AERIAL, AN ESA DRONE APPROACH TO CONQUER MARS ATMOSPHERE

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ABSTRACT

AERIAL is the ESA approach to build a first drone prototype capable of flying in Mars. The design of the vehicle must account for the challenges of flying in an atmosphere with characteristics different from that of Earth as well as for the inaccessibility to the Aerobot once launched.

The aim of the project is to produce a technology demonstrator to retrieve valuable information regarding the aerodynamic, thermal and overall performance of the vehicle once tested in the relevant facilities that emulate the Mars environment. As such, it will the first step towards the European aerial exploration of Mars.

1. INTRODUCTION

In April 2019, for the first time ever, an autonomous Unmanned Aerial Vehicle (UAV) successfully took off from the surface of Mars proving that it is possible to fly a vehicle in the Martian atmosphere. Europe is currently investing its technology and expertise to enhance the possibilities of Martian autonomous flight. The ESA project AERIAL is one of the approaches into this challenge by prototyping an autonomous Aerobot fully capable of flying in the conditions of Mars (atmosphere, temperature, pressure, dusty environment). As such, it will be designed and manufactured for testing and concept validation in facilities that emulate the Martian atmosphere.

Flying in Mars has many associated challenges due to the peculiar environment: a low-density and low temperature atmosphere, requiring a specific blade design and dedicated thermal dissipation means; unavailability of a Global Navigation Satellite System (GNSS), suggesting visual navigation solutions and inaccessibility to the aerobot once launched, requiring an investment in system autonomy and failure tolerance.

This paper will provide the approaches considered for the development of the Martian UAV to tackle the aforementioned challenges.

2. MARS ATMOSPHERE

The Martian atmosphere is the critical aspect to consider for conducting a flight. It is characterized by a very low density, low temperature, CO_2 composition and low gravity. Table 1 depicts a comparison between the atmospheric conditions in Mars and in Earth.

Table 1. Atmospheric conditions comparison

Parameter	Units	Earth	Mars
Density	kg/m^3	1.225	0.015
Temperature	K	288	223
Speed of sound	m/s	340.3	233.1
Gravity acceleration	m/s^2	9.8	3.7

Mars density is two orders of magnitude smaller than that of Earth. A low-density atmosphere implies lower dynamic pressure and Reynolds number. Low dynamic pressure translates into smaller lift forces than in Earth for the same airspeed. Low Reynolds number implies the blade will be working on the subcritical regime ($Re < 5 \cdot 10^4$) differentiated by poorer aerodynamic performances.

The low temperatures, while beneficial for the cooling requirements of the motors, are detrimental for battery performances and compressibility effects due to the low speed of sound.

The peculiar atmosphere of Mars drives the need of designing a specific blade with improved aerodynamic performances at low Reynolds as well as an adequate thermal system for heat dissipation.

2.1. Blade Design

Blade design for the Martian atmosphere is one of the most critical aspects of the Aerobot design. Low-Reynolds regimes are not the typical scenarios for blade design and thus conventional airfoils are not well fitted for the purpose of this mission. An analysis of the aerodynamic profiles of a traditional airfoil and a cambered flat plate at low Reynolds (Re) numbers is depicted in [1].

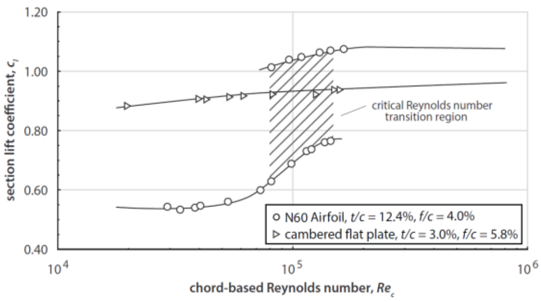


Figure 1. Lift coefficient profile for low Reynolds number regime, [1]

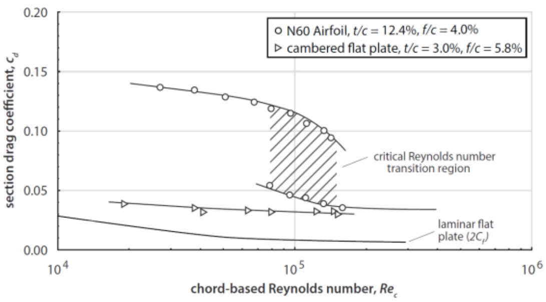


Figure 2. Drag coefficient profile for low Reynolds number regime, [1]

Both in Figure 1 and in Figure 2, it can be seen that traditional airfoils such as the one depicted suffer a sharp transition in aerodynamics around Re = 10^5: there is a drop in lift and a drag increase. On the other hand, such dominant performance degradation is not seen for flat plate airfoils making them more suitable for Martian flight applications.

In an effort to draw away from traditional airfoils, the aerodynamic performances of low thickness double-edge plate profiles as suggested in [2] are evaluated. Figure 3 depicts the chord-normalized profiles that have been designed for analysis at different blade span sections. The maximum chord of the blade is 12.4cm at the blade root and the minimum is 7cm at the blade tip.

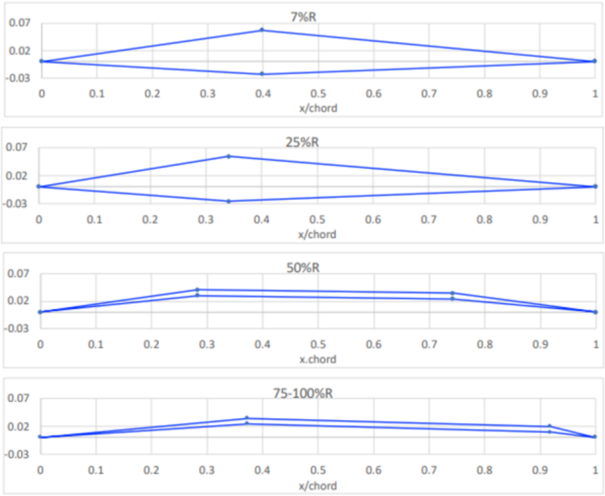


Figure 3. Low thickness double-edge plate profiles.

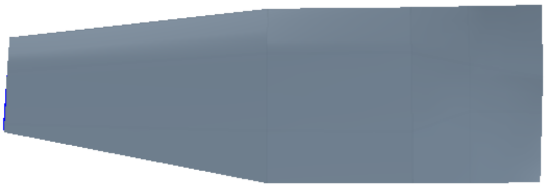


Figure 4. Constructed blade for aerodynamic analysis

The blade generated from the presented profiles for the analysis (Figure 4) will have, as a first approach, a short span which reduces the Mach and vehicle size for given rpm (revolutions per minute) and a large chord which increases the Reynolds number over the airfoil for given rpm.

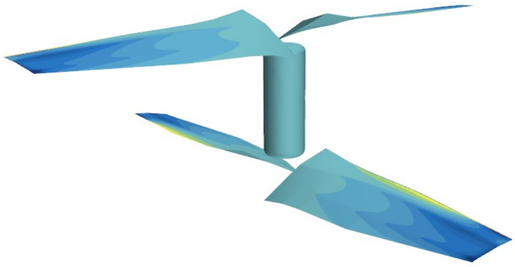


Figure 5. Reference rotor

A reference rotor was developed with the proposed blade design for the aerodynamics evaluation (Figure 5). The reference rotor is constituted of upper and lower coaxial rotors with the lower rotor having a higher pitch to counteract the vertical jet influence of the higher rotor. The simulation conditions considered that both rotors have equal but opposite angular velocity, their nominal rotational speed is 5000rpm and no wind nor ground effect is simulated.

The blade aerodynamic performances achieved after the preliminary analysis are depicted in Table 2. An important conclusion retrieved from the analysis is that the aerodynamic interactions between upper and lower rotors introduce a series of fatigue cycles in the blade that must be accounted for in the structural design.

Table 2: Aerodynamic performances of the analysed blade

	Upper blades	Lower blades
Mean lift coefficient	0.74	0.665
Mean drag coefficient	0.095	0.135

The main drawback of this configuration despite being, preliminarily, more suitable for Martian flights is that its manufacturing is very challenging due the very low thickness of the structure. New analyses are now being performed with blade profiles that are more similar to that of Ingenuity [3] since its manufacturing is not as complicated.

2.2. Blade Manufacturing

The rotor blades will be constructed from high performance composite materials to achieve maximum stiffness while reducing the weight as much as possible. The blades will be molded with top and bottom molds and cured in a single shot to get a no seams monolithic structure. The blade will have a solid laminate hub root to mechanically attach them to the rotating group. The blades will be statically and dynamically balanced in sets.

2.3. Thermal System Design

The rejection of the heat generated at the propellers is a critical ability to fly in the Martian atmosphere characterized by its low temperature and the presence of poor convection thermal exchanges. As such, a dedicated thermal system design must be implemented.

After a preliminary thermal analysis, it was concluded that several approaches must be combined to optimize the heat dissipation: the use of black kapton, specific motor selection and the use of a dissipative surface.

A motor closed housing covered with black kapton would be beneficial to decrease the temperature as well as avoiding any functional damage due to Martian dust. Black kapton material is typically used for insulation in space missions for its enhanced thermal properties.

The selection of motors with low power consumption would also be beneficial since less dissipation would occur. As such, the power consumption was one of the criteria considered in the motor selection trade-off.

The use of a fin as dissipative surface at motor housing level would help decrease the motor temperature. Similarly, the utilization of thermal conductive coupling between the motors and the structure would drive the power dissipation to the structure where more dissipative surface is available.

3. AEROBOT DESIGN

While the thermal system and blade designs are driven by the atmospheric characteristics of Mars, the motor and motor configuration selection as well as the navigation system implementation are affected primarily by different factors. The selection of the motor configuration is characterized by the need of fault tolerance that will ensure system viability even if specific motor failure occurs. On the other hand, the navigation system development is mainly influenced by the requirement of having an autonomous UAV since the communications delay between Earth and Mars would prevent smooth operation otherwise.

3.1. Aerobot Architecture

A preliminary design of the Aerobot is presented in Figure 6 where its architecture and main subsystem components are depicted.

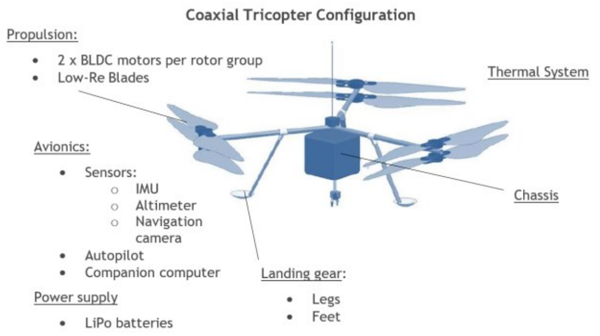


Figure 6: Aerobot architectural description

3.2. Motor Configuration

A trade-off was performed to select the most suitable UAV configuration for a Mars mission.

Coaxial, quadcopter, synchropter, coaxial-tricopter and coaxial-quadcopter were the configurations evaluated in the trade-off. The criteria considered for the trade-off were size, mass, power, complexity, safety, reliability, components availability, thermal design complexity and flight control complexity.

The coaxial-tricopter configuration had the best overall scoring out of all configurations studied. This configuration is also known as ‘Y6’ and is depicted in Figure 7.

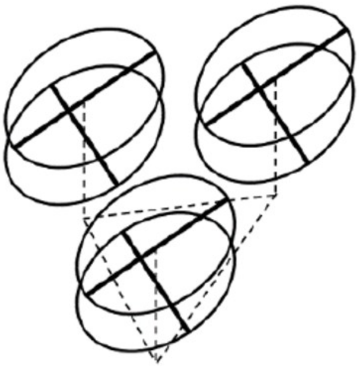


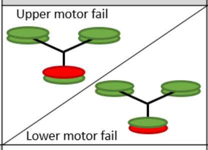
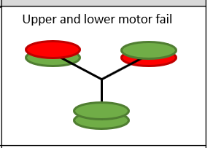
Figure 7. Y6 Configuration

The Y6 configuration main strong points are directly related to its number of motors. The total power, despite higher in hover than in other configurations, is shared among six small motors which eases the demands for the thermal control system. Also, no additional mechanisms are required for flight control since the control is performed via differential motor speeds which reduces the complexity as well as the power demands.

The strongest asset of a configuration with six motors is its ability for fault tolerance. This was the driving criteria for the selection of a coaxial-tricopter configuration. An analysis was made in terms of forces and torques balances throughout different fail cases, concluding that the Y6 configuration can still fly either with single or crossed-rotor dual failure.

The failure of one or more rotors will cause the different aerobot performances to be deteriorated. The required hover and forward flight power will increase as well as the motor dissipated heat and therefore the global drone temperature will be raised during drone operation. Furthermore, due to the faster degradation of the batteries because of the extra power feeding the healthy motors, the maximum achievable range by the aerobot will decrease inversely proportional to the number of inoperative motors. Table 3 presents a summary of the performed fault tolerance analysis and the achieved results.

Table 3. Aerobot fault tolerance analysis

	1 FAILED MOTOR	2 FAILED MOTORS
		
Continue flying?	✓	✓
Hover Power	∧	∧∧
Range	∨	∨∨
Motors diss. Power	∧	∧∧
Max. Temp. Increasing	∧	∧∧

3.3. Motor Selection

The motor selection was driven by blade performance requirements: they have to achieve a sufficiently large torque (around 0.2Nm) while remaining fairly small and light weight and they have to be able to sustain high revolutions (around 5000rpm). Also, as anticipated in the thermal system design, it is desirable for the motors to have low consumption so that dissipation is minimized. Martian dust must be considered as well to avoid premature motor degradation or performance downgrading.

The motors are brushless DC motors since they have significantly higher efficiency and performance and lower susceptibility to mechanical wear than their brushed counterparts. They also have higher torque to weight ratio and increased torque per watt of power. The preceding assets are of especial interest for a mission in Mars where performance requirements cannot be met at the expense of larger weights and sizes. Furthermore, the wear resistance is very relevant as well due to the inaccessibility to the UAV for repairs once launched.

The preliminary motors selected are the KDE Direct® KDE2315XF-965 (Figure 8) with the Electronic Speed Controller (ESC) KDEXF-UAS35. Typical UAV motors have been chosen due to their availability as well as excellent performance to weight ratios.

Figure 8. KDE Direct® KDE2315XF-965 motor

3.4. Avionics System

The avionics of the Aerobot are key for the autonomy of the system. As such, the selection of a proper autopilot framework combined with the necessary set of sensors was critical for the functioning of the Aerobot.

Autopilot

The Open-Source Autopilot PX4 was selected as the autopilot software for the Aerobot. PX4 not only has the advantage of being open-source, but it also has a considerable support community and offers compatibility with multiple peripherals and flexibility to develop.

PX4 consists of two layers: the flight stack and the middleware. The flight stack consists of the GNC algorithms for autonomous drones including the controllers and estimators for attitude and position (Figure 9). The middleware is a general robotics layer to support any type of autonomous robot providing internal/external communications and hardware integration. Additionally, the middleware includes a simulation layer allowing to run the PX4 flight code with a model of the vehicle and its environment.

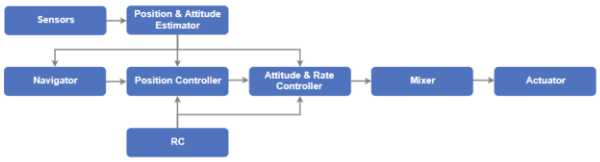


Figure 9. Building blocks of the PX4 Flight Stack (courtesy of PX4 website)

The autopilot hardware selected is the Pixhawk 4 since it is optimized to run PX4 and fits the SWaP requirements of the Mars mission. This autopilot is combined with the Holybro® Pixhawk 4 Power Model (PM07) to provide regulated power to the autopilot and the ESCs and to send information regarding battery voltage and current supplied to the flight controller and motors.

Sensors

The navigation and control of the Aerobot must be supported by a set of sensors that provide the necessary information to the autopilot.

Sensor selection was driven by performance requirements as well as compatibility with PX4 framework. The selected sensors for navigation are the following:

- IMU: for inertial measurements to support visual navigation. A tactic-level IMU is desired for accuracy and overall performance purposes.

- Navigation Camera: Intel® Realsense Tracking Camera T265 to provide odometry information

- Lidar: LeddarTech® LeddarOne for distance measurements.

As anticipated earlier, the navigation in Mars is challenging since it requires a GNSS-less system. As such, visual-inertial techniques are the selected approach for navigation. The PX4 software allows navigation through VIO (Visual Inertial Odometry) which enables to estimate local position and orientation and velocity of a moving vehicle by postprocessing the associated camera images combined with inertial measurements. A companion computer is required to carry out the computational load of visual-inertial navigation which exchanges information with the autopilot via the Mavlink communications protocol.

3.5. Structure and Integration

The Aerobot structure is constructed from high performance composite materials to achieve the highest strength to weight ratio. The chassis consists of cylindrical pressure vessels with mounting hard pointes for the motor arms and landing gear. The chassis will reduce the amount of metallic hardware and fasteners to reduce weight. The composite structure will have an integrated metallic heat exchanger to dissipate heat from the motors and ESC. The avionics tray will be removable for component integration and bench testing.

4. ANALYSIS AND TESTING

4.1. Simulation

The PX4 middleware simulation layer allows to simulate the flight code in (Software-In-The-Loop) SITL and, together with Gazebo robotic simulator, the state and performances of the Aerobot. The objective of the simulations is to generate a model which can predict the behaviour of the Aerobot along the different performance profiles.

Gazebo software allows PX4 flight code to control a computer modelled vehicle in a simulated 'world'. The scripted files for the vehicle model can be modified if required and contain all the information about the physical drone's airframe, its motor layout and its mechanical characteristics (max. rpm, motor performances, aerodynamic coefficients, etc). Similarly, the 'world' model includes all atmospheric characteristics.

The simulation software contains different plugins which act as intermediaries between the Aerobot and the world. The motor model is the one responsible for generating the aerodynamic forces and moments. This model requires from the vehicle model to import its geometry and mechanical motor data to compute the forces and moments with analytical expressions derived from the BET (Blade Element Theory).

Connected with PX4 through Mavlink communications protocol, QGC (QGroundControl) acts as a ground station for the simulations (and for the real flights as well). QGC allows a complete control of the flight, enabling the creation of mission plans or the modification of vehicle parameters, feeding back PX4 with different control gains, number of batteries, maximum allowed velocities, etc.

Both Gazebo and QGC have different data display tools for certain data analysis in real time. However, an additional tool has been developed in MATLAB to complement the existing features of the simulator. With this tool, flight data can be post-processed and thoroughly analyzed and thermal evaluations can also be carried out.

4.2. Testing

The Aerobot will undergo two phases of testing. The first phase is to produce the propulsion breadboards to test the propulsive system alone. The second testing phase will subject the completed Aerobot to the performance tests.

For the first phase of testing, three modular different breadboards will be produced, assembled, integrated, tested, and analysed along a test campaign in Mars representative environment facilities. These self-thermally-regulating propulsion breadboards are intended to represent the behaviour of the drone propulsion plant working on Mars' atmosphere, in terms of thrust, power and temperature.

The three propulsion breadboards are planned to be tested in SENER Aeroespacial facilities. SENER TVC (Thermal Vacuum Chamber, Figure 10) will allow to perform the firsts tests under a minimum temperature and pressure environment, but without presence of dust nor wind.

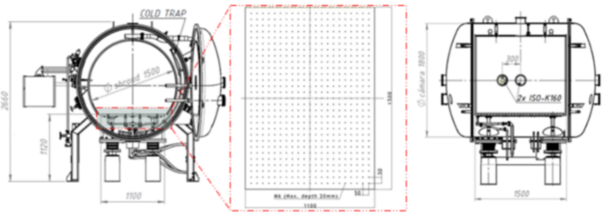


Figure 10. Telstar TVC-01 in SENER

A propulsion test bench controller was designed and successfully tested to measure the propulsion system performance, log performance data and control the motors speeds (Figure 11). The test bench controller measures the power input vs. the power produced by the rotors to determine the efficiency. The controller has a SD card reader that records all the performance parameters (thrust, volts, amps, rpm). The touch screen commands the speed of the motors and is used to setup simulator parameters.

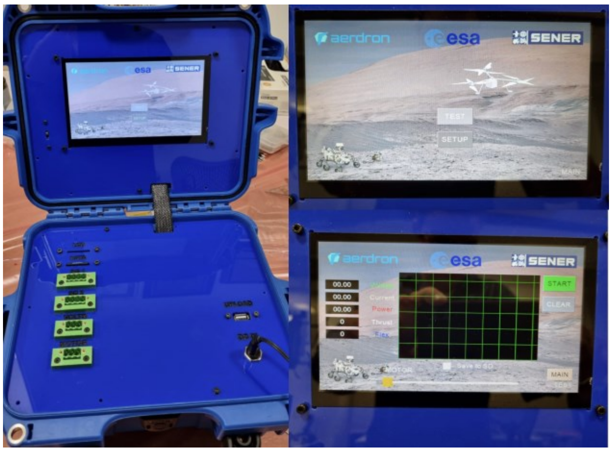


Figure 11. Propulsion test bench controller

For the second phase of testing, the completed Aerobot will be subjected to a representative Mars environment in the Mars Simulation Laboratory of Arhus, in Denmark. These facilities represent the state of art in Europe for Mars environmental simulation, being capable of reproducing a wide range of possible atmospheric conditions. Some of the most important and key features of these facilities for the carried tests are:

- Tank size of 2,5 m diameter and 8 m long.
- Pressure ranges from 0,1 to 1000 hPa with 2% accuracy.

- Temperature ranges from -150ºC to 50ºC with stability of 1ºC.
- Humidity control.
- Maximum wind flow of 20 m/s.
- Capability of including dust presence during tests.

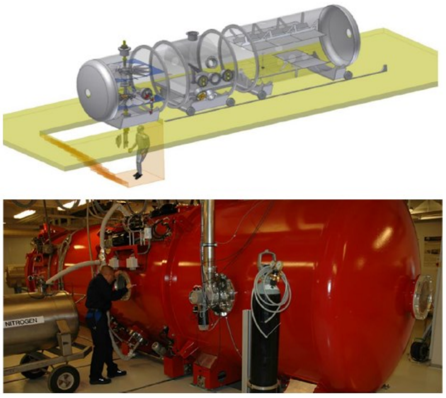


Figure 12. Arhus Mars simulation laboratory

The results of the tests campaign will guide the drone detailed design and will constitute direct feedback for the developed simulator. The conclusions retrieved after the Aerobot testing will provide the relevant information of the blades, motors and thermal control performances in a Mars simulated environment.

5. SUMMARY AND CONCLUSIONS

The main ambition for AERIAL is to develop a prototype of an UAV capable of flying in Mars. Several challenges have been encountered while designing a vehicle able to fly in a foreign planet with peculiar atmosphere. Different approaches have been selected to overcome them.

Flying in a low-density and low-temperature atmosphere requires a very specific blade design to achieve good aerodynamic performances in low-Reynolds regimes. Similarly, the Martian atmosphere requires for a targeted thermal system design suggesting the use of black kapton for the motor housing, the implementation fins for thermal dissipation as well as the selection of low-consuming motors.

The inaccessibility to the Aerobot once in Mars led to the selection of a fault-tolerant six-motor configuration that enables the vehicle to sustain flight if determined failures occur in the propulsive system. Furthermore, the lack of instantaneous communication with the Aerobot from Earth drove the decision of investing in an autonomous flight navigation and control software via an autopilot open software framework. The selected autopilot framework is compatible with visual-inertial navigation, essential to fly in a GNSS-less environment.

Finally, to assess the capabilities of the proposed design, testing in facilities that emulate the environment of Mars will be carried out on both the complete Aerobot and the propulsive system by itself.

6. REFERENCES

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