AERODYNAMIC DESIGN OF INNOVATIVE LAYOUT UNMANNED AERIAL VEHICLES SUPPORTED BY HIGH-FIDELITY NUMERICAL TOOLS

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ABSTRACT –
In the current study, a methodology for the aerodynamic design of fixed-wing Unmanned-Aerial-Vehicles (UAVs) is presented. The methodology is based on the three phases of aerodynamic design, i.e. the conceptual, preliminary and detail design phases. The conceptual design essentially refers to the initial design phase, where the first configuration layout is drawn based on the mission requirements, design specifications and regulations. Key UAV layout aspects are defined, and early trade studies are conducted. Having defined the overall platform shape, the preliminary design is in turn initiated, where each part (e.g. wing, fuselage, empennage) is analyzed in detail. The investigations are conducted synergistically with the other aeronautical disciplines, such as structures, propulsion, control and electronics, whereas optimization studies are also performed to fine-tune the UAV performance. Finally, during the detail design the construction drawings are generated taking into account manufacturability and production considerations. To facilitate the required calculations, a combination of both low- and high-fidelity tools and methods is employed. The low-fidelity tools refer to the Laboratory of Fluid Mechanics and Turbomachinery (LFMT) in-house sizing tools, which are based on well-established textbook methods and can provide a rapid and complete weight, aerodynamic, stability and performance analysis of a UAV platform. The high-fidelity methods refer to the Computational Fluid Dynamics (CFD) modeling that is performed to support the sizing calculations and to accurately extract the much-needed aerodynamic and stability coefficients of the aerial vehicle. The CFD modeling is conducted using the BETA CAE software (ANSA, META), coupled with the CFX flow solver. A step-by-step presentation of the UAV aerodynamic design methodology philosophy is made, emphasizing on the interaction between the various tools at each design phase. The sizing procedure of two of the LFMT UAV prototypes (RX-3, RX-4) is also presented, as representative fixed-wing UAV design case studies.

TECHNICAL PAPER –

1. INTRODUCTION

In a very broad classification, Unmanned Aerial Vehicles (UAVs) can be divided to the multi-rotor and the fixed-wing ones, based on their fundamental lifting mechanism. Although being relatively cheap and maneuverable, the multi-rotors are limited to small-scale surveillance and entertainment purposes for the time being, due to their considerable limitations in payload capacity and flight endurance. However, those limitations do not apply to the fixed-wing unmanned platforms and especially the medium-sized tactical and Medium Altitude Long Endurance (MALE) ones, which feature several advantages, such as the low operating cost, the ability to operate under adverse or hazardous conditions, and the increased flight endurance. As a result, they have a much broader mission range and are ideal solutions for a wide range of operations, e.g. fire detection, search and rescue, coastline and sea-lane monitoring, as well as security surveillance and defense-related missions [1].
Due to this large variety in mission type and corresponding mission requirements, the UAV design procedure can be as complex as in the case of full-scale manned aircraft. It should also be noted though that, according to recent research [2], "the global UAV market is projected to grow to USD 19.85 billion

by 2021, at a compound annual growth rate (CAGR) of nearly 13% over the forecast period", with the tactical and MALE categories being arguably the largest ones. Hence, more efficient and precise methods are needed, which allow for a rapid sizing procedure to be conducted, at the lowest possible time and resources.

In the present paper, the Laboratory of Fluid Mechanics and Turbomachinery (LFMT) in-house sizing methodology and tools are presented, which are based on well-established textbook methods and can provide a rapid and complete weight, aerodynamic, stability and performance analysis of a UAV platform. The high-fidelity CFD modeling methodology that is performed to support the sizing calculations and to accurately extract the much-needed aerodynamic and stability coefficients of the aerial vehicle is also presented. The CFD modeling is conducted using the BETA CAE software (ANSA, META), coupled with the CFX flow solver. The sizing procedure of two of the LFMT UAV prototypes (RX-3, RX-4) is also presented, as representative fixed-wing UAV design case studies.

2. SIZING METHODOLOGY

The LFMT UAV sizing methodology is presented in Figures 1 and 2. Based on the classic aeronautics theory, the aerodynamic design procedure is divided into three main stages i.e. the conceptual, preliminary, and detail design stages [3,4]. At first, the aircraft's mission profile is defined and the respective mission requirements are set. Based on these requirements, an initial concept is developed and the weight, aerodynamic and performance characteristics are estimated using dedicated sizing methods. That is essentially the conceptual design phase (Figure 1). In the preliminary design phase, each part of the aircraft is analyzed and optimized. For that purpose, more detailed calculation methods and sizing routines are employed, the external geometry is defined in detail and other disciplines are getting involved as well, such as structures and control, to perform a complete study of the aircraft (Figure 2). Finally, the detail design involves the construction drawings generation. To support the sizing calculations, dedicated tools are needed, which include the semi-empirical calculations from the early conceptual to the more advanced preliminary design phase. Moreover, higher-fidelity analysis methods, i.e. Computational Fluid Dynamics (CFD), are also employed. CFD can help a long way in increasing the aerodynamic and stability coefficient prediction accuracy, and in saving resources, both time and money, that would otherwise be spent in conducting experiments [5, 6, 7, 8].

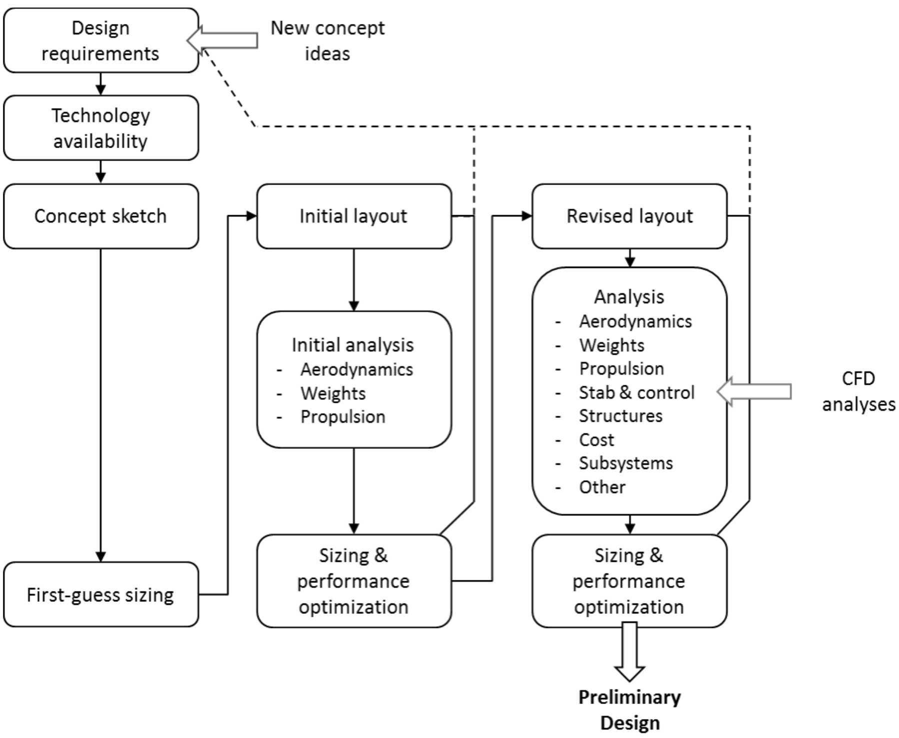

Figure 1 – LFMT conceptual design roadmap

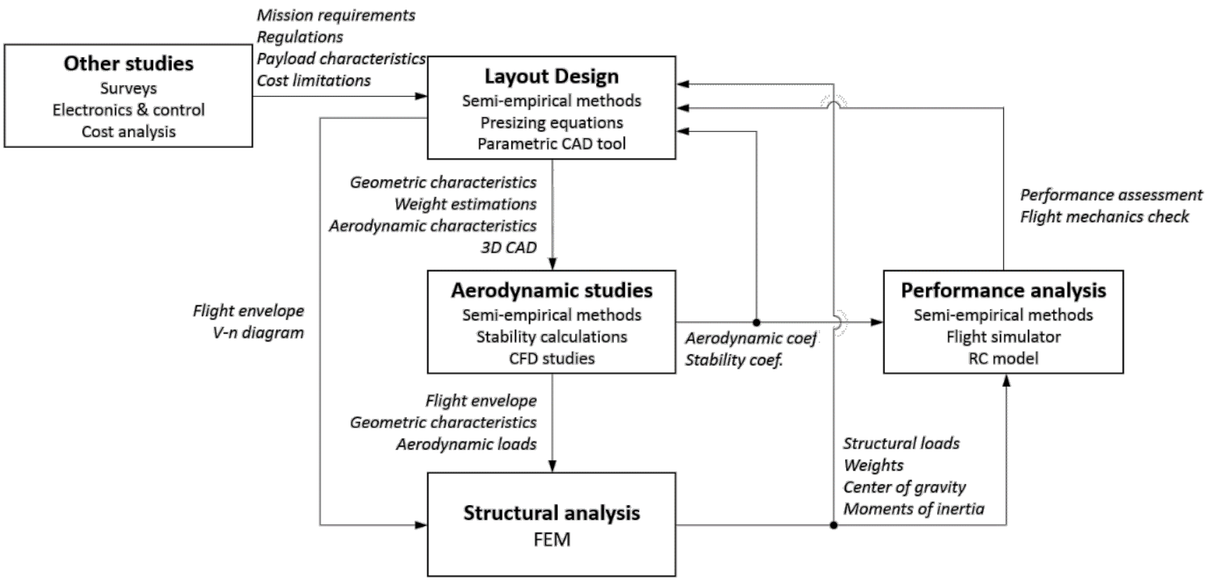

Figure 2 – LFMT preliminary design roadmap

In-house sizing tool

The LFMT tool is based on aircraft design methods, such as the ones described in [3,4,9]. It is a combination of analytical and semi-empirical presizing methods, whereas all the necessary modifications have been made to include the aspects of unmanned aircraft design. It can be used to carry out a complete layout design study and has been validated on commercial airliners and unmanned aerial vehicle configurations [10,11].

Based on theoretical, semi-empirical relations and statistical data, the presizing methods are used to calculate the first estimates regarding the weight and performance parameters. Typical examples of a theoretical and a semi-empirical relation are shown in equations 1, 2 and 3. More specifically, eq. 1 is a theoretical relation, also known as the Breguet equation. As thoroughly explained in [3] is used to estimate the range (R) or endurance (E), based on the flight conditions, the fuel consumption, the aerodynamics, and the fuel reserves of an aerial vehicle:

$$R = E \cdot V = \int_{W_{i+1}}^{W_i} \frac{V}{c_t} \frac{L}{D} \frac{dW}{W} \tag{1}$$

Moreover, equations 2 and 3 are two formulas used to estimate the weight components of an aerial vehicle. Equation 2 is used to estimate the empty (tare) weight fraction (W_e/W_0) of an aircraft in the early design phases, where very few information is available regarding its layout. Note that W_e and W_0 denote the empty, and the gross takeoff weight of the aircraft, respectively. Hence, statistical data and coefficients (e.g. A, C and K_{ws} in eq. 2) are used:

$$W_e/W_0 = A \ W_0^C K_{ws} \tag{2}$$

Equation 3 on the other hand, is used towards the final stages of the conceptual design phase and during the preliminary design phase. It is used to estimate the weight of the wing based on its key geometric and operational characteristics:

$$W_{(wing)} = F_c F_w 0.036 S_w^{0.758} W_{fw}^{0.0035} \left(\frac{A}{cos^2 \Lambda}\right)^{0.6} q^{0.006} \lambda^{0.04} \left(\frac{100t/c}{cos\Lambda}\right)^{-0.3} \left(N_z W_{dg}\right)^{0.49} \tag{3}$$

More details about the coefficients shown in equations 2 and 3 can be found in [3]. Overall, the presizing tool is very important during the aerodynamic design procedure, since the estimated parameters are essentially the only reliable guidelines that a designer can follow, before other experts are involved. Figure 3 presents a typical screenshot of the module, where part of the conceptual design calculations is shown. The presizing tool can also be used to carry out performance analysis studies of aircraft configurations. Moreover, it plays an important, albeit not as crucial, role during the preliminary design phase, as it can be used to quickly evaluate possible changes in the layout. However, a more thorough presentation of this phase is beyond the scope of this study, due to the fact that it is a combination of various disciplines and methods. More details can be found in [3,11].

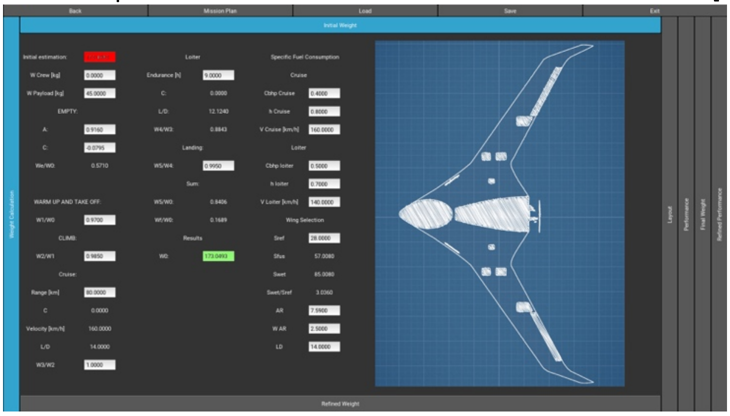

Figure 3 – Screenshot of the LFMT in-house sizing tool

CFD methodology

The CFD computations are performed to provide the supporting aerodynamic and stability coefficients and data, which are in turn used in the sizing procedure (Figures 1 and 2). This philosophy ensures that the prediction accuracy of the aerodynamic and stability data is kept at high levels, allowing for a more detailed and optimized results. Regarding the CFD methodology, the first step is to draw detailed 3D CAD models using commercial and in-house tools [12]. The CAD models serve as the base for the computational grids. More specifically, the ANSA software [13] was used for the grid generation. The computational modeling is carried out with the commercial code CFX (ANSYS® Academic Research CFD/CFX, Release 18.2), whereas the META software [14] is used for the post processing of the simulation results.

Indicatively, for the case studies described in this paper, the grid for the external flow analysis for both the RX-3 and RX-4 consists of approximately 8.000.000 computational nodes. Following a general rule of thumb, 20 inflation layers are implemented on the walls so that the y+ does not exceed a value of 5 and that the boundary layer phenomena can be properly modelled. In figure 4 the generated meshes of both the RX-3 and RX-4 prototypes are presented.

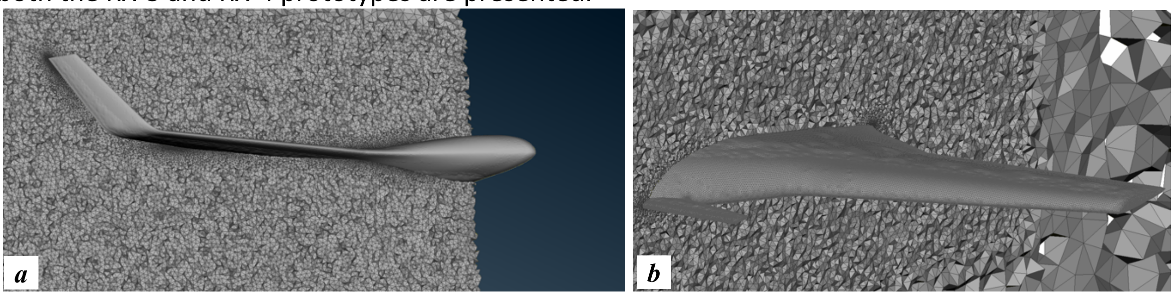

Figure 4 – RX-3 (a) and RX-4 (b) detailed mesh for external flow simulation

Finally, regarding the external flow simulation, the Reynolds-Averaged-Navier-Stokes (RANS) equations are solved, coupled with the Low-Reynolds Spalart-Allmaras (S-A) turbulence model [15]. The S-A turbulence model has been widely used in aeronautical applications and has been proven to be an adequate turbulence model for predicting turbulent or transitional external flows around airfoils and wings, since it is capable to correctly correlate the occurring strong pressure gradients with the developed boundary layers (eq. 4). A wide range of angles of attack is examined to ensure that all possible flight conditions are investigated, including stalling.

$$\frac{D\tilde{v}}{Dt} = c_{b1}[1 - f_{t2}]S\tilde{v} + \frac{1}{\sigma}\left[\nabla \cdot \left((v + \tilde{v})\nabla\tilde{v}\right) + c_{b2}(\nabla\tilde{v})^2\right] - \left[c_{w1}f_w - \frac{c_{b1}}{\kappa^2}f_{t2}\right]\left[\frac{\tilde{v}}{d}\right]^2 + f_{t1}\Delta U^2 \qquad (4)$$

3. CASE STUDIES

RX-3

The main goal of the DELAER research project is the design, development, manufacturing and flight testing of a prototype Unmanned Aerial Vehicle System (UAS), which will provide direct support to Greek isolated territories and islands, via aerial delivery of lifesaving supplies and dedicated equipment. The system will be based on a large-scale, autonomous, fixed-wing, novel Blended Wing Body (BWB) UAV configuration, as well as a portable ground control station (GCS). The DELAER RX-3 mission involves cruising to the point of interest for up to 65km, payload delivery, and cruising back to the base of operations. RX-3 payload has been selected to support a wide range of humanitarian missions (life rafts, medical equipment, provisions etc.). The specifications of this novel BWB UAV are summed up in Table 1, whereas the configuration layout is presented in Figure 4.

The DELAER RX-3 design was based on the in-house sizing tools described in the previous section. These tools were adjusted to the needs of UAVs and tuned to incorporate the unique characteristics of the novel BWB platform. They have also been validated through the design of the HCUAV RX-1, the first large-scale Hellenic Civil UAV for surveillance missions, which has successfully undergone several flight tests. The layout design and sizing procedure is in compliance with FAA pt. 23 regulations and supported by high-fidelity aerodynamic analysis (CFD) and structural analysis (FEM) tools. The geometry used for the analyses was generated using existing parametric 3D CAD tools, which allow changes at the aerial vehicle configuration to be executed swiftly and accurately during design. The results were imported in a dedicated flight simulator software, for the evaluation of the key performance, aerodynamic and stability specifications of the RX-3.

Table 1 – DELAER RX-3 specifications

Flight characteristics	**Electronics specifications**	**Other specifications**
Cruise range 70 nm	Fully autonomous flight	Use of composite materials
Payload 110 lbs	Realtime video 720p quality	Payload insulation
Flight endurance up to 10h	Flight planning capabilities	Aerial drop payload delivery
Cruise speed 97 kts	Ability to link with the Hellenic Rescue Team Network	Data gathering & management system
Maximum velocity 135 kts Takeoff runway <394 ft Operation at adverse weather and 30 knots (8BFT) wind gusts	Tele-communications system with an SDR data-link	One-man, portable ground control station featuring double data-link, network equipment and folding antenna

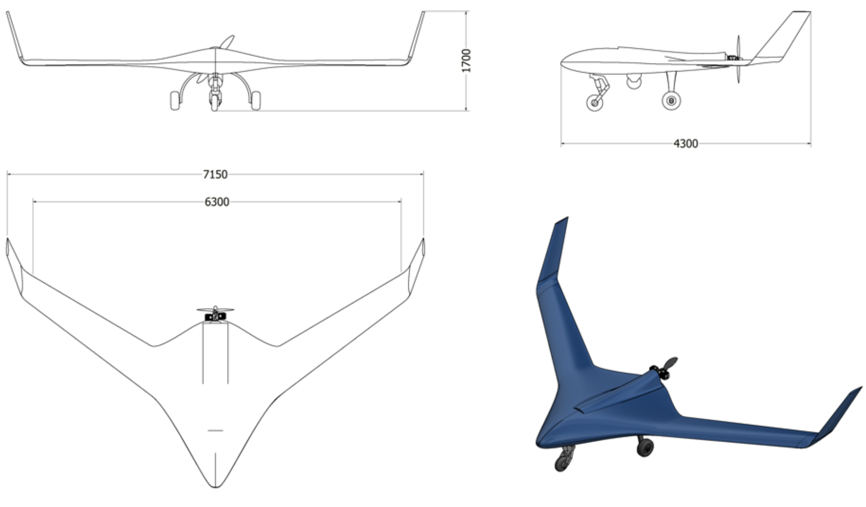

Figure 4 – DELAER RX-3 configuration layout

Moreover, in Figures 5 and 6 the results from the CFD analysis are shown. That is, Figure 5 shows the drag polar of the aerial vehicle. It is clear, that in lower angles of attack the two curves are in very close agreement. However, in higher angles of attack however the results deviate, as the analytical methods cannot predict effects due to stalling and viscous effects.

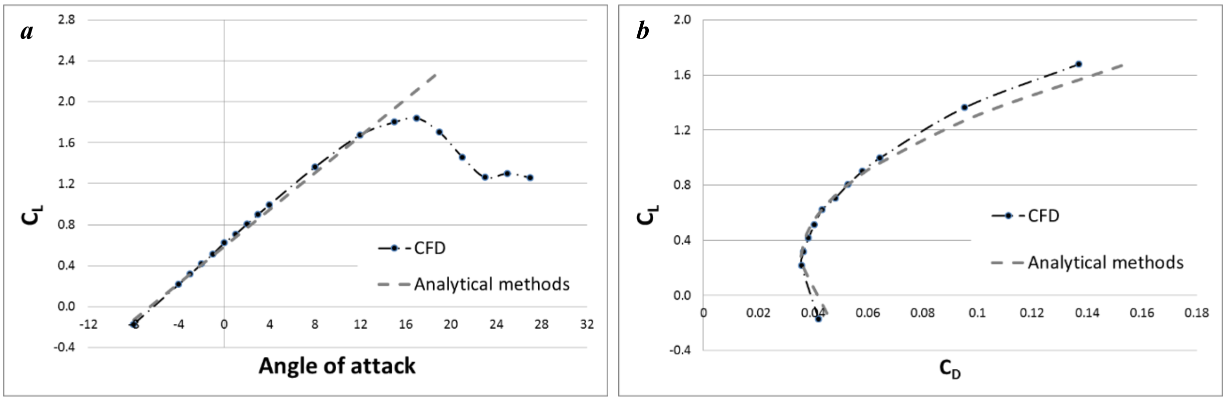

Figure 5 – DELAER RX-3 lift coefficient versus angle of attack (a) and drag polar (b)

In figure 6, the flow development near the winglets of the RX-3 is presented as well as the pressure distribution on the surface of the aerial vehicle. These kinds of distributions are used to calculate the aerodynamic loads that are applied on the RX-3 skin, thus providing the structural design analysis with the required information.

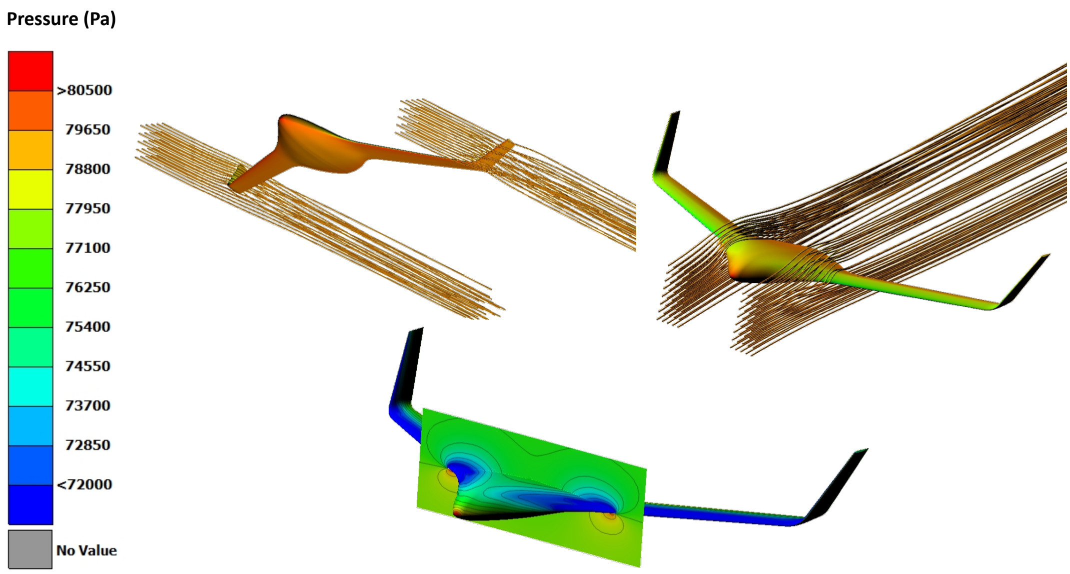

Figure 6 – DELAER RX-3 CFD pressure distribution and streamline visualization

<u>RX-4</u>

The MPU research project aims to develop a portable small UAS, capable of hybrid flight. The UAV will perform a variety of missions, including, photogrammetry, 3D mapping of urban areas, cartography, photogrammetry, search and rescue, inspections, patrols and precision pharming. The MPU RX-4 will be capable of performing both conventional take-off and landing (CTOL) as well as vertical take-off and landing (VTOL) and will carry a useful payload of 0.5kg, consisting mainly of a video camera equipment. The aim is to achieve a maximum take-off weight less than 4 kg, in accordance with the UAS Open Category CAT A1 [16]. Moreover, the UAV design will be modular, and the GCS will be a portable lightweight pack equipped with a laptop and integrated telemetry system, offering an increased portability. The relatively small pack size and weight of the system increase the number of possible deployment locations, and consequently its operational range. The specifications of the MPU RX-4 UAS are summed up in Table 2, whereas the configuration layout is presented in Figure 7.

The MPU RX-4 design was based on the in-house sizing tools described in the previous section. These tools were adjusted to the needs of UAVs and tuned to incorporate the unique characteristics of the novel VTOL platform.

Table 2 – MPU RX-4 specifications

Flight characteristics	**Electronics specifications**	**Other specifications**
Cruise range 0.8 nm	Fully autonomous flight	Use of composite materials
Payload 1.1 lb	Realtime video 720p quality	Obstacle avoidance system
Flight endurance up to 2h	3D mapping capabilities	Payload versatility based on the mission requirements
Cruise speed 33 kts	Flight planning capabilities	One-man, portable ground control station
Maximum velocity 70 kts	LiDAR sensors	Horizontal & vertical geo-fence
Vertical Takeoff and Landing		

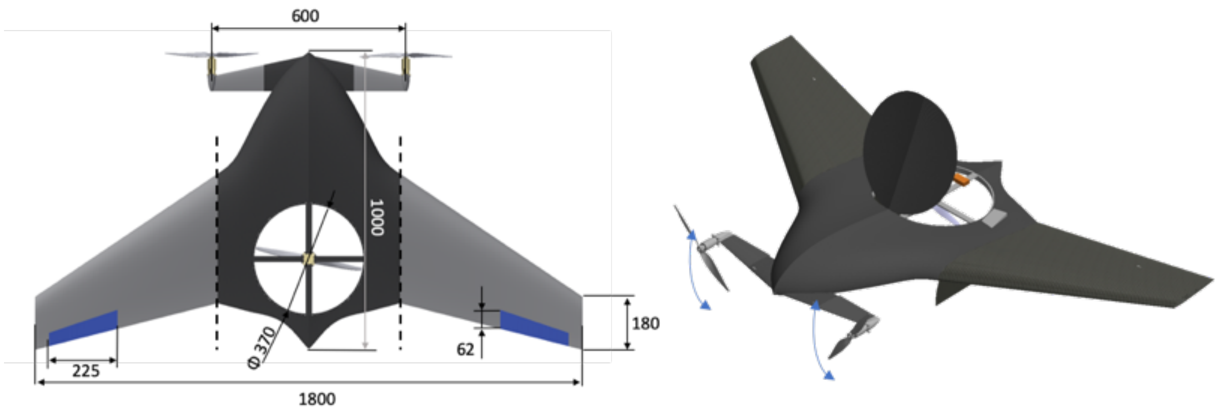

Figure 7 – MPU RX-4 configuration layout

Figure 8 shows the drag polar of the aerial vehicle, as well as the lift coefficient versus angle of attack, where is clear that in lower angles of attack the two curves are very close. However, in higher angles of attack the results deviate, as the analytical methods cannot predict effects due to viscus and stalling.

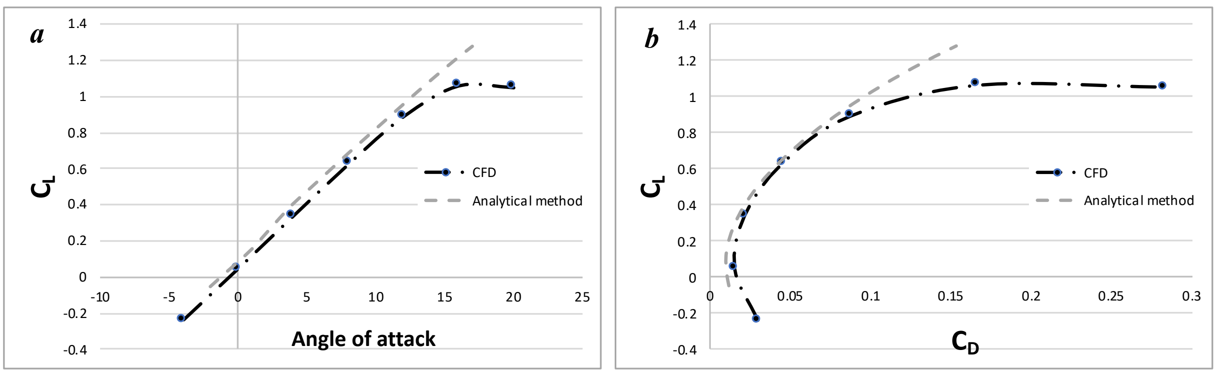

Figure 8 – MPU RX-4 lift coefficient versus angle of attack (a) and drag polar (b)

Moreover, in figure 9 indicative results of the CFD simulations are shown. More specifically, the flow behaviour near the tips of RX-4 wings and canards is presented with streamlines as well as, the pressure distribution on the RX-4 external surface is depicted.

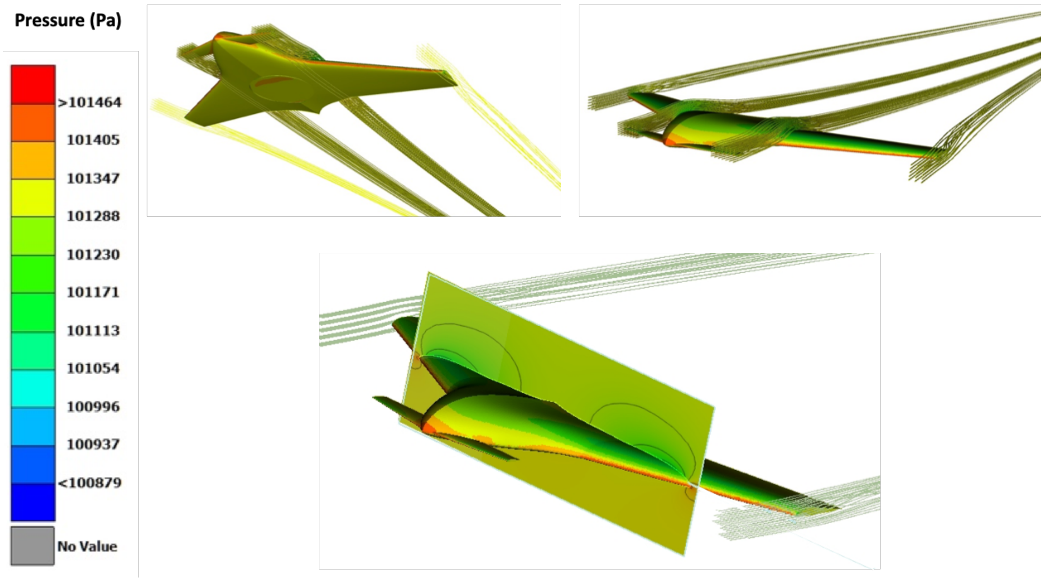

Figure 9 – MPU RX-4 pressure distribution and streamline visualization

The CFD results regarding the pressure distribution on the RX-4 external skin, are provided as input to the structural design procedure in order to configure the internal structural layout of the UAV.

4. CONCLUSIONS

The current paper presents the in-house sizing methodology and tools developed at the Laboratory of Fluid Mechanics and Turbomachinery (LFMT) for the aerodynamic design of fixed-wing UAV platforms. The high-fidelity CFD modeling methodology that is performed to support the sizing calculations and to accurately extract the much-needed aerodynamic and stability coefficients of the aerial vehicle is also presented. The methodology analysis is backed by two case-studies. The sizing procedure of two LFMT UAV prototypes (RX-3, RX-4) is indicatively presented, as are the corresponding configuration layout and performance results.

Concerning the sizing methodology, the traditional aircraft design methods are employed that combine analytical and semi-empirical presizing methods. To facilitate the calculations, a dedicated in-house tool has been developed, where the necessary modifications have been made to include the aspects of unmanned aircraft design. While the sizing tool provides the means for a rapid layout design study, the prediction accuracy of the aerodynamic and stability coefficients is questionable, given the complex nature of the examined configurations and the dominating flow phenomena. That is, the sizing methods use a low-fidelity approach that needs to be supported by higher-fidelity tools.

Therefore, to support the aerodynamic and stability predictions, high-fidelity CFD computations are conducted. Detailed 3D CAD models are initially drawn, followed by the generation of a fine quality grid. The flow analysis is carried out using a RANS approach, coupled with the robust, yet accurate, Spalart-Allmaras turbulence model.

Overall, using this approach that combines both low- and high-fidelity tools, an accurate and time-efficient UAV sizing methodology has been developed. This conclusion is supported by the case studies briefly presented in this work. Both configurations are based on innovative layouts and carry out unique and demanding missions, therefore their sizing and development is a challenging task. However, the sizing procedures of the RX-3 and the RX-4 prototypes conducted by a small group of Engineers are well into the preliminary design phase, which are scheduled to last less than 15 months' time, each. Hence, the fixed-wing UAV sizing approach and corresponding LFMT methodology presented in this paper is invaluable for the development of full-scale and fully-functional UAV prototypes.

5. AKNOWLEDGEMENTS

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