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Time-Efficient and Accurate Performance Prediction and Analysis Method for Planetary Flight Vehicles Design

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ABSTRACT

This article describes a cost- and time-efficient methodology that can be applied to design UAVs of diverse applications which relies on freeware and open-source analysis software. The methodology consists of an initial parametric multidisciplinary optimisation process that uses computationally inexpensive analysis tools. The optimal design is later refined using high fidelity tools. Finally, all the information is summarised in a way that allows introducing small changes to the design without the need to repeat the optimisation process. Throughout the design the user has full control of the process which allows him to make any necessary adjustments. A case study is provided describing in detail the application of this method in the design process of a solar-powered aircraft PRONTAS.

1 INTRODUCTION

At present there is a continuously growing interest in designing and testing new aircraft configuration, mainly thanks to the rapid development of unmanned aerial vehicles (UAV) which are relatively inexpensive to manufacture. The availability of this technology means it is no longer restricted to multinational aeronautical industry but also to smaller companies and experienced professionals. However, nowadays the majority of UAVs is inefficiently designed and relies on robust control algorithms and oversized propulsion system. According to Barton [4] about 70% any engineering product is determined by the design phase. Mistakes made at the initial stage of the design process should be therefore avoided as any change in the mature design is expensive to implement. Consequently, a comprehensive initial stage multidisciplinary design optimisation (MDO) process has to be carried out ensuring that the theory behind such process is well understood and the physical models are adequate. There is a wide variety of open-source tools that can be used as time-efficient parametric analyses for initial design. After generating a database, which can contain information about the aerodynamics, flight stability, structures, etc., it can be expanded using interpolation based on linear algebra. Finally, with the use of appropriate optimization algorithms, an optimal solution can be found. This solution can be further validated using software such as CFD solvers and its handling qualities can be tested in a flight simulator. The application of the method can be further expanded to extraterrestrial flight. Although at the moment rovers and satellites are more common in planetary exploration and until now only Vega mission [28] managed to take advantage of flying bleeps to explore Venus, there are many conceptual UAV designs, such as the AVIATR project [3], that will be probably used in the near future.

The main aim of this article is to present a rapid, robust and easily adaptable methodology to analyse and optimise UAV design. It is based on the idea of describing the geometry and flight conditions by parameters making it easily adjustable given any changes to the mission requirements, objectives or updated data from other disciplines, which often occurs in multidisciplinary design process. This methodology can also serve as a case study for academic environment. Finally, all the used tools are freeware and open-source making the technology more adaptable and accessible to teams with limited budget.

2 OVERVIEW OF THE DESIGN PROCESS

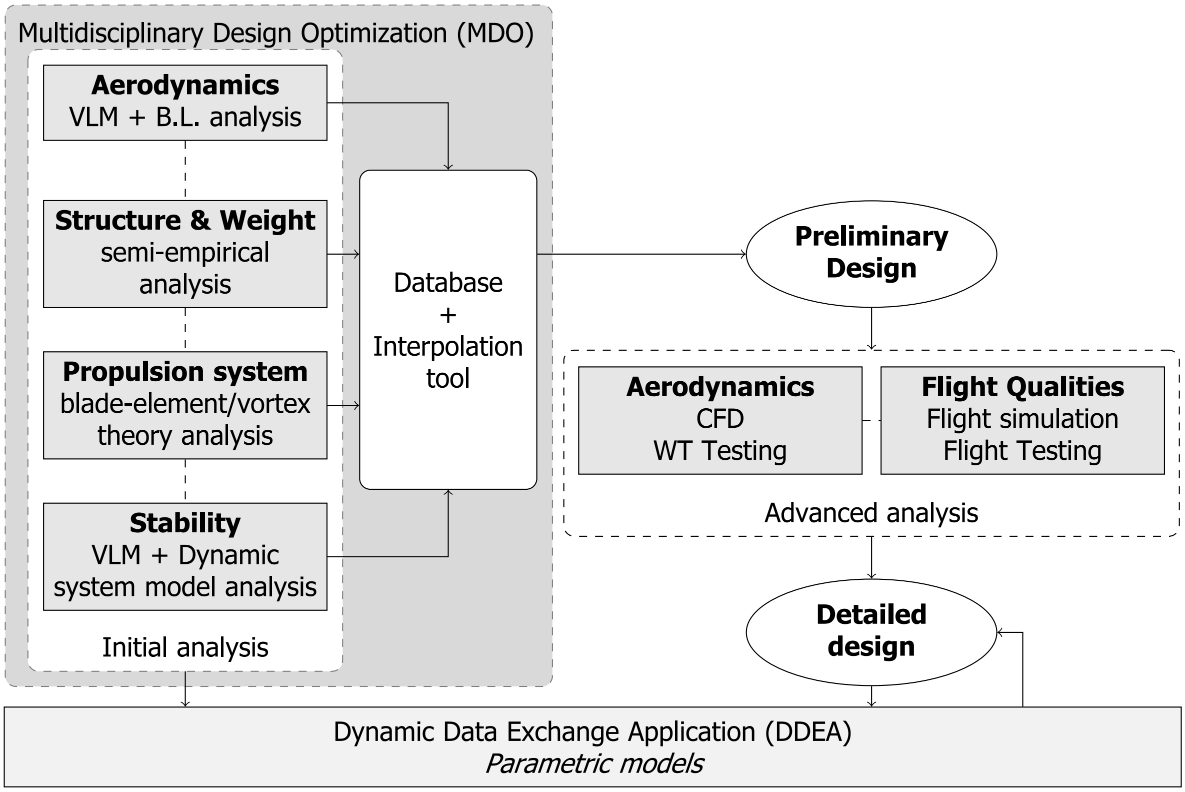


Figure 1: Design process roadmap

The main characteristic of the design methodology is using parametric models. A roadmap of such approach is shown in Figure 1 containing only a limited number of disciplines for comprehensive purposes. However, its extension to more disciplines, depending on the design requirements, is straightforward. The choice of those parameters depends on the design and they can refer to the geometry, flight conditions or the mission requirements. One needs to bear in mind that for a case of three-wing aircraft and considering only aerodynamics, optimising 3 parameters for each wing and using parameter vectors of length 4, 4^9 = 262,144 configurations need to be tested. This number has to be multiplied by the number of flight conditions that are to be tested. If one wants to test 6 angles of attack at 3 flight speeds and 3 flight altitudes, the number of states is $6 \cdot 3 \cdot 3 = 54$ giving a total number of analysis points of 14,155,776 yielding to the so-called curse of dimensionality. A computer equipped with Intel® Core™ i7-3930K @ 3.20GHz and 32GB of RAM using a parallelized code takes approximately 1 s per analysis point. This means that it would take 14,155,776 s $\approx$ 160 days. This time is further increased when there is less computational power available. The conclusion is that the parameter space, the number of dimensions, range and definition need to be carefully chosen and limited to the computational power and time-frame of the project. On the other hand reducing the number of analysis points reduces the precision of the optimisation process. A good way of mitigating this problem is using interpolation methods that are presented in Section 3.4.
The parameter grid is studied using initial analysis tools. Each discipline module uses time-efficient tools, described in Section 3, which allows to calculate each grid point thus creating the database. A suitable MDO process would then either only utilise the created database to find the optimal design or it would both use the database and occasionally calculate additional grid points along the optimisation path. The choice of this strategy process determines the optimisation algorithm to be used. One can use genetic algorithms that are very robust but are characterised by relatively slow convergence [29] or

standard local methods based on the gradient descent [16, 23]. A combination of both can be also used. Since choosing an appropriate optimization algorithm largely depends on the nature of the problem, it is not covered in this article and is left for the reader to investigate. A thorough summary of available multidisciplinary optimisation methods was done by J. Martins [21]. As a result, the MDO process gives a preliminary design which is further refined with Advanced analysis, structured in a similar way as the Initial analysis, giving the Detailed design.
The design parameters from each discipline and their relations are collected in a Dynamic Data Exchange Application (DDEA) creating a summary of each discipline and of the global design. They can be further improved using the Detailed design obtained through Advanced analysis. DDEA allows to introduce small changes to the design and to check by iteration its response due to those changes. For example, if the structural weight of the plane changes due to manufacturing inaccuracies, it can be easily checked how it influences the aerodynamic performance and hence the propulsive requirement. In such case the DDEA can quickly show if it is better to change the flight altitude or make the propulsion system work outside of its optimum.

3 INITIAL DESIGN TOOLS

This section presents initial design analysis tools. Although there exists multidisciplinary initial design freeware software, such as CEASIOM, the objective of this article is to present a methodology which is robust and easily modifiable and requires the user to know exactly what and how is calculated by the program, avoiding black-box type programs. Additionally, it stresses the importance of interchange of information between various disciplines done by implementing interfaces. For the purpose of this article, these were done in GNU Octave environment, but they can be also done in Python language which is suited for such applications.

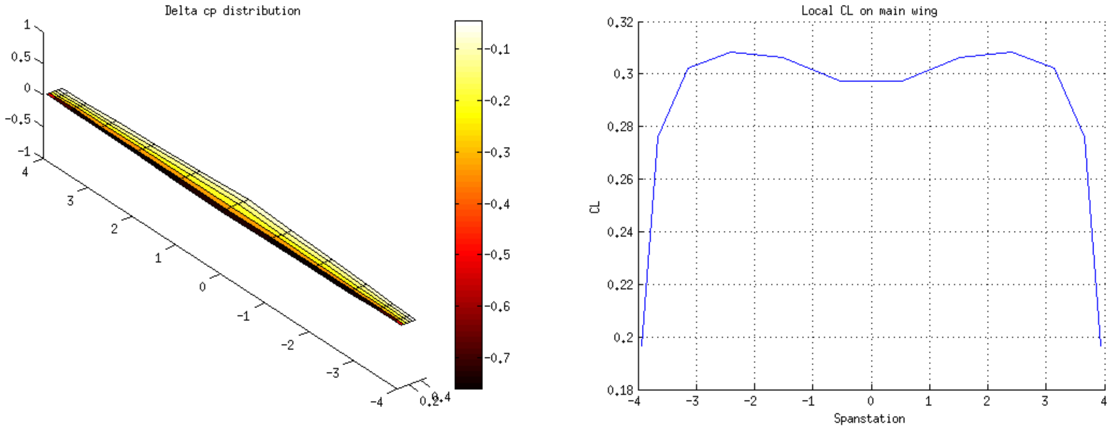
3.1 Aerodynamic analysis

This section describes the methodology of creating a aerodynamic database which can be later used in MDO process. The procedure involves creating an interface between Tornado VLM and XFOIL presented in Section 3.1.1 and 3.1.2 respectively.

3.1.1 Vortex Lattice Method

Vortex Lattice Method (VLM) is a numerical method usually used in early stages of aircraft design and in academic environment. It is a natural extension to the Prandtl lifting line theory [25] and therefore it can only be applied to lifting surfaces such as wings, horizontal and vertical stabilizers, etc. It models a wing as a infinitely thin sheet, neglecting profile thickness, of discrete vortices forming a lattice and solves a system of equations to obtain the circulation distribution. The method is based on potential flow and therefore it cannot calculate viscous drag nor predict viscous phenomena such as flow separation. Nevertheless, the method is very good at approximating lift and induced drag within the linear region of the wing lift curve. In comparison to the Prandtl lifting line theory, VLM can be applied to geometrically complex wings including for example high sweep, low aspect ratio [2].
In the initial stages of design, depending on the mission profile, the aircraft is optimised for cruise conditions, which should be within the linear region of the aircraft behaviour. Hence the VLM can be correctly applied. There are a few open-source programs released under the GNU General Public License that offer an implementation of VLM, such as AVL, xflr5 or Tornado. Tornado is recommended as it gives the user great versatility in adapting it to parametric optimisation. AVL and xflr5 could be also made parametric, however the process is not as straightforward and requires advanced programming skills. Finally, xflr5 incorporates a boundary layer analysis software called XFOIL, described in detail in Section 3.1.2, which makes this program more complete. It is therefore useful as a means of punctual

verification of the method based on Tornado presented in this article.
Tornado allows the user to define almost any aircraft geometry following a list of instructions asking for standard wing geometry parameters. The program allows to define several multi-section wings with control surfaces that interact with each other and, even though it neglects wing thickness, it asks for aerofoil geometry in order to calculate its aerodynamic properties like C_{La} and C_{L0}. In an analogous way the user can define the flight condition and reference point. The coefficient matrix output is very complete and serves not only to approximate the general performance of the aircraft but also its static stability, which will be explained in Section 3.2. Another important output is the lift distribution across the span, as shown in Figure 2b, for all wings which can be used in structural analysis and design.



(a) Wing geometry with C_P distribution

(b) Spanwise C_L distribution

Figure 2: Tornado graphical output for an example wing of NACA 0012 profile, 8 m span, 0.5 root chord, 0.4 taper ratio, 0º $c_{0.25}$-sweep at 20 m/s and 3º of angle of attack.

3.1.2 2D viscous analysis of boundary layer

Tornado lacks the ability to calculate viscous drag, which is crucial in approximating the general performance of the aircraft and its sizing. Fortunately, it provides the spanwise lift distribution over the wing which allows to produce a counterpart spanwise viscous drag distribution given an aerofoil polar data. Although a wing is a 3D object and polar data are available only for 2D profiles, it is still a good approximation of the 3D drag on the aircraft at the initial stage of design process. This section will describe XFOIL which is a widely used software written by Mark Drela for analysing 2D aerofoils.
XFOIL was presented for the first time during the Conference on Low Reynolds Number Airfoil Aerodynamics in the University of Notre Dame in June 1989 giving details on the general methodology [10]. It offers various geometry modification tools such as introducing flaps or improving the points distribution. These tools are very useful in the process of aerofoil development. Regarding the analytical part, XFOIL can perform inviscid analysis using a distributed linear-vorticity panel method. The viscous analysis is done solving standard compressible integral momentum and kinetic energy shape parameter equations. A great advantage of XFOIL is that the code solves iteratively the coupled viscous-inviscid equations for strongly interacting viscous-inviscid flows, such as low Reynolds number (Re) or transonic flows. This allows to accurately predict flow separation and reattachment at relatively low computational cost [15]. This is crucial as most UAVs fly at Re below 10^6.

3.1.3 Database preparation

Figure 3 shows the process of aerodynamic database preparation. Firstly, the geometry and flight condition input for Tornado code has to be adapted so that it runs in batch using the grid parameters as described in Section 2. The general idea is to first create a base geometry that later can be modified. In the case of a classical aircraft configuration, it would have three wings: main, horizontal and vertical tail. The number of sections per wing depends on the nature of the design. An analogous process can be carried out for the flight condition definition.
Having parametrized Tornado and knowing all the geometry and flight condition parameters that need to be tested, a viscous boundary layer needs to be added. XFOIL requires the aerofoil geometry, the angle of attack (or a vector of angles) and Re in the case of subsonic flight (M < 0.3) or Mach in the case of transonic flight. The list of arguments can be further expanded with the design of control surfaces arguments such as `hinge_position` and `deflection_angle`. For the purpose of this article, a simplified version of XFOIL application interfaced by the call of a function `xfoil_data = f(aerofoil,Re,AoA)` will be used.
Although XFOIL could be run at each analysis point, it is computationally inefficient and would drastically increase computation time. It is therefore much better to interpolate a pre-calculated database thanks to the a priori known geometry and flight condition data. In order to calculate the total drag, the C_{Di} values given by Tornado (corresponding to the induced drag component) should be updated with the viscous one (C_{Dv}) obtained from the XFOIL analysis. Tornado provides a discrete C_l distribution as a function of wing station as shown in Figure 2b. For a subsonic case C_{Dv} depends only on C_l and Re, which allows to calculate the spanwise distribution of local C_{Dv} from the 2D aerodynamic pre-calculated database. In order to calculate the total C_{Dv}, a surface integral needs to be performed.
If the XFOIL database is to be calculated a priori, caution has to be taken when choosing Re and angle of attack (AoA). Neglecting any changes to the local velocity, Re can be fixed. However, in order to avoid extrapolating, a small margin should be left on both of its extremes. In terms of AoA, only the global AoA is known and the local AoA will certainly change due to up- and downwash. This effect, including the neighbour wing interaction is taken into account by Tornado. However, in order to appropriately choose AoA for the XFOIL analysis, a wider range needs to be taken or a pilot study needs to be done using a sample of extreme geometries and flight conditions.
The methodology of generating this aerodynamic database has a certain number of limitations, mainly due to the nature of the VLM described in Section 3.1.1. Performing an inviscid analysis means that Tornado is incapable of detecting stall and which results in a constant increase of C_L with AoA. This aspect can be further improved by implementing an interative process using XFOIL stall prediction. Due to the same reason wake interaction with other wings is impossible to quantify. Finally, for low flight speeds and low taper ratios resulting in very short tip chords, local Re can become very small which can cause convergence problems for XFOIL.
These are only some of the problems that can be encountered during the process of database creation. Nevertheless, this database should be only used to optimize the design for cruise flight which will generally fall within the linear region of the used aerofoil, and at its peak efficiency. Therefore, in order to assess where this region falls, a preliminary aerofoil study should be performed before commencing with the generation of the database.
However, Figure 4, which compares the method's results with experimental data obtained for a toy model wing, proves that it is very accurate. The maximum and mean errors in lift coefficient prediction are 7.8% and 2.0% respectively. Their counterparts for C_D are 12.6% and 9.0%. In conclusion, small errors together with time-efficient calculation (as mentioned in Section 2) make the aerodynamic module a very suitable method for the initial analysis step.

3.2 Stability, structural and weight analysis

As mentioned before in Section 3.1.1, Tornado provides a matrix of aerodynamic coefficients that can also be used to calculate longitudinal and lateral static and stability and trim according to the methodol-

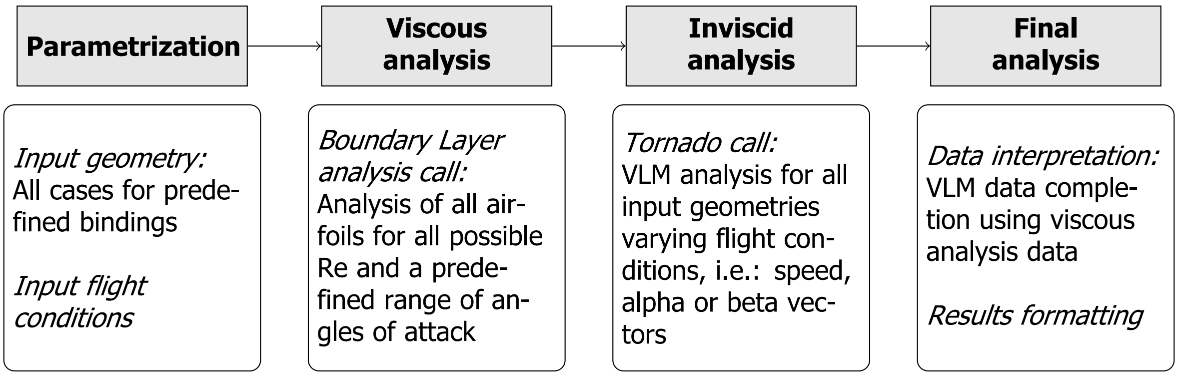


Figure 3: Aerodynamic database preparation flowchart.

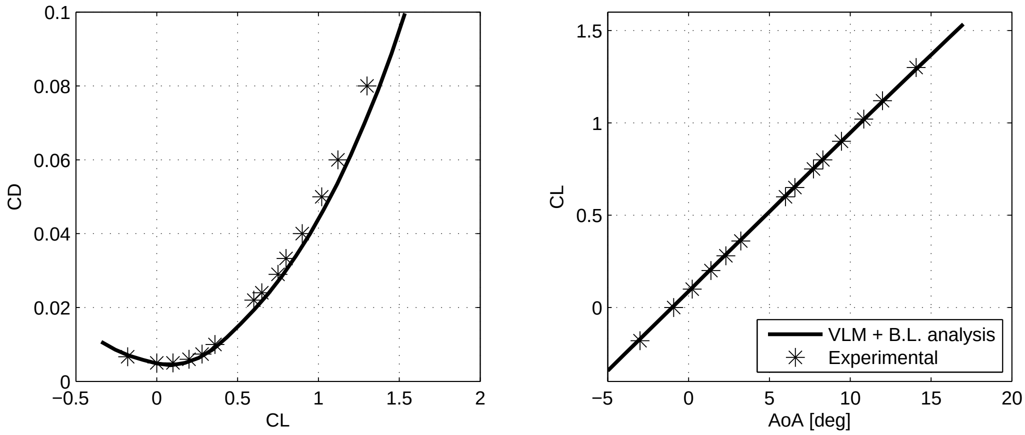


Figure 4: Polar and Lift curves comparing numerical and experimental results for a wing defined by aspect ratio 9, taper ratio 0.4 washout angle 2 deg and a constant profile naca 64-210. Experimental data are obtained from [1].

ogy presented by W. F. Phillips in Chapter 4 and 5 of *Mechanics of Flight* [24]. The book also provides stability criteria for static stability for conventional aircraft, which can serve as a guideline in assessing the stability of UAVs. Additionally, theory from Chapter 8 and 9 can be used to compute linearised longitudinal and lateral dynamics. This is done by solving an eigenvalue problem for longitudinal motion which detects and quantifies if the aircraft is prone to short- or long-period (phugoid) mode instabilities. Solving the eigenvalue problem for lateral motion revels roll, spiral or Dutch mode instabilities. A similar stability analysis using Tornado was performed for a small UAV by Cárdenas et al. [9].
Tornado gives the local spanwise C_L distribution which can be used assessing the wing structure properties. The most important is the structural weight which subtracted from the lift capabilities will give the weight available for other systems, fuel and payload forming an important criterion in the MDO process. An algorithm to analytically approximate the weight can be adopted using [26] and [27], which relates the weight of the aircraft to various design parameters. The statistical approach was developed for conventional aircraft and cannot be directly applied to UAV. However, semi-emipical methods are easily adaptable. Alternatively, NeoCASS (Next generation Conceptual Aero-Structural Sizing Suite) which is a software published under GNU's GPL 2.1, is capable of performing structural sizing and aeroelastic analysis [7, 8]. Similarly to Tornado, it can be easily adapted to parametric batch analysis.

3.3 Propulsion system analysis

Several kinds of propulsion systems exist but taking into account that most UAV fly at low speeds, only propeller-driven vehicle designs are considered. In order to design and analyse the propeller system, there exists a variety of software based on the classical blade-element/vortex theory. Probably the most reliable and relatively sophisticated is the QPROP which is a program predicting the performance of propeller-motor system [12]. Its propeller design counterpart is QMIL. Both are released under GNU General Public License.
QMIL can be used to design both propellers and windmill. The main input variables are aerodynamic profile properties, which can be obtained using XFOIL described in Section 3.1.2, basic rotor properties (number of blades, hub and tip radius), local C_L distribution over the radius normalized blade span and working point (inflow speed, rotational speed and either thrust or power). The program gives as output a complete rotor geometry with chord and twist distribution. It serves as input for QPROP [11].
QPROP uses advanced blade-element/vortex method to analyse propellers and windmills. It is accurate for very high disk loading and static-thrust cases. Two additional arguments that need to be given are inflow speed and rotational speed. As output gives both general and spanwise performance data [13].
Both programs can be easily integrated into Tornado and used to optimise the geometry and performance of the propulsive system. A study on propeller design for small UAV using QMIL and QPROP was done by I. P. Tracy [14]. If a commercial propeller is to be used or the propeller/motor system has been selected a priori, QMIL and QPROP can find the system operation point and thus the efficiency of the propulsive system which, together with the aerodynamic efficiency of the design, can be a crucial parameter in MDO process.

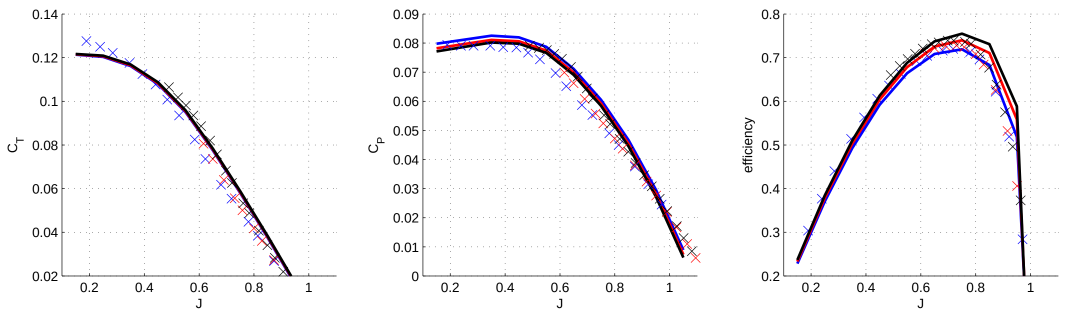


Figure 5: QPROP analysis output, shown as lines, and experimental data, shown as crosses, for a Graupner CAM Slim 10x8 propeller [5]. Blue, red, black colour corresponds to 3000, 4000, 5000 RPM respectively.

3.4 Database interpolation

Several interpolation schemes are commonly used for multidimensional databases. The most important difficulty in multidimensional interpolation is that accuracy decreases when increasing the number of dimensions. The database discretization characteristics in the parameter space is also crucial. Standard interpolation algorithms have been extended to multidimensional problems and are relatively fast tools (see [19] based on B-splines approach). However, they require strict preconditions for the spatial discretization of the parameters map. It needs to be be uniform and in most cases also dense. Kriging method, which is a statistical based interpolation model, is also widely used but is computationally expensive when the data size is big.
Interpolation methods based on decomposition techniques are proposed by Bui-Thanh ([6] using Proper Orthogonal Decomposition) and most recently by Lorente et al. ([20] using High-Order Singular Value Decomposition). HOSVD based interpolation method is robust and shows improvement in comparison

with classical methods. It is a quick and precise interpolation technique when it is applied to multidimensional databases.

4 ADVANCED DESIGN TOOLS

After the MDO process described in Section 2, a small number of candidates for the final design can be tested using higher fidelity software which require more computational power. This is done to verify the analysis done using initial design tools described in Section 3.

4.1 CFD

Firstly, the parametric design used in Tornado needs to be converted into a 3D CAD model in order to do further analysis. A very robust and simple option to use is OpenVSP released under NASA Open Source Agreement (NOSA) version 1.3. OpenVSP stands for Open Vehicle Sketch Pad and is a parametric aircraft geometry tool. It has geometry templates for many typical aircraft parts such as wings, propellers, fuselage, which are controlled by a set of parameters. OpenVSP includes a number of useful tools which can analyse mass properties and create CFD mesh.
The geometry can be then meshed and imported to a CFD software. The term CFD is referred to methods that resolve discretized Navier-Stokes equations on a discretized domain, usually using finite volume method. Further details on CFD theory are left to the reader to investigate. The most important conclusion is that if the problem is well defined, i.e. the model geometry and mesh are precise, the boundary conditions are correct, numerical discretization schemes and turbulence model are appropriate, the solution has high chances of giving precise and reliable results. This comes at a high cost of computational power and storage.
At present there are a few reliable open-source software available: OpenFOAM, SU2 and Gerris. OpenFOAM is in general a more mature and versatile code capable of accurately solving a variety of cases [30]. It is licensed under the GNU General Public Licence and its name stands for Open source Field Operation And Manipulation and has a vast library of solvers capable of solving incompressible, compressible, multiphase flows, etc. It also has most of the modern turbulence models implemented and supports multiple reference frame (MRF) modelling which allows to include moving geometries like propellers. OpenFOAM provides its meshing utilities called blockMesh and snappyHexMesh. However, they often lack sufficient control in mesh creation and more sophisticated finite volume grid generator such as Gmsh or SALOME.
From the point of reasonably good results and little time dedication to familiarise oneself with operating OpenFOAM and meshing software, the best solution is CFD Drone package. Drone CFD is a set of tool written in Python and based on OpenFOAM creating a Virtual Wind Tunnel. Its goal is to make accurate aerodynamic forces prediction with minimum CFD knowledge. It can be easily modified to suite different needs.

4.2 Flight simulation

The flight handling qualities and stability can be checked using FlightGear which is an open-source simulator. The model can be implemented using JSBSim, YASim or UIUC flight dynamics model. To implement the JSBSim model, the aerodynamic coefficients obtained in Tornado can be used. Most of the terrain graphics are available online which makes it possible to do the virtual flight testing in any location. One way of using FlightGear to check the static stability is to initialize the plane in trim at cruise cruise conditions, leaving it in autopilot mode to stabilise at first and then releasing it and then seeing if it can maintain a stable flight.
Whereas FlightGear gives a practical sensation of how the plane behaves in the hands of a human

operator, it is useful to combine it with Paparazzi. It is an open-source autopilot which for simulation purposes accepts Sim and JSBSim. The user can program flight plans to test where the designed aircraft is capable of performing the necessary manoeuvres.

4.3 Wind tunnel and flight testing

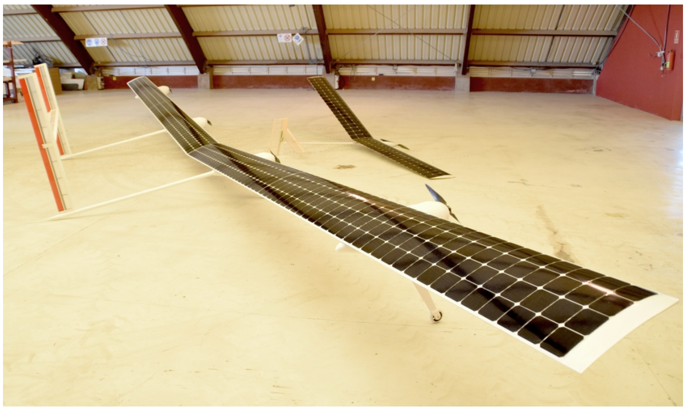
Until now there were no differences between the design procedure of terrestrial and extraterrestrial as in all of the programs the atmosphere and gravitational field could be adapted to the numerical analysis. However, if the design is to be tested in a wind tunnel or in real flight, depending on the size of the model and capabilities of the tunnel, a scaled model may need to be used. In terms of terrestrial subsonic design, it is usually sufficient to maintain geometric similarity by proportional scaling and dynamic scaling by maintaining Re constant. However, if the aircraft is to fly in extraterrestrial atmosphere and wind tunnel or flight testing needs to be done to validate the design, a much detailed analysis of similarity parameters needs to be done. A methodology presented by A. I. Moreno López et al. [22] can be used to optimize such tests. The data used in such test can further verify the validity of initial design tools described in Section 3.

5 METHODOLOGY APPLICATION

The above methodology has been already applied twice: for the design of a planetary exploration UAV "Perigeo" and a terrestrial solar-powered UAV which is further detailed in this section.

PRONTAS (esp. *PRO-totipo N-o T-ripulado de A-vión S-olar*) is a project of a prototype solar-powered

(a) An isometric view.



(b) The prototype and a scaled model used in the conceptual design stage.

Figure 6: PRONTAS project.

aircraft of 16 m span with unlimited autonomy (see Figure 6). The project was developed by ITER[1], Aernnova and UPM. The plane was designed to fly at 8000 m and carry a payload of 6 kg. The conceptual design specified that, due to safety reasons, the plane would be driven by four propellers. These are the initial restrictions imposed on the MDO process by the project. As a result, the main optimisation parameters were cruise speed, discretized chord length (multiple of solar cell width), wing area, distance between the aerodynamic centre of the wing and the horizontal tail and horizontal tail chord length. It allowed to create a parameter grid. All other parameters were fixed due to the mentioned restrictions. The design optimisation process of the aerofoil of the wing was prior to the MDO in order to maximise

[1]Instituto Tecnológico y de Energías Renovables S.A. (eng. *Institute of Technology and Renewable Energy*), leader of the project

the space available to the solar panels without loosing aerodynamic efficiency at low Re. NACA 0012 was used for the tail section.
The global MDO process contained several modules: aerodynamics, structures, stability and energy. The aerodynamic module was implemented using the methodology described in Section 3.1.3. The structures module was based on a simplified model assuming a monocoque structure. The skin was assumed to be made of carbon fibre epoxy resin composite layers 0.181 mm thickness each and density of 1,624 kg/m^3. The number of layers of each element depended on weight and aerodynamic loads it had to withstand and the interior was filled with expansive foam of 25 kg/m^3. The stability module was based on the methodology presented by Phillips [24] described in Section 3.2. The energy module included the technical specification of the solar cells and batteries to be used. C_T and C_P curves were provided by manufacturer and calculated the efficiency of the propulsion system. According to the daily energy available and energy required for constant flight, the module calculated the battery mass needed to store the surplus energy. Since the number of parameters used in the MDO was small, no interpola-

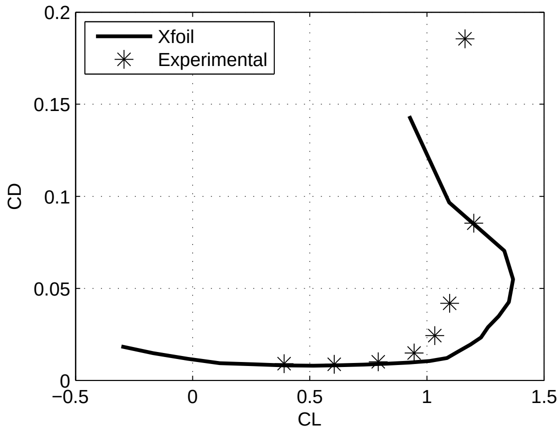
Parameter	Value
cruise speed [m/s]	22.0
wing chord [m]	0.54
wing area [m^2]	8.64
wing-tail distance [m]	2.13
tail chord [m]	0.20

Table 1: MDO process results.

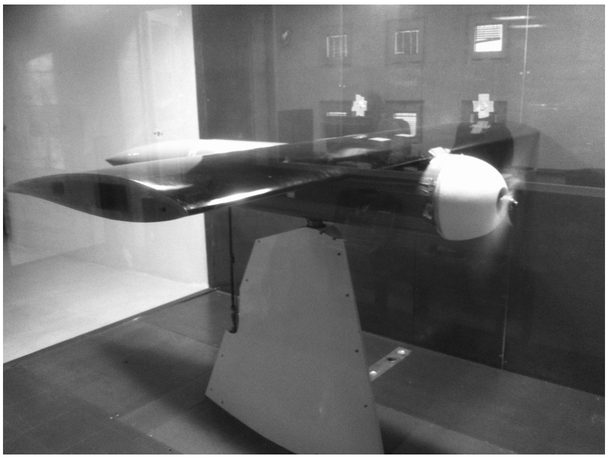
tion methods were used. The final result is summarised in the Table 1. This information, including the main aspects of individual modules, was summarised in a DDEA so that it could be further improved by including data from advanced analysis tools.

In terms of aerodynamics, the XFOIL data were verified and corrected using wind tunnel tests performed at the ITER wind tunnel designed using the methodology provided by González [18]. The forces were measured by a balance designed by González using [17]. A comparison of those two methods can be seen in Figure 7a.
A detailed design based on the preliminary design was implemented in CAD software and the structure was analysed using FEM software. This allowed to detail the internal structure design features, such as wing ribs and spar. Consequently, a more realistic estimate of the wing structural mass was calculated to be 20.12 kg in comparison to 23.96 kg provided by the initial structure module. The CAD model also allowed to integrate all the subsystem elements, giving a better total mass estimation, inertia tensor and centre of gravity position.
The stability module was further expanded with a gust analysis which defined atmospheric flight envelope. The plane handling qualities were qualitatively checked by virtual flight testing implementing a JSBSim model of Prontas in the FlightGear simulator (see Figure 7c).
The energy module was further improved by updating solar cell and battery specifications. The propulsion system was tested in the ITER wind tunnel in configuration with the wing (see Figure 7b).

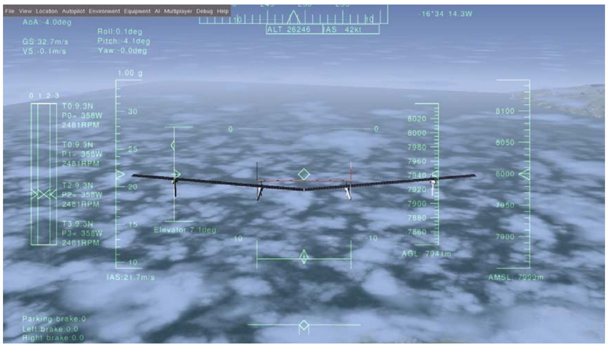
Since the project involved various companies and many professionals from different disciplines, a suitable way of data interchange had to be chosen. Nowadays the most widely used form of DDEA are spreadsheets (see Figure 8) due to their numerous advantages. The data is always visible, linked and can be iteratively and automatically updated by the spreadsheet. They permit mixing different types of information (e.g. numerical, textual, graphical, etc.) and the data can be easily filtered and arranged in form of graphs or tables. Finally, they are very accessible to people without a strong programming background.



(a) A comparison between XFOIL and wind tunnel test for PRONTAS aerofoil done at Re=4.1·10^5.



(b) A wind tunnel model of the propulsion system in configuration with the wing test in ITER wind tunnel.



(c) PRONTAS model implemented in FlightGear simulator.

Figure 7: Advanced design tools applied in the PRONTAS project.

6 CONCLUSIONS

This article comprises the design process of planetary flight vehicles from its early phases until a suitable detailed design is obtained. The initial analysis tools have been demonstrated to be time-efficient, robust and sufficiently accurate. Furthermore, these tools are flexible and adaptable to unconventional configurations. The advanced analysis stage proposes accurate and easily accessible tools which allow to refine the preliminary design obtained by the MDO process. The incorporation of a DDEA during the design process organises the information exchange among project participants and also improves the robustest of the methodology since it allows to implement small changes in the detailed design without loosing the validity of the MDO selection. The PRONTAS project, whose objective was to design an solar-powered UAV, has demonstrated that the methodology can be successfully employed in designing UAVs that use relatively new technologies.

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TECHNOLOGICAL PARAMETERS		Actualization		
Name [Unit]	Value	Responsible	Date	Time
Efficiency of the propulsive system	0.76	UPM/ITER	auto-update	
Solar cells efficiency	0.23	ITER	17/10/2012	12:00
Energy density of the bateries [Wh/kg]	255	ITER	23/02/2013	18:30
Energy per volume of batteries [Wh/l]	400	ITER	17/10/2012	12:00
Battery density [kg/m^3]	1569	ITER	auto-update	
Payload [kg]	6.00	ITER	17/10/2012	12:00
Flight autonomy	Indefinitely	ITER	17/10/2012	12:00

WEIGHT SUMMARY		Actualization		
Name [Unit]	Value	Responsible	Date	Time
Total structural mass[kg]	40.03	ITER/AERNNOVA/UPM	auto-update	
Battery volume [m^3]	0.044	UPM	17/10/2012	12:00
Battery volume used [%]	42	ITER	auto-update	
Battery mass [kg]	29.09	ITER	auto-update	
Total mass of the aircraft [kg]	75.12	ITER/AERNNOVA/UPM	auto-update	
Total mass of the aircraft (5% over the current estimation) [kg]	78.58	ITER/AERNNOVA/UPM	auto-update	

AERODYNAMICS SUMMARY		Actualization		
Name [Unit]	Value	Responsible	Date	Time
Lift coefficient	0.702	UPM	auto-update	
Induced drag coefficient	0.00616	UPM	auto-update	
Parasitic drag coeffient of the aerofoil at the target Cl	0.00935	UPM	auto-update	
Total drag coefficient	0.02106	UPM	auto-update	
Estimated efficiency of the aircraft	33.34	UPM	auto-update	
Drag per unit mass of the aircraft [N/kg]	0.294	UPM	auto-update	
Total drag of the aircraft [N]	23.12	UPM	auto-update	
Total power needed for flight [W]	671.1	UPM	auto-update	
Wing loading [kg/m^2]	9.09	UPM	auto-update	

ENERGY SUMMARY		Actualization		
Name [Unit]	Value	Responsible	Date	Time
Energy consumed by the flight systems [W]	10	ITER	17/10/2012	12:00
Other energy consumption [W]	25	ITER	auto-update	
Power consumption [W]	706	UPM/ITER	auto-update	
Time of solar energy collection during the day [h]	13.7	ITER	auto-update	
Time without the sun [h]	10.3	ITER	auto-update	
Solar power available [W]	1,248	ITER	auto-update	
Power available for charging the batteries [W]	542	ITER	auto-update	
Energy available to charge the batteries [Wh]	7,419	ITER	auto-update	
Battery degradation [%]	10.0	ITER	17/10/2012	12:00
Energy stored in the batteries [Wh]	7,419	ITER	auto-update	
Battery mass [kg]	**29.09**	ITER	auto-update	
Energy needed to fly overnight (inc. battery degradation) [Wh]	8,001	ITER	auto-update	
Battery energy surplus [Wh/day]	-582	ITER	auto-update	
Extra energy stored in batteries [%/day]	**-3.4**	ITER	auto-update	
Energy collected by solar panels [Wh/day]	**17,093**	ITER	auto-update	
Total energy needed for flight [Wh/day]	**16,947**	ITER	auto-update	
Energy surplus [Wh/day]	146	ITER	auto-update	
Energy surplus [%/day]	**0.9**	ITER	auto-update	

FLIGHT CONDITIONS		Actualization		
Name [Unit]	Value	Responsible	Date	Time
Cruise speed [m/s]	22.0	ITER	17/10/2012	12:00
Flight altitude [m]	8,000	ITER	17/10/2012	12:00
Season	Summer	ITER	17/10/2012	12:00
Geographical latitude [deg]	28	ITER	17/10/2012	12:00
Ambient temperature [K]	236.15	UPM/ITER	auto-update	
Air density [kg/m^3]	0.5252	UPM/ITER	auto-update	
Atmospheric pressure [Pa]	35,599	UPM/ITER	auto-update	
Dynamic viscosity [Pa s]	1.53E-05	UPM/ITER	auto-update	
Kinematic viscosity [m^2/s]	2.91E-05	UPM/ITER	auto-update	
Reynolds number	4.08E+05	UPM/ITER	auto-update	
Mach number	0.07	UPM/ITER	auto-update	

AIRCRAFT DIMENSIONS		Actualization		
Name [Unit]	Value	Responsible	Date	Time
Length [m]	2.51	UPM	auto-update	
Width [m]	16.00	UPM	auto-update	
Height [m]	2.05	UPM	auto-update	

WING GEOMETRICAL DATA		Actualization		
Name [Unit]	Value	Responsible	Date	Time
Aspect ratio	29.63	UPM	auto-update	
Wing area [m^2]	8.64	UPM	auto-update	
Wing span (without wingtips) [m]	16.00	UPM	auto-update	
Mean aerodynamic chord of the wing		0.54	UPM	auto-update	

PROPULSIVE SYSTEM EFFCIENCES		Actualization		
Name [Unit]	Value	Responsible	Date	Time
Motor	0.91	UPM/ITER	23/07/2013	17:00
Propeller	0.85	UPM/ITER	17/10/2012	12:00
Drive	0.98	UPM/ITER	17/10/2012	12:00
Total	0.76	UPM/ITER	auto-update	

Legend:
Input cell (cells to be modified)
Normal cell hold calculated data or data copied from other cells
Calulated important data

Figure 8: A snapshot of the spreadsheet summarising general data of the Prontas project.

Nomenclature

AoA angle of attack $[rad]$, also referred to as alpha

C_D total drag coefficient

C_L lift coefficient

C_l lift coefficient of an airfoil

C_P coefficient of power

C_p pressure coefficient

C_T coefficient of thrust

C_{Di} induced drag coefficient

C_{Dv} viscous drag coefficient

$C_{L\alpha}$ lift curve slope

C_{L0} lift coefficient at zero angle of attack

J advance ratio

M Mach number

Re	Reynolds number
B.L.	Boundary Layer
CFD	Computational Fluid Dynamics
DDEA	Dynamic Data Exchange Application
HOSVD	High-Order Singular Value Decomposition
MDO	Multidisciplinary Design Optimisation
RPM	revolutions per minute
VLM	Vortex Lattice Method
WT	Wind Tunnel

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