DESIGN AND OPTIMIZATION OF A VERSATILE UAV FOR OBSERVATION AND RESEARCH USING THERMAL COLUMNS FOR EXTENDED ENDURANCE

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Abstract

This paper presents the conceptual design of Vulture — a multipurpose long endurance UAV, with a maximum take-off weight of 25 kg. Its implemented ability to identify and use thermal columns for extended endurance makes it stand out from the competition. The paper begins with defining the aircraft's preconditions along with an exemplary mission profile. It is followed by a description of the methodology used to select the configuration and optimize the construction in order for it to meet the established requirements. The approach to locating and centering thermal columns is presented afterwards. The paper is summarized by calculations demonstrating the accuracy of the design and its performance.

1 Introduction

Fixed-wing Unmanned Aerial Vehicles (UAVs) have been of interest to the field in recent years due to their reliability and wide variety of applications. Yet there are barely any long endurance aircraft with a Maximum Take-Off Weight (MTOW) of below 25 kg on market. These light UAVs have the advantage of minimum certification regulations in Europe and the USA (Federal Aviation Administration), which allows the implementation time to be considerably decreased. Experience in designing and building such aircraft, gained by the authors throughout their participation in SAE Aero Design competitions, was extremely beneficial for the project. The work presented during previous ICAS conference [1] by fellow students was the first attempt at commercializing a platform build for the mentioned competition. Similarly, this paper is aimed at designing a platform that would have exceptional traits and be competitive with other UAVs on the market.

One of the most desirable features of UAVs is an increased endurance. Benefiting from [2], the authors could familiarize with the concept of small long-endurance UAVs.

Being airborne for longer can allow the platform to perform specialized missions, such as patrolling, photography or data analysis. Aiming to focus on this trait, Vulture is equipped with an algorithm for locating and availing of thermal columns, allowing it to significantly reduce its fuel consumption while performing an extended operation. When designing the aircraft, research conducted in [3] was used as scientific assistance. The principal areas of the study were flight duration, platform versatility and weight restrictions.

MTOW	**25 kg**
Empty weight	10-12 kg
Maximum fuel weight	11 kg
Maximum payload weight	10 kg
Endurance	**>20 h**

Table 1 Design requirements

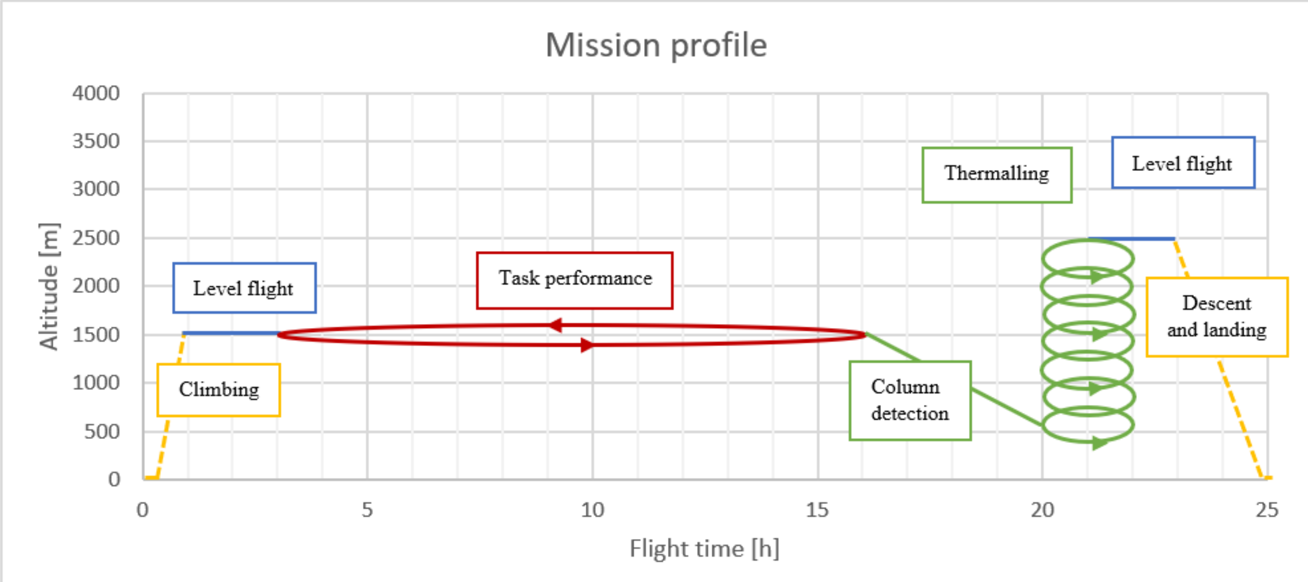

Fig. 1 Mission profile

2 Mission profile

The graph in Fig.1 shows an illustrative mission profile the aircraft might fulfill. The main part of its mission is task performance (being e.g. patrolling or photography), shown in red, and Standby Mode, shown in green. The Standby Mode is characterized by climbing (if needed), column detection and thermalling, described in detail in section 6.
Thanks to the aircraft's versatility it can perform diverse missions, differing in duration and range.

3 Study

Optimizing the platform's aerodynamics and implementing the ability of determining thermal columns could enable its endurance to exceed 25 hours, depending on the flight conditions. In order to achieve this feature, different configurations of the aircraft were debated.
The intention of maximizing flight endurance was followed by the clear decision of including a large fuel tank in the wing. This creates unavoidable difficulties with manufacturing and installation of such a tank, due to its size. Ultimately the tank was positioned inside the fuselage, to simplify its manufacturing and eliminate problems with mounting the fuel pump.
The fuselage itself was optimized to a more aerodynamic shape, which had to be compromised by fitting in all necessary equipment as well as the tank. The high wing monoplane configuration simplifies the mounting of the fuselage and leaves plenty of space for appliances, which was critical to the project, as the platform is to have interchangeable modules.
The decision to use a pusher propeller was influenced by the requirement to embed a wide-angle camera to provide good visibility and the need to adjust the fuselage modules with ease. In addition, the slipstream would not affect measurements carried out by data collection tools.
Applying a single tail boom would require for the engine to be raised, due to the large diameter of the propeller. This would be adverse, as it would increase the wetted surface, causing the aircraft's drag to increase. A twin boom attached to the wing allows the engine to work without interference, even with a large diameter propeller. A V-tail has been chosen as it is a lightweight configuration and does not disturb the slipstream. This configuration has a more complex control system than a conventional tail. It requires a complicated kinematic system, although this does not apply to UAVs, which are entirely automated. This con-

figuration has many advantages, including less drag and mass, which is why it was ultimately chosen.
It was decided to employ a piston engine, as they are still more efficient than electric ones. Furthermore, an alternator can be used to power electronics during flight. An engine with low fuel consumption [4] was selected and subject to further calculations.

4 Aircraft optimization

During the design process of a long endurance UAV minimizing drag is key. The aircraft's ability to use thermal columns to extend endurance relies on specific qualities that support gliding.
During level flight the wing's drag accounts for 40-75% of the overall drag, depending on the speed of the platform. Drag created by the fuselage varies from 10% to 20%, while the tail subjects to just a few percent. Therefore, wing design is an essential aspect of the project, ensuring best performance both in engine driven flight and while thermalling. Further design requirements included good stall and thermal loitering characteristics, low minimum speed and resistance to surface contamination. The wing design process, described in detail in [5], consisted of three stages: airfoil selection, planform design and 3D design.

4.1 Airfoil selection

Estimating the cruising altitude at 1500 m allowed to calculate the aircraft's operating Reynolds number at around $3 * 10^5$. For such a low value, Michel Selig's catalog [6] was used to establish potential airfoils. The main requirements for them were:

- Maximum lift coefficient $C_{Lmax} > 1,5$
- Lift-to-drag ratio $L/D > 80$
- Sink function $E = C_L^3/C_D^2 > 7500$
- Airfoil thickness $t > 10\%$

Four airfoils complying with mentioned requirements were further considered: S8055 (12%), SD7043 (12%), SD7062 (14%), SD7090 (10%). Airfoils of various thicknesses were chosen in order to compare their qualities.
SD7062 provides the highest lift coefficient among the airfoils, which allowed the reduction of the wing area. It also shows to have the highest sink function, guaranteeing the lowest energy demand.
However, achieving 16 m/s of minimum speed would require to implement slotted flaps, causing the wing's mass to increase significantly. Therefore, additional airfoil optimization was carried out using XoptFoil software (based on X-foil) to adapt it to the operating flight conditions. A higher lift coefficient for angles of attack above 12°, greater sink function of design $C_L = 0,706$ and a minimal thickness of 13,6% were imposed in the process. The obtained airfoil has an increased sink function and L/D for C_L over 0,5. The maximum lift coefficient has been improved to $C_{Lmax} = 1,8$, what also resulted in a worsening of stall characteristics. The new airfoil's (PPI03) characteristics are shown below.

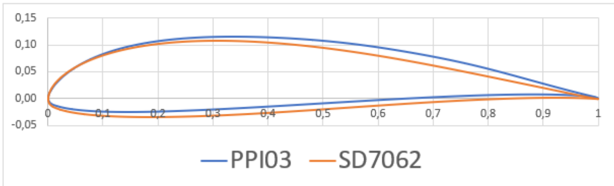

Fig. 2 PPI03 and SD7062 airfoils

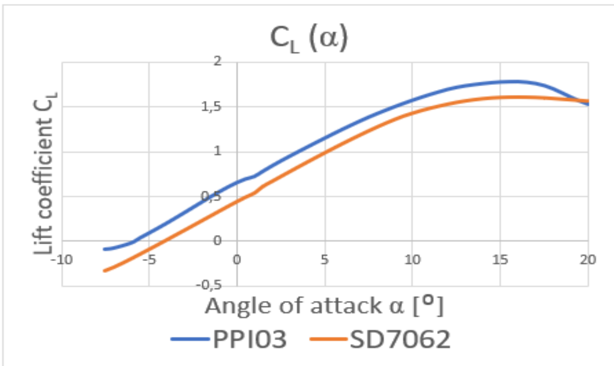

Fig. 3 Lift coefficient vs Angle of attack

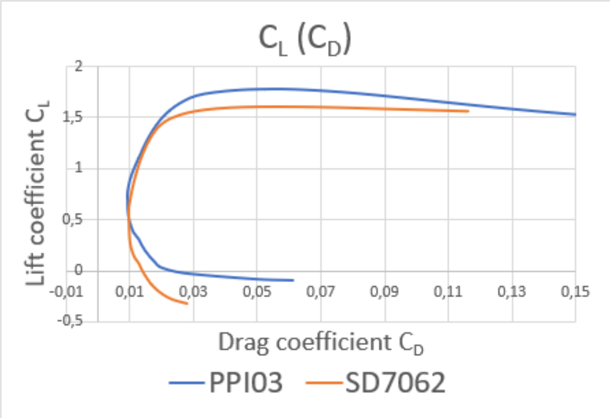

Fig. 4 Lift coefficient vs Drag coefficient

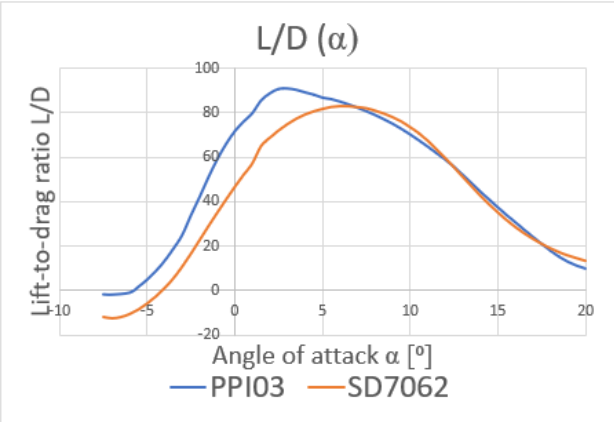

Fig. 5 Lift-to-drag ratio vs Angle of attack

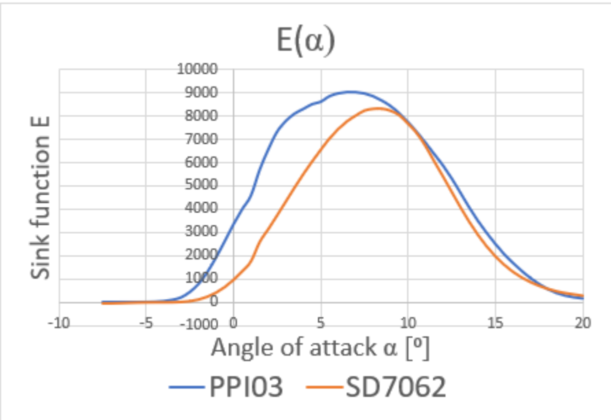

Fig. 6 Sink function vs Angle of attack

4.2 Planform design

During the process of planform design special attention was paid to select an appropriate taper ratio, influencing both lift distribution and stall characteristics.
An elliptical wing planform provides the best aerodynamic performance, but is difficult to manufacture. Thus a trapezoidal planform with a taper ratio of 0,6 was taken as a good starting point for further optimization. The aspect ratio of the wing was set to 16,2 in order for it to be able to support gliding.

4.3 Wing 3D design

The analysis of the 3D model of the wing with a trapezoidal planform and a straight trailing edge (no sweep) was carried out using the XFLR5 software.

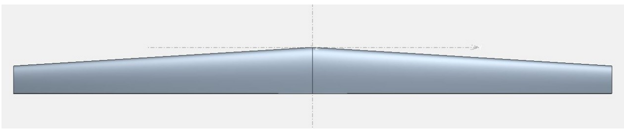

Fig. 7 Wing planform before optimization

The calculated lift distribution showed that flow separation would initially occur halfway between the wing's axis of symmetry and the wingtips. This would be very inconvenient for maneuverability in case of said flow separation, as ailerons are located nearby. Another encountered problem was high parasite drag, especially for large angles of attack. A modification of the wing was conducted, retaining the wingspan and wing area. As a result the planform was approximated to a more elliptical shape, improving its aerodynamics.

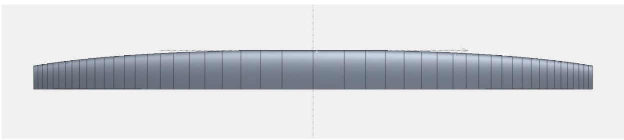

Fig. 8 Wing planform after optimization

The wing's lift distribution still wasn't satisfactory, because of excessive induced drag. This issue was eliminated by implementing washout. Using AVL v3.36 software it was established that the required angle of washout at the wingtips amounts to 8 degrees. To eliminate the incidental loss of lift and issues with wing manufacturing it was decided to use supplementary high taper ratio wingtips, what provided necessary lift distribution and improved the wing's performance at large angles of attack.

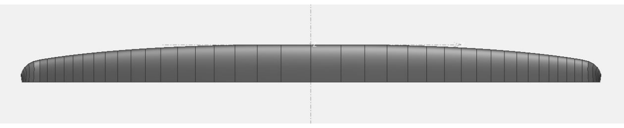

Fig. 9 Wing planform after adding winglets and washout

Washout was approximated for several sections of the wing, to simplify its manufacture.

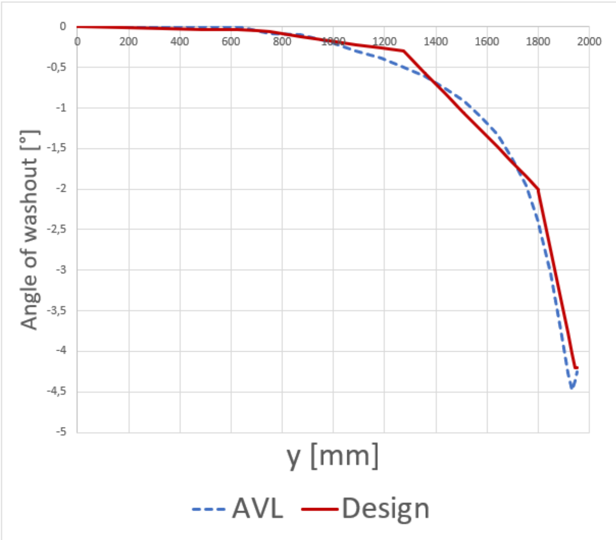

Fig. 10 Wing washout

The wing is characterized by a high aspect ratio of 18,1 (after adding winglets), suitable for glider aircraft. Along with an airfoil adapted for the low Reynolds number, a low drag coefficient is provided. Modifying the planform and applying washout improved the wing's performance, increasing the lift-to-drag ratio and sink function. Due to the additional airfoil optimization the value of maximum lift coefficient of the wing equates to $C_{Lmax} = 1,77$.

4.4 Fuselage optimization

The aircraft's fuselage was adjusted to assist its overall glider character.

Having a large fuel tank and electronic devices integrated in the fuselage, maintaining the best possible aerodynamic properties was an undoubted design challenge.

The most common solution employed in present-day UAVs includes attaching a camera underneath the fuselage, providing the ability to point it in any direction. In Vulture's case this layout is inacceptable, as the camera would cause great drag and affect the aircraft's general aerodynamic characteristics. Instead, the monitoring device is mounted at the front of the fuselage, a much more unusual solution, but one that provides a more satisfying aerodynamic performance.

Furthermore, the camera is equipped with a specifically designed and manufactured composite fairing, to ensure a sleek transition of surfaces between the camera unit and the remaining part of the fuselage.

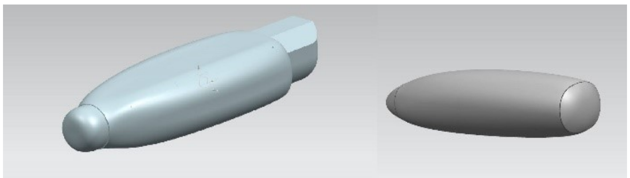

Fig. 11 Fuselage shape optimization

The linkage of the wing with the fuselage is another component that has a major influence on the aerodynamics of the aircraft. Proper design of this element allowed a substantial decrease of the drag generated by the platform itself. Different fuselage configurations were considered, employing ANSYS software to calculate and optimize the chosen solution.

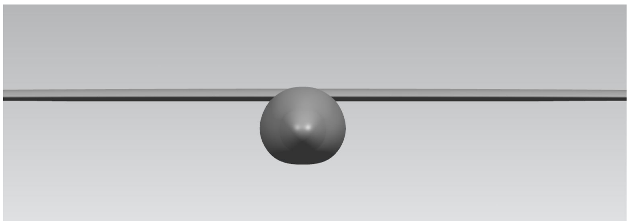

Fig. 12 Fuselage and wing linkage before optimization

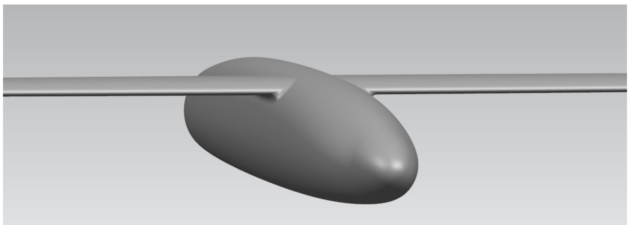

Fig. 13 Fuselage and wing linkage after optimization

5 Structure type and mass estimation

Wanting to keep the structure lightweight but durable the majority of elements were thought to be made out of composite materials. Data of a initially selected engine [4] has been used for the purpose of further calculations.

The wing is a semi-monocoque construction, with two spars. The shell is a sandwich-structured composite made of Herex [7] foam and $160g/m^2$ carbon fabric layers. The spar caps are made out of unidirectional carbon fibre, up to 7 layers on the upper cap and 5 on the bottom one. Stabilizers, similarly to the wing, are sandwich-structured with Rohacell [8] foam and $200g/m^2$ carbon fabric. The tailbooms are made mostly out of carbon fibers. The fuselage is a composite structure consisting of $200g/m^2$ carbon fabric, additionally reinforced with carbon-Rohacell [8] frames in crucial points.

The table below shows an estimation of the aircraft's empty weight. All the elements have been taken into account, including the engine, empty fuel tank and electronics essential for flight. The aircraft's mass lies within the range of 10-12 kg, as assumed in section 1. Calculations show that the Center of Gravity is located in 33,5% of the Mean Aerodynamic Chord (MAC), while in configuration with a full fuel tank it moves to around 25% MAC.

Element	**Mass [kg]**
Wing	3,15
Fuselage	2,1
Undercarriages	0,45
Electronics (including battery)	1,84
Engine with propeller	2,54
Camera and hardware	1
Tailbooms	0,16
Stabilizers	0,34
Total	**11,58**

Table 2 Empty mass estimation

6 Use of thermal columns

The use of thermal columns for extending endurance is performed in two steps — detection and centering. When not performing a particular task, the aircraft goes into Standby Mode and moves within the borders of the Waiting Zone, restricted by the operator. If it is daytime, the aircraft switches to Column Searching Mode, climbs up to 1500 m (if needed), turns the engine off and starts to soar in a straight line, on condition it stays within the Waiting Zone.

6.1 Column detection

Detection of columns is feasible using energy formulas, derived in [9]. Basing on the lift-to-drag ratio of the platform, the fall velocity w can be calculated, for a given flight velocity V. The platform's specific energy and it's derivative is calculated using simple formulas:

$$e = \frac{V^2}{2g} + h \tag{1}$$

$$\frac{de}{dt} = \frac{V\frac{dV}{dt}}{2g} + \frac{dh}{dt} \tag{2}$$

The derivative of specific energy netto can be referred to as derivative of specific energy de/dt adjusted by the derivative of fall velocity dw/dt for given aircraft velocity V:

$$\dot{e}_{netto} = \frac{V * \dot{V}}{2g} + \dot{h} + \dot{w} \tag{3}$$

The netto derivative is calculated and subjected to Kalman filtering continuously. If the calculated value is greater than a given threshold of 3 m/s (adjustable by the operator), the aircraft goes into Column Centering Mode.
If the aircraft reaches a minimal altitude given by the user (depending on the terrain), it climbs back up to 1500 m and repeats the process.

6.2 Column centering

In the Column Centering Mode, the aircraft uses Extended Kalman Filter to constantly update the thermal's strength, radius and positioning - north and east of the aircraft. The used model assumes:

- At given altitude, the thermal is stationary with respect to surrounding air.
- Wind affects the velocity of the thermal and the aircraft uniformly.
- The thermal column has a single core providing maximum lift.
- The vertical air velocity of the thermal's horizontal cross section is approximated by a bell-shaped distribution.

The algorithm of identification and parameter estimation of a thermal, described in [9], leaves the loiter radius of the platform in the thermal as a constant, to be given by the user. This results in an suboptimal aircraft motion. The following algorithm of thermal column use was developed for increasing the soaring efficiency.
Total vertical velocity of the aircraft while thermalling consists of vertical air velocity and the aircraft's sink rate, corrected by bank angle.

$$w_{sum} = w_{thermal} + w_{glide} \tag{4}$$

The thermal's model described in [9] gives the vertical air velocity at a given point (x, y) of the thermal (distinguished by its radius R), the maximum vertical velocity W and the thermal column's center at (x_0, y_0) as:

$$w_{thermal}(x,y) = W * exp\left(-\frac{(x-x_0)^2 + (y-y_0)^2}{R^2}\right) \tag{5}$$

According to the equation derived from the polar function, the aircraft's minimal sink rate while gliding can be estimated using the equation, given the air density ρ, surface area S, aspect ratio A_e, minimum drag coefficient C_{Dmin} adjusted by the bank angle θ.

$$w_{glide} = -\sqrt{\frac{32 * mg\sqrt{C_{Dmin}}}{\rho * S\sqrt{(3\pi * A_e)^3}}} * \frac{1}{\sqrt{\cos^3\theta}} \tag{6}$$

When loitering, the relation between the bank angle and the loiter radius, derived from the equation of the centripetal acceleration, can be described by:

$$\cos\theta = \sqrt{1 - \frac{2m}{S * C_L * r}} \tag{7}$$

As a result, the derivative of w_{sum} can be taken with respect to the loiter radius.

$$\begin{aligned} \frac{d}{dr} w_{sum} = & \frac{-2W}{R^2} * r * \exp\left(\frac{-r^2}{R^2}\right) + \\ & + \frac{3m}{2SC_L} * \sqrt{\frac{32 * mg\sqrt{C_{Dmin}}}{\rho * S\sqrt{(3\pi * A_e)^3}}} \\ & * \frac{1}{r^2} * \left(1 - \frac{2m}{SC_D} * \frac{1}{r}\right)^{-7/4} \end{aligned} \tag{8}$$

Where $g, \rho, A_e, S, R, W, C_L, C_{Dmin}, m = constant$ are given. For each step, the flight controller numerically solves the equation:

$$a * r * b^{r^2} + \frac{c}{r^2} * \left(1 + \frac{d}{r}\right)^f = 0 \tag{9}$$

With $a, b, c, d, f = constant$.
This gives the optimal radius of loitering for current mass and current parameters of the thermal. When entering a new thermal column, the flight

controls estimate the platform's present mass and lift coefficient of maximum sink function using the aircraft's polar function. These calculations are possible using fuel consumption parameters, monitored by dedicated software.
The maximal height the aircraft can achieve while thermalling is distinguished by its ceiling — 3000 m.

7 Performance

In order to calculate the aircraft's performance, its polar function was determined. The parasitic drag generated mainly by the fuselage, stabilizers and undercarriages has been taken into account.
After wing analysis was performed using XFLR5 software, Ansys Fluent was implemented to analyze the pressure distribution on the wing's surface. The results did not show any interference adverse effects caused by the concave corner of the wing-winglet intersection.
In the next stage characteristics of the wing-fuselage unit along with the undercarriages were calculated. The obtained results served in determining the polar function's factors.
The polar function was then used to calculate the theoretical range and flight endurance at the altitude of 1500 m and for cruise speed of $V = 25m/s$. The calculations considered the loss of drag due to a decreasing angle of attack during fuel consumption.
The aircraft proved to satisfy the requirements of a long endurance flight. Depending on the amount of fuel taken onboard, the UAV shows the ability to fly for almost 24 hours on fuel itself. Assuming favoring weather conditions, its performance can be extended by numerous hours, using the implemented thermal column algorithms.

Fuel [kg]	Endurance [h]	Range [km]
3	7,6	690
5	12,9	1162
7	18,3	1642
9	23,6	2122

Table 3 Flight range and endurance

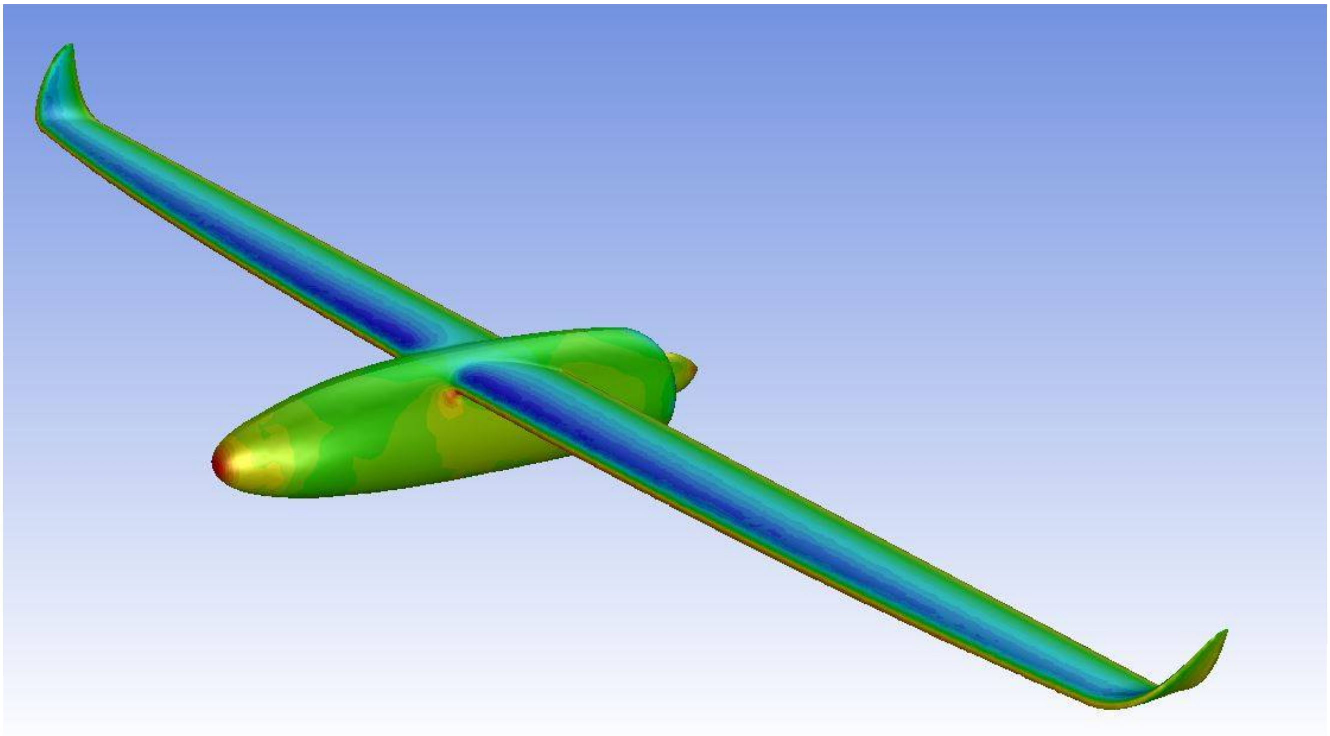

Fig. 14 Pressure distribution

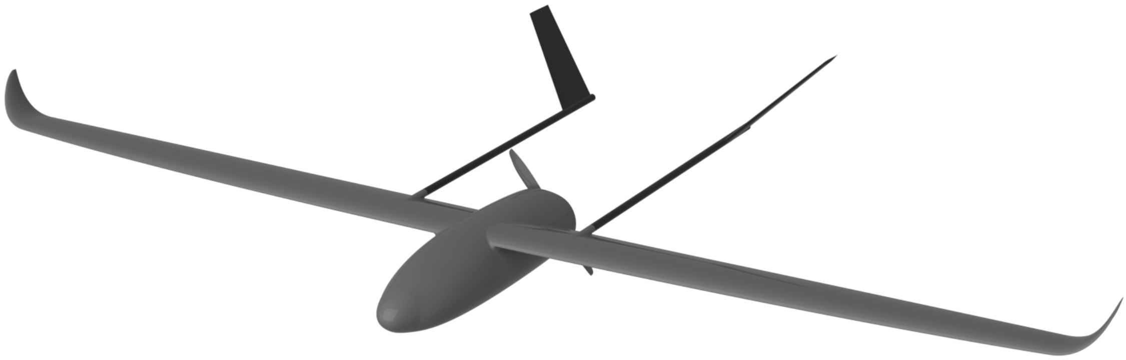

Fig. 15 Aircraft visualization

8 Further development

Vulture is a still developing project. In the near future the fuselage will be improved, taking into consideration the interchangeable modules. It is planned for the aircraft to have at least 3 modules containing different devices, fitted for different missions. More attention will be paid to programming the aircraft to facilitate its piloting.
Wishing for the aircraft to be commonly available, a cost analysis will be made to assure it will be affordable. Additionally, a dedicated container will be designed, to secure the platform during transportation. It is also intended to develop an assembly system, so that no more than 2 people are needed to ably prepare the aircraft to flight.

9 Final conclusion

Focusing on the careful design of the wing has resulted in an 18,1 aspect ratio and $C_{Lmax} = 1,77$, enabling Vulture to act as a glider aircraft when needed. A pusher propeller configuration with a V-tail appears promising, as it leaves enough space for the user to adjust the camera and equipment inside the fuselage, to accordingly fit his needs.
Using mostly composite materials allows the aircraft's empty weight to be kept to a minimum, simultaneously increasing the maximum payload weight up to 10 kg. A piston engine with a low fuel consumption additionally extends the flight time, while maximizing the use of fuel taken onboard. The implemented algorithm, used for finding and centering thermal columns increases the time of the aircraft being airborne, which allows it to perform longer and more complex tasks. Vulture is a unique UAV design with versatile applications, fitted to the user's needs. Its further development will make it a more elaborate aircraft, commonly available to the public.

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