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LIGHTWEIGHT UAV FOR EMERGENCY MEDICAL SERVICE

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Abstract

This article presents the innovative UAV project for emergency medical services. Designed UAV combines VTOL characteristics that are vital to perform such an emergency medical mission with fast forward flight capability that is also crucial in case of such mission. The main purpose of the designed UAV is to deliver the required medical package to the place where access is difficult and the estimated arrival time of a conventional ambulance is too long. The cost of the support of such UAV could be significantly lower than in the case of a medical helicopter, which is not necessary in less serious cases. Designed UAV can be also used for the fast delivery of essential medical substances (e.g. blood).

Keywords: UAV, VTOL, aircraft design

1. Introduction

The selection of the configuration was the first and crucial step of the design [1]. After analysis of many different copter configurations together with selected crash reports analysis, the so-called hybrid UAV [2] which is the coaxial quadcopter configuration crossed with a conventional airplane, was selected [3]. All power units for VTOL capability are electric and they are doubled for redundancy purposes, while the maximum T/W (thrust to weight ratio) is about 2.0. Such configuration allows to sustain stable flight (vertical phases) in case of one motor failure. Two versions of the vehicle are designed: fully electric (propulsion systems for the forward flight and VTOL are electric) and mixed where forward flight unit is a small piston engine.

The required payload is 3 kg with dimensions of 30x30x50 cm. The medical package is to be safely dropped on a parachute or UAV will land very close to the place of delivery of the package. MTOW cannot exceed 25 kg and the required endurance is 1h for fully electric propulsion and 2 h for the mixed one. The range is to be 40 km for fully electric configuration and 150 km for the mixed one. All the expected performance parameters make design the real challenge. Especially the design of VTOL system which balances conflicting requirements of massive thrust (more than 50 kG) and minimal own weight is very demanding. For efficiency, safety and redundancy reasons, this system is dedicated and optimized only for VTOL maneuvers and takes no part in forward propulsion, and yet has had to be optimized weight-wise to address payloads requirements.

Moreover there are many unknowns connected with the effect of VTOL propellers on the forward flight, especially aerodynamic drag, which was investigated experimentally in the Wind Tunnel [4]. Presented UAV is to be equipped with the communication system allowing the BVLOS missions and sense & avoid systems that provide safe vertical landing in urban/populated areas.

Paper presents all phases of the project: conceptual design and preliminary design, including MDO optimization [5, 6, 7] of the configuration (aerodynamics, stability, structure, performance). The manufacturing aspects are also presented. The maiden flight of the presented UAV was expected in spring 2020, however due to the COVID-19 pandemic program is slightly delayed and the first copter-flight was performed in November 2020 and the first flight with the transition from vertical to horizontal flight was performed in May 2021. The UAV was named "PW Chimera" (PW - Politechnika Warszawska, Chimera as a creature with parts from multiple species).

1.1 Main Assumptions

The primary purpose of the designed UAV is to deliver a parcel of relatively large size and medium weight (Table 1). The aircraft should be capable to takeoff and land on a spot in a limited area, or to drop the payload in flight. This forced a wide fuselage and a load position close to the center of gravity (Figure 1). The expected performance characteristics are the result of the assumed mission profile and depend on the type of propulsion system.

Table 1 – Main performance characteristics

Propulsion type	full electric	piston/electric
range (radius)	40 km (20 km)	150 km (75 km)
max. airspeed	80 km/h	140 km/h
operational ceiling	0-150 m AGL	
MTOW	25 kg	
Payload	3 kg	
Payload dimensions	30x30x50 cm	

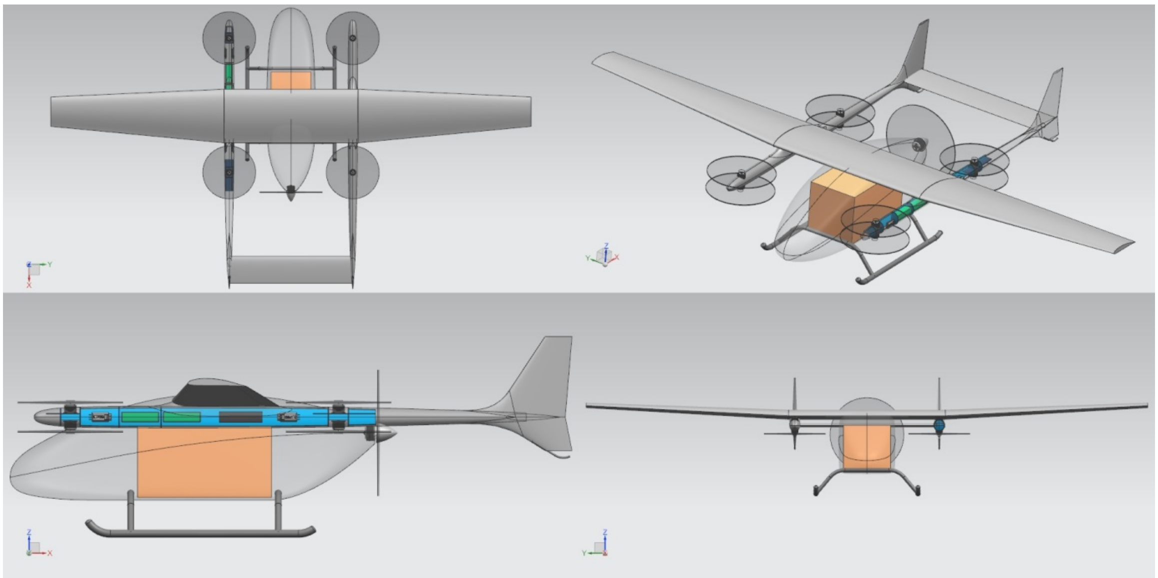

Figure 1 – UAV PW Chimera - 3 projections and general view - initial design

The primary purpose forced the mission profile. Three basic mission profiles were assumed: cruise(1), loiter-monitoring (2), delivery and return (3). The aircraft was designed with two types of propulsion system for level flight: an electric motor and a fuel engine (Figure 2). In both configurations VTOL propulsion was realized with electric motors. Electric motor for a level flight gives reliability, easy maintenance and the aircraft does not need any fossil fuel, which makes it clean and less complicated. On the other hand fuel has a much higher energy density, compared to the amount of energy that can be stored in the batteries, but does not have the listed advantages of electric propulsion (Figure 3). VTOL motors are always electric due to the number of motors required, fast control response and reliability. Time needed for takeoff, or landing in the VTOL configuration was estimated for about 2 min. Taking this into account the batteries capacity was calculated. The maximum take-off weight (regulations) limits the weight (capacity) of the batteries for forward flight in case of full electric version or fuel amount in case of the piston engine.

The number of different VTOL aircraft configurations is possible to choose. A careful review of the state of the art of the VTOL aircraft reviled, which types of configurations were successfully built and performed well. Many of the reaming configurations were able to takeoff, but didn't succeed for various reasons, like for example: less stable flight, low mechanisms reliability, high costs of maintenance. The selected configuration should be efficient, possibly simple and with high rate of probability of success basing on the historical data.

Figure 2 – Two PW Chimera: full electric (left), mixed propulsion (right)

1.2 Safety issues

As the designed UAVs are intended for flights over populated areas, flight safety considerations were a very important issue. Two safety solutions were implemented, allowing either for the continuation of the mission or a safe emergency landing - redundant VTOL motors and rescue parachute. The redundancy is based on the use of eight electric motors for the hover, mounted in four sets with coaxial propellers, giving a total thrust of twice the weight. The following scenarios were considered taking into account the failure of the power units for both forward and hover flights:

- one VTOL electric motor failure - this results in the second motor being turned off (diagonally) and other motors increase thrust by 33% - this solution allows for sufficient thrust to control the UAV, continuing the flight until a safe landing at the designated aerodrome,
- forward motor/engine failure - causes the vehicle to hover and land in a safe place,
- critical failure of the control system or inability to apply the above scenarios - this results in the use of a rescue parachute.

Figure 3 – PW Chimera - full electric version

2. Aerodynamics

Three basic types of aerodynamic configurations were chosen for more careful investigation: Quad Plane (Figure 4), Tail Sitter (Figure 5) and Tilt Prop (Figure 6). Every configuration has its own pros and cons [8]. Quad Plane configuration is very simple and robust. This is a straight forward connection of multicopter with airplane. It doesn't have any moving parts, except propellers. Control of the mulitcopter configuration and the airplane configurations is rather well known. The transfer function of switching between the flight modes can be easily blended. The main drawback of the configuration is that the VTOL propulsion is used only for takeoff and landing for a very small percentage of the time of the mission. During the flight in the airplane mode VTOL propellers (turned off) are the source of additional drag and together with VTOL motors additional mass. Tail Sitter configuration

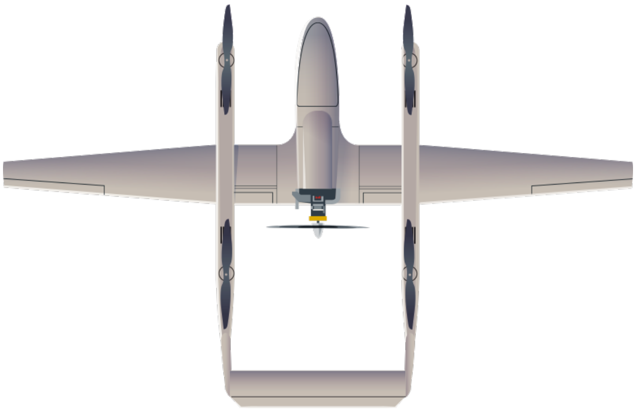

Figure 4 – Quad plane [9]

Figure 5 – Tail sitter [10]

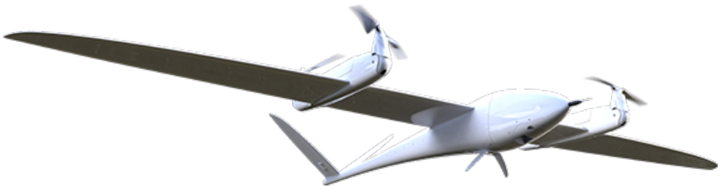

Figure 6 – Tilt prop [11]

[10] has the advantage that the same propulsion system is used for vertical takoff and landing as well as for level flight. No additional mass or drag is generated. The drawback is that the constant pitch propeller cannot be equally efficient for both takeoff and cruise conditions. A variable pitch propeller would be a better solution but the mechanism of variable pitch adds additional mass and complicates the structure especially in a small size UAV. The mechanism may be also the source of frequent malfunctions. Another serious disadvantage is the position of the aircraft on the ground during takeoff and landing, from which the configuration has name Tail Sitter. The position is less stable, which can make landing maneuver difficult and needs wide supports, which add mass. This position and large wing surfaces make this configuration also very pronounced for side winds. Tilt Prop and Tilt Rotor [11] configurations are similar and will be discussed together. The difference between them is that in the Tilt Prop configuration motor with a propeller can change orientation angle to the rest of the aircraft body and in the Tilt Rotor configuration orientation of the whole wing is changed with the VTOL propulsion system mounted on it. For this configurations aircraft remains in the horizontal position, which is opposite to the Tail Sitter configuration, but also uses the same propulsion system for VTOL and level flight, which is opposite to the Quad Plane [9] configuration. The drawback is, that it needs an additional mechanism for orientation change of the propulsion system. This adds mass and complexity, which may reduce reliability. As in the Tail Sitter configuration a variable pitch propeller is needed for the best performance in different flight conditions, with all its pros and cons.

After going through all the possible configurations and investigating potential advantages and disadvantages the Quad Plane configuration was chosen. The reliability was the driving factor to choose the configuration, with some reduction of performance coming from the drawbacks of the configuration. To even increase redundancy of the aircraft eight VTOL motors in H configuration were planned, which enables to safely land even if one of the VTOL motors breaks.

The aerodynamic analysis covered two basic issues: the test of the aerodynamics of VTOL drive and

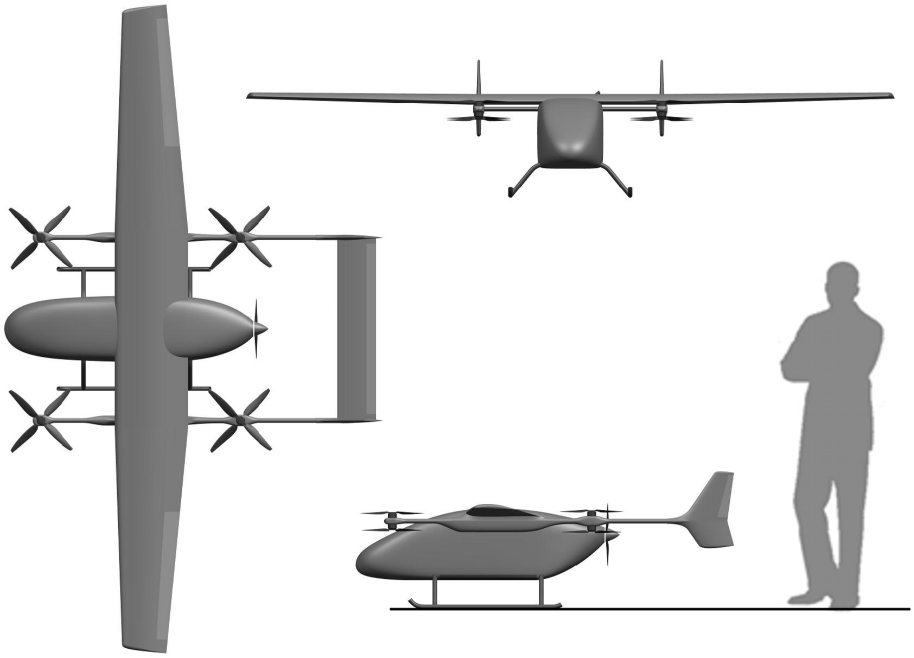

Figure 7 – UAV PW Chimera - three view

the calculation of the aerodynamic characteristics of the UAV treated as fixed wing airplane. The first issue was related to the measurement of the thrust of power units performing vertical maneuvers and their influence on aerodynamic drag during horizontal forward flight. The second part of the analysis concerned the classical aerodynamic analysis, including basic aerodynamic characteristics, flying qualities properties (stability) and performance.

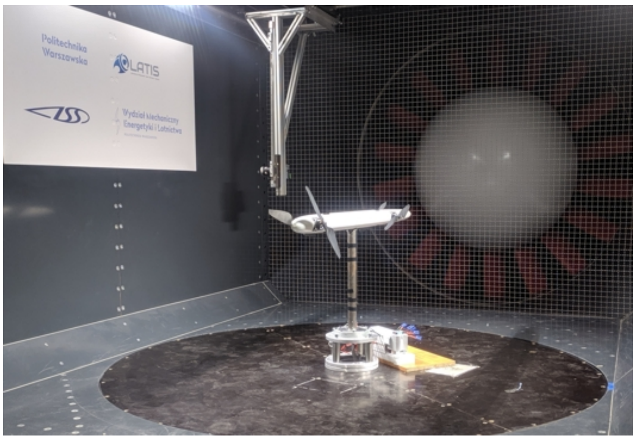

Figure 8 – Test stand of VTOL propellers in the wind tunnel

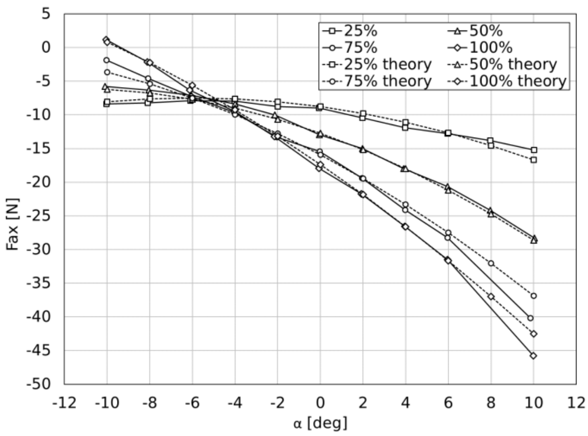

Figure 9 – aerodynamic drag due to the hovering propellers

2.1 Hovering propellers

The fundamental question was the thrust that due to the assumed redundancy should be close to twice a weight. The second issue was the aerodynamic drag induced by propellers working in the plane parallel to the airspeed of UAV. The experience collected during flight tests of UAVs in similar configuration showed unexpectedly high aerodynamic drag of propellers. Because the problem of the aerodynamic drag caused by propellers is not well described in the literature, therefore special experimental investigation have been carried out [12]. The test stand in the wind tunnel is presented in Figure 8. The wind tunnel test proved the assumed total thrust and showed the real aerodynamic drag induced by hovering propellers (Figure 9):

- Coaxial configuration proved full redundancy for any one of the front rotors failure, and limited redundancy (controlled crash landing) for tail rotors as a consequence of their smaller thrust.
- Rotors mounted on the top of beams are generating less thrust (c.a. 10%) than the bottom ones due to the blockage effect. This resulted in a redesign of the tail beams to reduce the cross section in the working area of the propellers (Figures 3 & 7).
- Drag force produced by working VTOL propulsion system can be approximated by equivalent sphere shape with 0.5m diameter.

2.2 Aerodynamic characteristics

The aerodynamic characteristics were computed using low and high fidelity aerodynamic analyses methods. Basic aerodynamic characteristics and stability derivatives were computed using 3D panel method (PANUKL package [13]) as it is enough good for most characteristics. Particular cases were analyzed using MGAERO package [14] based on the multigrid method [15] which solved the Euler equation and using Ansys-Fluent software [16], mainly for reliable aerodynamic drag results.

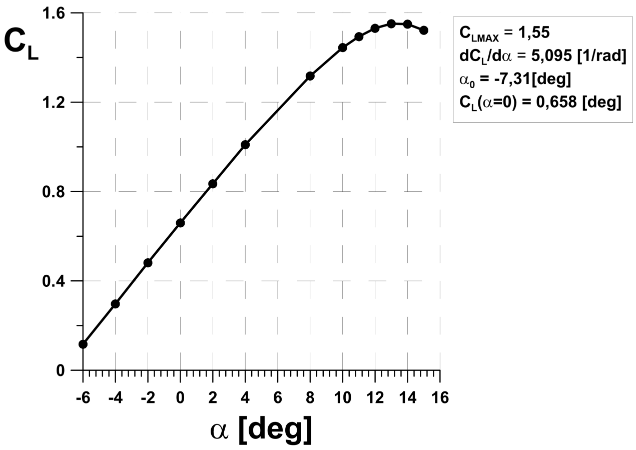

Figure 10 – Lift coefficient versus angle of attack

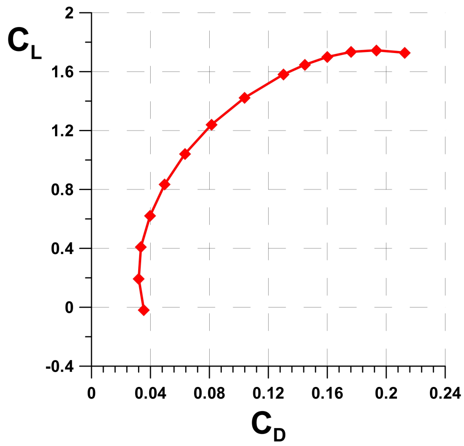

Figure 11 – Drag polar

The obtained results proved the correctness of the initial assumptions. The maximum lift coefficient (Figure 10) reached the value high enough to satisfy assumed stall airspeed and aerodynamic drag (Figure 11), despite wide fuselage, should allow to reach satisfying maximum airspeed and climb ratio.

2.3 Stability analysis

The dynamic stability analysis was preceded by the determination of stability derivatives needed to estimate the static margins and directional stability. Both basic pointers, i.e. pitching moment vs. angle of attack (Figure 12) and yawing moment versus sideslip (Figure 13) are correct from the stability point of view. The static margin (HN) presented in Figure 14 corresponds to the position of the CG in 36% of MAC (Mean Aerodynamic Chord) and relates to typical mass breakdown (batteries, payload, etc.). Within the dynamic stability analysis, made with the use of SDSA package [17] [18], typical modes of motion were recognized and all of them satisfy the criteria based on CS-23 [19] regulation or MIL [20] specification. The most critical mode results, i.e. Dutch roll characteristics are presented in Figure 15 against the background of CS-23 criterion: "Any combined lateral-directional oscillations ("Dutch roll") occurring between the stalling speed and the maximum allowable speed appropriate to the configuration of the aeroplane must be damped to 1/10 amplitude in 7 cycles ..." which can be translated into the ratio of damping to frequency.

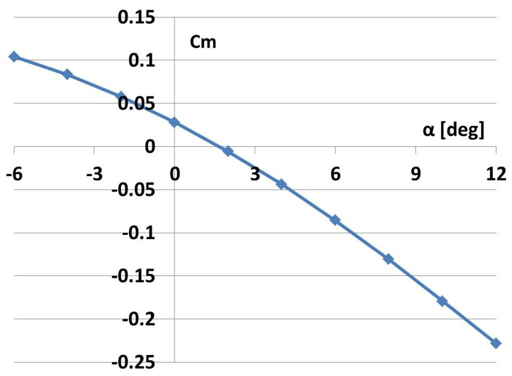

Figure 12 – Pitching moment coefficient versus angle of attack

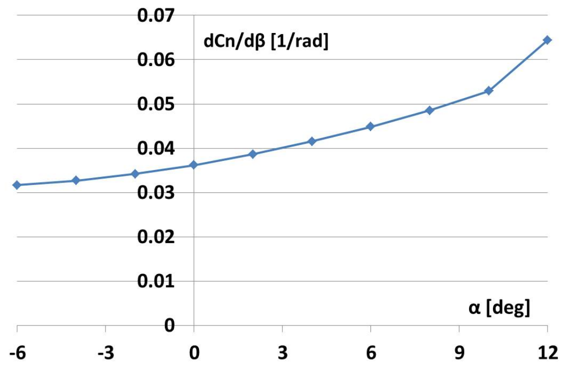

Figure 13 – Yawing moment coefficient versus sideslip angle

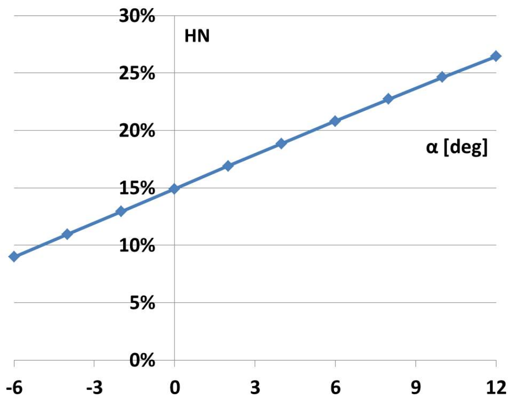

Figure 14 – Static margin versus angle of attack

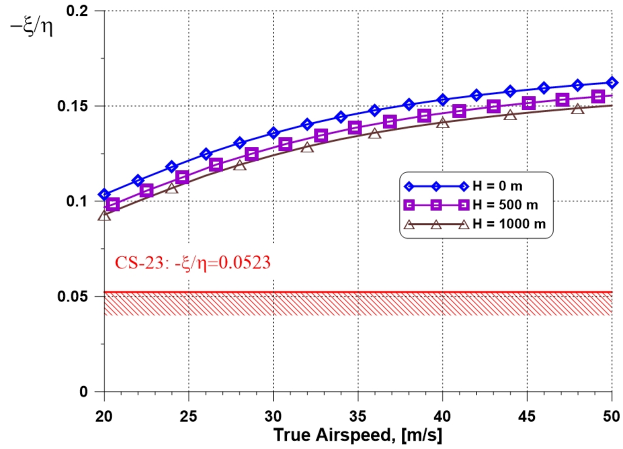

Figure 15 – Dutch roll - CS23 criterion

3. Electric installation

Electric installation in the presented Quad Plane is divided into the following power independent subsystems:

1. Avionics – auto pilot, GPS navigation, telemetry, remote control etc.
2. Propulsion systems for vertical take off and landing and for fixed wing forward flight (FW FF)

Avionics has independent from the propulsion subsystem source of electric power in form of a separate set of lipo batteries which is situated in the nose of the airplane. Avionics power source consists of two batteries connected separately to provide redundancy for control systems, in case when one battery fails. The main electric propulsion subsystem in all-electric configuration powers VTOL and FW FF motors from one battery set. The design of this power supply was tailored to the very high requirements of the VTOL configuration. During hovering maneuvers, the presented UAV requires a very high T/W ratio in the vicinity of 1.5 to 2 due to controllability issues, inertia, wing drag and the required flight safety levels. This configuration requires powerful electric motors in the range of 1.5 to 2 kW. With the VTOL system consisting of 8 motors, the total required power rises up to 15 kW. Transporting such high electric power requires a high-current installation with an appropriate cabling cross-section.

3.1 Aluminum vs. copper

The material of choice for aircraft electrical installation is usually copper (Cu), due to its excellent conductivity, flexibility and bending strength. These excellent characteristics are, unfortunately, paid for by the high density of this metal, i.e. its weight - see Table 2. The rarely used and slightly less conductive material is aluminum (Al). But its advantage lies in weight which is 3.3 times lighter than copper. From the properties of Al and Cu presented in Table 2, it can be noted that while copper is 1.6 times more conductive than aluminum per volume, aluminum is in fact 2.1 times more conductive than copper per weight. This means that with the same conductivity (or resistance), cabling made from Al will be 2.1 times lighter than from Cu at the cost of a larger volume and bigger thermal expansion (by 30

Table 2 – Material properties (sorted by conductivity)

Material	Conductivity σ at 20℃ [S/m]	Density ρ [g/cm^3]	Thermal expansion		Resistivity × density	
			Linear coefficient at x10^{-6} K^{-1}	Volumetric coefficient at x10^{-6} K^{-1}	[(g·mΩ/m^2]	Relative to Cu [%]
Silver	6.30×10^7	10.5	18	54	166	111
Copper	5.96×10^7	8.9	15	51	150	100
Gold	4.11×10^7	19.3	14	42	427	285
Aluminium	3.77×10^7	2.7	23.1	69	72	48

Electric power transport system designed for this aircraft in accordance with DIN 43671 standards for Cu weights 1968 g, while in case of aluminum its weight drops down to 920 g, thus saving over 1 kg, that can be used for additional payload. It is worth noting that the mass fraction of cabling weight in relation to the payload weight is equal to 65% for Cu installation, while for Al it is only 30%. In the extremely mass sensitive VTOL configuration this is a significant weight saving.
Above mentioned DIN standards relate to continuous ampacity (current-carrying capacity) of electric busbars, while the designed VTOL system works at a time for about 1 minute only during take-off and landing maneuvers. The aircraft then enters the long cruse phase without the use of VTOL motors, during which the power transport system can cool down. Thus, the cabling cross-sections suggested by the standards can be safely reduced, decreasing even further the weight of the cabling and the entire aircraft.

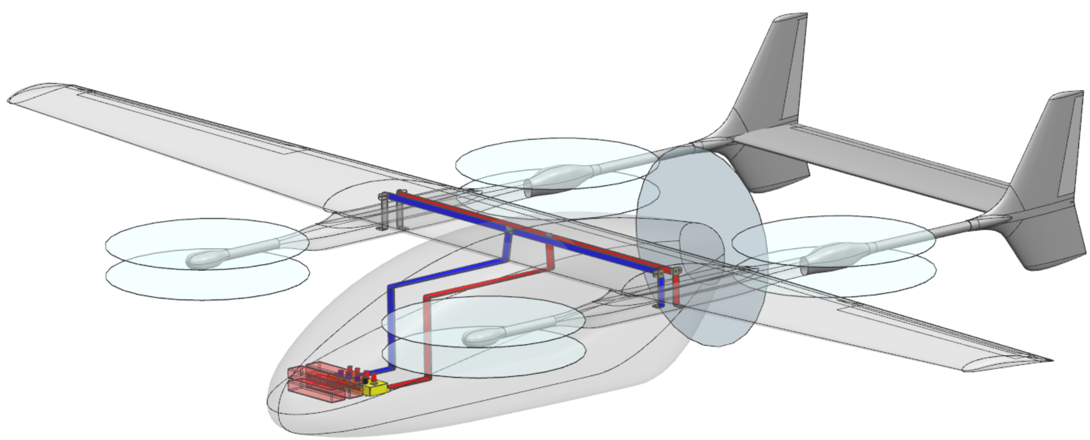

Figure 16 – UAV PW Chimera - Busbar structure

3.2 VTOL busbar system

An electric power transport system based on aluminum busbars was chosen to supply the VTOL installation. The use of such systems in airplanes is not a new idea and is successfully used in

electrical installations in large airplanes such as the Airbus A380 to save weight [21]. Of course, these are high power installations that are not commonly used on smaller aircraft. However, in VTOL airplanes, the use of busbars is justified by the weight saving, despite the greater amount of work necessary for its design and maintenance. The aluminum busbars are not flexible and their routing, interaction with the structure and technological breakdown must be taken into account in the design phase of the entire aircraft structure.
The location of the busbar system within the aircraft structure is shown in Figure 16. The installation connects battery packs located in the nose of the aircraft with 8 VTOL motors mounted on the tail beams in front of and behind the main wing. The busbars go from the nose section through the fuselage to the center wing where they split and join the two tail beams. The busbars end in the middle part of the tail beams with terminals boards to which the ESC (electronic speed controller) power cables are attached, and then to VTOL motors.
Forward propulsion motor installed at the end of the fuselage is connected to the busbar system in the center wing section where it splits to the left and right tail beam. For clarity it is not depicted in Figure 16.

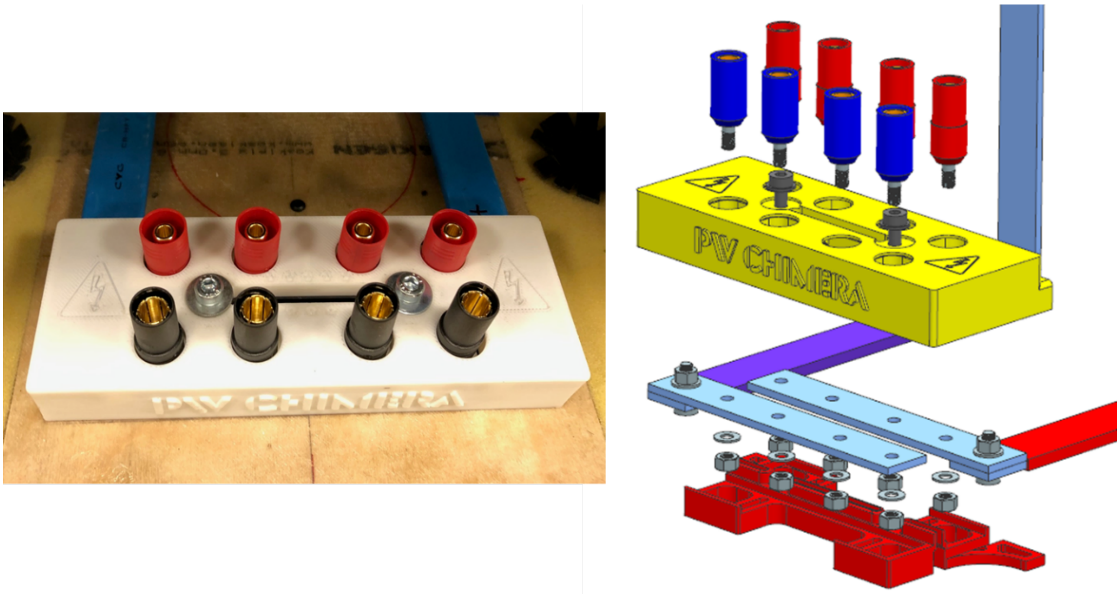

Figure 17 – Battery connection box

The busbar system consists of a battery pack connection box (Figure 17) and ten sections of specially designed busbars interconnected by a screw with self-locking nuts and galvanized washers. The battery connection box was made in 3D printing technology (Fused Deposition Modeling - FDM) and contains two sections of the busbar as terminal boards to which the battery connection sockets are screwed. The box has been designed in such a way as to prevent accidental shorting of the battery packs.

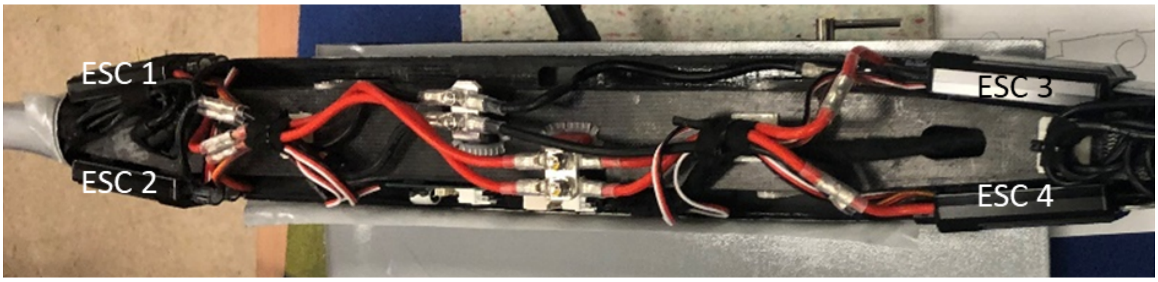

Figure 18 – Tail beam connections to ESC modules

The rest of the busbar system connected to the battery connection box is insulated with heat shrink tubes for protection. The system is divided into several sections according to the technological breakdown of the aircraft structure: fuselage, center wing and tail beams. The fuselage section busbars are attached at their two ends to the battery connection box and busbars in the center wing section. The busbars of the center wing section are attached to its ribs through heat-shrinkable insulation and polyethylene edge covers. The tail beam section is connected to the center wing section and serves as terminal boards for ESC (Electronic Speed Control) modules connection (Figure 18).

4. Summary - first flights

The first flight tests were carried out for the full electric version and required some tuning of the automatic control system. First the hover phase was exercised (Figure 19). This part of the tests took few months, mainly due to the winter weather and COVID lock-down. In may 2021 the first forward flight with a transition phase was performed (Figure 20). The test flights proved that all assumed performance parameters were achieved. The test of the transition phase showed that the effectiveness of horizontal acceleration depends strongly on the initial pitch angle. A negative pitch at the beginning of acceleration significantly reduces its' time and total energy consumption. The aircraft is stable in all flight phases. Preliminary tests of performance characteristics gave maximum airspeed above 25 m/s and climb ratio about 2.3 m/s in the case of "airplane" mode. For the mixed electric/piston version all performance characteristics are expected to be much better.

Figure 19 – PW Chimera - prototype - hover test (January 2021)

Figure 20 – PW Chimera - cruise test (May 2021)

The first flights don't allow to formulate far-reaching conclusions. They will only be possible after a complete program of flight tests. However, already now some advantages can be pointed out, such as fast vertical takeoff and landing. All flight phases show good flying qualities that gives a chance for success in real missions giving an advantage over multicopters and fixed wing aircraft.

5. Acknowledgment

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7. Copyright Statement

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