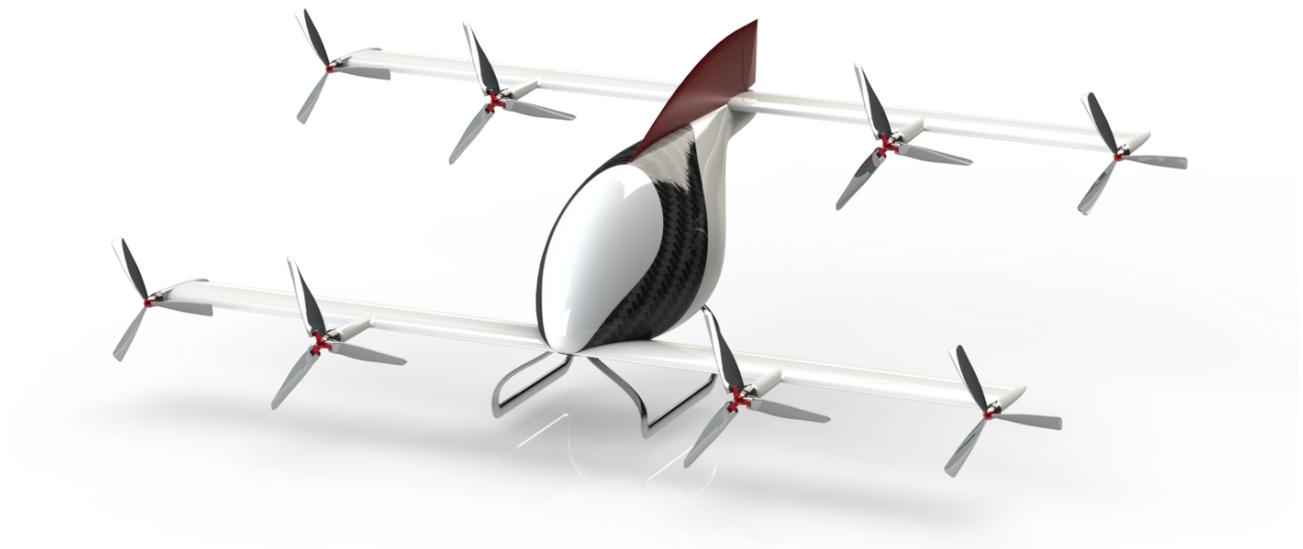


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NASA / DLR Design Challenge 2020

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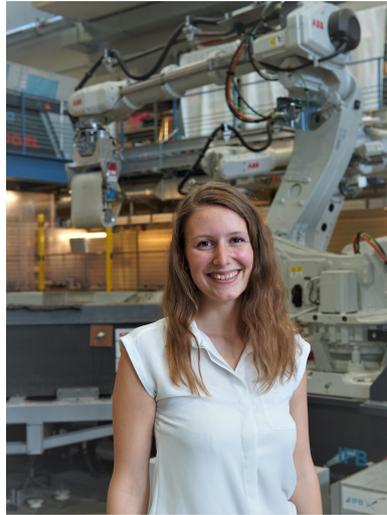
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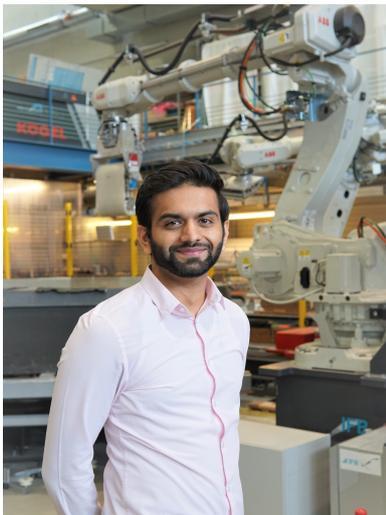
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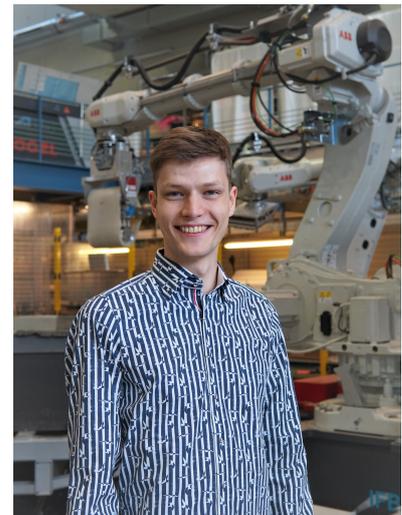
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Abstract

aIRO is an autonomous parcel delivery system that replaces the labour and therefore cost intensive last mile in an urban delivery process. This report demonstrates the aeronautic and economic challenges that are encountered during the construction of the delivery system. For the success of the project, the acceptance and safety of the general public are of crucial importance. To be able to safely manoeuvre in urban areas, redundant systems with VTOL capabilities are centrepieces of aIRO. This is implemented by using a combination of a tandem- and multicopter configuration with electric driven propellers. This design reduces the risk to personnel and assets on ground to a minimum. On system side, a highly capable, passive-radar based Detect and Avoid System provides input for the ground based flight path control via 5G-Network. This surrounding infrastructure will be installed on specialised ground stations. These are capable of a fully automated turnaround of the UAV in less than two minutes. The resulting high frequency of flights, together with the system complexity being ground-based, enables the business scenario to enter into market in 2025 and to reach break-even until 2031. Further an approach is shown how to safely ingrate the aIRO into the airspace through a network based remote ID technology and its certification through a Light UAS Operator Certificate.

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Abbreviation

A	[m]	Wing Surface
b	[m]	Wing Span
c	[m]	Wing Depth
c_L	[-]	Lift Coefficient
$c_{L,cruise}$	[-]	Lift Coefficient during Cruise
$c_{L,max}$	[-]	Maximum Lift Coefficient
c_D	[-]	Drag Coefficient
$c_{D,min}$	[-]	Minimal Drag Coefficient
c_M	[-]	Moment Coefficient
D	[N]	Aerodynamic Drag
E	[Wh]	Energy
e	[-]	Oswald-Factor
g	[m/s ²]	Gravitational Acceleration
L	[N]	Lift
l_μ	[m]	Chord Length
m_0	[kg]	UAV Total Mass
P	[W]	Power
Re	[-]	Reynolds Number
RPM	[1/min]	Rotational Speed
t	[s]	Time
V	[m ³]	Volume
x, y, z	[m]	Cartesian Coordinates
x_{COM}	[m]	Location Center of Mass
x_{NP}	[m]	Location Neutral Point
α_1	[°]	Angle of Attack Front Wing
α_2	[°]	Angle of Attack Rear Wing
λ	[-]	Taper Ratio
Λ	[-]	Aspect Ratio
ρ_0	[kg/m ³]	Air Density at Sea Level
ρ_{8000ft}	[kg/m ³]	Air Density at 8000ft

Nomenclature

ADS-B	Automatic Dependent Surveillance - Broadcast
AOA	Angle of Attack
ARC	Air Risk Class
ATM	Air Traffic Management
B2C	Business to Customer
BIEK	Bundesverband Paket & Express Logistik
BVLOS	Beyond Visual Line of Sight
CFD	Computational Fluid Dynamics
CFRP	Carbon Fiber Reinforced Plastic
COM	Center of Mass
CPI	Consumer Price Index
CS	Certification specification
DaA	Detect and Avoid
DAB	Digital Audio Broadcasting
DAL	Development Assurance Level
DC	Direct Current
DHL	German parcel, letter and express service, founded by Adrian Dalsey, Larry Hillblom und Robert
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DoD	Depth of Discharge
EASA	European Union Aviation Safety Agency
EBIT	Earnings Before Interest and Taxes
EDLC	Electric Double Layer Capacitor
FAA	Federal Aviation Administration
FC	Flight Control
FCC	Flight Control Computer
FFM	Frankfurt am Main
FLARM	Acronym based on 'Flight Alarm', Traffic Awareness and Collision Avoidance Technology for General
FOR-DEC	Facts, Options, Risks and Benefits - Decision, Execution, Check
FTA	Fault Tree Analysis
GNSS	Global Navigation Satellite System
GRC	Ground Risk Class
GRP	Glass-Reinforced Plastic
HW	Hardware
IMU	Inertial Measurement Unit
JARUS	Joint Authorities for Rulemaking on Unmanned Systems
LiDAR	Light Detection and ranging
LiS	Lithium-Sulfur
Li-Ion	Lithium-Ion
LSA	Light Sport Aeroplanes
LUC	Light UAS Operator Certificate
NP	Neutral Point
OSO	Operational Safety Objective
PA	Polyamid
SAIL	Specific Assurance and Integrity Level
SORA	Specific Operations Risk Assessment
SW	Software
SWOT	Strength Weakness Opportunity Threat
TMPR	Tactical Mitigation Performance Requirement
TAT	Turn Around Time
UAS	Unmanned Aerial System
USP	Unique Selling Point
USS	UAS Service Supplier
UTM	Unmanned Aerial System Traffic Management
VLOS	Visual Line of Sight
VTOL	Vertical Take-Off and Landing

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1. Introduction

Due to the growth in the online market, delivery services are facing increasing challenges: A highly-developed infrastructure and a rising amount of labour is needed to satisfy the customers needs. Most cost-consuming of the delivering process is the last mile. This is why this work will look into possibilities of a fully-automated last-mile delivery using Unmanned Aerial Vehicle (UAV) in urban areas. The projects name "aIRO" is a composition of the autonomous abilities of the drone and its main design feature, the "Iroquois" empenage.

The frame of this work is given by this years' NASA/DLR Design Challenge 2020. Its main task is to develop a fully autonomously parcel delivery system. This covers the development of the Unmanned Aerial System (UAS) itself, including all required systems, as well as the ground station and its functionality. Furthermore, a safety concept is demanded. The whole project is describes by a business case to guarantee its profitability [19].

1.1. Operational Scenario

The UAV is designed to compete against conventional delivery services on the last mile of the delivery process. Therefore, aIRO will be the connection between customers and large delivery enterprises to act as a service provider for the latter. To ensure the success of aIRO, a market analysis (Appendix ??), potential influences on the project were identified (SWOT-Analysis (Appendix ??) and a stakeholder analysis was performed (Appendix ??). Based on the results, a Unique Selling Point (USP) is defined to set the goals for the systems design: Special attention has to be paid to the management and marketing department of potential customers (e.g. DHL, amazon, Hermes). The delivery with aIRO reduces costs by autonomously distributing packages to ground stations without human intervention. Moreover, the problem of reliability of the last mile delivery can be solved. Currently there is a lack of competition in the market and quick cost cutting down the road can counter potential competitors.

1.2. Mission Scenario

The UAVs' task is the delivery of a package with a maximum size of 15x15x15cm and a mass up to 2.5kg. The starting platform is located 2,500m above the see level or below, with a maximum size of 15x7,5m. The UAV has to climb to a height of 120m above the platform within a radius of 1,500m. On a flight level of 120m to 150m the UAV covers a distance of 15km. To complete the mission in less then 20 minutes, the aIRO travels with a true airspeed of 100km/h. Furthermore, the UAV has the ability to fulfill two round trips with total distance of 60km. Meanwhile, the UAV has to withstand rainy conditions as well as side winds up to a speed of 20kn. After landing under the same conditions as at take-off, the UAV, in cooperation with its ground station has to perform its (un)loading and recharging process fully automated. [19].

Chapter 2 guides through the main decisions during the design process, followed by a description of the used systems in Chapter 3. Finally Chapter 4 explains the developed safety concept to ensure a harmless integration into the airspace including the certification process. Additionally to the UAS, Chapter 5 explains the assembly of the ground station and its turn around process. Afterwards Chapter 6 evaluates the costs more in detail, Chapter 7 concludes by summarising the key technologies and offering further perspectives for aIRO.

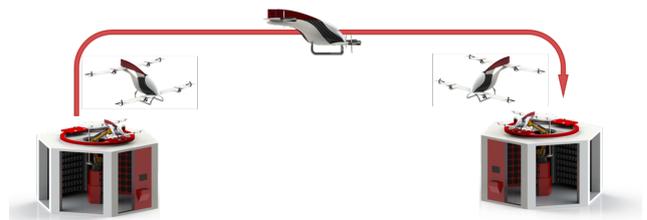


Figure 1: Flight Mission

2. Design and Configuration Process

2.1. Design Process

Primarily developed by the DLR and Lufthansa in the 90's for pilots and air traffic controller, the FOR-DEC method was established as a versatile tool for complex decision-making. Figure 2 shows the applied design process as an optimised version of the FOR-DEC method [23]. The primary definition of the requirements in a first step (Facts), is followed by developing possible design options (Options) to fulfil these requirements. In a further analysis the different design options are being evaluated (Risks and Benefits) and the most promising option gets chosen (Decision) for a detailed definition. In a fifth step (Execution) the chosen option is being developed in detail and integrated into the current version of the UAV. In a last step (Check) the design options are being verified to achieve all design goals and fulfil the demanded requirements. Therefore, former decisions are being reevaluated and revised if necessary. Following the FOR-DEC method in each design decision (see Figure 3) includes a regularly reevaluation. A structured design process leads to comprehensible decisions and minimizes the risk of errors.

2.2. Flight Principle

The flight course can be separated into two different flight conditions. The requirements demand a climb rate of 120m within 1500m (see Chapter 1.2). An urban flight environment extends this demand in order to avoid obstacles [19]. This results in an almost vertical height profile and the demand for vertical takeoff and landing (VTOL) capabilities. Contrarily, cruise depicts a flight profile at a constant altitude of 120m for a distance of 15km and demands a high aerodynamic performance. This leads towards two opposing basic configuration; a fixed-wing UAV and VTOL multicopter. With the choice of a hybrid version of fixed-wing- and a multicopter configuration, aIRO combines both basic configuration. Hence, aIRO does not only fulfil the requirements, it also per-

forms efficient and independent in both flight conditions.

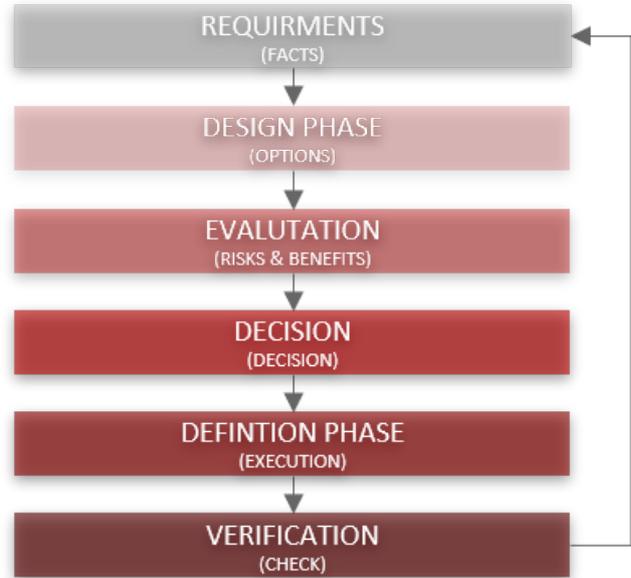


Figure 2: FOR-DEC Method

2.3. Wing Configuration

With the objective of meeting the requirements of an efficient cruise, the integration of lift generating surfaces is almost inevitable (see Chapter 3.6). aIROs configuration naturally supports the multicopter as well as the fixed wing configuration and makes a perfect fit for a hybrid version. A tandem configuration includes wings for the lift generation during cruise. Designing the wing independent of the body, enlarges the possibilities in wing design. An optimised airfoil selection increases aIROs efficiency during cruise which reduces the power demand. Furthermore, the combination of the elevator and the ailerons reduces the wetted surface and thus the drag coefficient, while performing with a excellent longitudinal stability[22]. Meanwhile, the wings provide enough lever arm relatively to the COM to separate the engines along the wings. This increases the impact of a single engine and enables a precise controllability of the UAV during landing and takeoff. Furthermore, the tandem configuration leads to an unsophisticated accessibility of the body and thus an easy payload integration.

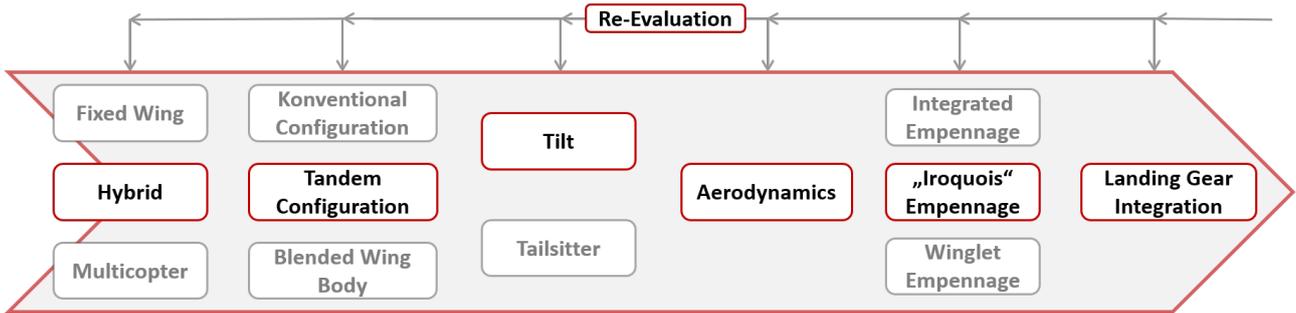


Figure 3: Design Process and Decision

2.4. Payload and Battery Integration

aIRO combines payload and battery systems and integrates it into the body. Shaping the body around the payload increases aerodynamic quality of the UAV. This again leads to an more efficient cruise and a reduced power consumption. Moreover, an integrated payload provides a suitable protection of the parcel against rainy weather conditions. The combination of the battery systems and the payload minimises aIROs turn-around-time (TAT) (see Chapter 5). Instead of recharging the battery, the next parcel with charged batteries can be loaded into the drone. The cylindrical shape guarantees easy access for autonomous loading and unloading. A precise interlock guarantees for both, structural integration and connected power supply.

2.5. Propulsor Integration

aIRO comes with a total of eight tiltable, electrical engines from two types. A subdivision of the propulsion system for both flight conditions opens up the possibility to optimise the drives and blades for their purpose (see Chapter 3.1). The outer four

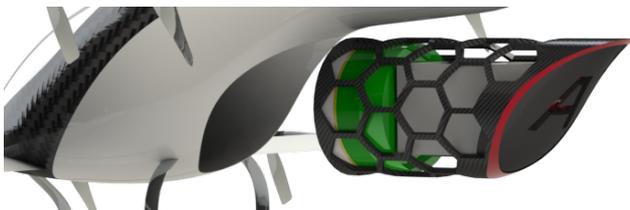


Figure 4: Loading of the Payload and Battery Package

engines are mounted as wing tip propeller in tractor configuration. This decreases the induced drag of the wing by attenuating the wingtip vortex by the propeller slipstream[48]. The inner four drives



Figure 5: Tilted Engines

and blades are optimised to generate lift during takeoff and landing. During cruise they fold back automatically to reduce drag. Both sets of engines have the ability to support each other to ensure manoeuvrability even in case of an engine loss. In order to avoid a single point of failure within the propulsion system, all engines are tilted separately (see Figure 5). This is of special interest, as Chapter 4 shows that the propulsion system can lead to several critical conditions. Due to widespread industry practices, tilted engines can be acquired at low costs while at the same time being operationally proven which indicates a sufficient reliability. Furthermore, in the improbable case of failure they can be replaced individually, cost and time-effective.

2.6. Aerodynamics

Suitable airfoil selection and wing design are crucial for the performance of the UAV and its aerodynamic efficiency. Hence, it is vital for the reduc-

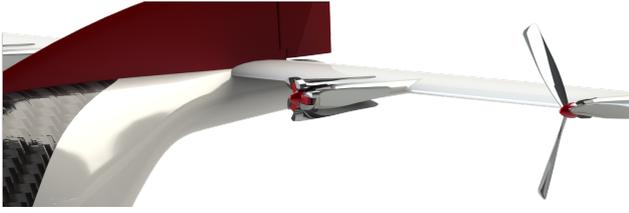


Figure 6: Rear Wing in Cruise Configuration

tion of operational costs to select the most fitting aerodynamic properties for the aircraft.

2.6.1. Airfoil design



Figure 7: Airfoil SD7032 [15]

The main focus of the airfoil selection process is based on horizontal flight (cruise). Numerous parameters such as minimal drag during cruise, high aerodynamic efficiency and smooth stall characteristics are vital for selecting the desired airfoil. The table Appendix ?? compares various parameters of different airfoils. The Selig Donovan SD7032 airfoil stood out during the selection process. Due to its excellent aerodynamic characteristics, it fulfills the demanded requirements. In particular, the SD7032 performs well at low Reynolds numbers through an excellent lift to drag ratio (L/D) and a wide range of values for c_L [15]. Furthermore, the SD7032 is already widespread in industry as it is already used in model sailplanes.

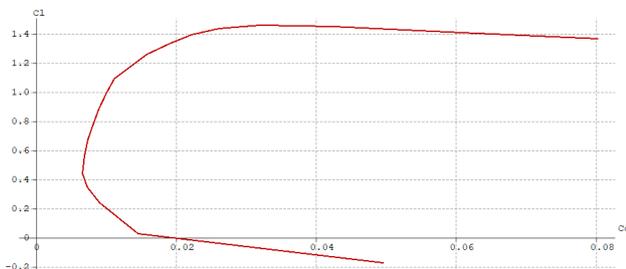


Figure 8: Polar Curve: c_L/c_D

Parameter		Value
Wingspan	b	1.80 m
Chord length	l_μ	0.20 m
Wing surface	A	$0.360m^2$
Aspect ratio	Λ	9
Taper ratio	λ	1
Reynolds number	Re	378,989
AOA front wing	α_1	2°
AOA rear wing	α_2	0°
Lift coefficient front wing	$c_{L,front}$	0.6215
Lift coefficient rear wing	$c_{L,rear}$	0.4143

Table 1: Wing Parameters

2.6.2. Wing design

A tandem wing aircraft has two independent lift generating wings. Additionally, the rear wing fulfills the function of an elevator. Avoiding an interference of both of the wings is crucial for the tandem configuration. A CFD simulation (see Appendix ??) shows that the interference is small enough to be neglected due to the given positioning of the wings. As the Mach number is low (see Appendix 5) and to keep production costs and effort as low as possible, the wing design is kept very simple. Thus, it is designed as an untwisted, untapered and unswept rectangular wing, without dihedral or anhedral and without any aerodynamic twist. As discussed in Chapter 3.1, during cruise configuration the wing tip propeller are in use, which enable increased propeller efficiency and less induced drag compared to a conventional design [48].

2.6.3. Stability Study

To ensure pitch stability for aIRO in horizontal flight, the front wing must provide more lift than the rear wing. In order to achieve this, there are a few possibilities. In the following some options, which are easy to implement, are listed:

1. The front wing has a higher angle of attack than the rear wing.
2. The rear wing area is smaller than the front wing area.
3. The rear wing has a lower-camber airfoil.

Masses	
Payload	2.5 kg
Structure	4 kg
Propulsion Systems	2.34 kg
Battery Systems	4.22 kg
Communication Systems, Sensoring	1.7 kg
Power Distribution, FC, Parachute	3 kg
Total	17.76 kg

Table 2: Mass Estimation

The first concept of identical wings with different AOA was chosen to reduce costs and complexity in the production process of the UAVs. With regard to stable flight condition, the dynamic stability is essential for aIROs configuration. Due to an identical wing design, the neutral point of aIRO, is located in the center of the neutral points of both wings ($x_{NP}=0.525$ m , tandem). As expected from tandem wings, it is close to the middle of the UAV [30]. Together with the center of mass (COM) ($x_{COM}=0.46$ m) a stability measure of 32.5% results. The mass estimation which characterizes the COM is shown in Table 2. Additionally, the Angle of Attack (AOA) of both wings are depending on the location of COM. The COM lies at 40% percent of length of the UAV. Therefore, the front wing has to provide 60% (104.53 N) of the total lift and the rear wing 40% (69.69 N). By using the lift equation, the necessary lift coefficient of each wing can be calculated. Together with diagrams in Appendix ??, the required AOA of each wing can be determined (see Table 1). These parameters have been optimized for the operational height of aIRO of 120 m above sea level. Operating ground stations 2600 m above sea level (approx. 8,500 ft) means flying in air with a lower density. Therefore, a higher AOA is needed to provide the necessary lift. An increase of 1° pitch increases the lift of the wings enough to maintain cruise altitude.

2.7. Stabilizer and Control Surfaces Integration

aIRO combines the elevator with the aileron and integrates it into the rear wing which reduces the wetted surface and thus the induced drag. The vertical stabilizer is composed of a dorsal fin, in-

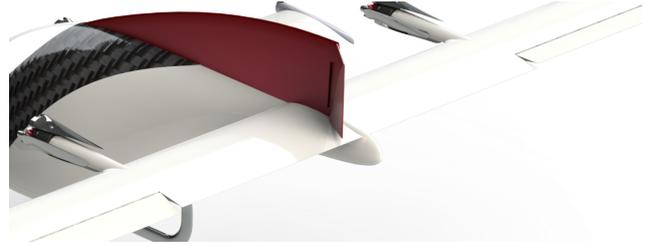


Figure 9: Empennage

tending to reduce aIROs side wind vulnerability and a control surface to control the drone (see Figure 9). This allows aIRO to fly safely and agilely in windy conditions, leading to aIROs iconic, eponymous Iroquois. Using stabilisers and control surfaces instead of steering with the drives has come along with different advantages. Especially gusty weather conditions demand a dynamic flight control. Avoiding rapid variation of the engine speed not only lowers the electricity consumption, it prolongs the life time of the propulsion system as well as it reduces the noise pollution of the UAV[38].

2.8. Landing Gear Integration

Landing on skids convinces with an easy integration into the body. Due to four connecting points it reduces the chance of structural damages after heavy landings. A low cross-sectional area of the skids minimizes its drag and thus the power demand. The position of aIROs COM ensures the stability after landing. Into the ground station integrated positioning systems fit the skids and guarantees a precise positioning for the unloading and loading process.



Figure 10: Landing Gear

2.9. Structure

For the preliminary design of the structure, the materials are selected by their load type, fracture toughness, durability, weight and costs. In addition, the selected materials have to be weather resistant and be coated with an UV-protective lacquer. The certification specification for UAVs is not developed so far (see Chapter 4.1). Therefore, it is assumed that the materials used in the UAV are certified for aviation purposes. Looking ahead, the structure will be designed according to JARUS [17].

The airfoil used in aIRO (Figure 7) has a small relative depth of 10% for aerodynamic reasons (see Chapter 2.6) and has a wingspan of 1.8m. However, the wing can handle all occurring loads, since the wing load of 25kg/m^2 for aIRO is lower compared to modern sailplanes ($30 - 60\text{kg/m}^2$ e.g. see [39]). Nevertheless, the wing needs a sufficient stiffness to limit bending during flight. The wings are designed with a continuous spar to minimize stresses at the wing root and to simplify the wing-body connection. To fulfill the strength and stiffness demands, the wings are made out of carbon fibre reinforced plastics (CFRP). Since the front and rear wing have the same cross-section, only one manufacturing tool is required which brings an economic advantage.

The fuselage (Figure 24) of aIRO is a conical shell, which can be manufactured well with organosheets. This material offers the advantages of being easy to produce and has a good fracture toughness.

The vertical stabilizer (Figure 9) is built by a sandwich construction with a thermoplastic profile filled with foam. This design fulfills the stiffness requirements and can therefore withstand strong loads such as side winds (see Chapter 1). The Iroquois is connected to the fuselage by ultrasonic fasteners.

The landing gear (Figure 10) is realized with skids like those found on conventional helicopters. The production will be done by bending standard thermoplastic tubes. This offers the possibility of a simple and economic integration of the landing gear.

Battery, payload and systems are protected by a

cylindrical frame (Figure 4). A standard glass-fibre reinforced plastic (GRP) tube with $\pm 45^\circ$ layers is used. Since the component does not experience high loads, mass can be saved by integrating cut-outs by water stream cutting. The selected materials lead to a total mass of the structure of approximately 4 kg.

3. Systems

3.1. Propulsion

As stated in the Chapter 2, the vehicle is chosen to have VTOL capacities. Additionally, it needs to be able to fly efficiently in cruise mode. The propulsion system needed will be designed in the following.

3.1.1. Flight Phase I: Cruise

In cruise flight, lift is generated by the wings of the UAV. Forward thrust is needed to compensate for the experienced drag on the aircraft. Considering the efficiency of the propellers results in a total power demand of $163W$ (see Appendix ??). Subsequently, the software xRotor [2] was used to design a suitable propeller blade for this mission phase. In a parameter study, the rotational speed was varied to optimize for efficiency and noise. This leads to a rotor diameter of 300 mm at a rotational speed of about 3500 RPM. At the average level of 120 m, the noise immission on the ground amounts to 4 dB. Further reduction of the RPM leads to even less noise. However, the efficiency will start to drop off again and a further reduction in noise is not necessary (see Appendix ??). The associated blade geometry is shown in Figure 11. Following the requirement of Chapter 2.5 for a VTOL-support-mode, the thrust will be evenly distributed among the propellers.

3.1.2. Flight Phase II: VTOL

[b!] During VTOL, the aircraft behaves like a

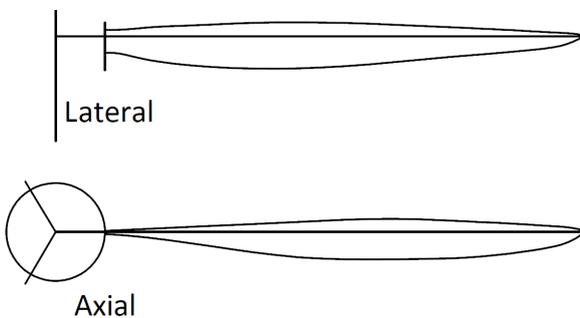


Figure 11: Geometry of the Cruise Propeller [xRotor]

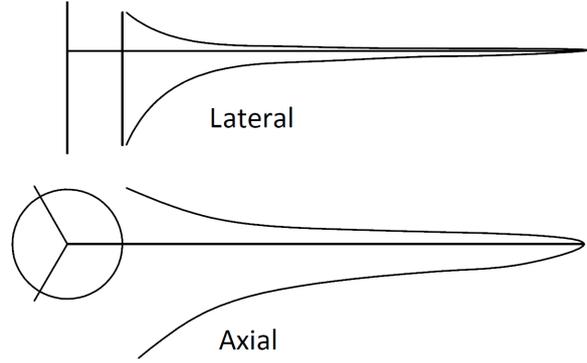


Figure 12: Geometry of the VTOL Propeller [xRotor]

multicopter. Lift is generated solely by the engines. Therefore, thrust needs to exceed the gravitational force on the aircraft. The resulting thrust requirement is ten times higher than the drag on the aircraft experienced during cruise phases. In addition, airflow velocity on the rotor is significantly lower than in cruise. The resulting rotor differs highly to the propeller designed in Chapter 3.1.1. Varying the same parameters as before, shows that efficiency increases with the rotor diameter, whereas the noise level decreases (see Appendix ??). Efficiency increases by enlarging the diameter and reducing the rotational speed. For an integration in aIRO, the maximum possible diameter of the rotor is limited by the length of the boom, which prevents interaction of the rotor's vortex with the wing. The space between fuselage and wingtip propeller is limited as well, leading to a maximum rotor diameter of 400 mm at 11000 RPM. A higher RPM would increase the root chord of the rotor over the diameter of the engine so it could not be attached. The resulting blade largely differs from the cruise propeller as shown in Figure 12. The Figure of Merit resulting from xRotor, together with the disk actuator theory were used to calculate the total power consumption of $4787W$ for VTOL (see Appendix ??). This also includes a safety margin of 25% to account for cross wind effects.

3.1.3. Noise

Adhering to federal noise regulation is vital to the authorization of the UAS. Still, the acceptance of

3.2.2. Non-Cooperative

For non-cooperative obstacles, further separations have to be made. Stationary objects, such as buildings and power lines will be covered by a geofencing system, explained in Chapter 4.2.1. Therefore, the main task will be to avoid UAVs, which do not have or have lost connection to UTM. Such obstacle dimensions are oftentimes below one meter. Furthermore, the fast travelling speed of aIRO, up to $100km/h$, result in a high detection range needed. Consequently, requirements for the DaA system need to be defined so that the sensors are able to replace the "see and avoid" capabilities of a pilot, which covers $+/- 115^\circ$ on the horizontal plane and $+/- 15^\circ$ on the vertical plane. To cover these angular ranges as well as the total range of human eyes, multiple sensor-technologies for UAVs are currently discussed and compared. But to get reliable data a combination of e.g. thermal, optical, acoustic or electromagnetic would be needed [36]. Each detection strategy is limited by specific characteristics, such as resolution, range or angle of detection. Focusing finally on the cost- and mass-effectiveness of aIRO, on-board systems lack in these capabilities.

In fact, UAV technology should not be seen as another adaption to manned aviation but as a milestone in aircraft history. Hence, the opportunity is provided to think of completely new "sense" capabilities which are not limited to replacing humans. Therefore, sensors should not replace pilots inside the cockpit with on board systems but allow the UAV to manoeuvre safely through airspace.

Another approach is the idea of ground-based sensor systems. Especially in the given scenario with fixed operation areas, as well as a high number of UAVs operating in the flight zones, the benefits of a ground-based system are significant. Abandoning the classic approach of overcoming the lack of "sense" capabilities of each UAV with sensors, will lead to less required sensors and less weight on board. Only 5G transmitters are installed on the UAV to receive commands resulting from relevant airspace data (see Chapter 3.4).

Surveillance of airspace can be performed with different radar methods. aIRO will use a more modern approach called passive radar, using al-

ready existing electromagnetic waves in the area to detect intruders. The Hensoldt Holding GmbH claimed to be able to track F-35 jets, which are designed to have a small radar cross-section, at more than $100km$ distance [42].

For a reliable passive radar a high density of transmitters, such as digital audio broadcasting (DAB) or telecommunication, as well as receivers are needed. DAB has several advantages such as the use of orthogonal frequency division and a signal which is easily decoded into noise-free signals [9]. Moreover, lower frequencies with wave length of the size of UAVs would increase the small radar cross section making UAVs hard to detect by conventional radar [40]. Further, a long integration time will allow better Doppler resolution [41] needed to determine the velocity of intruders. Hence, passive radar does not only meet the needs for a safe integration into the U-Space better, public acceptance will also be higher, because no additional radiation is transmitted. As transmitters are widely spread in urban areas and are already existing, meaning that no additional costs for illuminators is needed, aIRO uses a setup, where only one receiver, surrounded by four illuminators, is needed. Since it is already possible to track a micro UAS in $1.2km$ distance [41], way less sensor e.g. on rooftops are needed than UAVs profit from. In strategically important locations, such as between skyscrapers, additional antennas are necessary.

The computational resources used for the analysis of the passive radar's data will be included in the ground-based servers to reduce the complexity and the power demand of the UAV. Taking the shown approach, it offers a lot of possibilities for the future. Given that any UAS operator will need reliable data for safe operations, any other UAS operator in the cities can use the same system without additional resources. This is why the data or the needed infrastructure can be either developed by or sold to UTM service providers.

3.3. Communication

Thinking of the future, the commercial use of UAVs has to be regulated and safely integrated into the airspace, as the U-Space project proposes

it. Similar as ADS-B for manned aviation, the remote ID will include position, height, velocity, direction and flight number if available and broadcasted regularly. The most promising approach for businesses like parcel delivery is a network solution as the FAA Notice of Proposed Rule Making [8] proposed it. In the proposed solution each UAS is sending its information to an USS through 5G in the given scenario. This ensures traceability of the UAVs, especially in high frequented airspace of urban areas. Additionally, the misuse of the airspace needs to be prosecutable by the FAA or comparable European agencies. Especially for the latter, a solution is needed to store data and identify operators even after landing. Further, UTM can use this information to optimize their airway management, so launches can be performed more frequently. For aIRO's purpose, the more detailed information provided by UTM is advantageous and especially since the expected costs are neglectable as shown in Figure 22 which is why the network solution is favored.

Keeping in mind the recreational background of many remote pilots, it has to be further discussed if special zones in rural areas could be developed to allow remote ID through broadcasting (e.g. Bluetooth or WiFi).

3.4. Flight and Flight Path Control

Similar to the computing resources of DaA systems, the main Flight Control Computer (FCC) is integrated in ground-based servers. For the data link between the UAV and its FCC, the 5G network is used, which allows to transmit data in real time. Through the Command and Control link, telemetry data is sent from the UAV and commands calculated in rented servers are sent to the UAV. Since sensors and transmitters can be integrated redundantly, the 5G network itself has the highest risk of a Single Point of Failure. To prevent this scenario a basic FCC is integrated on-board. This FCC provides less capabilities to be as small and lightweight as possible. In this scenario, DaA data is not taken into account, so the UAV flies directly to the next ground station or other predefined safe spots, as known from a "return home" function. This function provides ro-

bustness and security against hostile attacks, e.g. installed jammers.

Sensors on board are Global Navigation Satellite System (GNSS) sensors for the position, Inertial Measurement Unit (IMU) sensors for the orientation as well as the position, barometer for the height and an air data module for the winds. GNSS modules receive their signals with a significantly lower frequency compared to an IMU sensor with an update rate from easily 100Hz. However, IMU sensors are highly unreliable as the calculated position drifts significantly from the real one after two integration. A barometer is needed for the same reason. The sensor fusion of different types are combined by using Kalman Filters.

Hence, the UTM approves the flights and sets a trajectory, the UAS flies to the next way point through a path tracker, implemented with input/output linearization and cascaded control loops. In loops where model uncertainties or actuator faults come into account, Incremental Non-linear Dynamic Inversion is used for its robustness [27].

In case the DaA system senses an intruder in the predefined airway, the UAS flies predefined avoidance maneuvers depending on the situation. Such an alarm of the DaA system forces the path tracker to override the next waypoint and sets it to a point which is on the avoiding path. After the avoidance maneuver, the actual waypoint gets its priority back and the flight is continued.

3.5. Landing

As described in Chapter 5, the distance between two landing sides is very small. Following the educated guess of experts from the ATM and UTM, the minimum accuracy for VTOL can be decreased to several centimeters, assuming the system is able to operate accurate enough. Necessary for accurate flight maneuvers is the accuracy of position, height and environmental factors such as wind [25][26]. The needed accuracy for precise VTOL cannot be provided by installed GNSS, IMU or barometer sensors alone. To increase accuracy, different solutions are being discussed such as visual based sensors, laser altimeters and LiDAR. Finally, LiDAR was chosen due to its accuracy as well as the

possibility to provide the distribution of wind for different heights. This is a huge advantage, especially considering the worst-case scenario of wind velocities of up to $20kn$. Knowing the wind in advance will allow to adapt the position of the UAV during VTOL, so that it can be positioned around its vertical axis to not face any cross winds at all. These cross winds would add turbulence to the maneuver as the fin offers a huge area to attack. Measuring the Doppler effect in atmospheric back scatter, LiDAR systems are also able to improve the performance of the control system as shown in [35]. Coming back to a light UAV and the given infrastructure with ground stations, money and weight is saved as well by integrating the LiDAR in the ground station. For emergency landing, the controls do not have to be as accurate as usual.

3.6. Energy Supply

3.6.1. Design Requirements

As already analyzed in Chapter 2, a VTOL capable UAS with fixed wings is chosen for the given mission requirements. The vastly different thrust needed for the two mission phases (VTOL and cruise) is shown in Chapter 3.1. This leads to a power demand of $4787W$ for vertical ascend, $4284W$ for vertical descend and $163W$ for cruise, as shown in Figure 14 (calculation in Appendix ??). In VTOL phases, a lot of power in a short

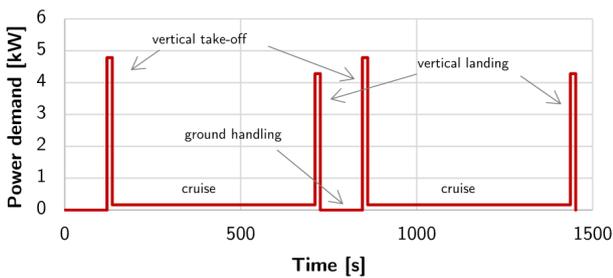


Figure 14: Propulsion Power Demand Round Trip

period of time is needed. Therefore, an energy source with very high specific power is needed. In cruise phases, comparatively less power is needed, because gravity can be overcome by lift provided by the wings. The energy source for this phase

should be optimized for energy density. The varying power demand is defining for the selection of the energy source, since the energy storage system has to be dimensioned by the most demanding mission phase. At the same time, an over dimensioning of the energy system has to be avoided to reduce mass and costs. Moreover, to prevent hazardous events analysed in Chapter 4 and provide sufficient reserves, the energy supply will be installed with reserves and redundancy, which would reinforce the need for mass reduction.

3.6.2. Energy Storage Design

	Weighting	Lead-Battery	Li-Ion-Battery	Li-Air-Battery	LiS-Battery	Ultracapacitors	Fuel Cell
Specific energy	5	-2	0	2	1	0	1
Specific power	4	0	0	0	0	2	0
Safety	5	1	0	-2	1	2	0
Environmental impact	1	0	0	0	1	2	2
Cycle life	3	-1	0	-1	-1	2	2
Readiness	4	0	0	-2	-1	-1	-1
Specific volume	2	-2	0	1	-1	-1	0
Cost	4	2	0	0	2	-2	-2
Complexity	4	0	0	0	0	0	-1
Score		-4	0	-9	10	12	-3

Table 3: Energy Storage Comparison [18]

The advances in electric propulsion offer the promise of high efficiency. This results in economic benefits and reduces environmental impact, but their energy storage is still challenging. Therefore a comparison of possible storage systems was done in Table 3. State of the art Lithium-Ion-Batteries (LiIon) have been used as reference and compared with present and future technologies that should enter the market within the next five years. The weighting was made with aIRO in mind. The table shows promising potential in both Lithium-Sulfur-Battery (LiS) as well as Ultracapacitor technology. For further analysis these two technologies have been under further investigation for the mission requirements discussed in Chapter 3.6.1, which are either high power or high energy demand. Figure 15 shows parameters of LiS-Batteries, typical state of the art airworthy LiIon-Batteries, and Ul-

tracapacitors (also known as electric double layer capacitors (EDLC)). Additionally, a hybridization of the later two was included: Li-Ion-Capacitors.

As visualized in the diagram, a distinct feature of batteries is their high specific energy. On the other side, capacitors score with high specific power. Another significant fact that has to be taken into account is the cycle life of both technologies. Cycle life is the effect of deteriorating capacity with growing charge and discharge number, also known as Depth of Discharge (DoD). Whereas cycle life of batteries is typically a few thousand, cycle life of Ultracapacitors is oftentimes close to a million. LiIon-Capacitors, because of its nature as a hybrid, meets parameters in between the two mentioned technologies. Further, Figure 15 shows the calculated battery mass for the given mission profile. To get a realistic estimate, an additional 10% wrapping mass for battery packs has been added [20]. Additionally, it has to be mentioned, that all Capacitors provide their power by losing their own inner voltage. Therefore to keep voltage in the circuit constant, especially for the electric motors, the mass of a DC/DC converter has to be added to the calculated capacitor masses. For even deeper mass analysis, the required battery mass for either one of the mission phases (VTOL and cruise) was also calculated. The table shows, that the most fitting energy storage for cruise phases are the LiS-High-Energy-Batteries and LiIon-Capacitors for VTOL phases. Knowing the varying demands of different mission phases, the optimized energy system is a hybrid, allowing separate optimizations for each state. The hybrid system architecture saves mass and costs. The selected energy system leads to a total mass of approximately of 4.22kg (Chapter 2.6.3). Costs of both energy storage technologies used in aIRO are predicted to decrease substantially in the next five years. The price for LiIon-Capacitors will decrease by 10 times within the next five years [6] and prices for LiS-Batteries will fall well below conventional Li-Ion-Batteries because of cheaper elements used in creating them [13].

3.6.3. Powertrain Integration

To achieve the needed power and energy capacity, batteries and Li-Ion-Capacitors have to be combined in parallel and serial. The batteries are directly wired to the DC bus. Since capacitor cells have a low voltage, a bidirectional interface circuit is required [12]. The capacitors are connected with a bidirectional DC/DC converter to ensure constant voltage for the electric motors and allow charging of the capacitors when power demand is low. By using this architecture, the Li-Ion-Capacitors used for the start can be recharged during cruise phases and reused for landing to further reduce the system mass. Additionally, a battery management system with the ability to monitor the battery parameters like cycle life and performance is used to increase safety and decrease down-time. Furthermore, while processing the UAS on the ground, systems are cut off from the main power supply. Button cells are used to maintain power supply during ground handling to avoid long TAT caused by time needed for rebooting and system checks. The integration of the power supply is visualised in Figure 4.

3.7. Recovery System

The main aspect of using a parachute recovery system is to minimize the damage to people due to reducing impact energy and the possibility of hazardous accidents with humans, assets on ground and to the UAV itself in case of a crash landing. To save mass, a parachute system is used [37]. Hence, the selection of a suitable parachute design adapted to the aIRO application is crucial for a controlled crash landing. For the given mission a hemispherical canopy was chosen due to its high opening accuracy, high drag, low oscillation and low opening force coefficient [49].

In case of any unsafe flight condition, as for instance loss of power or excessively high descend rate, the flight control computer ceases to give safe signals to the parachute system, which leads to an automatic deployment of the parachute. Even if the whole energy on board is lost, the parachute system uses integrated capacitors to deploy [44]. The parachute system is integrated in the tail section of the UAV, where the required volume of

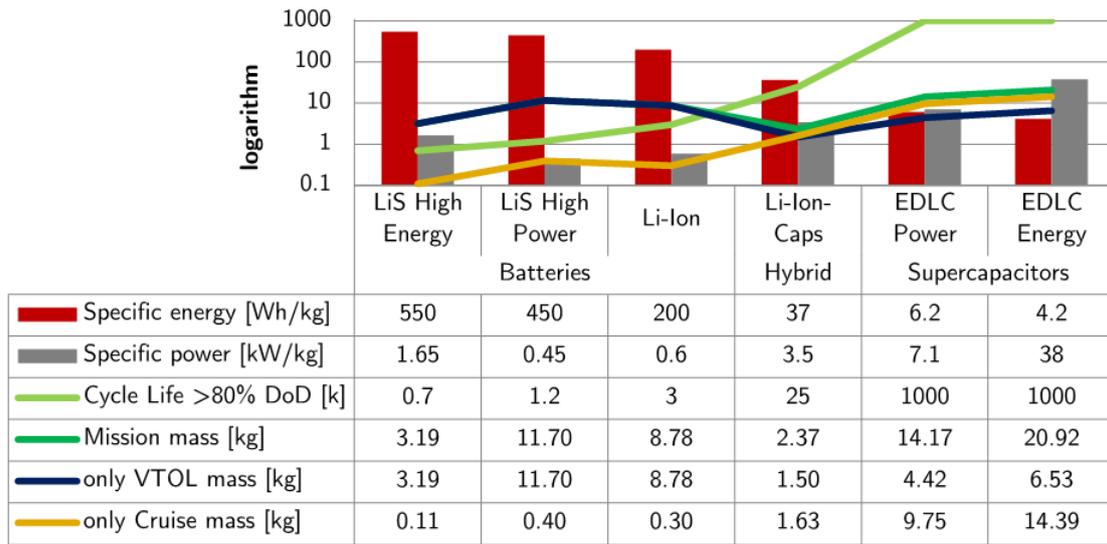


Figure 15: Battery Mass vs. Ultracapacitor Mass with Different Cell Technologies [1], [3], [4], [5], [6]

round about $V = 0.0015m^3$ [43] can easily be provided by the fuselage and unfurls via extraction technology (not pyrotechnic) in less than one second at a minimal rescue height of five meters [31]. Furthermore, it is reusable and can be refolded back in operational state in a very short period of time. Similar systems exist already on the market. The values chosen here in Table 4 are estimated values, referring to existing systems.

Type	Value
Minimum Rescue Height	5m
Weight Parachute	0,5kg
Opening Time	1s
Dimension	∅100x190mm

Table 4: Parachute Parameter [43] [44][31]

4. Safety and Regulations

The approval of any airborne vehicle or airborne mission in general by the competent authority is mandatory for all UAS. The different safety and regulatory requirements that have to be met to operate a UAS described in this report are explained in the following chapter.

4.1. Regulations

Although regulations for UAS are not fully developed yet, the aIRO project is based on existing recommendations. In general, the EASA follows the work of the think-tank JARUS, which is trying to overcome the gap between technical possibilities of UAVs and the lack of regulations. The following chapter is an elaboration of already proposed ideas and will offer a future road map.

To allow different types of UAVs and their operators appropriate permissions, [46] and [45] differentiate between an 'open', a 'specific' and a 'certified' category. Given the operational scenario (transported goods, m_0 , etc.) it can be assumed, that the 'specific' category is applicable to aIRO¹.

So far, a SORA would be proposed in the 'specific' category and approved by the Landesluftfahrtbehörde to give clearances for each flight. However, a decision is needed if UAS, such as aIRO, would need one certification for the entire UAS or a clearance for every single flight, as it is currently performed.

Compared to existing processes, a general vehicle certification similar to manned aviation would be obvious, keeping the amount of flights in mind. However, this would require all suppliers to get certified somehow and therefore result in a huge increase in costs and effort. Besides, compared to manned aviation, the risk applied by UAS to people on ground is way lower due to lower kinetic energy of the UAV and therefore fewer hazardous scenarios.

Since the rules are not fully developed yet, it would be the best approach to be covered under

¹Small violations of the 'specific' requirements, like the operational height, are neglected for this assumption. Such violations would not justify the extra effort for a 'certified' category. An exception of the authority is therefore assumed.

the Light UAS Operator Certificate (LUC) category, which will be implemented in the future. In the given scenario the UAS as well as the system or component manufacturer will have to get certified just like in manned aviation, but with less and appropriate effort. It can be seen as a compromise between a certification and a permit to fly. As the certification process will take less effort, one has to cope with the disadvantage, that only standardized scenarios can be flown. This means that during the LUC process a SORA is approved as well, which can be used as a standard scenario for every UAS and its flights. Since the scenario will be the same for different regions and the certification of aircraft in general is federal responsibility, the Luftfahrtbundesamt will most likely be responsible.

So far, it is not published which requirements a manufacturer or a UAS has to fulfill to get approved according to LUC. For further considerations it is assumed that the certification process will only focus on the most critical system parts as shown in Chapter 4. The safety analysis performed on the aIRO system will show that the focus during development will rely on special parts of systems. A Complexity Level III can be assumed [7], which will lead to DAL requirements to ensure a safe UAS. The certification costs are calculated for the business case and considered in Table ???. It can be assumed that the Level of Involvement from authorities during the development and certification phase will be higher than for a standard certification process, because authorities cannot benefit from experiences.

To get a first idea of the Operational Safety Objectives which one could expect from the SORA, the most important steps are analysed for aIRO and can be seen in Chapter 16. Detailed explanation for the decisions are explained in Appendix B.0.1 and the resulting Operational Safety Objectives can be found in [24].

After the certification process is done, the integration into the U-Space will be the second challenge. As it is known for commercial airways, it is likely that the UTM will reserve parcel airways and block it from other uses. To start a mission we assume an automated permission is in place, which is likely to get implemented in the next years [26]

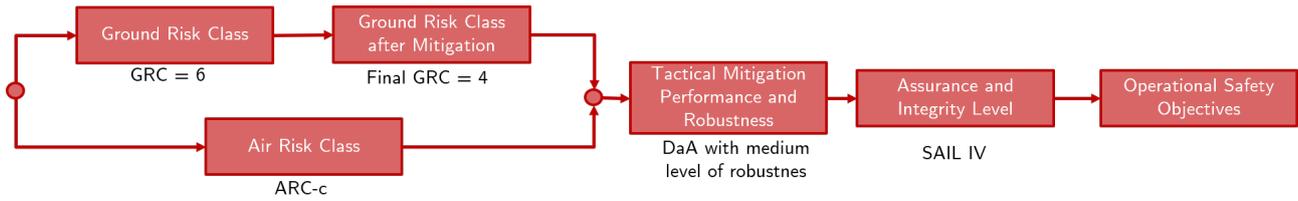


Figure 16: SORA Process with the Results in Accordance to aIRO

[25].

4.2. Safety

To introduce autonomous UAVs, the acceptance of the general public is one of the most important limiting factors. As known from aviation, accidents have the biggest impact on public opinion. Therefore, to guarantee the success of the project and be allowed to fly over populated areas and in non-closed airspace, risk management is performed.

4.2.1. Safety Concerns and Mitigations

Summed up, safety in a UAS context can be categorized into three different categories: The risk to people on the ground, risk to (critical) infrastructure, such as highways, and the risk of a mid-air collision. To mitigate safety concerns, requirements are set at the beginning, monitored through the complete design process and validated by achieving milestones.

*Risk to People on Ground The worst case scenario to people on ground is the loss of an aircraft leading to a crash. This risk is addressed by a Functional Hazard Assessment similarly done in manned aviation. It is assumed, that a certification in accordance to LUC will require a safety assessment with fewer tests to pass and lower test depth. Therefore, a Function Hazard Analysis on aircraft level was performed (see Table ??), allowing for a more detailed design to focus on critical conditions. Due to the limitations in this report, only catastrophic events are shown if they are also expected to occur with a high probability. A Fault Tree Analysis (FTA) was performed to allocate budget for probabilities of failures. Since no data for UAS is currently available, it is assumed,

that society will accept an injury to people every 10^{-6} hours similar to manned aviation regulated in CS-25. Furthermore, assuming that every tenth crash on ground in urban areas will directly collide with a human, the top level event 'Crash on ground' is allowed to occur every 10^{-5} hours. In Figure 17 the probability for different events is split reasonably to receive probabilities of failures for any involved system. Getting more detailed in the design process, tools such as Markov Analysis or Failure Mode and Effects and Criticality Analysis are used to prove that the requirements are achieved or if adaptations have to be performed while allocating the budget for probabilities.

The FTA performed visualizes the fact that no Single Point of Failure exists that leads to a catastrophic event, which has to be proven thorough the safety analysis. The assumptions made for system failures within the safety analysis are very conservative. For the overall system reliability lower probabilities are expected and thus successful mission completion is not compromised. The introduction of the additional safety measure "parachute" bears the potential of a potentially catastrophic event by inadvertent deployment of the parachute. Appropriate countermeasures are considered.

*Risk of Mid-Air-Collision The risk of mid-air collision is predicted to become an issue especially considering the growing UAS traffic volume. Hence, a concept is needed to ensure that each vehicle, unmanned or manned, will stay separated. The first step is to obtain a flight clearance from the Air Traffic Control as described in Chapter 4.1. Furthermore, the DaA system will be able to help steering clear of intruders in predefined airways. Naturally, the DaA system has to be installed with an appropriate level of robustness which is explained in the FTA shown in Figure 17

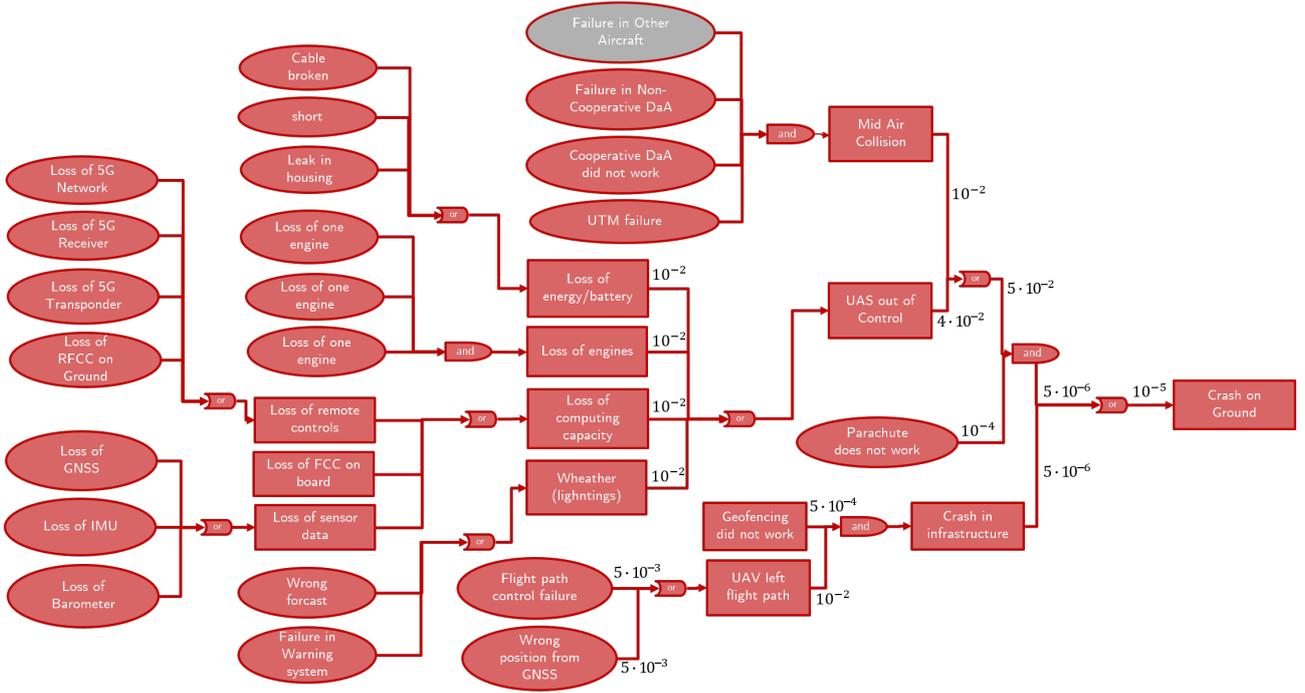


Figure 17: FTA for the aIRO System with Proposed Probabilities

as well as in the SORA in Appendix B.0.1.

Risk to Critical Infrastructure

Collisions with any construction is likely to occur especially if UAVs fly in denser cities. Therefore, a system has to be implemented that ensures a safe distance between the UAV flight path and any infrastructure in the environment. Certainly, it is easy to detect buildings in the flight path with e.g. cameras or LiDAR systems, but small objects like power lines are hard to detect, particularly considering true air speeds of 100km/h and unfavorable lighting conditions like sunset. Hence, reliable geofencing data is needed. Common UTM providers are currently in cooperations with geofencing providers and are expected to offer reliable data in the near future. Furthermore, not only infrastructure has to be marked with no flight zones. Overflying gatherings of people as during sport events or rescue operations, dynamic geofencing will be considered [26]. Knowing the drawbacks of the DaA system, blind spots have to be excluded as well.

4.2.2. Safety Culture

Accidents from all different industries have shown, that the responsible handling of faults and the implementation of a whistle blowing system inside a company significantly influences the probability of incidents to occur and a sufficient safety culture could mitigate such risks [11] [32].

To be able to act before incidents happen and not just react to them, every employee has to be trained in this common safety culture with the aim of establishing a spirit of confidence if someone reports a potential hazard to the management. It is of special interest, that the management is taking this safety culture as serious as any other employee to maintain their role model and to build confidence in the team.

5. Ground Station

5.1. Requirements

The ground station operates completely autonomous. It is the interface between the customer and the UAS. Thus, the accessibility for different groups of interest needs to be granted. While private customers are only able to access each individual delivery, commercial customers need to be capable of restocking large numbers of packages at the same time. This will be specified in Chapter 5.3. The storage specifications are derived by the business case (see Appendix ??). Therefore, each ground station needs to be capable of storing up to 500 packages. Additionally, enough batteries to provide maximum frequented ground-handling cycles need to be stored and reloaded. The used LiS-Batteries have a maximum charging duration of $4h$ [3]. At a TAT of two minutes [19], while performing a full reload of each battery, 120 charging slots need to be installed in the ground station. The features and turnaround timeline of the UAV are further explained in the following.

5.2. UAV Ground Handling

After landing, the UAV is unloaded by the robotic arm. In the next step, the battery system is shifted to the charging station and the package is separated to be stored in a paternoster shelf. This technology was chosen to increase the number of packages stored per used space. The vehicle will then be re-energized by inserting a new, fully-loaded battery package instead of waiting for the previous, empty battery to recharge. The collaborating mechanisms needed to perform these tasks are shown in Figure 19 while the timeline is displayed in Figure 20.

5.3. Customer Access Interface

aIRO differentiates between private, or end customers, and commercial customers (e.g. DHL, amazon etc.). As stated in the Chapter 5.1, private and commercial customers need to be considered separately. Therefore, two different access possibilities are implemented. After interaction

with the visual interface, the robotic arm hands out the individual package to the private customer through a secured output mechanism. Meanwhile, commercial users can interact with the package shelf in a more direct way to save time: The shelves are designed with the opportunity to rotate to 180° around their vertical axis as shown in Figure 18. This enables an access to the package shelf without actively entering the station which reduces the level of qualification necessary.

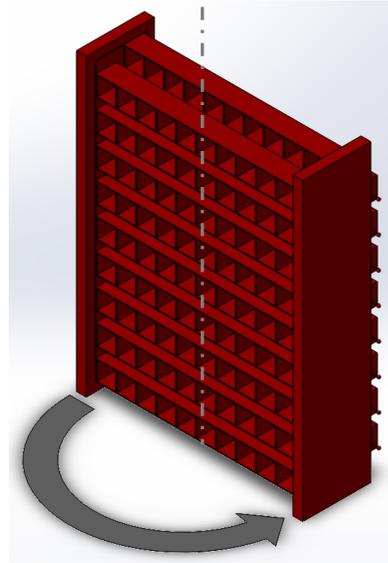


Figure 18: Rotatable Paternoster Shelf

5.4. Station Layout

The hexagonal layout combines the advantages of a rotational and a squared design. On the one hand, it allows the combination of multiple stations, while on the other hand, the accessibility of the robotic arm is fully used. The interior is designed to be modular, each side-wall can be configured to match the individual requirements of the stations location. For instance, shelf modules to store packages can be exchanged for more battery charging stations or the other way around, due to identical side lengths. Furthermore, the ground station is dimensioned to fit into two parking slots.

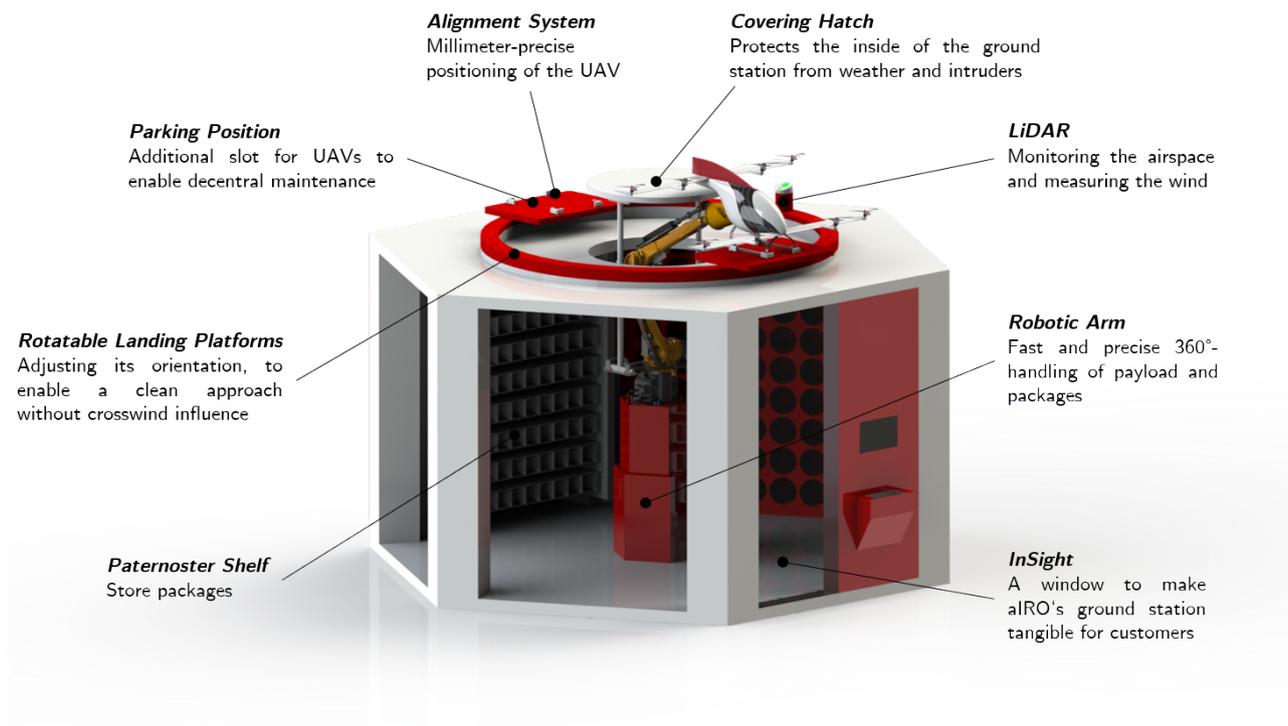


Figure 19: Ground Station - Main Features

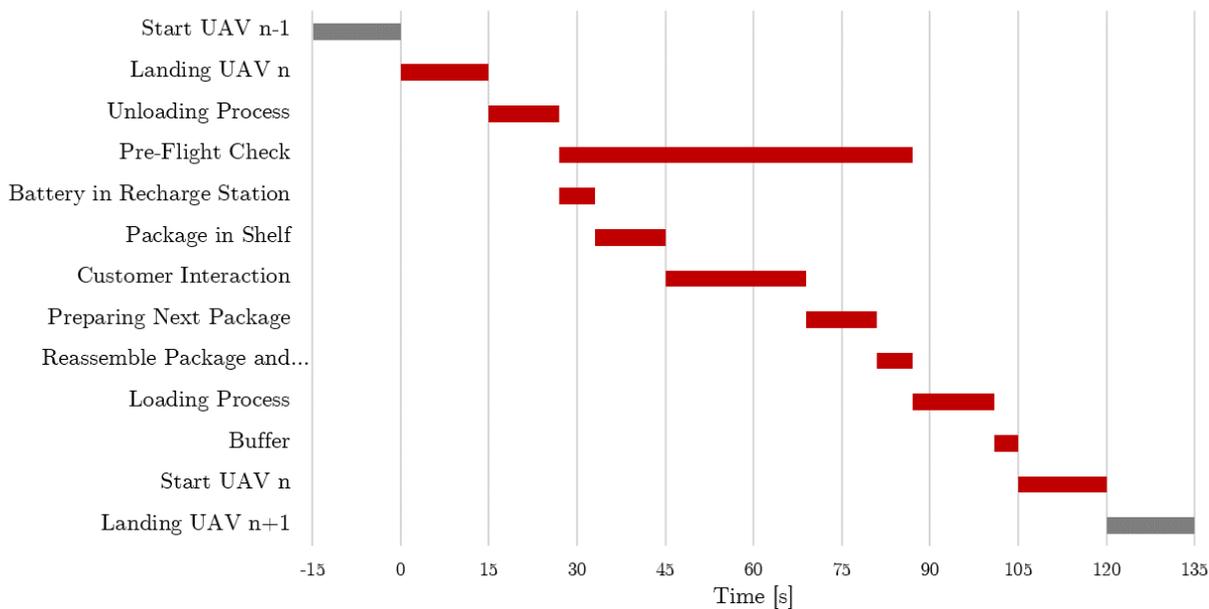


Figure 20: Turnaround Process

6. Cost Estimate

Most important for the success for any project is its profitability, so it is very important to estimate all costs as accurately as possible at this stage. The flow of money is divided in revenue, investment and running costs, which will be explained in detail in the following sections. This cost estimation is performed over the period from year 2020 to 2035. Entry into market will be in year 2025 in Frankfurt am Main (FFM). With this business case and cost estimate a break-even point is expected between the years 2031 and 2032 (see Figure 23).

6.1. Revenue

The revenue is made up of the price per delivered package and the volume of packages per year the project is able to deliver. The last mile of the package delivery is in general between 30% and 50% of the total delivery costs [34]. Being conservative, 30% will be assumed for further calculations, keeping in mind that this will be the minimum amount the last mile will cost. For instance the cost for the smallest package from the market leader DHL is 3.79€ [14], leading to a revenue for the last mile with approximately 1.14€. Therefore, the costs for aIRO have to be lower for the success of the project. The delivery price is assumed to be 0.99€ per package, meaning that DHL for instance will only have to pay 87% compared to before. The revenue depends on the package volume. Therefore, the population of each city was modulated from year 2025 to 2035. In combination with the packages sent and the market share, the revenue can be calculated. Detailed calculation can be found in Appendix ???. With a package volume of approximately 600 million over the 10 years, aIRO can generate a revenue of about 594 Mio.€.

6.2. Minimum Selling Price per UAV

As the UAV will not be sold (see Chapter 1), the minimum selling price is an important key figure in the overall project. As the development costs of an autonomous UAS vary widely compared to manned aviation, the engineering costs

taking into account the development, are calculated with a Gantt-Chart (see Appendix ??). To estimate the other costs, the DAPCA IV Model [21] is used (see Appendix ??). These include development support, flight test operations, tooling, manufacturing, quality control, materials, avionics, engines, batteries and certification cost. In the end, a *Quantity Discount Factor* of 0.06 is used, taking into account that workers do not work efficient eight hours a day. Covering all the cost and a manufacturer's insurance, one drone has a minimum selling price of about 7,300€. Compared to UAS which are currently on the market, the price seems very low although the complexity is even higher. This is caused by the immense amount which will be produced. The calculation shows, that the minimum selling price for UAVs will drop sharply as soon as UAVs enter into mass market and will spread the development costs on more units.

6.3. Infrastructure Costs

To complete the cost estimation of the UAS, the installation of its ground station needs to be taken into account. Therefore, the different cost factors of the system described in Chapter 5 were estimated. The most expensive factor is the robotic arm. Thus it is chosen to be bought refurbished by the manufacturer and will cost around 25,000€ each². The costs for the building itself were calculated using a fix cost per used volume of 390€/m³ [33]. Additionally, the costs for LiDAR were considered at 2,000€ per unit³. Costs for other systems such as the loading or storing mechanism were calculated by comparing them to existing products. Added together, the ground station will cost approximately 45,300€. The costs for the overnight storage of the UAVs is calculated in a similar process and is scalable with the number of UAV's (see Appendix ??).

6.4. Operational Costs

As the business model offers a package transport system with a UAS and its ground station, both,

²Assumption from comparison websites.

³Assumed with comparable LiDAR-Systems like DJI Livox LiDAR.

the UAS as well as the ground station are important to determine the operational cost per year. In addition, a depot is necessary to stock the UAV's over night. Further, employees are needed to keep the business running either on a management level, marketing or further development. At least the interest for the needed loan is taken into account. Therefore, the operational costs can be split in costs per UAV, costs per ground station, depot, general costs and capital costs. As seen in Figure 21, the operational costs for the UAVs are dominant with 77% of total operational costs. A more detailed break down shows the considerations (see Figure 22), which are the insurance⁴, maintenance⁵, UTM⁶, energy costs⁷, computing costs on ground⁸ and the use of 5G technology⁹. For the ground station and the depot, the maintenance and the electricity are considered. In addition, the ground station needs the rent for parking slots. General costs cover on top of the maintenance team ten employees for upcoming tasks as well as the rent for their offices. Recycling is performed cost-neutral, since the costs of the parts to be disposed of are covered by the reutilization of other system parts.

6.5. Cash Flow Analysis

6.5.1. Cash Flow

In order to calculate the break-even point and to determine whether the business case is worthwhile, the cash flow over the development (2020 – 2024) and operational phase (2025 – 2035) is considered. To achieve this, all income and expenditure for each year is collected. The red line in Figure 23 shows the cash flow without loan. It is assumed that a syndicated loan taking by a bank

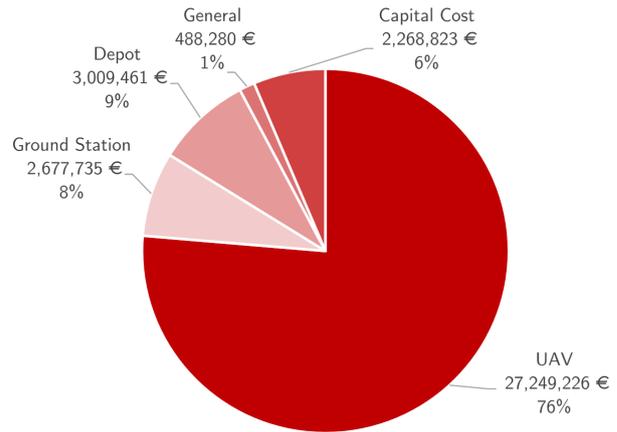


Figure 21: Total Operational Costs

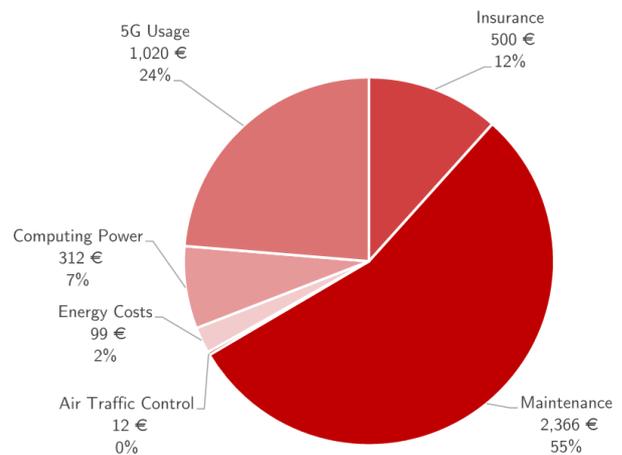


Figure 22: Operational Costs per UAV

as usual for this amount of money. The interest in this case are the amount of the Euribor¹⁰ and a ranking for the company¹¹. The business model shows that until year 2032 any debts are payed off. The graph has the typical shape of a company that launches a new product. The maximum loan is reached in year 2029 with nearly -95.6 Mio.€. However, it only takes three years until the balance is positive. The break even point will be reached between the years 2031 and 2032. The curve rises steadily until 2035, when it reaches a value of approximately 165 Mio.€. The immense

⁴Private communication with the insurance of Allianz SE.

⁵Assuming every 48h maintenance is needed, taking 1h, by a salary of 3,500€. These includes replacement parts as well.

⁶UTM service by Droniq costs 125€ per year and operator. It is assumed that one will need five licenses per city as no better offer could be made.

⁷Calculated with current energy costs.

⁸Estimate of needed capacity, costs for servers from Google.

⁹Offers from Deutsche Telekom AG for unlimited 5G use are about 85€ per month, needed for every UAV.

¹⁰0.1%, although it is even negative in June 2020

¹¹0.4% is estimated

profit can be used to reinvest in new technologies, to exploit the market further or to launch a new UAV. After ten years in the market, it is also a reasonable time to invest in future projects as described in Chapter 7.2. This strengthens the company and gives it a larger market share.

6.5.2. EBIT

EBIT is a frequently used figure from the profit and loss account of a company. It makes companies more comparable among themselves, since taxes and interest rates differ in each federal state. The calculation of EBIT according to the cost of sales method is applied here according to [10]. Figure 23 shows the EBIT for each year (grey line). In 2024, a small drop in EBIT can be seen which is due to the production of UAV and ground stations for FFM. In 2025, there is an increase because the first UAV's deliver packages and generate revenue and simultaneously the production rate is low. From 2026 up to 2029 the production rate and the investments are higher than the income. This will change in year 2030. The last step of the expansion phase is done and the EBIT increase very fast. The last five years the EBIT rise up to approximately 56 Mio € in year 2035.

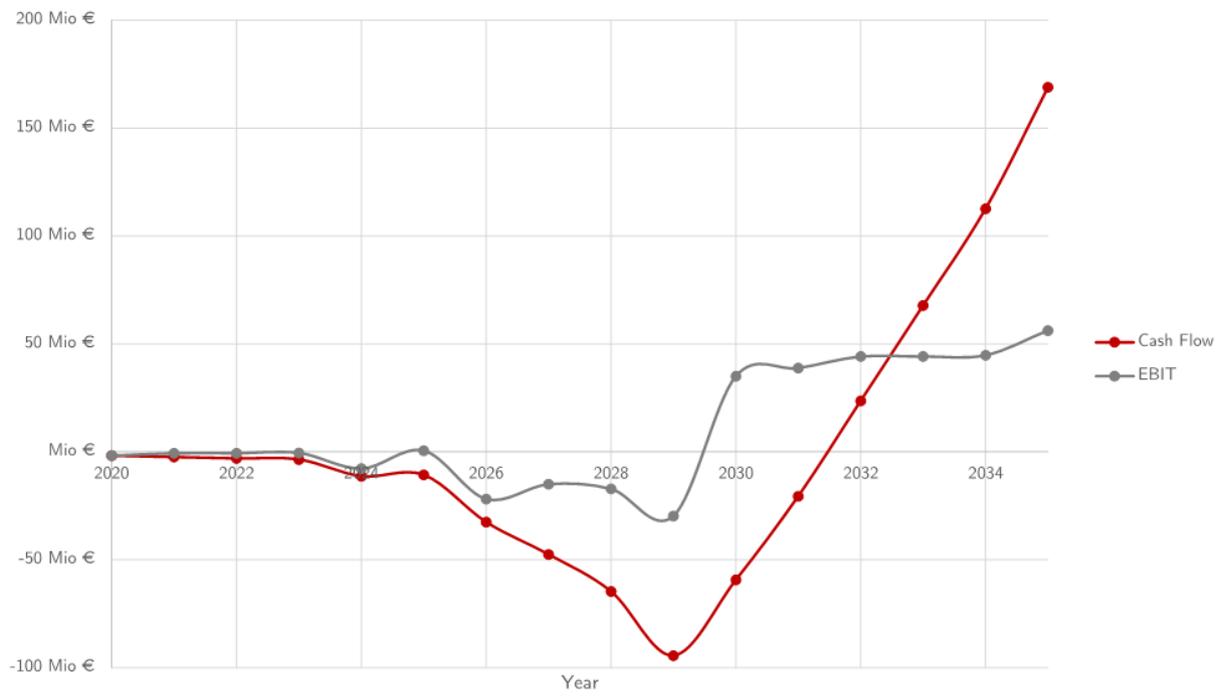


Figure 23: Cash Flow and EBIT

7. Conclusion and Perspectives

7.1. Synergies and Key Technologies

Tandem Wing: The tandem configuration naturally supports a multicopter as well as a fixed wing configuration. This configuration guarantees flight stability during VTOL and high performance during cruise. The inclusion of the elevator into the rear wing leads to a reduced drag coefficient. A spacing of the wings in z-direction simplifies the payload integration and enables an aerodynamic body design.

Airfoil Design: Optimized airfoil for cruise phase with minimal drag, high aerodynamic efficiency and smooth stall characteristics at low Reynolds numbers with excellent lift to drag ratio.

Carbon Fibre Structure: Using Carbon Fibre as the base material for the structure of both body and wings, unlocks liberties in the body and wing design. It is convincing with a high stiffness and light weight. Due to the arrangement of carbon fibres, loads can be attenuated.

Dual Drive Integration: Separating the requirements on the drive into VTOL and cruise allows the optimisation of each drive for its mission. Meanwhile, it guarantees a redundancy in case of engine failure in any flight condition and prevents a single point failure.

Propeller design: Efficient and low-noise propellers optimized for each mission phase.

Wingtip Propeller: Placing the engines for cruise flight at the wingtips not only has a positive impact on the lift distribution of the wing, it also reduces the induced drag of the wings [48].

Hybrid Power System: Similar to the Dual Drive Integration, a Hybrid Power System ensures a high performance of the battery system in both flight conditions. The ability of the capacitors to emit high amounts of power in

a short period of time matches the demand of VTOL. Moreover, LiS-batteries have a high energy density which matches the requirements for cruise.

Modular Ground Station: The modularity of the ground station gives the opportunity to produce and build it in a cost effective way. They can be fitted for the local demands and are flexible enough to adjust to changing conditions.

Passive Radar: Outsourcing the DaA system from the UAV itself, decreases costs and mass while monitoring the entire airspace.

5G-Communication: Using latest network technology allows to save mass on the UAV especially for redundancy and shows its advantages in combination with ground based DaA or LiDAR systems. Installing one FCC on board ensures the "return to home" function in case of malfunctions.

LiDAR: Including a LiDAR system into the ground station leads to a high accuracy during VTOL (measurement of position is more accurate and winds are known) and therefore requires less safety distance and simultaneously saving weight and costs for sensor on the UAVs.

Safety Concept: A holistic safety concept is developed which is included in the overall design process leading to a save the UAS. Accordingly, a possible certification process is outlined.

Recovery System: To further reduce the risk of hazardous events, a parachute system was integrated to control a crash landing

7.2. Perspectives

The UAV is designed for package delivery in an urban area, but the system is not limited to this sector. Further steps could lead to a usage for hospitals, for a in house delivery at bigger sites of big companies, universities or similar institutions or delivery in more rural areas. These upgrades could be conceivable with aIRO, as

these operational scenarios are similar.

Hospital Usage During several operations tissue samples have to be analysed. Even bigger cities usually only have one laboratory for multiple hospitals. The aIROs service can be build up next to the hospitals and laboratories. aIRO is able to avoid traffic jams and speeds up the transportation of the samples. Saving time is indispensable to life.

In House Delivery For factories or other institutions, which cover huge areas, in-house mail takes a lot of resources and time. Installing a few ground stations at strategic points and buying a small amount of UAVs can save a lot of man hours walking or driving for one package. The installation would require a bigger investment, the infrastructure can only be used by the institution itself and the amount of deliveries is not expected to nearly reach full capacity. In this case the sale of the infrastructure and UAVs will be preferred, while keeping the maintenance service in house.

Package Delivery in Rural Areas In last mile delivery, rural areas require a lot of man hours compared to the revenue it generates. One reason is, that postmen have to overcome large distances for a small amount of households and packages. This is why a flexible package delivery concepts with UAVs for villages with a very little population would help last mile delivery to decrease costs immensely. aIRO can easily be transformed into an long version by including an enlarged LiS-battery. With that aIRO is capable to fly the double range. A ground station can be installed in the village center and a transformed package van, functioning as the hub for takeoff. A similar concept is proposed by warehouse in cooperation with UPS [29].

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Appendices

A. Configuration

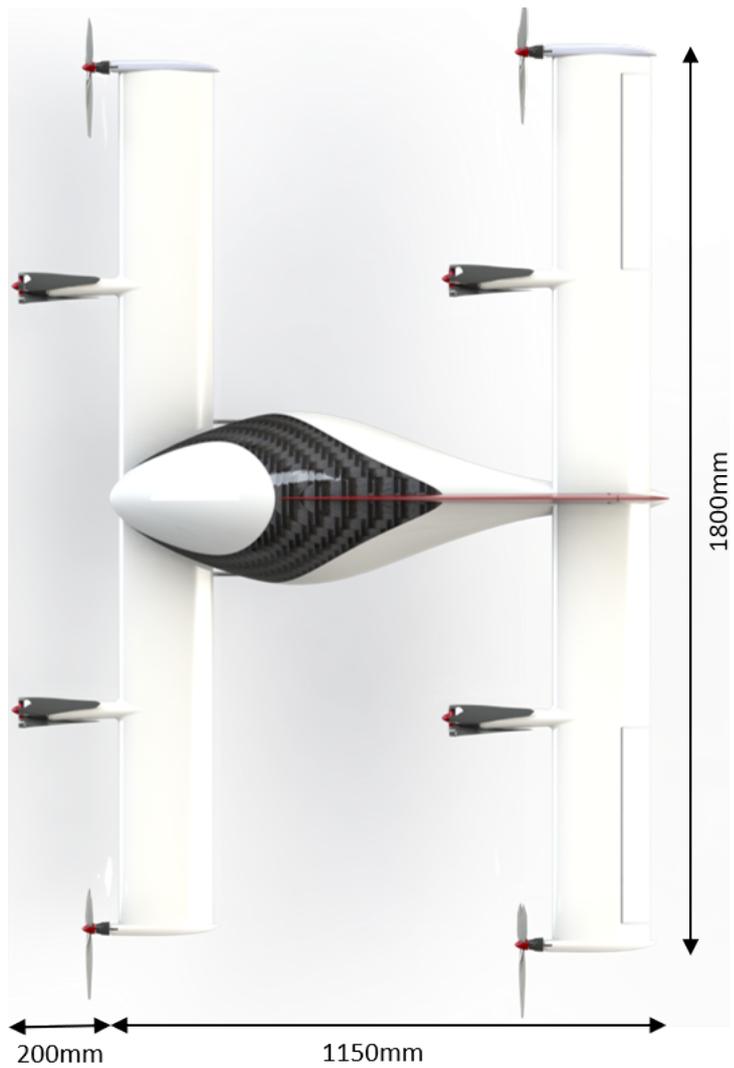


Figure 24: Top and Side View

Category	Parameter	Value
Mission Parameter	Velocity	27.78m/s
	Mach Number	0.081
	Reynolds Number	378, 989
	Density Operating Altitude	1.211kg/m ³
Dimension UAV	Length	1150mm
	Width	1800mm
	Height	678mm
Dimension Propeller	Wing Tip Propeller	∅30mm
	VTOL Propeller	∅40mm
Mass	Payload	2.5kg
	Structure	4kg
	Propulsion Systems	2.34kg
	Battery Systems	4.22kg
	Communication Systems, Sensors	1.7kg
	Power Distribution, FC, Parachute	3kg
	Total Mass	17.76kg
Wing Design	Wing Span	1.80m
	Chord Length	0.20m
	Wing Surface	0.360m ²
	Aspect Ratio	9
	Taper Ratio	1
	AOA Front Wing	2°
	AOA Rear Wing	0°
	Oswald Number	0.8
Stability	Neutral Point	0.525m
	Center of Mass	0.46m
	Stability Measure	32.5%

Table 5: Configurational Parameter



Figure 25: Front View

B. Safety and Regulations

B.0.1. SORA

The aim in this paper is not to explain the SORA process, for further information see [28]. A summary of the done SORA is given, which is not complete so far. Parts where unknowns could lead to changes are highlighted.

Step #1: Concept of Operation Description

The concept of Operation has to be defined in the future.

Step #2: Determination of the intrinsic UAS ground risk Class (GRC)

The UAV of this project does not exceed a wing span of 3m and its kinetic energy during cruise is approximately 7kJ. Nevertheless, its GRC cannot be determined for sure, as the operational scenario for flights BVLOS and in a populated area is not covered so far. As the GRC for BVLOS is always one higher compared to the one for VLOS, the GRC is assumed to be 6. Hence the further analysis will demonstrate, it could be even 7 with the same consequences.

Step #3: Final GRC determination

To mitigate the GRC several opportunities are proposed. Although the most effective would be a strategic mitigation, it is not applied here, to make sure that the operations can be fulfilled without further limitations. Another option is to reduce the impact on ground. We will implement functions guaranteeing this mitigation strategy with high robustness what lead to a **final GRC of 4**. To achieve this, a parachute will be installed in the tail of the UAV. It is also made sure, that this parachute has a very reliable function as otherwise it could lead to even more harm. Following [28] Annex B, several functions or training for maintenance has to be approved by the National Aeronautic Association. Even the whole function has to be shown in flight tests and be approved by a competent third party. Although this mitigation will increase the Level of Involvement of the EASA and increase costs as well, it is chosen to minimize the risk of fatalities on ground to an acceptable.

Step #4: Initial Air Risk Class

Given our Flight Level and the operational scenario in an urban area, the ARC can be determined to ARC-c

Step #5: Application of Strategic Mitigations to determine Residual ARC (optional)

This step matters only if the applicant does not agree with the initial ARC. Taken into account, that our business model should be as easy to adapt to other big cities as possible, the advantage in this step is not used yet.

Step #6: Tactical Mitigation Performance Requirement and Robustness Levels

To mitigate the risk of mid-air collision, Tactical Mitigation Performance Requirement is performed with DaA systems. For operations BVLOS in ARC-c both, Tactical Mitigation Performance Requirement and its Level of robustness have to be implemented on a medium level, meaning that the DaA system will be equal to currently used systems in manned aviation to aid the pilot. Considering the presented DaA systems, aIRO does even have higher capabilities.

Step #7: Specific Assurance and Integrity Level Determination

The SAIL according to the specific Concept of Operation is determined by the final GRC and the ARC. In the given scenario with described mitigations, a SAIL of IV is achieved.

Step #8: Identification of the Operational Safety Objectives

OSOs will help to evaluate the defense within the operation. For a SAIL of IV, the according recommended level of robustness are defined. Each of the 24 OSOs will be taken into account for the development of the UAS with exception to OSO#14-OSO#20 (Human Error) and OSO#22 (Adverse Operating Conditions), because they address the remote pilot crew, which does not exist in the given scenario. The OSOs and their consequences are listed in [28] Appendix E and will require for instance the development of certain SW with a DAL matching the failure conditions a malfunction of the SW could lead to.

Step #9: Adjacent Area/Airspace Considerations

As for UAVs operating in the Specific Category "no probable failure of the UAS or any external system supporting the operation shall lead to operation outside of the operational volume" ([28] page 29), precise requirements have to be formulated. These requirements apply to the given scenario as gatherings of people in the adjacent area are possible and not approved so far. Therefore, no single failure shall lead the UAV to leave its approved airspace. This will be performed by geofencing on the one side and a trajectory with a security factor towards possible gathering approved by Air Traffic Control. Furthermore, the autopilot will be calculated from the ground station but a emergency function on board of the UAS will be able to do an emergency landing. During the development, the probability of 10^{-4} has to be kept in mind as well as that the SW and HW have to be developed with appropriate DAL standards.

Step #10: Comprehensive Safety Portfolio

It is kept in mind that before the SORA approach is taken into place, JARUS differentiated between safety risks and other risk in [16]. Other risk like privacy or environmental are not addressed so far and need further investigations.

B.1. Function Hazard Analysis

In the following detailed design process, a closer look at the entire Functional Hazard Analysis is recommended, which shows that the UAS can fail in at least 103 different failure conditions during different operational phases.