirements are statements which are defining what functions need to be done to accomplish the mission objectives of a planned UAV.[11] The specifications should be detected in close cooperation with the other stakeholders of the project. That means that the enginering team and the cusstomer should work together on the requirements. Functional requirements delivering the general idea for the creation of a new aeroplane. This requirement type is focusing on the general expectations of the future aircraft.[1] These requirements are more high-level requirements which are delivering general ideas to answer major questions such as the best fitting aeroplane type and the desired degree of automation.[1]

3.3 Performance requirements

Performance requirements defining how well the drone shall perform the desired mission.[11] Typical performance requirements are: the flight speed, flight altitutde and range. The requirements can be determined by analysing data from past projects or through benchmark studies. It is very common that that requirements in the list are contradicory. In that case the it is need to search for a compromiss or to define which requirement is more important.[1]

3.4 Manufacturing requirements

These requirements are considering the factors for the manufacturing of the future UAS. They could define the general manufacturing methods and processes as well as the degree of standardization and unification. It is important to consider also those kind of aspects due to the facts that not considered manufacturing requirements could lead to high product costs for the company and at the end for the customer. [1]

3.5 Economical requirements

This requirements are focusing on economic problems and goals. They are one of the most important ones for the customer which means that they should be always considered. Typical requirements are life-cycle-costs, maintenance costs and development budget.[1]

3.6 Laws and Regulations

The accelerated commercialisation of UAS in the last years lead to problems government and legislators have to face. They had to define applicable restrictions for the dangerous use of the technology.
This paragraph trying to give an overview of relevant extracts of the regulations. For the regulation of the development and operations of drones, two lawmaking entities are responsible. The first one is the European Aviation Safety Agency (EASA), which is the Aviation agency of the European Union and the Civil Aviation Authority (CAA), which is the domestic Agency of the United Kingdom.
Both institutions have classified UAVs in 3 relevant types: Small Unmanned Aircraft (SUA), Light Unmanned Aircraft Systems (LIGHT UAS) and Unmanned Aircraft Systems (UAS). The SUA systems are air vehicles with a mass with less than 20 kg, while the LIGHT UAS have a mass between 20 kg and 150 kg. For both of these classes, the CAA is responsible. For the UAV class for drones with more than 150 kg is the EASA taking account.[6]

Mass Category	Mass (kg)	Responsible Regulatory Body
SUA	0-20	Civil Aviation Authority
LIGHT UAS	>20 - 150	Civil Aviation Authority
UAS	> 150	European Aviation Safety Agency

Table 3.2: Table of the current EASA and CAA UAV classification[6]

For all these different drone types are different laws and regulation relevant. At this point, only the relevant regulations which are affecting the development process are listed. For the Category SUA, following regulations are relevant:

- do not require any standards of airworthiness.
- A serviceable “fail-safe” mechanism to terminate the flight following the loss of signal or detection
- Must be ensured that payload on the model/aircraft is secure
- Flights must comply with any conditions

- CAA permission is required for any commercial flights

For the Category LIGHT UAS the relevant regulations are relevant, but additionally, the following regulations are also important:

- Not exempt if, regardless of maximum speed, mass it can sustain in level flight > 70 kt (81 mph).
- Aerobatics prohibited.
- Conditions of exemptions will prohibit tasks such as aerial inspections, flight close to, objects or installations representing risks in the event of damage due to any impact by the UAV.
- Conditions of exemptions will prohibit participation in any public flying display (except with CAA written permission)

Chapter 4

Conceptual Design

4.1 Introdcution

During the conceptual system design phase (commencing with the need analysis), one of the primary objectives is to develop and define the specific design-to requirements for the system as a first approach. The results from these activities are coupled, integrated, and included in a system specification. As already discussed in chapter2 is one of the main objectives of the conceptual design phase to define a design that is suitable for the requirements of the system. The Conceptual design is the earliest and most critical aspect of the UAV system development and design process. The choice of favoured aircraft configuration, which will finally be responsive to the unique customer specification, is the primary responsibility of this design phase. As the name is already saying is this phase focusing on the conceptual level. That means that no much calculation is needed. Most of the decisions are general decisions which are made by mere comparisons of different concepts by weighting the importance by taking the requirements to account. [36] This chapter will discuss some of the essential concepts in the UAV design and also presents a method to compare different approaches on the concept level.

4.2 Types of UAVs

In general, can be distinguished between three UAV types which can operate. These types are fixed-wing, rotorcraft and hybrid drones. All of them got specific advantages and disadvanteges in their performances. It is in the responsibility of the engineers to define which configuration is suitable for the desired mission. In this section, these three types are being introduced.[31]

4.2.1 Fixed-Wing

Fixed-wing UAS are causing the lift by using air stream around the wing frame. The stream is generated by the movement of the aircraft due to the application of thrust. Fixed-Wing configuration reaches longer distances and can carry heavier payloads than the other two configuration types. Another benefit is that fixed-wing UAVs can usually fly at higher velocities while using less power to do so. One of the big disadvantages is that a fixed-wing cannot take off or land vertically and usually need a long runway. That means they are not applicable to operations in an urban operation scenario. [31] The fixed-wing can be distinguished can in subtypes which also have different characteristics which should be taken to account during the conceptual design phase.

Conventional Conifguration

This configuration is the most used one. It is the one with the smallest development and life-cycle costs due to the fact that it is already well known and used for decades. Because of that, it was optimized which leads to the fact that it is highly efficient. That makes that configuration also highly compatible with newer configurations. A big advantage is that this type of aircraft can create high control forces due to the fact that the control surfaces got a big distance to the centre of gravity. A disadvantage is the high interference drag and that this configuration tends to stall on high angles of attack or low speeds. [30]

Delta Wing

This configuration got its name because the wings are shaped like the greek character delta (delta). Unlike the conventional configuration got the delta wing no elevator and the aileron is integrated into the wing. The lift of wing in low speeds flight the lift is created by vortex which is called vortex lift. To create a sufficient lift in subsonic flight does the aircraft need to own a high angle of attack, which is on the other hand leading to higher drag in the subsonic flight. An advantage is a high stall angle of attack. Furthermore, the sweep angle of the wing allows an economical use of the aircraft in hypersonic areas, which is the reason why a lot of fighter jets are delta wings.[30]

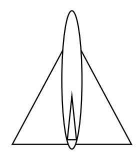

Figure 4.1: A Delta Wing Aircraft

Flying Wing

The flying wing has no fuselage and no tail. Typically got a tendency to unstable behaviour, which is one of the reasons it is not used that much. Modern flight control systems and airfoil design allowing a safe use of that configuration. It is very good to handle for a pilot due to the fact of higher manoeuvrability and it got a favourable payload weight fraction. On the other hand, it is very expensive in design and maintenance.[35]

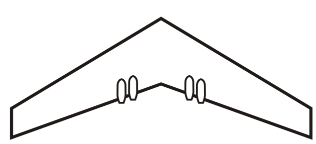

Figure 4.2: A Flying Wing

Box Wing

(boxwing benefits in literaure)
The biggest factor for drag is the lift dependent induced drag, which is seen as vortices at the wingtip this drag can be reduced dramatically by the box wing configuration. the concept is to separate the pressure areas on the top and the bottom of the wing. Another advantage is that this configuration is highly stable. On the other hand, it got high structure weight and the disadvantage of an altered control handling for pilots.[2]

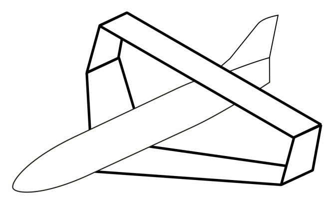

Figure 4.3: A Boxed-Wing Aircraft[42]

Blended Wing Body

The blended wing body is a concept in which the fuselage and the wing are producing a lift. This fact is leading to a more efficient flight. This configuration is a candidate for a more sustainable flight in future air transport due to the fact of less structure for the same amount of payload compared to conventional aircraft.[18] The Blended is able to increase the travel capacity dramatically.[14] A bigger disadvantage and problem in human transportation is the passenger acceptance due to the fact that not much windows are available for the passengers and that higher forces in dependency of the seat position are attacking on the passengers during the flight.[28] But these problem are not affecting the area of UAV operations.

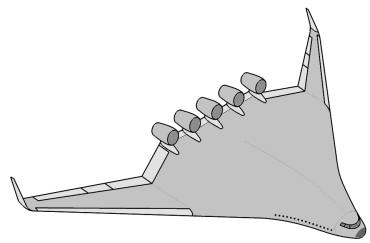

Figure 4.4: A Blended Wing Body[25]

4.2.2 Rotorcraft

Rotorcraft unmanned aircraft vehicles can have a single rotor (helicopter) or numerous rotors (multi-copter). The most popular one is the quadcopter with a wide range of commercial use cases. Rotorcraft drones are only suitable to work at shorter distances. They usually have a smaller structure weight to payload ratio compared to fixed-wings. The most significant advantages of rotorcrafts are the ability to take off and land vertically. This capability allows them to pick up and deliver goods without the need of an airfield, making them ideal for delivering and picking up in densely populated areas. [31]

Helicopter/Monocopter

Helicopters have one rotor on the top which is spinning a set of rotor blades attached to the central mast to generate the lift. By following newtons third law ("actio = reactio") does the rotor inducing an opposite torque on the airframe to counter that torque on the airframe, a tail rotor is needed. Otherwise, would the airframe spin in the opposite direction as the rotor which would lead to an uncontrollable air vehicle. [21]

Multicopter

Rotorcrafts which are featuring multiple sets of rotor blades are called multi-copters. Typical applications of this type using 4 to 12 rotors to obtain lift. The control movements (yaw, roll, and pitch) are not generated by control surfaces but by changing the lift and moment of the rotors which is influencing the motion of the aircraft.. [21]

4.2.3 Hybrid

Hybrid UAVs are merging the benefits of fixed-wings and rotorcraft systems, which enables them to take-off and land in both ways upward and horizontal. This inclination empowers them to cover long distances and carry high weight shipments. Despite the fact that the first VTOLs were developed in the 50s of the past century, this technology is still an undeveloped concept and not that much used as the other two UAV approaches.[31]

4.3 Major Components

Wing Vertical Position

The vertical location is an important design parameter which should be specified during the conceptual design. When we talk about the vertical wing position we classify between three types: shoulder wing, mid wing and low wing. Each of them got advantages and disadvanteges and it is the job of the engineers to find out which configuration is the best fitting for the mission. [34; 37]
Shoulder wings or also called high wings got the benefit that it allows placing the fuselage closer to the ground. [34] That allows loading and unloading cargo without cargo-handling gears. With a high wing, engines got a sufficient clearance without excessive landing gear. Also, a plus is the increasing lateral stability, because of the dihedral effect. Negative is the lower ground effect on the wing, which leads to longer take-off runs. The Drag of the wing is increasing due to higher induced drag. The lateral control of the aircraft with a high-wing is not that sufficient compared to a low wing because the aircraft tend to have more lateral stability. Another disadvantage is that the visibility of the pilot is not that good.Low wings have a better takeoff performance, compared with high wings, because of the ground effect. Because of less lift, the wing produces less downwash which leads to a more powerful wing. Disadvantages are the wing generates less lift. Additionally, an aircraft with a low wing has a higher stall speed compared to a shoulder wing aircraft, which means that it has lower airworthiness.[37] Mid wing is something between high and low wing. The advantage is that a mid-wing allows the placement of engines and bombs under the wing, without excessive high landing gears. That is one of the main reasons many

fighter jets are mid-wings.[34] A downside is that the wing is going through the fuselage, which takes away space for payload or people. An alternative is it split the wing and attach it to the fuselage, but that makes the aircraft heavier.[37]

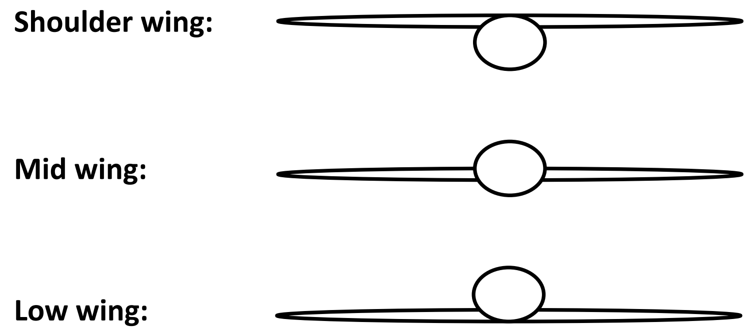

Figure 4.5: Sketches for the differnt Vertical Wing Positions

Tail Configuration

The most common one is the conventional tail. Nearly 70% of the aircraft are using this configuration. [34] It provides adequate stability and control. The T-Tail is also a preferred configuration which is used a lot. It allows a smaller tail and is better to prevent damages caused by aeroelastic effects. Also, the T-Tail allows placing engines on the aft fuselage. A disadvantage is the possibility of a getting caught into a deep stall on t-tails. [19] The H-Tail is used to arrange the vertical tail in the calm air during high AoA conditions. The v-tail configuration enables to decrease the total tail area and with that the drag characters of the rear. V-Tail may offer the longitudinal and directional trim role adequately, but it has insufficiencies in maintaining the aircraft longitudinal and directional stability. Also, the V-Tail design is more responsive to Dutch-roll tendencies than a conventional empennage.[37]

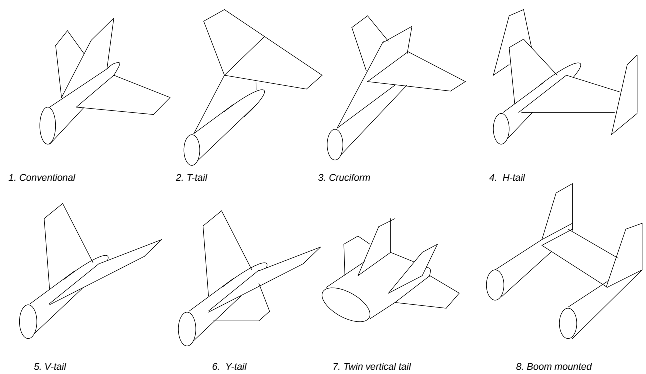

Figure 4.6: Examples for different Tail Designs[37]

4.4 Decission making in the Design process

The Decision Matrix is a table that allows a team of engineers to systematically distinguish, analyse, and rate the strength of relationships between sets of requirements. The matrix is principally useful for studying substantial quantities of decision factors and evaluating each factor's relative weight.[45]

Criteria	Weight (1-5)	**Fixed-wing**		**Hybrid/VTOL**		**Rotor-craft**	
		Score (1-5)	Total	Score (1-5)	Total	Score (1-5)	Total
Design Simplicity	4	4	16	2	8	5	20
Ease of Manufacturing	4	3	12	2	8	4	16
Cost	3	3	9	2	6	3	9
Reliability	4	4	16	4	16	3	12
Mission Task	5	4	16	4	16	3	12
Weight Efficiency	5	5	25	4	20	3	15
Mission Tasks	5	3	15	5	25	4	20
Total			126		107		119

Figure 4.7: Example for a Weighted Decision Matrix

Chapter 5

Preliminary Design

5.1 Introduction

During the Preliminary Design Phase, four major UAV design factors getting defined. These variables are the UAV maximum take-off weight (WTO), the Wing reference area (S), the Engine thrust (T)/Engine power (P) and the Autopilot preliminary estimates. Those four parameters will dictate the UAV measurements, the production costs, and the complexity of estimations. Besides the mentioned major topics also few other non-important UAV parameters such as UAV zero-lift drag coefficient and UAV maximum lift coefficient are initially expected in this phase too. This Section will give an outlook on some approaches to determine the demanded parameters. Because of the restricted page number of this work will be the approaches for the thrust calculation and the autopilot not discussed.

5.2 Initial Sizing

The Initial Sizing is one of the most important calculations in the aircraft design.[34] It determines the size, the weight and the manouverabilty of the Drone. It is a very important step to secure the mission fit of the aircaft and the sucesfull operations.

5.2.1 Takeoff-Weight Estimation

The take-off weight of an aircraft can be descibed as a summation of all integrated systems components of the aircraft.[44; 34] That means that the total weight buildup of an UAV could described as:

$$W_0 = W_{payload} + W_{battery} + W_{empty} = W_{payload} + W_{battery} + \left(\frac{W_{empty}}{W_0}\right) W_0$$

The empty weight is estimated as a fraction which is can be used from past projecs. The toal weight is defined as:

$$W_0 = \frac{W_{payload} + W_{battery}}{1 - \left(\frac{W_{empty}}{W_0}\right)}$$

Empty Weight Fraction

The Empty weight of the aircraft can be estimated statisticly by histrocial trends which are described as diagrams and can be found in research papers and documentations..[34] The formula for the Empty Weight to Total Aircraft Ratio can be described as:

$$W_{empty} = \left(\frac{W_{empty}}{W_0}\right) W_0$$

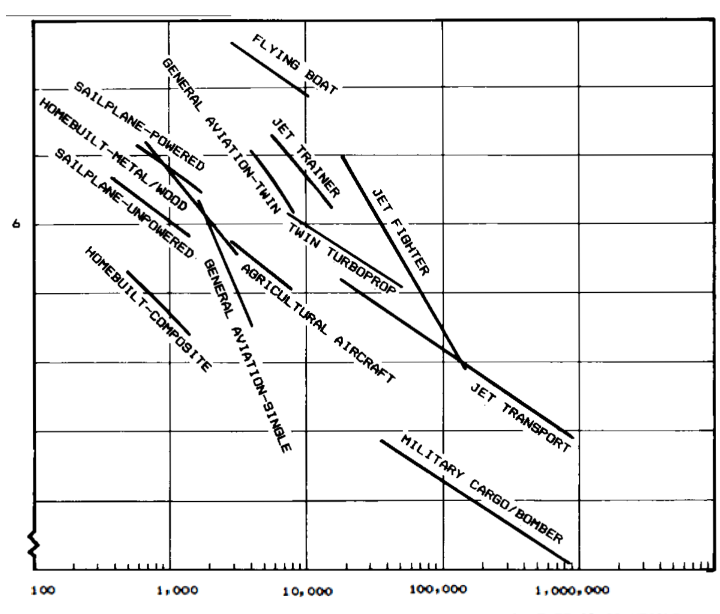

Figure 5.1: Diagram of the Empty-Weight Fraction vs. MTOW.[34]

Battery Weight Esimation

To define the battery weight we need to define the total energy which is needed for the operation of an UAV. That can be made by using the customer requirements to create a possible mission scenario which can be used to estimate the demanded power supply for on mission. With that paramter the engineers can determine the number and weight of the batteries which are needed. [44]

$$E_{total} = \sum E_i = E_{Mission} + E_{Cruise} + ...$$

$$W_{Battery} = \left(\frac{Total-Requiored-Energy(Wh)}{Battery-Power-Density}\right)$$

Payload Weight Esimation

The payload weight is the total weight of all avionics and sensoring systems, as well as the cargo which needs to be transported. The weight of that should be estimated by summing up all needed components and demanded cargo weight.[44]

5.2.2 Wing Area

The estimation of the wing area is one of the crutial actions in the initial sizing process. To estimate the size the designers need to determine a specific wing-loading for the Aircraft. The wing loading is defined as: $Wing-loading = \left(\frac{W_0}{S}\right)$. The wing size can be determined by using the demanded stall speed of the aircraft, because that is the most crtical part where the speed function reaching a minimum. To compansate that S must have a minimum size to still suplly a certain lift to the drone.

$$L = \frac{\delta}{2} v_{Stall}^2 S C_{L_{MAX}}$$

$$S = \frac{L}{\frac{\delta}{2} v_{Stall}^2 C_{L_{MAX}}}$$

For the other the density is the value on the operating altitude used and the for the maximum lift coeffiecent is the maximum lift coefificent of the wings used. Another way of defining is to use accessible tables with wing-loads of different projects, which are defiend out of experiences and statsitics of different missions. With that it is poosible to benchmark and determine the first inital size step to start tests and simulations.[9]

Chapter 6

Detail Design

6.1 Introduction

The Detail design phase of the UAV systems and components represents a significant role in the prosperity of the flight operations and manufacturing of the future UAV. The systems which are already have been ruffly defined, in the previous steps, are getting analysed again in the highest possible resolution. This chapter presents some of the analytical approaches for detailing the wing and structure systems of an aircraft. Because of a restricted number of pages, it is unfortunately not possible to go more in-depth to describe computational approaches to optimise the aircraft systems by using simulations, but that usually is something which would happen in a real development process.

6.2 Airfoil and Geometry Selection

6.2.1 Airfoil

The airfoil is the property which generates the lift. It is one of the essential entities on the aircraft and with that something which should be chosen very carefully. Following parameters are describing the airfoil:

- chord length
- camber

- leading edge radius
- thickness
- Max. camber position
- The position of max. thickness

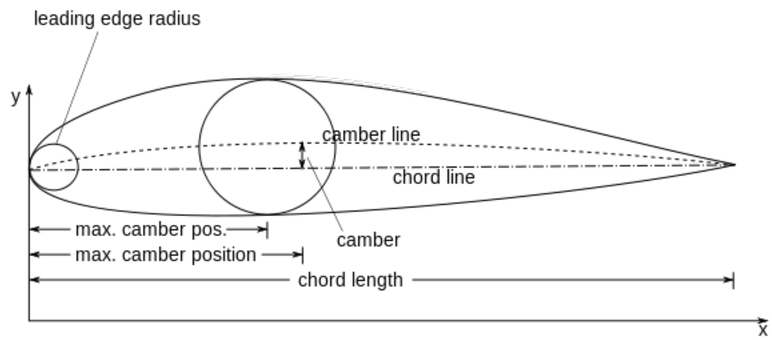

Figure 6.1: An Airfoil with all relevant parameters

If the Wingarea is already defined the information of the operations requirements for the minimum speed (stall speed)and cruise speed can be used to find a matching airfoil for the mission. A perfect matching airfoil would be an airfoil which can supply the needed C_L at stall speed and would additionaly have his $\left(\frac{C_L}{C_D}\right)_{MAX}$ at the Cruise speed. To have the $\left(\frac{C_L}{C_D}\right)_{MAX}$ at the cruise speeds means that the airfoil is flying in his most efficient operations point. Which means that the fuel consumption is at his minumum during that time.

$$L = \frac{\delta}{2} v^2 S C_L$$

$$C_L = \frac{W}{\frac{\delta}{2} v^2 S}$$

6.2.2 Aspect Ratio

The aspect ratio is an important parameter in the wing design and is defined as followed:

$$\lambda = \frac{b^2}{S}$$

The aspect ratio reduces the primary drag source during the flight, the induced Drag. That relationship between these two parameters can be described with the following equation:

$$C_{D_i} = \frac{C_L^2}{\lambda \pi}$$

A significant disadvantage of a large aspect ratio is that the mass of wings with a high aspect ratio is significantly larger than the mass of wings with a tinier aspect ratio. Because of that, the engineers need to find a compromise between this two influences.[38]

6.2.3 Wing Sweep

The Sweep of wings is interesting for drones with higher travel velocities because the wing sweep increases the critical mach number. That means that an air vehicle can fly at a higher speed without creating compression shocks and wave drag. Both mentioned circumstances are hypersonic effects. But this phenomenon can also appear in a subsonic flight since the airstream is getting locally accelerated by the airfoil.[38] Another positive effect is that the use of the sweep increases the lateral stability.[34] A disadvantage is the fact that the mass of wing with a sweep generally higher.[38]

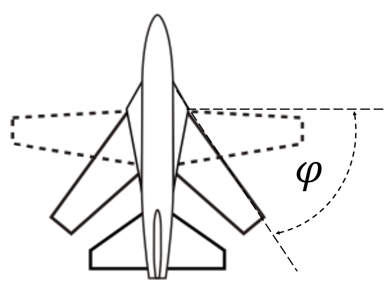

Figure 6.2: An aircraft with a Wing Sweep

6.2.4 Dihedral

The dihedral angle is the angle within the plane axis and the wing.[34] During a sideslip, a positive dihedral angle produces a moment around the longitudinal axis, which causes the wings to levelling. That means that a positive dihedral angle is leading to positive stability at the lateral axis.[38]

6.2.5 Taper Ratio

The Taper Ration influences the distribution of the lift along the span of the wing. As proven by the Prandtl wing theory early in the last century, the minimum drag to lift and the minimum induced drag occurs when the lift is distributed in an elliptical form on the wing. This mode happens when a wing has a matching twist or when the wing platform is shaped elliptically.[34] However, that kind of wing is costly to manufacture. On the other hand, the easiest way is to build a rectangular form, but that wing would have 7% more drag than an elliptical wing with same aspect ratio.[34] With tapering a rectangular wing, it is possible to achieve nearly an elliptical distribution by not increasing the producing cost significantly.[34] As equation is, the taper ratio is defined as:

$$\lambda = \frac{c_{\bar{Tip}}}{c_{\bar{Root}}}$$

Figure 6.3 shows the influences of the taper ratio on the lift distribution over the wing.

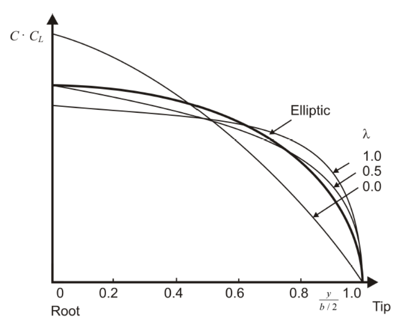

Figure 6.3: Lift Distributing in dependecies to the Taper Ratio

6.2.6 Wing Tips

The main reason for the induced drag is the pressure differences between the two wing sections, the upper and the bottom wing. The Air wants to compensate the high-pressure area on the bottom with the area with lower pressure on top. That behaviour motivates the air on the bottom of the wing to move to the top of the wing. This phenomenon is visible as big vortices on the wingtips. Since the induced drag is the most significant origin for drag during the flight, the engineers should focus on minimising that impact. One possibility to minimise it is the integration of Winglets which can be used as a barrier between the airflows on the top and bottom. A disadvantage of winglet is that it adds weight on the wing tip which increases the flutter tendencies.[34]

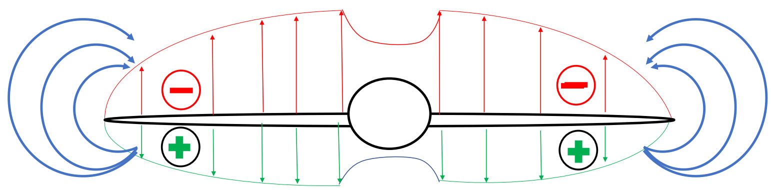

Figure 6.4: The lift distribution on the wing with vortices on the wing tip

6.3 Aircraft Structure

The airworthiness of an aircraft needs to be ensured at all time. The structure of aircraft has to able to resist and absorb all loads during the flight. The mechanical stress in the structure can be classified into two groups: static and dynamic stresses.[22] The static stress is the stress which is related to a particular flight phase inside of the flight envelope and can last from a few seconds to the longer duration of the flight. The dynamic stress is mainly caused by vibration phenomena in which the airflow around the flight vehicle is interacting with the aircraft structure this is also known as aeroelastic effects.[22]Because of the complexity of the aeroelasticity, this assignment will not explain these an will only focus on the static stress effects.

6.3.1 Airworthiness Requiremtns

During a flight, the loads on the aircraft structure can quickly gain a multiple of the tare weight of the aircraft. The behaviour of these loads can be displayed in a diagram which is called flight envelope. The Flight Envelope displays the loads with a unitless variable called loads factor n over the flight speed. [24]

$$Lift = nW = \frac{\delta}{2}v^2 SC_L$$

The Flight Envelope displays the loads with a unitless variable called loads factor n over the flight speed. The EASA and FAA regulations intend for UAVs above the 20 kg the proof that the aircraft can operate in a given flight envelope without any structural damages.[5]

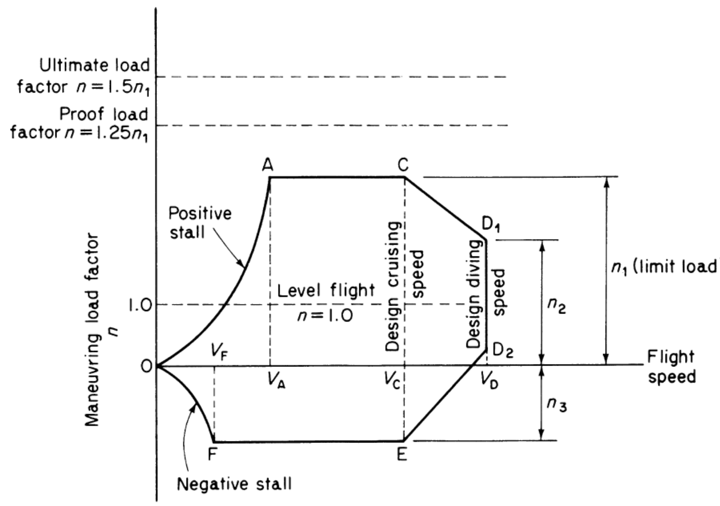

Figure 6.5: Example for a Flight Envelope[22]

6.3.2 Stress Analysis

As in sectoin 6.2.5 already described can the lift distribution on the wing, in the best case, assumed as an elliptical. That leads to the following distribution function over the wing.

$$L(x) = L_0\sqrt{1 - \left(\frac{X}{b}\right)^2}$$

The Equation can be used to calculate the stress on the structure caused by the lift. The main internal stresses of the structure are bending and torsion stresses caused by the Lift. [26]

$$Q(x) = \int L(x)\, dx$$

$$M(x) = \int Q(x)\,dx$$

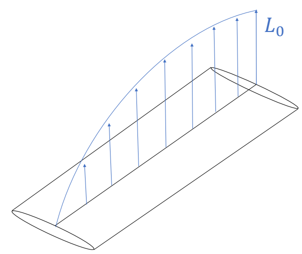

Figure 6.6: Sketch of the assumed Lift Distribution over the wing

To calculate the stress in the wing, the wing can be simplified to an beam(Airframe Stress Analysis and Sizing). That makes the analyical calculation much easier and alaows the first approximation and sizing of the beams and choosing of the matirials.

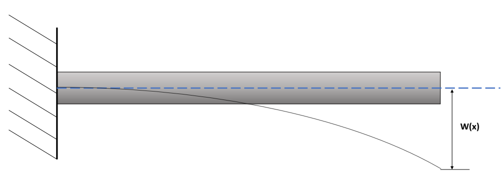

Figure 6.7: The simplified model for a bent wing

6.3.3 Spar Types

In general, wing construction is based in three fundamental design types: the Mono-spar, the multi-spar and box beam. The mono-spar wing joins only one central longitudinal segment in its construction. The structure gets additionally supported with ribs or bulkheads which provide the required contour or form to the aerofoil. The multi-spar wing is similar to the mono-spar, but it incorporates more than one central longitudinal fragment in its construction. The box beam structure uses two spars with connecting bulkheads to provide additional strength and to give a shape to the wing. [27]

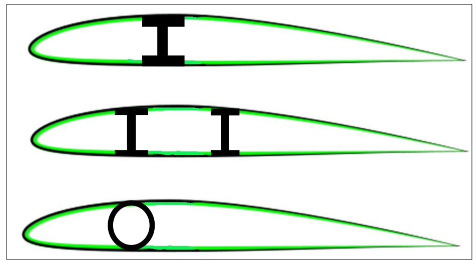

Figure 6.8: Illustration of three spar types

6.4 Material

The successful development and operation are significantly dependent on the right material choice for the structure and components of an aircraft. Escpailly in the aerospace sector is the topic of materials a critical one since the materials need to be as light as possible and reliable as possible. They need to resist high temperatures, enormous loads and extended operating hours.<

For the choice of materials can the engineers choose out of a variety of materials which all got their benefits and drawbacks. It is the job of the engineers to find the best fitting materials for the specific requirements of each operations area of the future drone. The most popular substances in the aerospace sector are steel compounds, aluminium alloys, fibre reinforced composites and sandwich structured composites.

In the following sections will introduce some of the mentioned materials briefly and give an outlook which parameters need to get opposed during the decision making.

6.4.1 Metalls

The most commonly used material types in the aerospace sector are metals. They are most likely sue because of the excellent stress resistance and low manufacturing costs. Other benefits are the isotropic behaviour and the fact that metals are highly researched, which makes them highly trustworthy. The disadvantages are for example that the partially high weight and the fact that they can corrode. The most used metal in the aerospace sector is aluminium alloys, followed by steel. (megson)

6.4.2 Composite

Recently are composites gaining more importance. They are providing, similar to metals, high-stress resistance but having the benefit that they are very light. That can help to make aeroplanes lighter and with that more efficient. (Iranian)

The idea behind composites is that a composition of two or more materials can create a composite which has a beneficial behaviour for specific use-cases. Frequently used composites are fibre reinforced composites which can be classified into three classes: Metal Matrix Composites (MMC), Ceramic Matrix Composites (CMC) and Polymer Matrix Composites(PMC).

6.4.3 Material Selection Criteria

During the selection process in which the engineers are searching a suitable material, a broad range of influences is essential. An engineer needs to occupy oneself with all advantages and drawbacks in comparison to the operations requirements. Additionally, he needs to pay attention to the influences on the whole aircraft system. Figure 6.9 shows a table of different material parameters which can influence the choice of the.

class of material	Material	density (kg/m3)	□y (Mpa)	Elastic Modulus (Gpa)	Elongation %	Temperature limite oC	Cost $/lb
aluminum (reference)	2024 T3	2800	510	72.5	10	280	3
aluminum	7075 T6	2800	586	71.7	4	250	3
maraging steel	C-250	7920	1620	183	5	1000	5
steel	4340	7830	1900	170	11	1100	1
titanium	8Al-1Mo-1V	4370	1000	121	8	800	15
wood	spruce	560	67.5	14.5	0	200	2
composites	glass-epoxi	1960	730	44.6	0	350	2.9
composites	graphite-epoxi	1540	1080	312	0	350	32
composites	Boron-Aluminum	2800	840	241	0	600	320
composites							

Figure 6.9: Table with a comparison of different materials[20]

Chapter 7

Conclusion

Within this assignment, The Aerodynamical and Structural Design of Unmanned Aaerial Vehicles, has been exhibited. The first overview of about the pruposes and objectives of this work were given in chapter one. Chapter two gave a concise prologue to the general procedure of the different steps inside the design process of UAVs. Chapter three delivered definitions and explanations of relevant requirement types and provided a brief outlook about applicable laws which are influencing the development process. Chapter four presented the conceptual design phase. It supplied a viewpoint about distinct types of UAVs and proposed a tool which can help engineering teams to find the best suitable decision. The fifth section is dealing with the preliminary design phase and introduced the reader to relevant methods for the initial sizing. The sixth part of the assignment presented suitable configurations and approaches for the detail design phase.It also gave a brief overview of the aircraft structure of the wing and material which can be used during the design. All the objectives declared in the preface of the work have been successfully achieved. The aerodynamical and structural design process of Unmanned Aerial Vehicles was briefly introduced. Since the number of pages is restricted, it was not possible to explain in more detail the broad field of drones technology. Therefore it was needed to make compromises during the work. Because of that, it was necessary to focus on the basics of fixed-wing aircraft development. For further knowledge, it is recommended to have a look at the references which is providing a numerous number of books and papers.

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Appendix A

Use-Case: Medical Emergency Transportation UAV

A.1 Motivation and Backround

The United Kingdom has a population of more than 66 million people and a size of around 242,495 km2.[12] Every day more than 7,000 people in the UK are waiting for an organ transplant. While in the last year only 4,431 transplants were actually performed. [40]This shows the lack of organs and the importance of these resources and successful transplantation. On the other hand, organs are very sensitive and need both a very sensitive handling and very fast delivery to the people who are waiting for the organs. For example a heart needs to be transported in a time span of 4 hours, otherwise, it's not usable anymore. Every mistreatment and time extension could lead to a useless organ and maybe dying person. While the register lists are nationwide, the people are maybe more than 100 miles away from the demanded organs. This use case could benefit greatly from the commitment of drones which are carrying the organs fast and safely to the destination.

The current organ transport procedure is a highly complex process with a lot of associated entities. The hospital with the donated organ needs to contact an NHS approved transport operator. In dependencies to the distance between donor and receiver, the operator decides between a fixed-wing aircraft or the rotorcraft aircraft for the transport. Is the fixed wing of the chosen air vehicle the transplant need firstly transported to the nearest airport by car and of course it needs to land in an airport and be transported to the hospital by car again. That high amount of entities and switching are showing the considerable improvement a fixed wing solution could deliver to that area. [39; 13; 40]

With the help of VTOL unmanned aircraft systems (UASs) the operating time could be minimised and with that, the number of successfully transplants increased. The discussed approaches having the potential to improve the sector and to decrease the number of dying people in the United Kingdom. A possible case would be that every hospital has a drone and can use it in emergency circumstances for the transportation of organs. That could help to save the critical time and to help to improve this critical area. This assignment is showing an approach to design an air vehicle system by using best practice procedures from research and industry and significant simplifications. The intention of this assignment is not to deliver a perfect UAV but rather to present an early prototype which decrees of some of the basic features. Further steps, like detailed simulations and numerical stress analysis, are not part of this work, but an important during the development life-cycle of UAVs.

A.2 Problem Statement

The problem presented in this use-case is the limited time span in the long distance transporting of organs in the United Kingdom. This assignment proposes the use of VTOL drones to replace the current method of pilot controlled aircraft systems. The assignment discusses the design process of the VTOL in this specific operations sector and trying to find approaches for delivering an early prototype of the drone. The proposal claims to improve the process by reducing the time and the costs for the hospitals and the NHS. The used methodology does not deliver a readily completed development cycle and therefore not a finished aircraft. This work is rather discussing methods to enter the first iteration step and to provide a knowledge-based prototype which can be used for further simulations and flight tests. For this reason, different studies must be undertaken in order to develop a real-world outcome.

A.3 Aim and objectives

The primary goal of this assignment is to design the prototype of a VTOL UAS for the long distance organ transport under the consideration of aspects such as aerodynamics, stress analysis and materials selection.

To reach that goal different objectives have to be accomplished which are:

- Define the mission and operation requirements and translate these to technical requirements for the UAV design
- Pass the Conceptual design phase with the result of a defined aircraft configuration
- Initial Sizing of the Take-Off Weight, Wing area and the Thrust (Preliminary Design Phase)
- Detail Design of the Aircraft: airfoil design, stress analysis and wing structure design, power and propulsion systems

A.4 Requirements

For this Mission following requirements has been given:

- Minimum Speed - Stall Speed: $20\frac{m}{s}$
- Maximum Mission Range in England is 600 km and maximum time for critical organs is 4 hours –> Cruise Speed: $150\frac{km}{h} = 20\frac{m}{s}$
- To stay in the UAS Classsification of the CAA need the UAV have a MTOW of less than 150 kg
- Payload Weight is 20 kg regarding to the NHS information
- Maximum Wingspan of UAV need to be less than 12 meters since heliports of the hospitals have a minimum length and width of 12 meters for the landing of vertical land and take-off aircrafts[17]

- The manufacturing costs need to hold down as small as possible to hold the costs of the UAV as small as possible

A.5 Conceptual Design

A.5.1 Aircraft Configuration

The first step of the Design was it to determine the best suitable configuration for the Mission. For that, the three fundamental configuration types were distinguished in a weighted decision matrix, which is using the specified requirements to choose between the configuration models.For this particular mission, the decision has been given to the VTOL System, which is the only system that allows to operates in an urban environment and longer range flights.

Criteria	Weight (1-5)	Fixed-wing		Hybrid/VTOL		Rotor-craft	
		Score (1-5)	Total	Score (1-5)	Total	Score (1-5)	Total
Ease of Manufacturing	4	3	12	2	8	4	16
Cost	3	3	9	2	6	3	9
Control Complexity	3	3	9	2	6	3	9
Range	3	4	12	4	12	2	6
Speed	3	4	12	4	12	2	6
Robustness	3	4	12	4	9	3	9
Reliability	4	4	16	4	16	3	12
Weight Efficiency	5	5	25	4	20	3	15
Mission Tasks	5	1	5	5	25	3	15
Total			112		114		97

Figure A.1: Weighted Decision Matrix for the Aircraft Configuration

Concerning the subtypes of the fixed wing, the decision was compelled to use a conventional wing configuration because it owns apparent gains in the ease of design and the ease of manufacturing.

Criteria	Weight (1-5)	Conventional		Canard		Box-Wing	
		Score (1-5)	Total	Score (1-5)	Total	Score (1-5)	Total
Ease of Manufacturing	4	3	12	2	8	4	16
Stability	3	3	9	2	6	3	9
Maneuverability	3	3	9	1	3	3	9
Weight	3	4	12	4	12	2	6
Aerodynamic Efficiency	3	4	12	3	9	4	12
Ease of Design	5	4	12	4	9	3	12
Total			66		47		64

Figure A.2: Weighted Decision Matrix for the Wing Types

To make the chosen conventional wing more efficient, it is common in the aircraft design, to modify the wing geometry. The goal is it to produce an elliptical lift distribution across the wing. To diminish that behaviour the choice was made to adopt a tapered wing.

Criteria	Weight (1-5)	Sweep Wing		Tapered		Rectangular		Delta	
		Score (1-5)	Total	Score (1-5)	Total	Score (1-5)	Total	Score (1-5)	Total
Ease of Manufacturing	3	3	9	4	12	5	15	3	9
Aerodynamic Performance	5	3	15	4	16	2	15	3	15
Maneuverability	5	4	20	4	20	3	15	3	15
Weight	4	4	16	4	16	4	16	3	12
Total			60		64		61		51

Figure A.3: Weighted Decision Matrix for the Wing Geometry

Regarding the Vertical Wing Position, the decision was made to use the rectangular wing. That wing type provides considerable advantages in the manoeuvrability and the weight of the wing, which is something that has a meaningful contribution to the success of the operating drone.

Criteria	Weight (1-5)	High wing		Mid wing		Low wing	
		Score (1-5)	Total	Score (1-5)	Total	Score (1-5)	Total
Ease of Manufacturing	4	3	12	2	8	3	12
Stability	3	3	9	2	6	3	9
Maneuverability	3	3	9	1	3	3	9
Weight	3	4	12	4	12	2	6
Lift	5	4	20	4	20	3	15
Drag	4	3	12	4	16	3	12
Total			74		65		63

Figure A.4: Weighted Decision Matrix for the Vertical Wing Position

For the empennage, the high boom tail was chosen. That particular type provides benefits regarding stability and the weight, as well as that this type of tail is appropriate to integrate into to a VTOL system.

Criteria	Weight (1-5)	Conventional		T-Tail		V-Tail		High-Boom	
		Score (1-5)	Total	Score (1-5)	Total	Score (1-5)	Total	Score (1-5)	Total
Ease of Manufacturing	4	3	12	3	12	3	12	4	8
Stability	5	3	15	3	15	3	15	4	20
Drag	3	2	6	3	9	4	12	2	6
Weight	4	3	12	2	8	4	16	3	12
Integration to VTOL	5	3	15	3	15	3	15	4	20
Total			60		59		70		74

Figure A.5: Weighted Decision Matrix for the Wing Tail Type

A.6 Preliminary Design

A.6.1 Maximum Take-Off Weight

As in the assignment before described can be the weight estimated with the help of empirical data from prior projects. In that case, does the weight compile out of the summation of each weight component that is integrated into the aircraft.

$$W_0 = W_{organs-Cargo} + W_{payload} + W_{battery} + W_{empty} =$$
$$W_{organs-Cargo} + \left(\frac{W_{payload}}{W_0}\right) W_0 + W_{battery} + \left(\frac{W_{empty}}{W_0}\right) W_0$$

Consequently can the estimated weight calculated with follwing formular:

$$W_0 = \frac{W_{organs-Cargo} + W_{battery}}{1 - \left(\frac{W_{empty}}{W_0}\right) - \left(\frac{W_{payload}}{W_0}\right)}$$

Empty-Weight Fraction

As in the Diagram A.6 is shown is the empty-weight fraction for a UAV with a maximum take of weight of 150 kg around 0.625. [41]

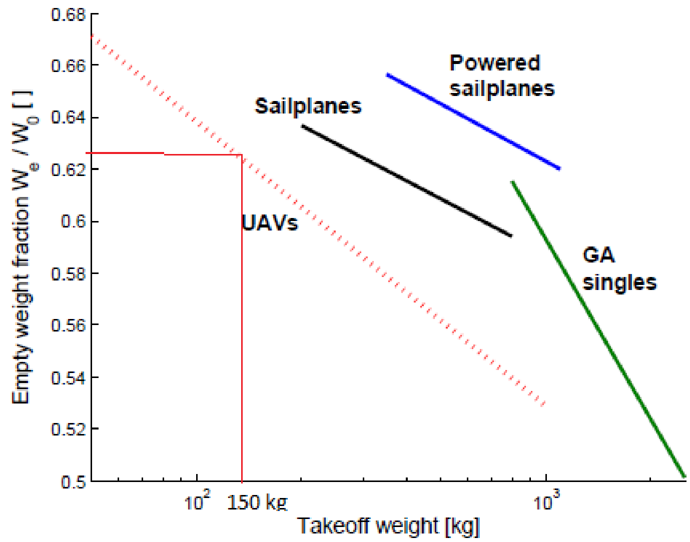


Figure A.6: Diagram of the Empty weight fraction of ther estimated MTOW[41]

Payload-Weight

Because of the uncertainty of the sensors which are going to be used for the unmanned aircraft later. It is the easiest way to estimate the weight of the payload, excluding the payload of the cargo, with the help of the payload weight of previous projects. The payload is including all relevant sensors and controllers which are needed for a successful operation. In a real design scenario need the engineers decide which sensors and subsystems are needed in the UAV. The payload weight is defined as the weight summation of all needed subsystems in the aircraft. To make it as easy as possible the used payload weight for this example the payload weight of the IAI panther which is in shown in figure A.7 and given from the articel of Ozdemir.[29]

Specification	 IAI panther	 IAI mini panther	 TURAC (VTOL)
MTOW (kg)	65	12	47
Payload (kg)	8,5	2	8
$W_{Payload}/W_{MTOW}$	0,13	0,16	0,17
Endurance (h)	4	1,5	1,42
Hover time (min)	3	3	10
Productivity (kg*h)	34	3	16
Power source	Electric	Electric	Electric

Figure A.7: Table of different UAVs and important Key Performance Indicator[29]

Battery Weight

In general, can the battery weight estimated by the actually needed energy for completing one mission. For that appraoch need the engineers know exactly the different mission states and their duration.

$$E_{total} = \sum E_i = E_{Mission} + E_{Cruise} + ...$$

$$W_{Battery} = \left(\frac{Total-Requiored-Energy(Wh)}{Battery-Power-Density} \right)$$

Due to the fact that that the goal of this example is not to provide an accurate weight of battery it can be assumed that the battery weight is 20kg.

Organs Cargo Weight

The organ which needed to be transported, from one hospital to the other, is kept in an ice box that is shown in figure A.8. Recording to NHS is the total weight of that box in its maximum 20 kg.

Figure A.8: Picture of the Ice Box for the Organ Transport[23]

Maximum Take-Off Weight

Under consideration of the factors introduced before, the calculated weight for the unmanned aircraft is:

$$W_0 = \frac{W_{organs-Cargo} + W_{battery}}{1 - \left(\frac{W_{empty}}{W_0}\right) - \left(\frac{W_{payload}}{W_0}\right)} = 129.33kg$$

A.6.2 Wing Area

The Wingarea is an essential parameter which is required to determine the aerodynamic performance of the aircraft and the wing. For the first step, it was decided to determine the aspect ratio of the drone. The aspect ratio is going to be defined by reviewing previous projects that are comparable to the UAV. Some of the comparable aircraft and their aspect ratio are listed in table A.1.

$$AR = \frac{b^2}{S}$$

Aircrafts	Aspect Ratio
IAI Heron	19
TAI Anka	22
Predator	22
AAI Aerosonde	≈ 15

Table A.1: Table of UAVs with their Aspect Ratio[7; 43; 32]

The chosen aspect ratio for the unmanned aircraft vehicle is :

$$AR = 16.66$$

Like already introduced in the requirements of this project is the maximum wingspan of the UAS limited to 10 meters. Because of the beneficial aerodynamic behaviour of the wing, it is better to have a big wingspan. Because of that fact it has been chosen to define a wingspan of actually 10 meters.

$$b = 10m$$

Consequently, we can calculate the wing are of the aircraft following:

$$S = \frac{b^2}{AR} = 6m^2$$

A.7 Detail Design

A.7.1 Airfoil Selection

To guarantee the best fitting aerodynamic behaviour, the airfoil should be chosen by considering the operations requirements. The requirements are giving information about the cruise speed and the stall speed, which is the minimum flight speed an aircraft can fly. As in 6 discussed should be the cruise flight speed operating in the area of (CL/CD)max to provide the most efficient behaviour of the airfoil. The stall speed should be around the maximum lift coefficient of the airfoil.

$$L = \frac{\delta}{2} v^2 S C_L$$

$$C_L = \frac{W}{\frac{\delta}{2} v^2 S}$$

For this example, the cruise speed is defined as 42m/s, and the stall speed is determined with 20 m/s. These values are leading to following coefficients.

$$C_{L_{Stall}} = \frac{MTOW}{\frac{\delta}{2} v_{Stall}^2 S} \approx 1.094$$

$$C_{L_{Cruisel}} = \frac{MTOW}{\frac{\delta}{2} v_{Cruise}^2 S} \approx 0.248$$

With the help of these values, it was possible to search in an airfoil database for the best fitting airfoil. The chosen airfoil that seemed to fit the best is the NACA 63A010 Airfoil, displayed in figure A.9.

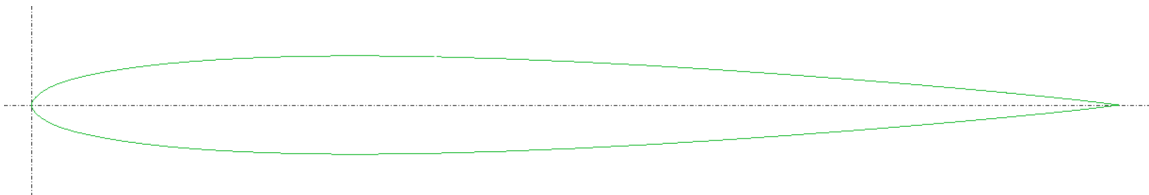


Figure A.9: Airfoil profile of the NACA 63A010 displayed in XFLR5

A.7.2 Wing Structure

To finalize the wing design, a wing structure needs to be defined. For that decision, a weighted decision matrix was created. The outcome of the decision process was to use a double spar, also called box-beam, wing strcutre solution for the absorption of the wing loads. The decisons process can be seen in figure A.10.

Criteria	Weight (1-5)	**Mono-Spar**		**Box-Beam**		**Multi_spar**	
		Score (1-5)	Total	Score (1-5)	Total	Score (1-5)	Total
Wind Load Resistance	4	3	12	4	16	5	20
Space	3	3	9	4	12	2	6
Cost	4	4	16	4	16	3	12
Reliability	4	3	12	4	16	4	16
Weight	4	4	16	3	12	2	8
Total			65		72		62

Figure A.10: Weighted Decision Matrix for the Material Selection

Load Estimation

To determine which section has to carry the most load the wing has to be assumed as a beam with a load distribution on it. The load distribution can be understood as an elliptical distribution with its maximum on the wing root.

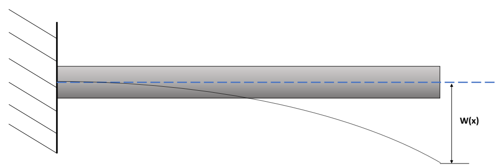


Figure A.11: A beam under Bending Loads

The equation of the lift distribution can be defined as a function which depends on x. In that case is x the distance to the wing root.

$$L(x) = L_0\sqrt{1-\left(\frac{X}{b}\right)^2}$$

In our case is L0 the maximum lift, which can be assumed with 1471.5 Newton. Regarding the maximum occurring loads for the airworthiness approved of the EASA.

$$L_0 = m \times g = 150kg \times 9.81\frac{m}{s^2} = 1471.5N$$

The sear force and the moment over the wing can be described with the following equations:

$$Q(x) = \int L(x)\,dx$$

$$M(x) = \int Q(x)\,dx$$

The distribution of the shear force and the moment for our case is shown in figure A.12. Both figures are showing that in both cases the maximum strain is been given in the wing root where x =0.

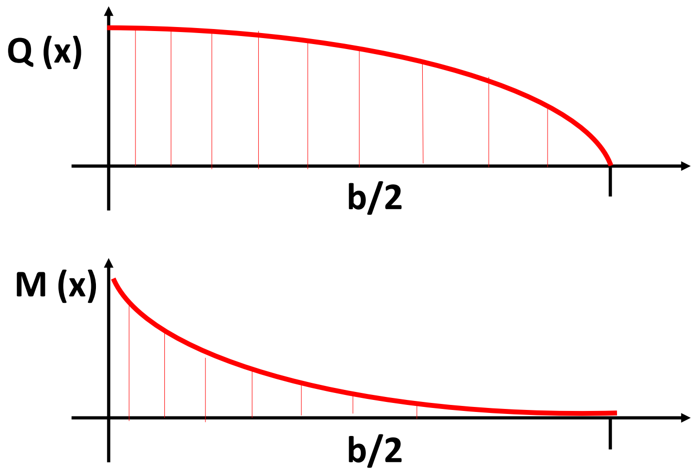


Figure A.12: Moment and Shear Force distribution over the Wing

The numerical value for the force and the moment are:

$$Q(0) = L_0 = 1471.5N$$

$$F_{Total} = \frac{\pi \times L_0 \times \frac{b}{2}}{4} = 5778.57N$$

$$M(x=0) = F_{Total} \times \frac{4 \times \frac{b}{s}}{3\pi} = 12262.5Nm$$

A.7.3 Material

In this step, the material of the wing is going to be determined. Essential for the material selection is the stress resistance and of course the weight or density of the material. In the decision matrix, given in figure A.13, can the decision-making factors be reconstructed. At the end a Carbon fiber reinforced polymer was chosen for the wing.

Criteria	Weight (1-5)	Carbon Fiber Composite		Glass Fiber Composite		Aluminium Alloy		Steel	
		Score (1-5)	Total	Score (1-5)	Total	Score (1-5)	Total	Score (1-5)	Total
Stress Resictance	4	5	20	4	16	3	12	5	20
Ease of Manufacturing	4	3	16	3	16	4	12	5	20
Reliability	4	3	12	4	16	4	16	5	20
Weight	5	5	25	4	20	3	15	1	5
Total			73		68		55		65

Figure A.13: Weighted Decision Matrix for the Spar Type selection

A.7.4 Stress Analysis of Wing Section

With the defined material and the defined inner wing structure, it is possible to design the spar section in more detail. Earlier we decided to use a box-beam approach for absorbing the loads. The box-beam solution provides to spars to consume the loads. Previous projects have been shown that good positions for the spars are at x= 0.15 and x=0.70 of the relative chord length.That is the reason why that practice is also used for this model.[8]

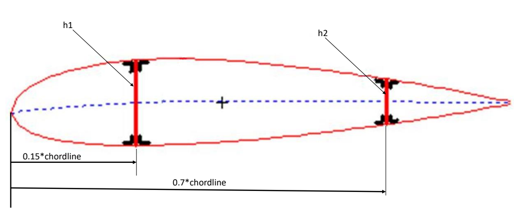


Figure A.14: Sketch of the Wing Airfoil and the Spar

The Spar hight is a function of the wing airfoil. For a NACA airfoil the hight for a specific chord position on the airfoil can be calculated as followed:

$$rel.-airfoil-thickness(x) = 5t[0.2969\sqrt{x} - 0.1260x - 0.3516x^2 + 0.2843x^3]$$

The variable t is the maximum thickness of the airfoil, which is in our case 10%. the variable is the distance from the leading edge of the wing. The variable t is the maximum thickness of the airfoil, which is in our case 10%. the variable is the distance from the leading edge of the wing. Since the values of the airfoil data are all normalised on the chord length, all received values have to be multiplied with the chord length of the wing to receive the absolute values. The mean chord line for our example is:

$$\overline{c} = 0.5m$$

This deliveres following hights of the spars:

$$airfoil-thickness(0.15) = h_1 = 0.0222m$$

$$airfoil-thickness(0.7) = h_2 = 0.0416m$$

In the following, the thickness of the spar parts and the thickness of the airfoil skin is going to be determined. The approach is it to calculate the skin thickness for the attacking loading types. The same hast to be done fo the spar parts. At the end of this step all needed thicknesses are known and the wing as completly defined.

Skin thickness-Load regarding of torsion

For the torsion stress, it can be assumed that the torsion will ab absorbed by the wing box. With that assumption, the approaches for the calculation of an idealized torsion can be used.[8]

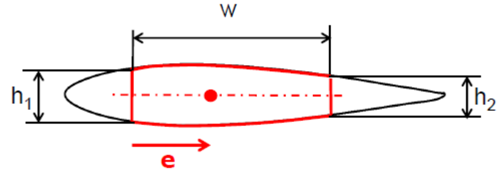


Figure A.15: The Box-Beam and relevant parameters

The width of the box is: $w = (0.7 - 0.15)\bar{c} = 0.275$

The postion of the shear center can be calculated with: $e = \frac{W}{1+\frac{h_2}{h_1}} = 0.0485m$

The average area of the box can be calculated as: $A_m = \left(\frac{h_1+h_2}{2}\right) w = 0.0088m^2$

The torsion moment due to the lift can be calculated as the lift with a lever arm to the shear centre. The lift vector can be assumed in the neutral point, which is mostly in the area of 0.25% of the chord line. That leads to the following lift moment:

$$T = F_{Lift} \times (0.55 - 0.25)\bar{c} = 220.725Nm$$

Now all needed parameters for the shear stress determination is known and the shear stress or in our case the thickness of the skin of the box can be calculated.

$$\tau_T = \frac{T}{2A_m t} \geqslant \tau_{Material}$$

$$t_T \geqslant \frac{T}{2A_m \tau_{Material}}$$

Skin thickness-Load regarding of bending

To design a fitting thickness of the skin due to bending we need to assume that the bending moment is not carried the spars (vertical parts of the box)and only absorbed by the skin which is on the top and the bottom of the wing box. With that assumption, it is possible to make a rough estimation for the skin. Another needed assumption for the calculation is that the box is a perfect rectangular.[8]

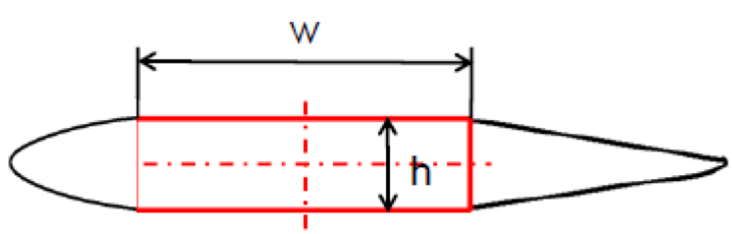


Figure A.16: Idealised Box-Beam

The box hight is: $h = \frac{h_1+h_2}{2} = 0.0319m$

The Force due to the bending moment in the skins is: $P = \frac{M_b}{h} = 384.4kN$

The normal stress in the skin can be described as:
$\sigma_{Structure} = \frac{F}{A} = \frac{P}{A} = \frac{P}{t_e w} = \frac{M_b}{ht_e w} \leqslant \sigma_{Material}$

The needed thickness for the skin due to bending is: $t_e \geqslant \frac{M_b}{h\sigma_{Material} w}$

Spar Web thickness-Load regarding of torsion and shear force

The vertical spar web mostly absorbs the torsion and the shear which is attacking the wing. That is the reason why it is needed to design a spar web which can resist that stress.[8]

The shear flow due to the shear force is: $q_V = \frac{Q}{h_t} = 46.12\frac{kN}{m}$

The shear flow due to the torsion can be described as:$q_{Torsion_{Spar}} = \frac{2xT}{2A_{,m}w} = 504\frac{kN}{m}$

The needed spar web thickness can be calculated as: $t_w = \frac{q_V + q_{Torsion_{Spar}}}{\tau_{Material}} =$

Spar Flange thickness-Load regarding of bending

The horizonal spar flange mostly absorbs the normal stress due to the lift bending which is attacking the wing. That is the reason why it is needed to design a spar flange which can resist that stress.[8]

The Force due to the bending moment in the upper spar part is: $P = \frac{M_b}{h} = 384.4kN$

The normal stress in the spar flange can be described as:
$\sigma_{Structure} = \frac{F}{A} = \frac{P}{A} = \frac{P}{t_e w} = \frac{M_b}{ht_e w} \leqslant \sigma_{Material}$

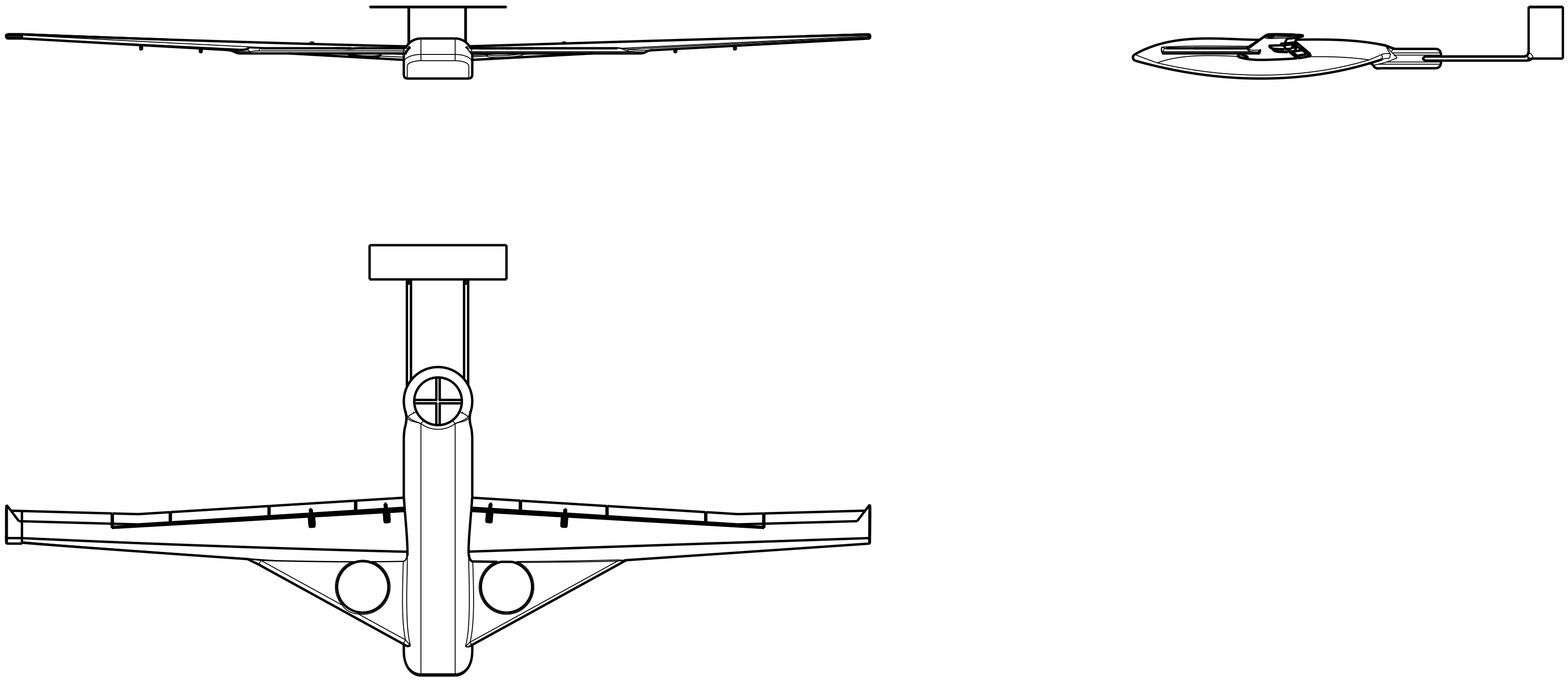
The needed thickness for the spar flange due to bending is: $t_e \geqslant \frac{M_b}{h\sigma_{Material} w} =$

A.8 Results

A.8.1 Aircraft

With all defined parameters and some further thoughts, it was possible to create a first CAD model of the designed unmanned aircraft. The Aircraft is a VTOL which can take-off and land in urban areas. It has two propellers in the front (left and right) and two coaxial rotors in the back of the aircraft. The front propellers can tilt to the front and create a transition from the vertical flight to a horizontal flight state.

Figure A.17: CAD Model of the designed UAV



DESIGNED BY: Johannes Autenrieb	Aircraft	Drone for UAS Intro	I	_
DATE: 20/11/2018	Course	Introduction to UAS	H	_
CHECKED BY: XXX	University	Cranfield	G	_
DATE: XXX		XXXX	F	_
SIZE A4		XXXX	E	_
SCALE	WEIGHT (kg)		XXXX	D	_
				C	_
				B	_
				A	_

A.8.2 Aerodynamics

A principal aerodynamic analysis of the aircraft has been made with the program XFLR5. The results were satisfying. The aircraft was tested in both the stall speed and the cruise speed. At first, just the aerodynamic behaviour of the wings is relevant. That means that for a first CFD simulation the aircraft has been idealized so that the propellers of the wing were not integrated. Both states are delivering a pleasing aerodynamical behaviour which is shown in the following diagram.

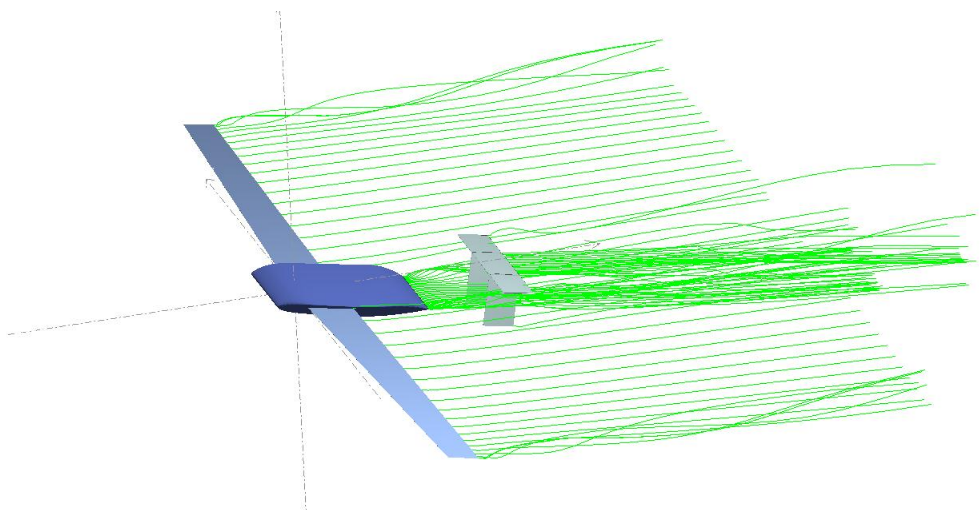


Figure A.18: CFD Simulation of the designed UAV

The graph A.19 shows the lift coefficient over the angle of attack. The diagram of the aircraft looks qualitatively good and exactly as it should be. Also the

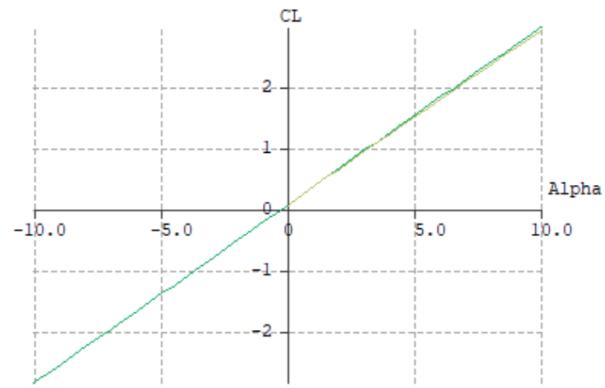


Figure A.19: Diagram with Lift Coefficient over Angle of Attack

Also figure A.21 with the lift coefficient over the drag coefficient looks qualitatively like it should in theory.

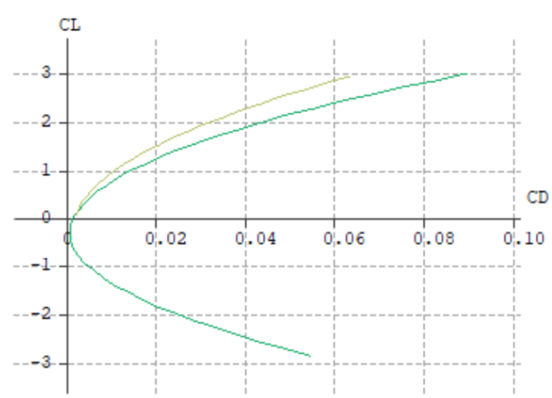


Figure A.20: Diagram with Lift Coefficient over Drag Coefficient

The last diagram is showing the pitch moment coefficient over the angle of attack. Picture A.21 is showing that the aircraft is having a negative slope in this behaviour. That is very good since that indicates that the plane owns static longitudinal stability. That means that the UAV shows a stable behaviour around the longitudinal axes.

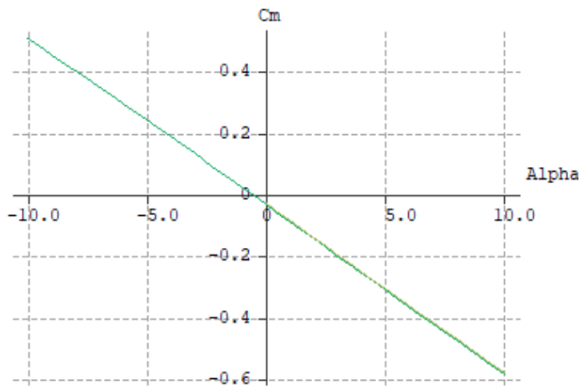


Figure A.21: Diagram with Moment Coefficient over Drag Coefficient