# DLR DESIGN CHALLENGE 2022: NEXT GENERATION FIREFIGHTING AIRCRAFT – FIREWASP

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**Abstract**

FireWasp is a medium-sized compound helicopter designed for aerial forest firefighting. As part of the DLR Design Challenge 2022, the aircraft is designed, a mission and performance calculation are 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 operate autonomously.
The fleet of compound helicopters is controlled from a mobile ground station and can be deployed anywhere. During the entire development process, the focus lies on maximising firefighting capabilities. Lastly, the payload system of FireWasp is a modular design, so that modules for other purposes than firefighting can be integrated.

**Keywords**
Compound Helicopter; Unmanned Aerial Vehicle; Aerial Firefighting; Wildfire; Fleet Operation

## ABBREVIATIONS

| | |
|---|---|
| ADS-B | Automatic Dependent Surveillance-Broadcast |
| AI | Artificial Intelligence |
| BRLOS | Beyond Radio Line of Sight |
| BVI | Blade Vortex Interaction |
| DC | Direct Current |
| DLR | Deutsches Zentrum für Luft- und Raumfahrt |
| EM | Empty Mass |
| EMF | Empty Mass Fraction |
| FCC | Flight Control Computer |
| GCS | Ground Control Station |
| GPS | Global Positioning System |
| INS | Instrumental Navigation System |
| IR | Infrared |
| LiDAR | Light Detection and Ranging |
| ML | Machine Learning |
| MMC | Mission Management Computer |
| MTOM | Maximum Takeoff Mass |
| PMF | Payload Mass Fraction |
| PM | Payload Mass |
| RADAR | Radio Aircraft Detection and Ranging |
| RLOS | Radio Line of Sight |
| SAF | Sustainable Aviation Fuel |
| SVS | Synthetic Vision System |
| UAS | Unmanned Aerial Systems |
| UAV | Unmanned Aerial Vehicle |
| ULD | Unit Load Device |
| VTOL | Vertical Take-Off and Landing |

## 1. INTRODUCTION

With climate change being one of society's most pressing challenges, extreme weather phenomena are likely to become the norm.
Wildfires in particular constitute a severe threat, not only to wildlife but also to humans and critical infrastructure. 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 also increase the risk across Europe. Primarily 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 method of combating wildfires and preventing their spread, especially in rural and inaccessible areas. While the deployment of aeroplanes and helicopters to the fire source is by no means new, the proposed novel approach aims to combine the benefits of the two – increasing efficiency and firefighting performance. The result of merging the two conventional configurations is called a compound aircraft.
Compound vehicles, also 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 viable compound aircraft. Recently the Airbus Racer was presented at the Paris Airshow in 2017 signalling a still lasting interest in the configuration [4].

## 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. The targeted cruise speed of 400 km/h is only achievable by taking advantage of fixed wing aerodynamics.
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 $\mathrm{PMF} = \frac{\mathrm{PM}}{\mathrm{MTOM}}$ is used as the iteration variable.
The DLR Design Challenge requirements state an entry into service by 2030. 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) 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. Thus, 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.

### 2.2. Challenge Requirements

The goal of this year's challenge is to develop a fleet of novel aircraft that maximises 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.
To display the firefighting capabilities of the novel aircraft, three distinct mission profiles are presented:
- Design Mission
- Coastal Scenario
- Inland Scenario

The vehicle must be able to refill using small water sources that might be surrounded by trees. In addition, the possibility to refill water at the airport can be evaluated in the performance calculation. The ability to precisely drop the water onto the seat of the fire is vital for the success of the mission. Thus, operation under impaired visibility needs to be guaranteed, allowing the aircraft to be deployed into areas of heavy

| Design Aspect | Weighting | Tailsitter | Tiltwing | Tiltrotor | Compound |
|---|---|---|---|---|---|
| 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** |

**TAB 1. Results of the pairwise comparison and value-benefit analysis**

smoke as well as during night. The present work will not touch on the subject of aerial firefighting strategies and methods, but solely considers the maximisation 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 between the fire and the nearest water source is 15 NM.

### 2.3. Design Selection Process

The following section elucidates the configuration selection process taking into account both aircraft and mission requirements. 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 and high cruise speed
2) hover and perform a vertical take-off.

Some of the additional design parameters taken into consideration during the selection are: stability properties, high manoeuvrability and complexity and maintenance of the drive train. An overview of all considered properties is given in Table 1.
To fulfil the two main requirements while not neglecting other design attributes is a challenging task. Therefore, only a handful configurations are considered. 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 1. 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. High values mean the aircraft excels in the field, lower values are associated with worse performance. Table 1 marks the compound aircraft as the most suitable option and provides the foundation for the extensive design process. 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, different design attributes are sorted in descending order of importance. Both hover and transition stability are inevitable for the success of the proposed configurations. Especially the first three concepts heavily rely on stability during the transition between vertical and horizontal flight. An absence 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. A high cruise speed has a significant influence on the initial response time which is the duration between the fire call and the first attack. High manoeuvrability is essential in difficult terrain, e.g. in mountain regions but also during water intake. Furthermore, it can be 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 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 behaviour for coaxial rotors. Moreover, coaxial rotors result in a reduction of power requirements. According to [7] the reduction can amount up to 15 % compared to single rotor configurations.

| Component | Mass in kg |
|---|---|
| Fuselage | 240 |
| Main Wing | 450 |
| Empennage | 30 |
| Engines | 330 |
| Main Rotor | 400 |
| Tail Propeller | 50 |
| Water Module | 100 |
| Actuators | 270 |
| Fuel System | 50 |
| Skids | 220 |
| Electronics | 230 |
| Drive System | 710 |
| Empty Mass | 3080 |

**TAB 2. Aircraft operating empty mass breakdown**

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, counteracting the rotor induced moment using pusher propellers in a compound configuration is a challenging task. In order to compensate the yaw moment during hover, both rotors on each side of the helicopter are required provide thrust in opposite directions. In cruise flight both rotors are needed to provide a forward force, compensating the yaw moment of the rotor via differential thrust. Thus, at least one propeller requires the ability to provide thrust in either direction. Furthermore, the failure of only one pusher rotor will inevitably lead to a thrust force. 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 study by [8] found an increase of Blade Vortex Interaction (BVI) noise of up to 35 dB compared to the BVI noise of a single rotor configuration.

## 3. VEHICLE DESIGN

A 3 side view of FireWasp was exported from OpenVSP [9] and is displayed together with a 3D rendering in Figure 1.

### 3.1. Empty Mass Estimation

The amount of payload an aircraft is able to carry is limited by two main factors:
1) the maximum take of mass MTOM
2) the empty mass EM

Since the maximum take-off mass is restricted by the task [5], the amount of payload is solely influenced by the empty mass of the compound aircraft.
To quantify the ratio between empty mass and MTOM of an aircraft, the empty mass fraction

$$\text{EMF} = \frac{\text{EM}}{\text{MTOM}} \tag{1}$$

is introduced.
Typical values for the empty mass fraction of conventional fixed wing aircraft range between 50 % to 60 % [10] or even 30 % to 70 % [11]. For helicopters, [11] suggests a fraction of 45 % to 80 % while studies by [12] propose an EMF between 42 % to 74 %.
During the design process the empty mass is computed using three different approaches. The first method is based on work by [12] and uses statistics to estimate the empty weight solely based on the MTOM. The EMF is computed to be approximately 55 %. A second methodology is taken from [13] and combines research by [14] and [15] to compute a fuselage mass. Afterwards, the empty mass is calculated based on a weight breakdown of helicopters into individual components. This procedure results in an EMF of 67 %. Both methods obtain values well within the range given by literature. However the compound design is not considered in the weight calculation of the above two mentioned approaches. To get a more accurate empty mass estimation, considering a compound aircraft, equations by [11, 16] found in the report of [17] 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 [13] is used supplementarily to estimate the mass of 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 wings and water module are added to obtain a final empty mass of 3080 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 [10–12]. The mass of all main components are shown in Table 2.
The centre 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. The resulting centre of gravity is displayed in Figure 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 between the centres of gravity with a full water tank and no water onboard must be 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 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.

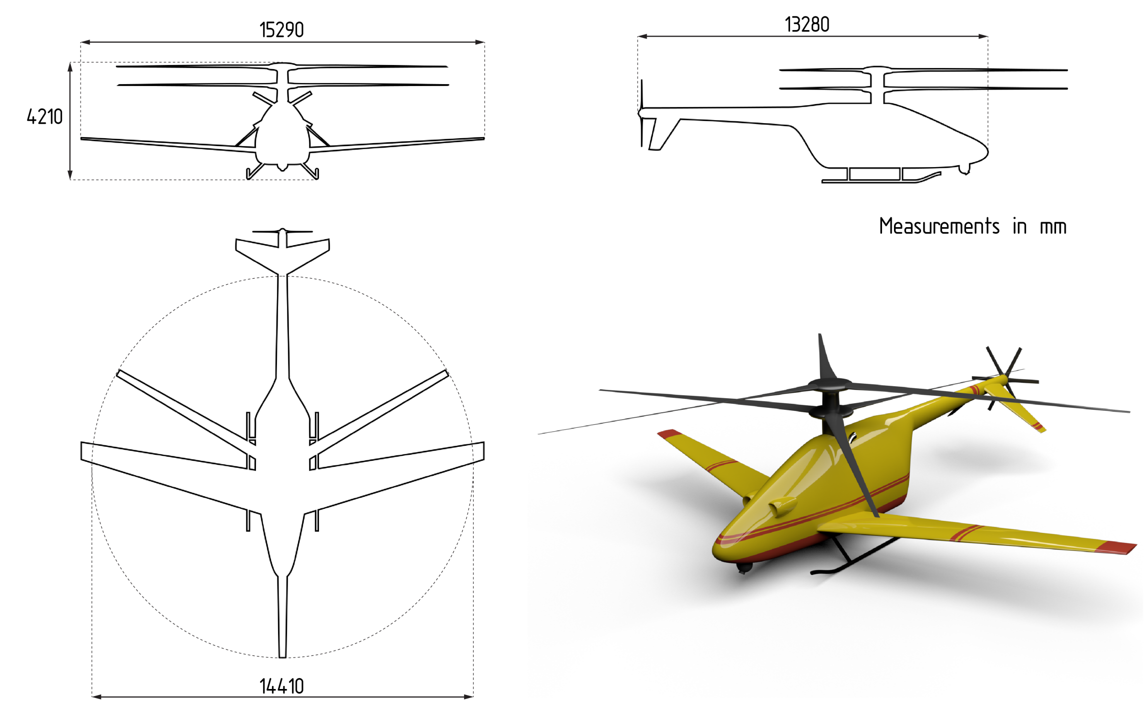
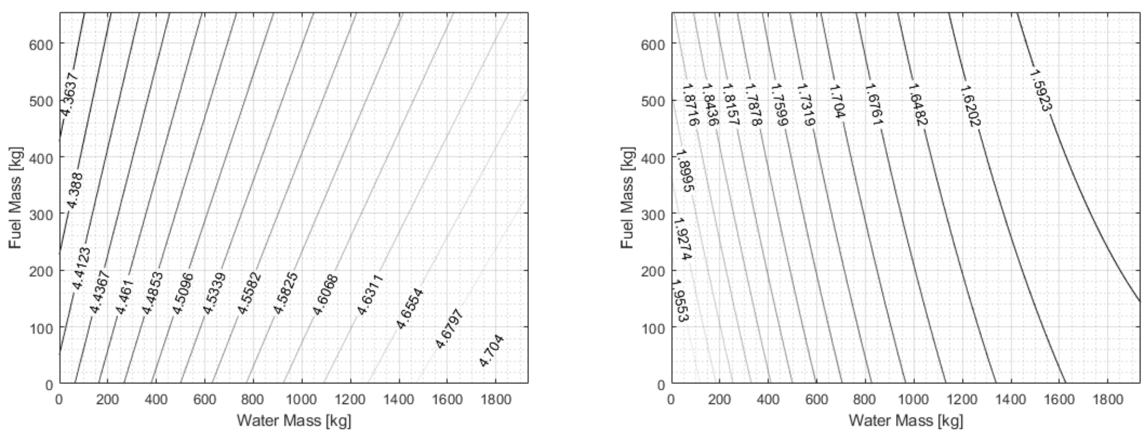



**FIG 1. Three-side view and 3D render of FireWasp**




**(a) Centre of gravity in axial-direction**

**(b) Centre of gravity in height-direction**

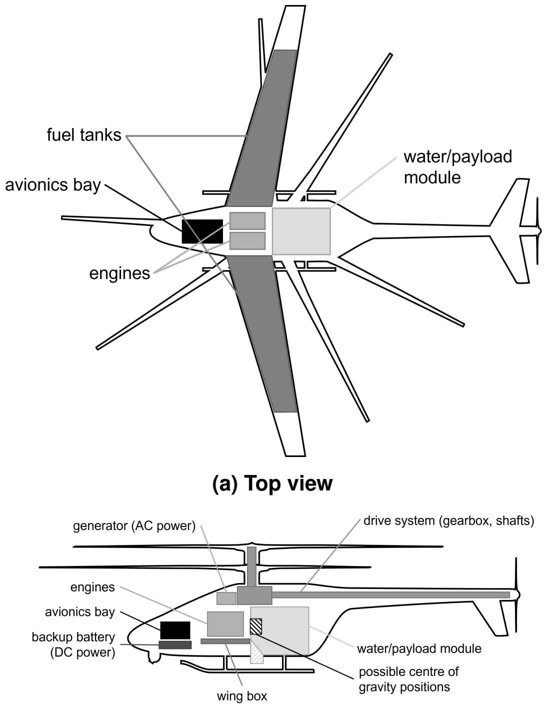
**FIG 2. Centre of gravity in axial- and height-direction in meter as a function of fuel and water mass**

### 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.

#### 3.2.1. Main Rotors

Due to the compound configuration of FireWasp, the most important tasks of the main rotors are vertical take-off, landing and hovering throughout water intake. Thus, the design point of the coaxial rotors is hovering at 2000 ft – reflecting the altitude of the water source in the design mission.
The two coaxial rotors each have three blades which is a common amount for tandem and coaxial rotor configurations with only few exceptions [18]. The rotor system is hingeless, which requires less parts than other rotor designs leading to less maintenance work and a lighter rotor hub. The former being especially important for coaxial rotors that require service work for two sets of rotor blades. The rotors are controlled by conventional hydraulically actuated swashplates.
The rotor diameter is calculated using the optimal power loading for hover derived with the momentum theory for coaxial rotors [19]. Blade tip speed is chosen as low as possible because of noise considerations and transonic drag losses while still providing enough angular momentum for safe landing during autorotation.
During cruise flight the blade tip speed is reduced by roughly 15 %. This speed reduction causes stall for the retreating blades in cruise flight. However, this




**(a) Top view**

**(b) Side view**

**FIG 3. Internal component Layout of FireWasp**

does not present the same issues for coaxial rotors as for conventional single rotor designs, because the resulting roll moment is compensated by the second rotor. 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 [20]. The rotor plane in cruise flight is not tilted and thus the main rotor does not provide any forward thrust during cruise.

### 3.2.2. Wings

The wings feature a high aspect ratio to minimise induced drag. The small chord also helps to reduce downwash blockage of the main rotors. The wing does not feature any high-lift devices because lift at low speeds is provided by the main rotors. A small dihedral angle increases roll stability. While wing sweep is not needed at the cruise speed of 400 km/h, the wings are 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 hub.

### 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 [21]. Furthermore, it reduces interaction between the empennage and main rotor downwash as well as the fuselage wake compared to a T- or H-layout. The vertical tailplane is sized according to small-sized single-engine aircraft. The empennage is sized by summation of the components of a conventional horizontal and vertical tailplane [17]. The calculation of the conventional empennage is based on [22].

### 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 wings 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 speed. The rotor diameter is chosen such that the blade tips lie above a straight line from the skids to the empennage. This ensures that tipping over backwards will not lead to ground contact of 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 [23]. 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 (SAF). The current blending limit for SAF has no scientific background but is rather set by the certification process [24], 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 aerodynamic shape reduces drag 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.
The engines are placed in front of the payload. The air intakes are in the forward section of the fuselage where the air is undisturbed by rotor downwash during cruise flight. This reduces load on the first compressor stage of the turboshaft engines [25].

### 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 [26]. 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 the above [27].

### 3.3.1. Unmanned Aerial Vehicle

FireWasp is equipped with fly-by-wire technology to safely control the aircraft. This enables autonomous and remotely controlled flight by providing an interface between the aircraft's actuators and electronic inputs [28].

Camera

FireWasp features conventional cameras to provide a colour view of its surroundings during favourable light conditions. In contrast to other vision systems, high resolution solutions exist for comparatively low prices. These cameras can be used to detect and avoid obstacles [29].

Navigation

UAVs require a number of instruments that provide information about the location, altitude and air data. Flight position, orientation, altitude and velocity are determined using an Instrumental Navigation System (INS) that combines three accelerometers coupled with three gyroscopes. In addition, a GPS system is installed to ensure more efficient autonomous navigation through the aid of satellite service. As GPS and INS are complementary, the fused GPS/INS system provides more precise and reliable navigation data. This data is provided to the flight control computer (FCC) to control the necessary actuators and maintain level flight or perform manoeuvres [30].
In addition, the UAV is equipped with a 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 safe flight, redundancy of sensors and computers is crucial [30]. For FireWasp, four FCCs and two MMCs are chosen [31].

Geographical Database

A geodatabase is fundamental to meet the required specifications of the proposed UAV concept. It includes high-quality drone photography and satellite images along with associated location data. Such geospatial technology ensures robustness in the processing of spatial data, thus ensuring safe autonomous flight. The database is frequently updated by overlaying new sensor data onto the available maps [32].

Thermal Sensors/IR-Camera

FireWasp requires infrared cameras to accurately identify water dropping spots and provide key information to firefighting forces on the ground, obtainable only by aerial access. Using this information, ground based response teams are quickly able to evaluate efficiency of water attacks, coordinate further dropping zones and anticipate flame propagation. A high thermal resolution of the camera ensures detailed imaging, despite impaired vision due to smoke, flames or challenging weather conditions [33].

Light Detection and Ranging (LiDAR)

LiDAR provides excellent angular resolution and accuracy. Furthermore, it is influenced less by weather conditions than optical cameras. A large field of view ensures good detection performance over a wide range of angles of attack [34].

### 3.3.2. Ground Control Station

A Ground Control Station (GCS) enables control, monitoring and mission data analysis of the FireWasp fleet. They are mounted on a mobile platform which allows a fleet of FireWasps to be deployed anywhere. It consists of two operating terminals devoted to aircraft and mission control, payload management, data analysis and system maintenance [35]. Each terminal provides flight controls as well as monitors for live feed footage and mission tracking. Computers for data processing, mission planning, maintaining UAV flight programmes and data cleaning are included in these stations. The antennas required for communication systems are also located at this station.

Synthetic Vision System

"A 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 symbologies and other information obtained from on-board sensors, data links, and navigation systems" [36]. To compensate for drawbacks of each of the navigational systems, a synthetic vision system combines the output of the aforementioned, providing a clear picture of the surroundings to the pilot even during adverse conditions.

### 3.3.3. Communication System

Network and communication systems are a vital part of any UAS. The Control and Communication (C2) Link provides the connection between a UAV and the GCS to transmit commands and return the status of the UAV. C2 architectures are usually classified as Radio Line Of Sight (RLOS) or Beyond Radio Line Of Sight (BRLOS). RLOS is commonly used during take-off and landing while BRLOS is usually utilised on the rest of the mission [37]. Detection and avoidance among the fleet vehicles and other aircraft is achieved with traditional ADS-B systems, working within the very high frequency radio range because currently no integration of unmanned traffic management into air traffic control is available.
A probable scenario for the future involves new communication technologies for UAVs. To benefit from the capabilities of these systems, FireWasp is already equipped with the necessary hardware. This includes Wi-Fi and 5G mobile network modules that enable fast and reliable communication between the vehicle fleet and to the outside. The addition of these novel communication methods provide further redundancy to the communication system of FireWasp. One aspect to consider with the implementation of these technologies are cyberattacks. Protection can be provided by encryption and advanced authentication methods [38]. The following measures can be taken to avoid loss of communication:

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

## 3.4. Modular Design

Since wildfire activity is influenced by the seasons, operation of the aircraft is limited to the summer months. To avoid periods of stagnation in usage during wildfire off-season, other applications for FireWasp are evaluated. The aircraft features a modular payload structure, which can accommodate payload modules of dimensions up to an AKE container. The AKE container – formerly also known as LD3 container – is the smallest of the most common Unit Load Devices (ULDs) [39]. Using this established standard allows existing containers and pallets to be used. Compared to the orientation of an AKE container in aeroplane cargo bays, its position is rotated by 90° such that the diagonally-cut corner faces forward. The resulting unused floor space in front of the module functions as an interface to the outside. The water module uses this interface for dropping and acquiring water.
A link provides electric energy and enables data transfer between payload modules and FireWasp. This also grants remote control to the payload module.

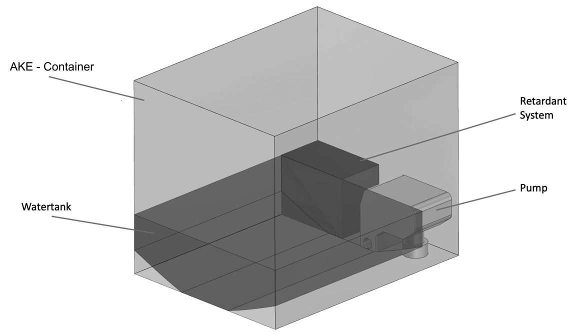



**FIG 4. Water module**

### 3.4.1. Water Module

Water Dropping

The water tank is designed in compliance with the AKE container dimensions. It is displayed in Figure 4. Angled side walls at the bottom achieve greater hydrostatic pressure benefiting a swift, focused and uninterrupted evacuation process. To empty the tank, two hydraulic drop doors open simultaneously facing outwards.

Water Refilling

A snorkel pump with a retractable hose is used to fill the water tank. Using a pump instead of water scooping allows water to be taken from anywhere – e.g. small lakes, rivers, and even water tanks. Current pumps are able to fill the water tank with a volume of 2000 litres in around 35 seconds [40]. An additional opening is installed on the rear top side of the tank, which allows refilling while FireWasp 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” [41]. The retardant is coloured to identify the application area. It can be filled into a 100-litre flame retardant tank while on the ground. The mixing process of water and retardant is not part of this work but is described in detail in [42]. A typical concentration of retardant foam is 0.4 % [43]. Assuming this concentration, a 2000-litre water load requires only 8 litre of foam concentrate. Hence, using a 100-litre flame retardant tank, the water can be dropped 12 times without refilling the retardant.

Water Tank Structure

Violent water movement, also called sloshing, can lead to impact damage of tank walls and ceiling. Furthermore, sloshing can impact vehicle stability especially when the external excitation frequency is close to the resonance frequency of the fluid [44]. To reduce aforementioned effects, vertical and horizontal baffles are integrated in the tank. The baffles must have a perforated structure, such that water flow is not obstructed

### 3.4.2. Other Modules

Besides the firefighting module, the following module concepts are presented.

Agriculture

Common uses for aircraft in agriculture are aerial application of insecticides or fertilisers, as well as seed and plant protection. Furthermore, FireWasp can be used for forest liming, which has seen increased interest over the last decade. Positive effects of liming are shown in a study by [45]. Desired characteristics of agricultural aircraft include all-round visibility, good-natured flight behaviour and high manoeuvrability even at low airspeed. Another valuable property is the ability to hover. The agriculture module consists of a tank for e.g. insecticides or fertilisers. Contrary to the water module, which is designed to unload all water at once, the agriculture module empties its tank contents continuously.

Master Module

As will be further explained in subsection 4.1, one vehicle of the FireWasp fleet is equipped with a “master module” that carries a radar. A radar system is necessary to monitor the presence of potential obstacles in the vicinity of the FireWasp fleet by rapidly scanning large areas of the environment [46]. Contrary to optical cameras and LiDAR systems, radar is not affected by impaired visibility at all [46].

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 are well suited to collect 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 [33].

Aerial Inspection and Maintenance of Long-Distance Power Lines

In today’s society, continuous energy supply is crucial. More often than not, electricity is provided to households and local industry by long-distance power lines. To maintain a reliable energy network, constant monitoring is inevitable. Airborne thermographic cameras are a reliable and efficient way to carry out these inspections.
The proposed payload module utilises infrared cameras for locating hotspots on power cables and insulators. These hotspots are indicators of material defects or system malfunctions. Even underground power cables can be reliably inspected with thermal imaging systems while alternatives such as standard video-cameras are less accurate. Furthermore, ground based inspections of power cables are significantly slower than airborne mapping [33].

## 3.5. Performance Calculation

The mission calculation is based on fixed wing preliminary design methods for cruise flight and helicopter design methods for vertical flight and hovering. For a conservative calculation, the transition periods are counted towards hovering during which more fuel is burned. Starting with an empty aircraft the required fuel for each flight segment – beginning with a fuel reserve – is determined and added to the current 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 for refilling. The number of attacks per flight is optimised by a brute force approach.
The zero lift drag and lift dependent drag determination of the fixed wing lift share of the aircraft is carried out via empirical formulas [22]. For validation the zero lift drag is also calculated using OpenVSP, showing little deviation. To account for interference between rotors and wings, the interference factors given in [47] are used. For a cruise speed of 400 km/h the wing lift is decreased by 5 % while the total drag is increased by 5 %. Having obtained the total drag and utilising the current aircraft mass, the required fuel mass for each segment can be calculated via the Breguet equation.
During the short hovering and transition periods fuel consumption is calculated under the assumption of constant aircraft mass. The required power for these segments is calculated using the blade momentum theory for coaxial rotors [48].
The Performance calculation is coupled with a mass iteration of the payload mass fraction $\mathrm{PMF} = \frac{\mathrm{PM}}{\mathrm{MTOM}}$ determining the required fuel mass and the maximum available payload mass. The following results were obtained for the design mission. The predetermined MTOM of 5670 kg is divided into a fuel mass FM of 655 kg, an operating empty mass OEM of 3080 kg and a payload mass PM of 1935 kg. In order to deliver the required amount of 11 t of water in the first attack, six aircraft are needed.
Over the entire 24 h mission 63 individual attacks are carried out by each FireWasp. In total the entire fleet is able to distribute 730 t of water to fight the wildfire.

## 4. OPERATION

### 4.1. Operational Concept

FireWasp is designed with fleet operation in mind. The fleet consists of several identical compound aircraft, but not all aircraft are equipped the same. In addition to FireWasps equipped with water modules, one vehicle – in the following referred to as guide aircraft – is deployed with a master module. While one pilot is dedicated to the guide aircraft, the pilots for water carrying vehicles are responsible for two FireWasps.

In the following paragraph the course of action during operation is elaborated in detail. In a first step, mobile GCS and a fleet of FireWasps are stationed in areas that are prone to wildfires. Upon fire detection the guide aircraft takes off to the seat of the fire analysing the terrain and gathering necessary information to further coordinate the operation. Based on the gathered information the target locations are determined and forwarded to the water dropping aircraft. At the same time the remaining aircraft are loaded with water and fly to the marked coordinates mainly autonomously. During critical flight conditions the pilot may take over control of the aircraft. These conditions include water intake and dropping, take-off and landing, flight in violent air over the wildfire and other unforeseen scenarios. If critical flight conditions are encountered and the pilot does not intervene within a certain time, FireWasp will transition into an emergency hover.

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.

The guide aircraft stays over the wildfire location to update the fleet and ground personnel on the current situation. Using RADAR, long range foreign object detection is possible to prevent interference with the operation. Another task of the guide aircraft is spotting and evaluating possible water sources for refilling. Circling over the location of operation, it can take advantage of efficient fixed wing cruise flight at low speed to maximise loiter time. Meanwhile, the rest of the fleet carries out multiple firefighting attacks before returning to the airport for refilling of fuel and retardant. Between each individual attack, FireWasp is able to refill water at any accessible water source. To optimise flight routes and firefighting strategy, flight data and missions critical information is logged and saved for further analysis and mission planning.

### 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 2022. The natural park is located a few kilometres 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. Contrary to widely used firefighting aircraft, the ability to hover prevents contact with salt water and therefore eliminates the risk of corrosion.

A more challenging scenario is aerial firefighting in a mountain region without a water source for refilling in the proximity of the fire. With increasing altitude the available power decreases which leads to less efficient rotary wing flight and thus increased fuel consumption. However, during cruise flight FireWasp is more efficient than helicopters due to its fixed wing configuration. In this case, the fleet has to fly back to the base of operation to refill water between successive attacks. Therefore, the comparatively low MTOM and associated low payload mass of FireWasp is considered a disadvantage.

## 5. CONCLUSION

FireWasp fulfils all requirements stated in the task of the DLR Design Challenge 2022. A fleet of six FireWasps is able to drop a total of approximately 730 t of water over the course of the 24 hour design mission.

From a mechanical standpoint, FireWasp successfully combines design and performance attributes of fixed wing and rotary wing aircraft. For flexible take-off, landing and water intake FireWasp features co-axial rotors that enable VTOL. This ensures optimal firefighting capabilities once the seat of the fire is reached. During cruise flight, the majority of lift is efficiently generated by wings. Thrust is generated by a single pusher propeller at the back permitting a high cruise speed compared to conventional helicopters of 400 km/h. This significantly decreases the critical initial response time of FireWasp.

FireWasp's hardware and software capabilities allow autonomous and remotely controlled flight which eliminates the need for on-board pilots and therefore contributes to the safety of firefighting personnel. The fleet concept is embedded into FireWasp's design to maximise its potential to fight wildfires continuously. Using a dedicated FireWasp identical in design as a guide vehicle provides an overview over the operation and improves mission management without requiring another type of aircraft.

Versatility is provided by a modular design giving FireWasp the ability to complete various mission profiles. This also benefits the holder of a FireWasp fleet economically by ensuring revenue can be generated even during wildfire off-season.

For these reasons FireWasp is the ideal next generation aerial firefighting vehicle, fighting the consequences of climate change effectively starting 2030.

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