FireWasp

Firefighting Aircraft
DLR Design Challenge 2022

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Confirmation for submission

The hereby submitted project work has been confirmed by the Head of the Institute of Aerospace System (IL) and is endorsed for the submission in the DLR Design Challenge 2022. The work has been done independently from currently enrolled students from the RWTH Aachen University without further assistance of our institute.

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Abstract

FireWasp is a medium-sized compound helicopter designed for aerial forest firefighting. As part of this year's DLR Design Challenge, the aircraft is designed, a mission and performance calculation is performed, and the necessary ground infrastructure is described. For all technologies an entry into service by 2030 is guaranteed.

FireWasp combines the positive characteristics of fixed-wing aircraft and helicopters to become the aerial firefighting vehicle of the future. To enhance the safety of firefighters, the compound helicopter features technologies that enable remote control as well as the ability to autonomously operate.

The fleet of compound helicopters is controlled from a mobile ground station and can be deployed anywhere. During the entire development process, the focus is maximising the firefighting capabilities. Finally, the payload system of the FireWasp is a modular design, so that modules for other purposes than firefighting can be integrated.

Kurzfassung

FireWasp ist ein mittelgroßer Kombinationsflugschrauber, welcher für die Waldbrandbekämpfung aus der Luft entwickelt wurde. Im Rahmen der diesjährigen DLR Design Challenge wurde das Luftfahrzeug entworfen, eine Missions- und Leistungsberechnung durchgeführt, sowie die nötige Infrastruktur am Boden beschrieben. Für alle Technologien ist die Indienststellung bis zum Jahr 2030 gewährleistet.

FireWasp kombiniert die positiven Eigenschaften von Flächenflugzeugen und Helikopter und wird somit zum Löschluftfahrzeug der Zukunft. Um die Sicherheit der Einsatzkräfte zu erhöhen, verfügt der Kombinationsflugschrauber über Technologien, die eine Fernsteuerung ermöglicht sowie die Fähigkeit autonom zu operieren.

Die Flotte an Kombinationsflugschrauber wird dabei von einer mobilen Bodenstation gesteuert und ist flexibel einsetzbar. Während des gesamten Entwicklungsprozesses steht die Maximierung der Löschleistungsfähigkeit im Mittelpunkt. Schlussendlich wird das Nutzlastsystem vom FireWasp modular gestaltet, sodass neben dem Löschmodul auch andere anforderungsspezifische Module aufgenommen werden können.

Contents

List of Symbols

General Symbols

m_{AC} .... Current Aircraft Mass
m_{empty} .... Empty Mass
m_{fus} .... Fuselage Mass
m_{to} .... Maximum Take Of Mass
m_{water} .... Water Mass
$s_{b,medium}$ .... Surface Area
V_{cruise} .... Velocity Cruise Flight
η_{prop} .... Propeller efficiency
κ .... Induction Coefficient
C_d .... Profile Drag Coefficient
t .... Time

Greek Symbols

σ .... Rotor Solidity

Abbreviations

AFDD .... Army Aeroflightdynamics Directorate
BEMT .... Blade Element Momentum Theory
BRLOS .... Beyond Radio Line of Sight
D .... Drag
DLR .... Deutsches Zentrum für Luft- und Raumfahrt
DOC .... Direct Operating Costs
EMF .... Empty Mass Fraction
FCC .... Flight Control Computer
FCS .... Flight Control System
FM .... Fuel Mass
GCS .... Ground Control Station
GPS .... Global Positioning System
IFR .... Instrumental Flight Rules
IMU .... Inertial Measurement Unit
INS .... Instrumental Navigation System
ISA .... International Standard Atmosphere
L .... Lift
LiDAR .... Light Detection and Ranging
MMC .... Mission Management Computer
MTOM .... Maximum Takeoff Mass
P .... Power

RLOS .... Radio Line of Sight
RPA .... Remotely Piloted Aircraft
RPM .... Revolutions per Minute
RPS .... Remote Pilot Station
SAF .... Sustainable Aviation Fuel
SFC .... Specific Fuel Consumption
STOL .... Short Take-Off and Landing
TLAR .... Top Level Aircraft Requirements
UAS .... Unmanned Aerial Systems
UAV .... Unmanned Aerial Vehicle
ULD .... United Load Device
VTOL .... Vertical Take-off and Landing

1 Introduction

With climate change being one of today´s societies pressing challenges, extreme weather phenomena are likely to become the norm.

Wildfires in particular constitute a terminating threat, not only to wildlife but also to humans and critical infrastructures. Even if most wildfires are caused by human actions, climate conditions have a great impact on the scale of destruction the fires can cause. While North America and Australia are especially endangered, rising temperatures increase the risk across Europe. Especially the Mediterranean countries are endangered by wildfires. According to [1] wildfires in the Mediterranean countries alone account for 85% of the burned area in Europe. A review by [2] predicts a further increase in wildfire danger of up to four percent per decade.

In order to cope with the rising threat, novel approaches to wildfire suppression have to be evaluated. Aerial firefighting is an effective way to combat wildfires and prevent the spread, especially in rural and inaccessible areas. While the deployment of planes and helicopters to the fire source is by no means new, the proposed novel approach aims to combine the benefits of the two to increase efficiency and firefighting performance. The result of merging the two conventional configurations is a so called compound aircraft.

Compound vehicles, referred to as compound helicopters, have been subject to research since the late 1940s with the Fairey FB-1 Gyrodyne being one of the first working designs, having its maiden flight in 1949 [3]. Since then, many attempts have been made to further drive the development of a viable aircraft. Recently the Airbus Racer was presented at the Paris Airshow in 2017 signaling a still lasting interest in the novel configuration [4].

In the context of this year's DLR Design Challenge, a compound concept was developed. Chapter 2 discusses the general thoughts of the design process before discussing the selection procedure of a feasible design based on both mission parameters and aircraft requirements. After the design freeze, first mass calculation are carried out before different design aspects of each individual component are discussed in more detail. Furthermore, the reader is introduced to the remote control technology needed to safely operate the aircraft from a distance. Before operational aspects are discussed in the penultimate chapter, firefighting capabilities are verified through a series of performance calculations. Finally, a conclusion on the present design study is drawn in the last chapter.

2 Concept

2.1 Aircraft Requirements

During the initial concept phase, four aspects were deemed essential to the success of the designed firefighting aircraft. Ordered by descending importance:

- Improvement over status quo
- Reliability
- Feasibility until 2030
- Flexibility

In order to be successful in the market of firefighting aircraft, the proposed concept has to provide distinct advantages over currently available alternatives. A major improvement over current technology is the remote control, which eliminates risk to human pilots manoeuvring in treacherous conditions. Another area of improvement is the ability to fly moderately long distances efficiently, while still having the capability to obtain water from water sources with limited aerial access. The current firefighting vehicles originate mainly from either the fixed wing or the rotatory wing category that excel in one of the two mentioned capabilities but lack effectiveness in the other one.

Fighting wildfires is a time critical endeavour. Thus, the dependable and quick deployment of firefighting aircraft is essential. To keep maintenance costs in check, the constant availability cannot be ensured only by regular service. Rather, the technology has to be as reliable as possible such that constant availability is facilitated by the design. This is one reason to use components that are available today and already have proven to be reliable. Due to maintenance cost concerns, it was also decided to use as few vehicles as possible which reduces the need to maintain a large fleet. This results in the unconventional decision of a fixed MTOM during the design process as given by the Challenge maximum requirements. Instead of iterating over the MTOM during preliminary design, the payload mass fraction $x = \frac{\text{PM}}{\text{MTOM}}$ is used as the iteration variable.

The DLR Design Challenge requirements state an entry into service by 2030. This is a very short time span by standards of the aviation industry even for smaller vehicles as can be seen by multiple delays in similar advanced aerial mobility concept programs. Therefore, innovation of the suggested aircraft results from combination of existing and proven technology rather than from innovative but unproven components. Choosing parts that already work reliably today, allows engineering work until 2030 to be focused on the development of few components, that are strictly necessary to be custom tailored – such as the fuselage –, as well as system integration and aircraft certification. Designing a vehicle for the given requirements, that is completely sustainable by 2030, requires performance compromises that were deemed too severe. Therefore, conventional propulsion via a turbine engine is implemented. However, to reduce the aircraft's impact on climate change – the consequences of which the vehicle is designed to combat – the usage of sustainable aviation fuels (SAF'S) is considered throughout the entire design process. This way, the environmental impact of the aircraft is reduced to a minimum.

While fighting wildfires is an important cause, producing an aircraft that only specialises in firefighting is not an economically viable strategy. Therefore, the DLR Design Challenge requirements suggest to study different applications of the developed vehicle without requiring a redesign. This is implemented here via a modular payload design, which allows to change mission objectives just before deployment. Thus, every single produced vehicle can be used for firefighting as well as for every other use case discussed later in this report.

The TLARs derived from these aspects are presented in Table 2.1a.

2.2 Mission Requirements

The goal of this year's challenge is to develop a fleet of novel aircraft that maximizes the amount of water transported to the seat of a wildfire within 24 hours [5]. During the design process the number of vehicles per fleet is not restricted by any guidelines. The only parameter that has to be considered is a minimum of 11 000 kg of water that has to be dropped onto the fire during each attack. The distribution amongst the vehicles can be chosen in compliance with the aircraft requirements.

The ultimate goal is to maximise the dropped water of the entire fleet over the 24 hour mission.

To display the firefighting capabilities of the novel aircraft, three distinct mission profiles are presented:

- Design Mission
- Coastal Scenario
- Inland Scenario

To ensure a continuous attack, the aircraft is ideally able to refill using even the smallest available water sources. In addition, the possibility to refill water at the airport can be evaluated in the performance calculation. Vital for the success of the mission is the ability to precisely drop the water onto the seat of the fire. Therefore operation under impaired visibility needs to be guaranteed, allowing the aircraft to be deployed during heavy smoke development as well as during nights. The present work will not touch on the subject of aerial firefighting strategies and methods, but solely considers the maximization of dropped water as a success factor.

The conditions of the design mission are set in the problem description of this year's challenge. The fleet will start at a local airport, which is located 75 NM away from the seat of the fire. The distance to the nearest water source is set to be 15 NM.

Topic	Requirement
Cruise Speed	400 $\frac{km}{h}$
Service ceiling	8 000 ft
MTOM	5 670 kg
Take Off Capabilities	VTOL or STOL
Piloted by	Remote
Payload Type	Modular Design
Fuel	SAF

(a) TLARs for firefighting aircraft

Topic	Requirement
Water per Attack	11 000 kg
Visibility	Impaired by smoke/soot
Noise	low during take off and landing
Fleet	communication and interaction
Environment	ISA Atmosphere +20 °C

(b) Mission requirements

Table 2.1: Summary of aircraft and mission specific requirements

2.3 Design Selection Process

The following section elucidates the configuration selection process taking into account both aircraft and mission requirements. As stated earlier, the goal of the concept is to merge the unique attributes of both the fixed wing and rotary wing configuration into one aircraft. Hence, the aircraft has to be able to: **1.** have an efficient cruise flight with a high V_{cruise} and **2.** hover and perform a vertical take-off. Some of the additional design parameters taken into consideration during the selection are: stability properties, a high manoeuvrability and complexity and maintenance of the drive train. An overview of all considered properties is shown in Table 2.2.

To fulfill the two challenging requirements while not neglecting other design attributes is a challenging task. As a consequence, only a handful aircraft configurations are up for discussion. Namely these are:

1. tail-sitter
2. tilt-rotor
3. tilt-wing
4. compound aircraft

Choosing the right type of aircraft is not an easy feat, since each concept offers a unique set of advantages and disadvantages for the task at hand.

To determine the most feasible configuration, all design aspects are evaluated through a pairwise comparison and are weighted accordingly afterwards. The result of the weighting process is displayed in Table 2.2. Subsequently, the satisfaction of each attribute is quantified for all four concepts. To quantify the degree to which the design parameters are fulfilled by the different aircraft, a grading scheme is applied. A grade between one and five is given out for each concept-property pair. The middle score,i.e. three, describes a neutral relation between a configuration and the parameter. Higher values mean the aircraft excels in the field, lower values are associated with below average performance. Based on the weighting and the allocation of scores for all parameters and configurations, an overall score for each aircraft can be quantified. Afterwards, the concept with the highest score is chosen as the design to go forward with. Table 2.2 marks the compound aircraft as the most suitable option and provides the foundation for the extensive design process.

Design Aspect	**Weighting**	**Tailsitter**	**Tiltwing**	**Tiltrotor**	**Compound Aircraft**
Cruise Speed	13.33 %	5	4	4	3
Transition stability	20.00 %	1	2	2	5
Hover stability	17.78 %	1	2	3	5
Noise while starting	2.22 %	2	2	2	3
Payload shift during transition	8.89 %	1	3	3	3
Manoeuvrability	25.56 %	3	3	3	4
Drive train complexity	6.67 %	4	2	1	3
Dead mass per attack	4.44 %	5	2	2	3
Fuel consumption per attack	11.11 %	5	3	3	1
Sum	100 %	**2.69**	**2.62**	**2.73**	**3.69**

Table 2.2: Results of the pairwise comparison and value-benefit analysis

Before the design of the compound aircraft is discussed in greater detail throughout the course of the report, some key thoughts and aspects of the pairwise comparison and the value-benefit analysis are presented.

During the pairwise comparison, the different design attributes are essentially sorted in descending order of importance. Both the hover and transition stability are inevitable for the success of the proposed configurations. In particular the first three concepts rely on stability during the transition process between vertical and horizontal flight. A lack of stability would most likely lead to terminating crashes. Out of the remaining aspects, high manoeuvrability and cruise speed are especially important for the success of aerial firefighting. The cruise speed has a significant influence on the response time of the aircraft and therefore, dictates the time until the first attack. A high manoeuvrability is essential in difficult terrain, e.g. in mountain regions and during water intake. It is also useful for potential evasive manoeuvres during water drop-off near the fire. Keeping fuel consumption low, yields several advantages. The fuel mass on board the aircraft directly influences the payload mass. The less fuel is needed, the more payload can be carried. Additionally a low fuel consumption is beneficial for ecological and economic considerations. Especially the direct operating costs (DOC) are associated with the fuel consumption.

Lastly, the ultimate design of the main rotor is determined. Both a conventional single rotor and a coaxial rotor configuration are considered. For high speed compound aircraft, studies by [6] find superior aerodynamic behavior for coaxial rotors. Furthermore coaxial rotors result in a reduction of power requests. According to [7] the reduction can amount up to 15 % compared to single rotor configurations.

Another major benefit of a coaxial configuration is the absence of a rotor induced yaw moment. While the yaw moment of a conventional single rotor helicopter is balanced via a torque rotor in the back, cancelling the rotor induced moment using pusher rotors in a compound configuration is a challenging task, especially without the use of electric motors. One pusher rotor on each side of the aircraft is needed to compensate the yaw moment. Since the rotors have to be able to rotate in different direction, additional gearboxes are required. In combination with a conventional wing geometry, also containing integral tanks for the fuel, this can lead to structural problems and integration concerns. To avoid all these challenging implementations, the present design opts for a coaxial setup.

While the advantages of a coaxial rotor justify its use, disadvantages have to be considered nonetheless. Especially noise emission is negatively affected by a coaxial setup. A research by [8] found an increase of Blade Vortex Interaction (BDI) noise of up to 35 dB compared to the BDI noise of a single rotor configuration.

2.4 Key Technologies

As already mentioned the FireWasp concept does not involve technologies that are not yet developed. The novel idea of the concept is the combination of existing and proven technologies. The exisiting key technologies of this design are the following:

- Partly remote controlled, partly autonomous drone
- Lift and propulsion compounded helicopter
- Advanced communication strategies
- Modular Design

3 Vehicle Design

A 3 side view of FireWasp was exported from OpenVSP and is displayed in Figure 3.1. There, a clay render of the model together with an AKE container and the water module is shown.

3.1 Empty Mass Estimation

The amount of payload an aircraft is able to carry is essentially limited by two main factors:

1. the maximum take of mass m_{to}
2. the empty mass m_{empty}

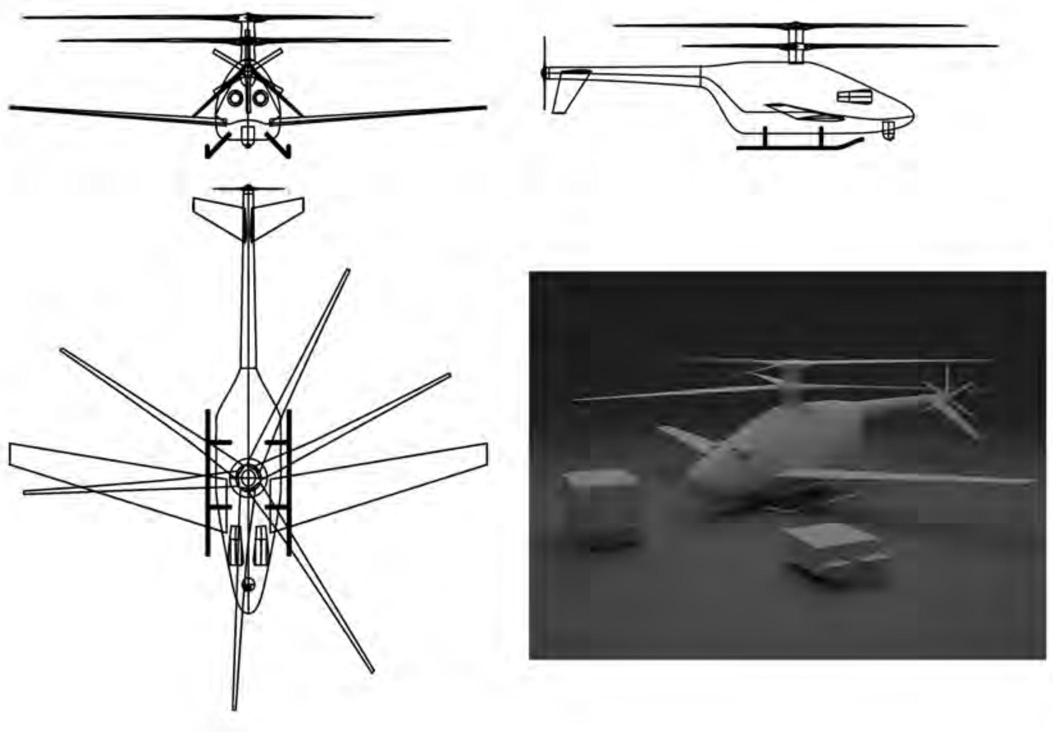


Figure 3.1: 3 side view and clay render of FireWasp

Since the maximum take-off mass was set as a constant parameter during the design process, the payload is solely influenced by the empty mass of the compound aircraft. To quantify the relationship between the empty mass and MTOM of any aircraft, the empty mass fraction (EMF).

$$EMF = \frac{m_{empty}}{m_{to}} \tag{3.1}$$

can be computed.

Typical values for the empty mass fraction of conventional fixed wing aircraft range between 50 % to 60 % [9] and 30 % to 70 % [10]. For helicopters, [10] suggests a fraction of 45 % to 80 % while studies by [11] conclude that the EMF varies between 42 % to 74 %.

The empty mass for the present design was approximated using three different methods, which are presented in order of increasing complexity and accuracy. The first is a statistical approach by [11] and solely relies on the maximum take of mass to compute the empty mass. Assuming a conventional helicopter configuration, the empty mass is calculated to $m_{empty} = 3\,180$ kg. Based on the result the EMF can be computed to approximately 55 % and corresponds well to values found in literature.

The second approach is taken from the study by [12] and determines a fuselage mass that is then converted into an empty mass. [12] combines the research by [13] and [14] to compute $m_{fus} = 210$ kg. Afterwards, the U.S. Army Aeroflightdynamics Directorate (AFDD) models [12] are used to obtain an empty mass for the helicopter. According to the AFDD model, the fuselage makes up 14.3 % of the total empty mass of a helicopter, resulting in $m_{empty} = 3\,860$ kg.

Both of the above models do not take a compound configuration into account and are therefore lacking the mass of the main wing. To get a more accurate empty mass estimation, considering a compound aircraft, equations by [10, 15] found in the report of [16] are used to compute the mass of each individual component. Since the paper does not offer equations for all components, the empty mass breakdown by [12] is used supplementary to estimate the mass of the electronics and skids as a fraction of the empty mass. Based on the component masses, the empty mass for a conventional helicopter is computed. Afterwards, the mass of the wing and water module are added to obtain a final empty mass of $m_{empty} = 3\,080$ kg. This mass corresponds to an EMF of 53.5 % and is therefore well within the range found for both fixed-wing and rotary-wing aircraft [9–11]. The mass of all components and their center of gravity are displayed in Table 3.1.

Component	**Mass in kg**	**x-Lever in m**	**z-Lever in m**
Fuselage	240	4.87	1.70
Main Wing	450	3.99	1.27
Empennage	30	12.28	2.09
Engines	330	3.30	1.65
Main Rotor	400	4.20	3.72
Tail Propeller	50	13.16	2.63
Water Module	100	5.18	0.92
Actuators	270	x_{CG}	z_{CG}
Fuel System	50	3.99	1.27
Skids	220	3.43	0.20
Electronics	230	2.30	1.65
Drive System	710	5.15	2.63
Empty Mass	3 080	4.42	2.01

Table 3.1: Aircraft operating empty mass breakdown and center of gravity values

The center of gravity is calculated with regard to the aircraft nose in the axial-direction and with regard to the ground in the height-direction. The centre of gravity of each individual component is determined in OpenVSP. Because electronics are present in each region of the aircraft, the centre of gravity of all electronic parts can be approximated by the total centre of gravity. The same logic applies to the actuators.

The resulting centre of gravity is displayed in Figure 3.2 as a contour plot with varying fuel and water mass. While the fuel mass is reduced slowly during flight, the water dropping process leads to a quick change of mass distribution. Therefore, the difference of the centre of gravity with a full water tank and no water onboard is small. The largest centre of gravity movements in both directions occur when no fuel is present. The maximum jump in axial direction is 30 cm, which can easily be adjusted for. The largest jump in height direction is 41 cm. This is a larger movement, but the direction of movement is less critical.

3.2 Components

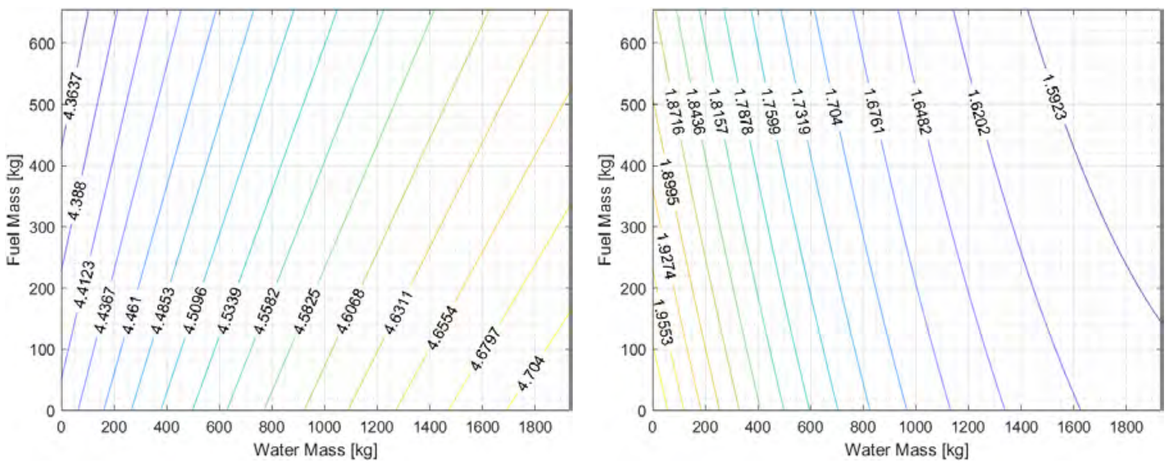
In the following sections, the most important components will be discussed. The internal arrangement of the largest components that simultaneously have the biggest impact on the centre of gravity are displayed in Figure 3.3.

3.2.1 Main Rotor

Due to the configuration of the aircraft, the most important task of the main rotor is vertical take-off and landing as well as hovering throughout the water intake process. The design point for the main rotor is hovering at 2 000 ft reflecting the altitude of the water source in the design mission.

The two coaxial rotors each have 3 blades. This is the standard amount for tandem and coaxial rotor configurations with only few exceptions [17].

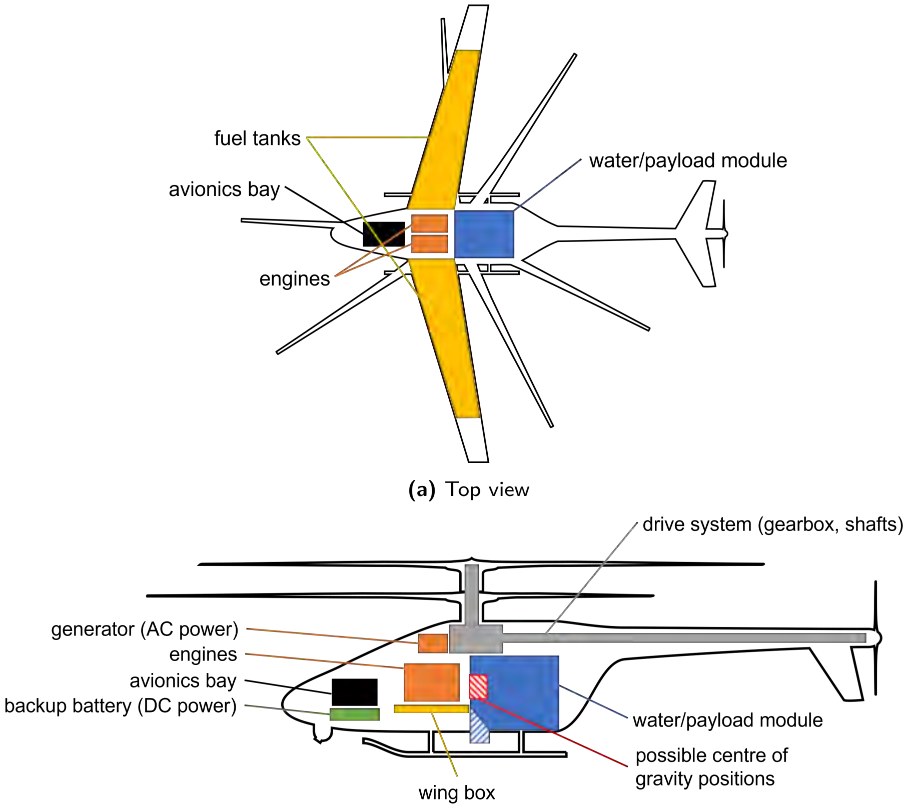
The rotor system is hingeless, which requires less parts than other rotor designs leading to less maintenance work. This is especially important for coaxial rotors that require service work for two sets of rotor blades. The rotors are controlled by conventional hydraulically actuated swashplates.



(a) Centre of gravity in axial-direction

(b) Centre of gravity in height-direction

Figure 3.2: Centre of gravity in axial- and height-direction in meter as a function of fuel and water mass



(a) Top view

(b) Side view

Figure 3.3: Internal component Layout of FireWasp

The rotor diameter is chosen based on the optimal power loading for hover derived using the momentum theory for coaxial rotors [18]. The following assumptions were used: a rotor solidity of $\sigma = 0.1$, profile drag of $C_d = 0.015$ and an induction coefficient of $\kappa = 1.15$. The latter two quantities use common values according to [18]. The solidity is chosen iteratively such that local lift coefficients of the rotor blades lie between 0.3 to 0.7. This range contains common design lift coefficients for aerofoils. Therefore, the drag coefficient is comparatively low in this region. The tip speed is chosen as low as possible because of noise considerations and drag losses. However, a lower limit is set by the requirement to have enough angular momentum for safe landing during autorotation. Based on the Kamov Ka-26 helicopter, a value of 180 $\frac{\mathrm{m}}{\mathrm{s}}$ was used [19]. While the Ka-26 helicopter is significantly lighter, the smaller rotor diameter and thus smaller moment of inertia counteracts this difference in mass.

In cruise flight the tip speed Mach number shall not be higher than 0.8 to reduce wave drag. Thus, during cruise the main rotor is limited to about 200 revolutions per minute. This corresponds to a reduction in rotational speed of about 15 %. This speed reduction causes stall for the retreating blades in cruise flight. However, this does not present the same issues for coaxial rotors as for conventional helicopters because the resulting roll moment is compensated by the second rotor.

For calculations during preliminary design the blade element momentum theory (BEMT) for coaxial rotors was used as presented in [20]. This implementation allows the optimisation of a linear twist distribution along the rotor blades. A taper ratio of 0.5 is chosen, which is a good compromise between aerodynamic efficiency and structural integrity. This taper ratio is also a common value for current helicopters [19]. The main rotor parameters are presented in Table 3.2a.

During preliminary design no final decision was made regarding aerofoil choice. The optimisation of aerofoil distribution along the blades requires high fidelity tools such as large scale CFD simulations to correctly assess performance. Generally, it is important to have thicker aerofoils in the inner two thirds of the rotor blades for structural support and good L/D at medium speeds. As a starting point for further optimisations the Onera OA212 aerofoil is chosen. The outer region of the rotor requires thin, transonic profiles that have a high drag diversion Mach number. This is due to the high speed of the outer section of the rotor. The OA206 profile is used as an initial aerofoil for high fidelity calculations. Due to the downwash of the upper rotor, the most efficient rotor design is achieved by separately designing the two coaxial rotors. The design point of all optimisations is hovering and the optimisation goals are low power requirements as well as low noise emissions.

During cruise flight the main rotor only provides a fraction of about 10 % of total lift. A lift fraction in this region is deemed optimal for a similarly designed aircraft regarding rotor and wing design in [21]. The rotor plane is not tilted and thus the main rotor does not provide any forward thrust during cruise.

3.2.2 Wing

During the cruise flight the compound helicopter relies on its wing to provide lift. A large portion of drag of fixed wing aircraft results from induced drag, which is significantly influenced by the wing aspect ratio. Thus, to reduce drag, a large aspect ratio of 12 is chosen. The resulting small chord helps to reduce downwash blockage of the main rotor. Furthermore, the induced drag can be reduced by having an elliptical lift distribution. This is approximated by using a taper ratio of 0.4, which also reduces the wing bending moment due to a reduced total lever arm for the lift force. The wing area is determined by defining a cruise lift coefficient of 0.55. To increase roll stability, a dihedral angle of 4° is used. Wing sweep is not needed at the low cruise speed. However, the wing is swept by 15° to place the wing box in front of the water module while having the aerodynamic centre of the wing approximately in the same location as the main rotor.

3.2.3 Empennage

For aerodynamically efficient control and stability improvement at high cruise speed, the compound helicopter employs an empennage with rudders. A downward facing V-tailplane is chosen for several reasons. It has a lower drag penalty than the conventional T-configuration [22]. Furthermore, it reduces the interactions between main rotor/fuselage downwash/wake and the empennage which would be higher for a T- or H-layout. Because no outwards engines are installed and an induced yaw moment by the main rotor due to tail plane rotor failure is not possible with the coaxial rotor configuration, the vertical tailplane can be sized according to small-sized single-engine aircraft. The empennage is sized by summation of the components of

Quantity	Value
Diameter	14.41 m
Solidity	0.1
Root chord	0.5 m
Blade taper ratio	0.5
Linear twist	−10°

(a) Main rotor parameters

Quantity	Value
Aspect ratio	12
Wing span	13.92 m
Root chord	1.66 m
Taper ratio	0.4
Mean aerodynamic chord	1.23 m
Wing Sweep	15°

(b) Wing parameters

Table 3.2: Quantities for Main rotor and wing

a conventional horizontal and vertical tailplane [16]. The calculation of the conventional empennage is based on [23].

3.2.4 Propeller

In cruise flight the aircraft employs a pusher rotor for forward thrust. Using only one propeller is justified because it is not a safety critical component. In case of failure the aircraft can glide because of its wing and land safely with the help of its main rotor. The propeller is connected via a clutch to the main gearbox, which provides the ability to turn off the propeller in slow horizontal and hover flight. The fixed gearbox ratio is chosen such that the optimal rotational speed of the propeller is achieved when the main rotor is slowed down to its cruise flight rpm.

The rotor diameter is limited such that its tip lies above a straight line from the skids to the empennage. This ensures that tipping over backwards will not damage the propeller.

3.2.5 Engine

To keep development cost and certification efforts low, an already existing engine is embedded in the aircraft design. A suitable match is the newly developed and recently certified Safran Arrano 1a engine, which powers the new Airbus H160 [24]. An important property of the engines is a free running power generating turbine, which allows the reduction of rotational speed without significantly impacting the provided power. This feature is used in the Airbus H160, and will also allow the compound aircraft to turn down rotor rpm during cruise flight. In order to reduce the environmental impact of the aircraft the Safran Arrano 1a engines are certified to use up to 50 % sustainable aviation fuel. The blending limit for SAF has no scientific background but is rather set by the certification process [25], meaning it could be raised by 2030 to enable an operation exclusively with SAF.

3.2.6 Fuselage

The fuselage of the compound helicopter has two essential purposes. On the one hand, it must withstand the aerodynamic loads to protect the payload and internal systems. On the other hand, its form must be aerodynamic to reduce the drag force during cruise flight.

The fuselage is shaped around the dimensions of an AKE container which represents by far the largest internal component by volume. A door at the back of the fuselage allows easy access to the payload module. The tail boom is placed such that an AKE container fits underneath.

As it is common for conventional helicopters, the fuselage is not pressurized because of the low cruise altitude. The engines are placed in front of the module. The air intakes are in the forward section of the fuselage where the air is undisturbed by the rotor downwash during cruise flight. This reduces load on the first compressor stage of the turboshaft engines [26].

3.2.7 Other Systems

Following the industry trend towards “more electrical aircraft”, the designed compound helicopter does not have a central hydraulic system. The actuators powering aileron, elevator and rudder use electro-hydrostatic actuators, that provide their own closed hydraulic system and only require electric power from the onboard systems. Similarly to conventional helicopters, a generator is connected directly to the main shaft and provides all electrical power. Avionics require DC power that is provided by transform-rectifier units. A small battery delivers backup power.

3.3 Remote Control Technology

Since the aircraft is an unmanned aerial vehicle, it is controlled with various degrees of autonomy at different stages of flight. For example, the aerial vehicle can be controlled partially autonomous or fully autonomous. In both cases, such unmanned aerial concepts are usually named as Unmanned Aerial Systems (UAS). The UAS consist of three main components:

1. Unmanned Aerial Vehicle (UAV)
2. Ground Control Station (GCS)
3. Communication System, that connects them to ensure the link between each other [27].

3.3.1 Unmanned Aerial Vehicle

FireWasp is equipped with fly-by-wire technology to safely control the aircraft. This is the most suitable system to permit controlling the autonomous flight as it is assumed to take place in Instrumental Flight Rules (IFR). The fly-by-wire system acts as an interface between the aircraft's actuators and electronic inputs which allows autonomous and remote controlled flight. Fly-by-wire is a generally used name for the flight control system (FCS) that uses computers to process flight control data by the pilot(or autopilot) and submits calculated electrical signals to the individual actuators of the flight control surfaces [28].

Navigation

In order to fly accurately, UAVs require the installation of proper navigation instruments. These instruments allow the detection of the flying location and altitude, the ground and air speed, the angle of attack and the barometric pressure among many others. This is necessary not only to sense information and safely control the UAV, but also to send this processed information to the other aircraft. For this reason, the following navigational devices are taken into account for the installation in the proposed UAV concept.

The flight position, orientation, altitude and speed of UAVs are determined using the Instrumental Navigation System (INS) that combines three accelerometers coupled with three gyroscopes (Inertial Measurement Unit - IMU) connected to a processor to deliver the full inertial outputs. In addition to this, a GPS system is also installed to ensure a more efficient autonomous navigation through the aid of the satellite service. As GPS and INS are complementary, the fused GPS/INS system provides more precise and reliable navigation data. These data are successively provided to the FCS to maintain level flight [29]. The flight control computer (FCC), which is a significant component of the FCS, can control the necessary actuators and perform flight manoeuvres.

In addition, the UAV should be equipped with Mission Management Computer (MMC). This device contains the pre-configured mission plan for command and control of the UAV and the management of the payload. For a safe autonomous flight, a proper number of redundancies of the main FCS components is necessary: in this specific case, four FCC and two MMC are recommended [30]. For other sensors, a redundancy is suggested [29].

Geographical Database

A Geodatabase is fundamental to meet the request of augmentative capabilities of the proposed UAV concept. The Geodatabase includes high-quality drone photography or satellite images along with the imagery metadata of a single take for providing general information about the area of interest. Such geospatial technology ensures robustness in the elaboration of spatial data while ensuring a safe autonomous flying. It is worth noticing that the Geodatabase is frequently updated by overlaying new sensor data to the available maps to avoid any possible inaccuracy in positioning [31].

Furthermore, the vehicle's ability to sense the external environment depends on the capability of the sensors on board. Accordingly, systems such as cameras, RADAR and Light Detection and Ranging (LiDARs) should be integrated for both, the safety of the UAV and other aircraft in air or close to the ground as well as the operations to be carried out.

Thermal Sensors / IR-Camera

Remote sensing infrared cameras are required for FireWasp to fulfil its main mission of extinguishing fires as well as providing key information for forces on the ground. With the support of a thermal imaging camera, FireWasp can monitor the accuracy of dropping water over forest fires. Despite smoke and flames in the proximity of the camera, the high thermal resolution of the imaging system allows monitoring the water dropping. Using this information, ground based response teams are able to quickly evaluate how efficient the water attack is and where more attacks are needed. Furthermore, the infrared monitoring provides ground forces with a high resolution and detailed overview of the current flame propagation. This key information would otherwise impossible to receive from the ground due to a lack of accessibility to the terrain. The collected information enables a better coordination and efficiency of the firefighting operations on the ground, regardless of challenging weather conditions such as smoke or fog [32].

An example of such a system is the WESCAM MX-10. It features 4-axis active stabilisation and a multispectral sensors that allows the usage during day and night time and adverse weather conditions [33]. For these reasons, the WESCAM MX-10 is deemed necessary to be installed in FireWasp.

RADAR

A radar system is needed to monitor the presence of potential obstacles in the vicinity of the aircraft while operating in critical conditions, e.g., where visibility is challenging as in the firefighting case study. They are designed to rapidly scan large areas and they are not affected by bad weather, smoke and dust in comparison to optical cameras as well as LiDARs [34]. However, radars lack of sufficient angular resolution to detect small natural and man-made obstacles such as trees, power lines and poles [35]. To compensate this lack, an additional LiDAR system is required.

Light Detection and Ranging

Light Detection and Ranging provides excellent angular resolution, accuracy and less dependability to adverse weather. This is combined with its good detection performance over a wide range of incidence angles. Thus, it can detect obstacles in front of the UAV very effectively [35]. As already mentioned, in aerial firefighting operations it is critical to detect possible obstacles like treetops to ensure a safe flight. For this work, the SICK LMS-511 LiDAR is considered as reference. It has a resolution of 30 mm at a distance of 80 m, which is deemed sufficiently accurate for our case [36].

3.3.2 Ground Control Station

A Ground Control Station (GCS) enables the control and monitoring of the UAV and the exploitation of the information provided by the UAV. Thus, it is a significant element to be taken into account.

A typical GCS consists of one or more operator stations for aircraft control, mission control, payload operation, payload data analysis and system maintenance [37]. There are various consoles and sticks for vehicle and task control including payload operation. These consoles also contain monitors for systems such as mission tracking and navigation. Computers for data processing, computing, mission planning, maintaining UAV flight programmes and data cleaning are also important equipment at these stations. The antennas required for communication systems are also located at this station.

Synthetic Vision System

“Synthetic Vision System (SVS) is a display system, in which the view of the external environment is provided by melding computer-generated external topography scenes from on-board databases with flight display simbologies and other information obtained from on-board sensors, data links, and navigation systems” [38]. During firefighting missions, the pilot’s visibility may be poor during night flight and due to smoke caused by the fire even a large spotlight is installed on the aircraft. In these cases, this system allows the pilot to see a computer-generated simulation of the environment. The information used to display warnings usually comes from GPS, INS and LiDAR. In emergency condition, this means that a system that can relieve the pilot’s workload is always better for safety and the mission accomplishment (less human error, less stress, faster response, better accuracy).

3.3.3 Communication System

Network and communication systems are a vital part of UAS.

C2 Link

The C2 Link provides the connection between UAV and the GCS for transmitting commands (Control) and returning to the GCS the status of the UAV (Communication/Telemetry). C2 architectures are usually classified as "Radio Line of Sight" (RLOS) or "Beyond Radio Line of Sight" (BRLOS). On the one hand, the RLOS is a direct radio link, which is established between the Remotely Piloted System (RPS) and the Remotely Piloted Aircraft (RPA). It is often used during take-off and landing. On the other hand, the Beyond Radio Line of Sight (BRLOS) is a satellite communication link that is used directly for connecting to the RPA because the distance between them is very large compared to the curvature of the earth. The BRLOS is usually utilized on the route [39]. The Detect And Avoidance (DAA) among the fleet vehicles and other aircraft is assumed to be performed with traditional ADS-B systems, working within the VHF frequency as at the time of the manuscript, no integration of the Unmanned Traffic Management (UTM) into the ATC is available.

In the future, UAVs are equipped with more than only the conventional communication technologies. A hybrid framework can be a promising solution, where various variants of wireless systems assist the direct communication among the vehicles of the formation fleet as well as with local GCS. This permits also that the UAVs are connected to the network. These technologies ensure reliable transmission in real-time, potentially also extending the VLOS and the operability range. Thus, it allows to warn the environment quickly (or vice versa), which is fundamental in critical operation like firefighting or in operation within the urban environment, as the proposed concept is envisaged as modular vehicle. The selection of the optimal

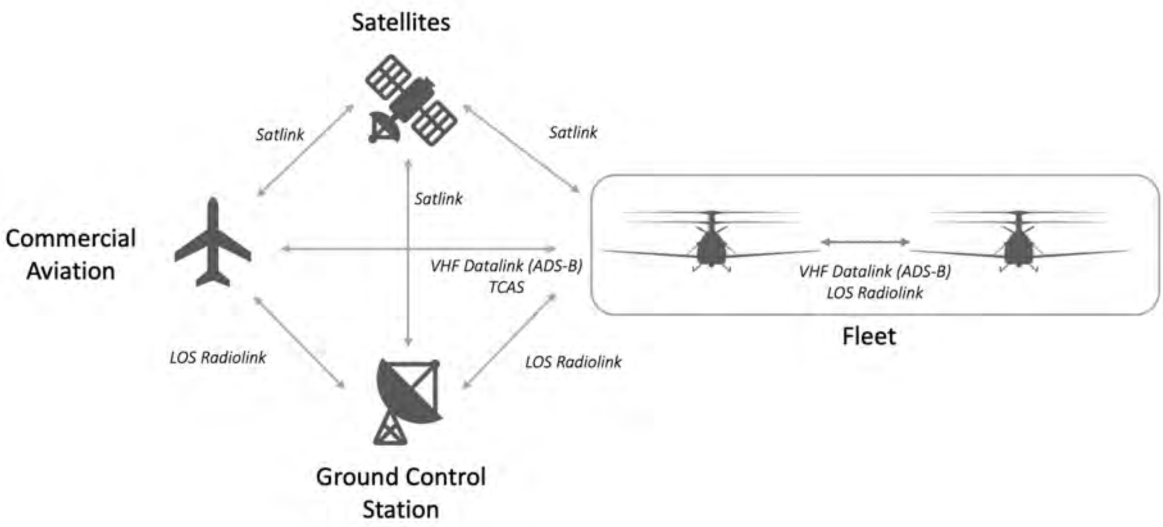


Figure 3.4: Communication system overview

communication technologies is done depending on the circumstances, e.g. the signal availability and quality. For this reason, it is essential that the autonomous vehicles are connected, when available, to the Cloud (i.e. Internet of Things – IoT) with 5G WiFi frequency band (i.e. 5.8 GHz) and/or via LTE band (around 2 000 MHz). This constitutes also a sort of redundancy in case of communication loss by exploiting the frequency diversity rather than installing multiple systems with the same function and radio frequency. In addition to that, a massive use of Machine Learning/Artificial Intelligence algorithms is required to tackle the remote case of total loss of communication. Pre-programmed flight routes with the assistance of the aforementioned algorithms make a safe flight also offline possible. Advanced algorithms are also fundamentally applied within the UAV as they can protect from cyber-attacks by implementing encryption and authentication strategies. More details can be found in [40].

Consequently, the following links along with their antennas (transmitter and receiver) must be assured and are summarized in Table 3.3.

In case of loss of communication, the following mitigating measures can be taken:

	Radio Frequency	Function	Other
UAV to Sat	1.2 GHz to 1.6 GHz	GPS Navigation, Weather Info	BRLOS
UAV to UAV	1 090 MHz	DAA	ML/AI Algorithms
UAV to Network	1.4 GHz to 2.1 GHz (LTE) 2.4 GHz to 5.8 GHz (Wi-Fi)	Route Planning, Control & Command	Cellular network, may extend the VLOS
UAV to GCS	400/900 MHz - 1.3 GHz	Telemetry, Video, Info, Control & Command	RLOS
GCS to GCS	Wired Network	Info Transmission	Network, Fibers, Among main GCS and other GCSs

Table 3.3: Various communication technologies for different transmitters and receivers

- Device physical redundancies (multiple devices)
- Frequency diversity
- Multiple C2 technologies, cellular network and Wi-Fi
- Pre-programmed flight, ML/AI enhancement (loss of GPS).

3.4 Modular Design

Since wildfire activity is influenced by the seasons, the aircraft will mostly be used for firefighting during the summer months. To avoid periods of stagnation in use during the wildfire off-season, other applications for the aircraft are evaluated. The aircraft possesses a modular payload structure, which can carry arbitrary payloads up to the dimension of an AKE container. The AKE container – formerly also known as LD3 container – is the smallest of the most common unit load devices (ULDs) [41]. Using this established standard allows existing containers and pallets to be used. An easy adaption for newly designed payloads and flexibility is possible, because payloads are not restricted to usage in only one type of aircraft.

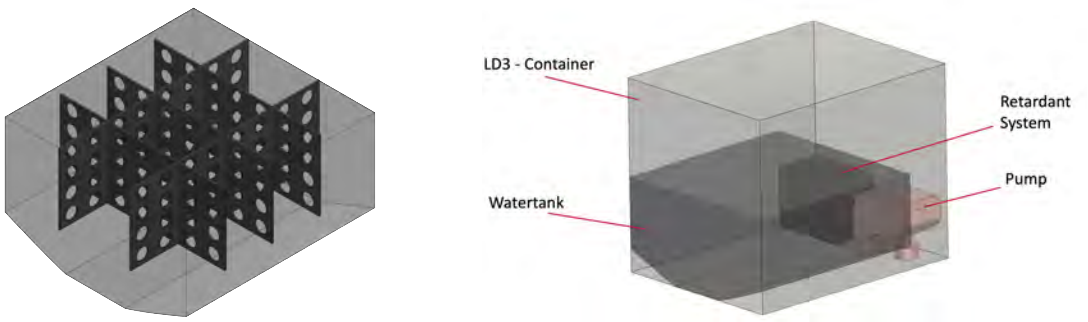
Compared to the orientation of an AKE container in aeroplane cargo bays, its position is rotated by 90° such that the diagonally-cut corner points forward. The resulting unused bottom area is used as an interface of the payload module to the outside, which the water module, for example, uses to drop and acquire water.

To enable the data connection with the water or other modules, the aircraft is provided with an interface. This interface also provides the electric energy to the modules. When loading the modules, they are connected via a cable to the aircraft, so it will be controllable from the GCS. The pilot then is able to operate remotely.

3.4.1 Water Module

Water Dropping

The water tank is designed narrow and deep in order to achieve a greater pressure generated by the water mass on the walls at the bottom of the tank. In this way, the load produced by the water mass is directed downwards for the evacuation process. Besides, as the tank's two drop doors open simultaneously and move out from the openings, the aforementioned aspects ensure an uninterrupted and quite precise flow during the evacuation process. This action is attributed to the operation of the hydraulic mechanisms for the drop-doors.



(a) Baffles integrated in water tank

(b) Water module

Figure 3.5: Water module

Tank Refilling

A so-called snorkel pump is used to pump the water. This pump allows water to be taken from anywhere - e. g. lakes, rivers, and even from water tanks. An example of such device is the pump used in the Helitak system, which is able to fill a tank of 2 000 l in around 35 seconds. All the specifications of such device are included in the datasheet reported in [42]. Once the pumping process is completed, the pump and the tube are retracted into the fuselage. A tube adaptor is installed on the top side of the tank facing to the rear of the aircraft for easy access. This also allows to refill the tank while the aircraft is on the ground.

Retardant

"A fire retardant is a substance used to slow, stop, or reduce the intensity of the spread of a fire. This is usually done by chemical reactions that reduce the flammability of fuels or retard their combustion" [43]. To make the application area recognisable from the air, it is usually coloured.

The retardant can be filled into the 100-litre flame retardant tank before the first flight and when refuelling. The typical concentration of the foam for the Canadair CL-415 is 0.4 % [44]. Assuming this concentration a 2000-litre water load requires only 8 liter of foam concentrate. This way, the water can be dropped 12 times without refilling the retardant. The mixing process between water and retardant is not part of this work but it is described in detailed in [45].

Inside of water tank

Highly localized impact force on tank walls or ceiling created by violent sloshing leads to tank damages and induces large momentum. The partially filled container with fluids affects the vehicle stability especially when the external excitation frequency due the sloshing is close to the resonance frequency the fluid [46].

To prevent water sloshing in a tank in motion, baffles are integrated in the tank vertically and horizontally on the inside of the tank. This concept is depicted in Figure 3.5a. Care must be taken to ensure that the baffles do not obstruct water outflow. For this purpose, the baffles must have a perforated structure (for water flow). This affects the vehicles stability, especially when the external excitation frequency due the sloshing is close to the resonance frequency of the fluid.

3.4.2 Other Modules

Besides the deployment for aerial firefighting, the following modules could be loaded onto the aircraft:

Use in the agricultural industry

Common uses for aircraft in agriculture are the aerial application of insecticides or fertilizers, as well as seeds and plant protection. Furthermore, the compound helicopter can be used for forest liming, which has seen an increase in interest over the last decade. The positive effects of liming are shown in a study by [47]. The characteristics of an aircraft used for agricultural task should include all-round visibility, good-natured flight behavior and high maneuverability even at low airspeed. The ability to hover is another valuable property that can be used. The agriculture module would consist of a tank for e.g. insecticides or fertilizers. Contrary to the water module, which is designed to unload all water at once, the agriculture module needs to some kind of dosage to ensure an even spray of fluid.

Master Module

The Master Module is used in the guide airplane. It is equipped with the radar and sensor systems mentioned in 3.3.1.

Airborne Thermal Mapping

Thermal mapping is an essential tool to measure wasted energy in cities. The airborne collection of this data facilitates the efficient development of sustainable zero energy concepts. Thermal imaging cameras from Infratec for example are well suited for collecting the necessary thermographic data, because they are robust enough to be used on flying object such as drones.

Additionally, airborne thermal imaging can improve remote maintenance of heating networks by giving accurate data to maintenance teams on ground. Thus, possible defects and leaks can be repaired faster and more efficiently [32]. The data acquisition components, as well as storage and processing tools can be stored in a modular compartment up to the size of an AKE container.

Airborne Inspection and Maintenance of Long-distance Power Lines

Long-distance power lines provide electricity to all private households and the local industry. Therefore, in today's society continuous energy supply must always be ensured. To achieve a reliable energy network constant monitoring is required. In order to allow reliable and efficient inspections, thermographic cameras can be installed on helicopters or drones such as FireWasp to relay monitoring-data.

The module utilises infrared cameras to locate hotspots on power cables or insulators. These hotspots are indicators of material defects or system malfunctions. Even underground power cables can be reliably inspected with thermal imaging systems. Alternatives such as standard video-cameras are less accurate. Furthermore, ground based inspections of power cables are slower than airborne mapping [32].

3.5 Vehicle Stability

Aircraft in steady flight has to operate at conditions where forces and moments are in equilibrium about the center of gravity which is known as trim flight [14]. The influence of forces and moments on an aircraft are measured by stability and control derivatives.

A selection of such important derivatives is mentioned below.
The heave damping derivative, Z_w, represents the change of rotor thrust following a perturbation in heave velocity. The value of the heave damping derivative for helicopters is dependent on the rotor disc loading. The contribution of the main rotor to Z_w decreases in magnitude after a certain speed due to the reduction in rotorspeed [48].

The M_w derivative is commonly referred to as the angle-of-attack stability derivative, and is generally destabilising the main rotor's contribution [49]. This derivative contributes significantly to the longitudinal short period modes of the helicopter and the vehicle's handling qualities. The stability derivative M_w is generally positive. For compound helicopter it is greater due to rotor loading across rotor disc to counter-act the aerodynamic download on the wing. As the configuration approaches high-speed flight, the wing begins to contribute to the stability derivative M_w.

Another important stability derivative is L_p, which is strongly influenced by flight speed. As the wing begins to offload the main rotor at the compound configuration, the magnitude of the stability derivative L_p increases.

The main rotor's natural tendency to provide a stabilising rolling moment following a perturbation of roll rate is strengthened by the wing's contribution.

Compared to a conventional helicopter, the compound helicopter will have greater drag damping. The roll damping from the wing and the increased roll inertia of the compound helicopter due to lift compounding reduces the roll agility of the helicopter [48]. But it is still sufficient for the use case.

A Flight Control System (FCS) supplied with derivative coefficients ensures that the aircraft remains stable in the air [50]. Even though the center of gravity is behind our aerodynamic center and therefore the longitudinal static stability is not stable, the aircraft is able to fly. The FCS also controls the instabilities caused by the mass distribution as mentioned in 3.1.

3.6 Performance Calculation

The mission calculation is based on fixed wing preliminary design methods for cruise flight and helicopter hovering. To be conservative during computation, the transition periods are counted towards hovering where more fuel is burned. The calculation is carried out backwards. Starting with an empty aircraft the required fuel for each segment – beginning with the fuel reserve – is computed and added to the aircraft mass.

The design mission results from the DLR Design Challenge problem description [5]. The aircraft starts at the airport fully loaded with water and flies directly to the wildfire. Having depleted its water tanks, the aircraft flies to the water source refilling the water tank. The number of attacks per flight is optimised by a brute force approach. For this purpose the mission calculation is carried out for 1 to 20 water attacks per flight. The number that leads to the highest amount of water dropped on the wildfire during the 24 h mission period is used for the optimal payload mass share of the MTOM.

The zero lift and lift dependent drag calculations of the fixed wing lift share of the aircraft is carried out via empirical formulas [23]. For validation the zero lift drag was also determined using OpenVSP. The drag coefficients deviated by less than 5 %, which is satisfactory during preliminary design. To account for interference between the rotor and wing, the interference factors given in [51] are used. For the cruise speed of 400 $\frac{\text{km}}{\text{h}}$ the wing lift is decreased by 5 % while the total drag is increased by 5 %. The required lift coefficient is derived using the current aircraft mass. Thus, the lift-to-drag ratio L/D can be computed and used in the Breguet equation.

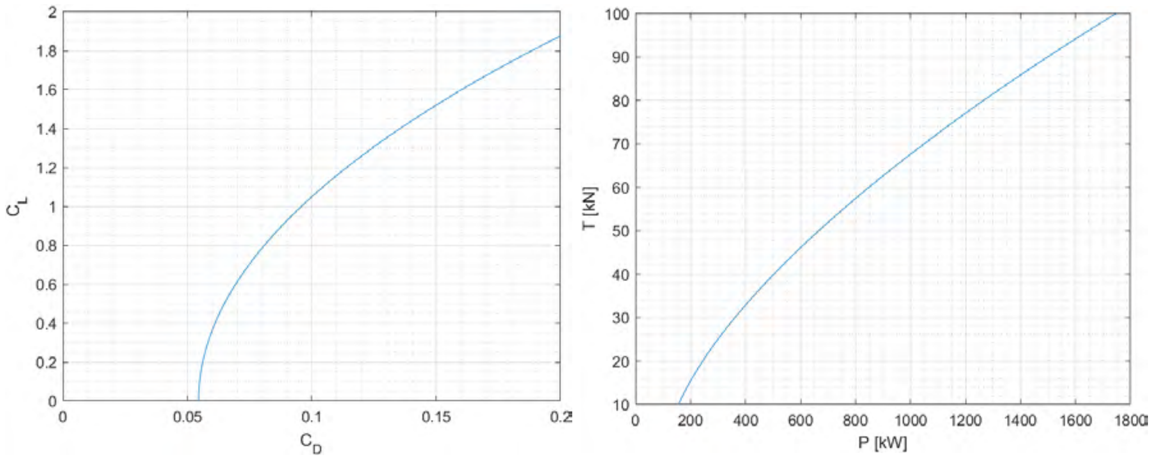
$$\text{FM} = m_{\text{AC}} \cdot \exp\left(\frac{\text{SFC} \cdot t \cdot g \cdot V_{\text{cruise}}}{L/D \cdot \eta_{\text{prop}}}\right) \tag{3.2}$$

Here, t is the time needed for the segment, V_{cruise} stands for the cruise speed, η_{prop} represents the propeller efficiency, g the gravitational acceleration and SFC signifies the specific fuel consumption. In Figure 3.6a the drag polar is given for the aircraft. The conservative assumption of a symmetric polar is introduced by [23] for preliminary design.

During hover the power-thrust curve obtained with BEMT is used. Because the hover time is comparatively short, the aircraft mass is conservatively assumed to be constant. Thus, the fuel mass for each segment can be calculated with the specific fuel consumption SFC, the required time t and power P.

$$\text{FM} = \text{SFC} \cdot t \cdot P \tag{3.3}$$

The mass iteration coupled with the performance calculations and mission optimisation yields the following results. The MTOM of 5 670 kg is divided into a fuel mass FM of 655.1 kg, an operating empty mass OEM of



(a) Drag polar for compound helicopter

(b) Power curve for coaxial rotor

Figure 3.6: Relations used during performance calculations

3 080.0 kg and a payload mass PM of 1 935.0 kg. Six FireWasps are equipped with a water dropping module in order to deliver the required amount of 11 000 kg of water with the first attack. Because a guide aircraft is also required, the total fleet consists of 7 FireWasps for the design mission.

Over the entire 24 h mission 63 individual attacks are carried out by each of the six water dropping FireWasps. In total the entire fleet is able to distribute 731 410 kg of water to fight the wildfire.

4 Operation

4.1 Operational Concept

The idea is to use a fleet of several aircraft to fight the forest fire more effectively. For this purpose, it is planned to use several compound helicopters from the same series production. However, they will be equipped differently.

The idea that a guide pilot takes off immediately upon fire notification and flies to the terrain, analyzes it and coordinates further action is pursued. This aircraft is equipped with the complete sensor technology including the radar system and sensors for autonomous flight. It will determine the coordinates at which the further aircraft will drop the water. Six compound helicopters are equipped with water tank modules and do not carry the same sensors as the first guide aircraft as displayed in Figure 4.1. In order to save costs, mass and staff, the six airplanes will fly autonomously and navigate to the coordinates determined by the guide aircraft. Due to critical flight conditions as at water dropping, pilots take over the control of the aircraft during this maneuver and will leave to autonomous flight again when conditions are safe and basic like hover, level flight, turns and climbs or descent. A pilot is responsible for two aircraft. Due to different water dropping coordinates, the aircraft are in alternating flight stages, so one pilot is usually just controlling one aircraft at a time. If no pilot is available when reaching critical flight stages, the helicopter will stay in hover mode and wait to be controlled next. In that case, three pilots to load and drop water and one pilot to control the guide aircraft are required. These pilots are stationed at the GCS, which is a mobile platform and can be transported to needed areas. Thanks to hover capabilities, the compound helicopter is able to refill the water tank at any water source e.g. lakes, rivers, portable tanks or reservoirs. Thus, the refill can be done at the nearest source. To optimize the flight routes and firefighting strategy, the flight data is saved for further analysis.

4.2 Other Wildfire Scenarios

In addition to the design mission, the firefighting capabilities are evaluated for two other scenarios imaginable in Europe.

First, the performance of the aircraft is evaluated for the region of Costa de Sol on the Spanish coast. The region has been affected by wildfire before, the most recent one raging in the Los Reales de Sierra Bermeja Natural Park in early June this year. The natural park is located a few kilometers away from the Mediterranean sea and stretches over an area of about 1200 hectares. The fleet can be stationed at the airport of Gibraltar (LXGB) located approximately 30 nautical miles south west of the natural park. With the aircraft departing from LXGB, the natural park of Los Alcornocales as well as the northern parts of Morocco can be reached within 25 minutes. Due to the proximity to the sea, water is widely available.

A more challenging scenario could be aerial firefighting in a mountain region with no water source to refill. In that case, the fleet would have to fly back to the base of operation to refill water between successive attacks. Compared to other aerial firefighting options on the market, the relatively low MTOM of the FireWasp would be considered as a disadvantage during such a scenario.

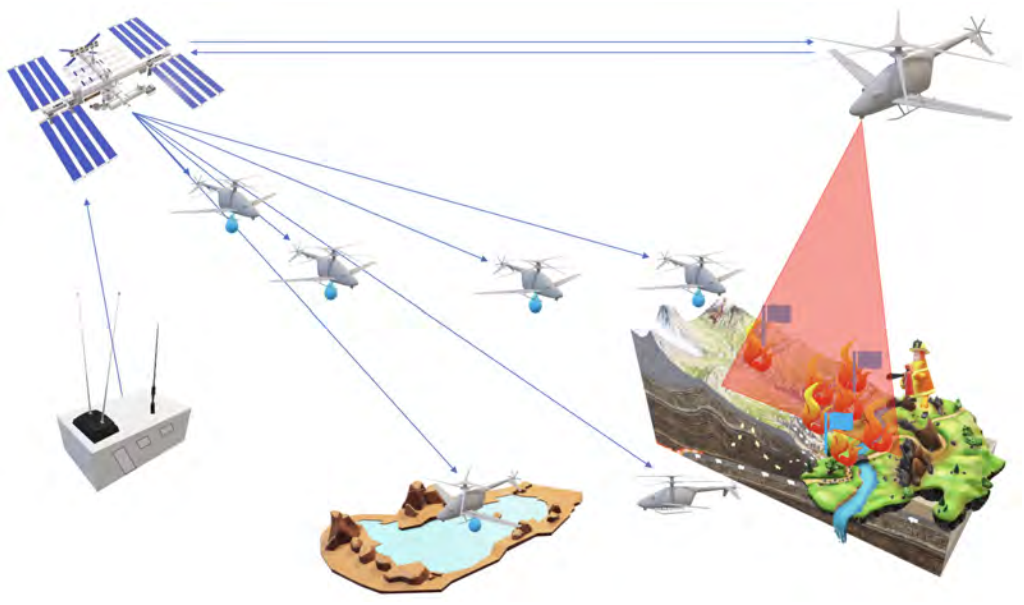


Figure 4.1: Operational concept overview

In conclusion, the fleet concept excels at firefighting while a water source is in the proximity of the fire seat, while it lacks potential to cope with missions of longer range. When planning the firefighting fleet of the future, the FireWasp fleet would be ideally paired with larger aircraft.

5 Conclusion

FireWasp fulfills all demands stated in the task of the DLR Design Challenge 2022.

A fleet of six water dropping FireWasps and one guide aircraft is capable of dropping a total of 11 610 kg per attack. The six water dropping aircraft are equipped with firefighting modules, each carrying $m_{\text{water}} =$ 1 935 kg. The guide aircraft does not have firefighting capabilities when carrying the master module, instead it is solely used for scouting and coordination of the fleet during the mission. Over the 24 hour long design mission, each aircraft carries out 63 attacks, amounting to a total water deployment of 121 900 kg. The entire fleet is able to fight the fire by dropping 731 410 kg of water on the fire.

FireWasp successfully inherits design and performance attributes from both fixed wing and rotary wing aircraft. During cruise flight, the majority of the lift is produced by the wing and the compound aircraft imitates a fixed wing aircraft. This is reflected in the utilised performance calculations. FireWasp has a high aspect ratio wing, keeping induced drag low and the chord length small to reduce rotor down-wash. Thrust is generated by a pusher type propeller at the back allowing a cruise speed of $V_{\text{cruise}} = 400\,\frac{\mathrm{km}}{\mathrm{h}}$. Compared to conventional helicopters this is a significant increase which allows the shortening the critical initial response time.

While hovering, helicopter characteristics are adapted. Contrary to most conventional helicopters, FireWasp relies on a co-axial rotor configuration. Therefore, the design can refrain from using an anti-torque rotor in the back. Additionally, a co-axial rotor results in lower power-requirements during hover flight.

Autonomous flight capabilities and remote control technology eliminate the need for on-board pilots and therefore contribute to the safety of firefighting personnel. In the future, the recorded flight and mission data can be used to create an evaluation scheme and data base for all flown missions. Based on that database, flight path optimization and mission pre-planning could be subject to future research to uncover further potential to increase firefighting efficiency.

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