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SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

Executive Summary of the Thesis

# Preliminary design of a fixed-wing VTOL UAV for Martian flight

Laurea Magistrale in Aeronautical Engineering - Ingegneria Aeronautica

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## 1. Introduction

The Mars 2020 mission by NASA attained a groundbreaking achievement by conducting the first powered flight in an extraterrestrial atmosphere, with Ingenuity, the Mars Helicopter. Ingenuity is a small rotorcraft, weighing just 1.8 kg, capable to fly in the thin Martian atmosphere, where lift generation is inherently very difficult. It exhibits a range spanning a few hundred metres and an endurance lasting a couple of minutes. Ingenuity paved the way for future aerial exploration of Mars and, potentially, other space destinations. Future scientific missions on Mars will require the large scale aerial exploration of the planet. To achieve extended range, cost-effectiveness, and compact design, a promising solution entails employing fixed-wing unmanned aerial vehicles (UAVs).

This project delves into the planetary environmental conditions of the Red Planet, comparing them with the terrestrial ones, in order to understand how these conditions influence the design and aerodynamics of fixed-wing UAVs. The preliminary design of an electric vertical takeoff and landing (VTOL) UAV is presented, developed for undertaking long-range missions on the Red Planet. A scientific mission in that scenario is outlined. Subsequently, the project introduces the preliminary design of a different eVTOL UAV, conceived for the purpose of undertaking a similar mission, to the one of the Martian drone, within the terrestrial environment. The objective is to evaluate the effects of diverse planetary conditions on different aspects of the design, with a specific emphasis on aerodynamics. This thesis concludes with a comparative analysis between Martian and terrestrial drones, followed by a brief evaluation of the possible applicability of fixed-wing UAVs in the extra-terrestrial atmospheres of Venus and Titan.

## 2. Martian environment

In the Martian environment, the only relatively abundant source of power is derived from the Sun. Solar radiation diminishes proportionally with the square of the heliocentric distance, resulting in less abundance on Mars compared to Earth, being the Red Planet at approximately 1.524 astronomical units from the Sun. Therefore, the average beam irradiance at the top of Mars atmosphere is equal to $G_{\text{ob,mean Mars}} = 590 \frac{\text{W}}{\text{m}^2}$ [1]. This is less than half, when compared to the average solar irradiance on Earth $G_{\text{ob,mean Earth}} = 1371 \frac{\text{W}}{\text{m}^2}$. The average value $G_{\text{ob,mean Mars}}$ requires further reduction, considering the opacity of the Martian atmosphere. In addition, it is necessary to account for the pro-

jection of the solar irradiance $G$ over an horizontal surface, which is related to the cosine of the solar zenith angle $z$.
The gravitational acceleration on Mars surface is $g_{\text{Mars}} = 3.72\ \frac{\text{m}}{\text{s}^2}$, equivalent to roughly 38% of Earth's gravitational acceleration $g_{\text{Earth}} = 9.81\ \frac{\text{m}}{\text{s}^2}$. The lower gravitational acceleration contributes to a favorable effect, enhancing the potential mission range. The atmosphere of Mars is composed by 95.1 % carbon dioxide, 2.59 % nitrogen, 1.94 % argon, 0.161 % oxygen and 0.058 % carbon monoxide [5].
The design of a fixed-wing UAV for Martian flight requires the draft of a simple analytical model of the Martian atmosphere. For this reason, a simple model developed by NASA has been considered, and implemented in MATLAB [2]. The atmospheric model presumes the following values of temperature, pressure and density, at 0 m altitude:

$$T = 242.15\text{K};\ P = 699\text{Pa};\ \rho = 0.0150\frac{\text{kg}}{\text{m}^3};\quad (1)$$

The Martian atmosphere exhibits a lower specific heat ratio compared to air on Earth. This, in conjunction with its significantly low temperature, results in a reduced speed of sound, equal to $c = 244.39\frac{m}{s}$, at zero metres altitude.

## 3. Effects on the design and aerodynamics of fixed-wing UAVs

The remarkably low atmospheric density of the Martian atmosphere significantly influences the attainment of adequately high wing loading values $\left(\frac{W}{S}\right)$. Consequently, the wing surface of the Martian UAV is expected to be oversized in comparison to typical terrestrial UAVs. This will affect the structural mass of the aerodynamic surfaces and the overall mass of the UAV. Furthermore, employing Blade Element Momentum Theory (BEMT), the low-density conditions in the Martian atmosphere pose significant challenges for executing vertical take-off, primarily attributable to increased induced power requirements.
The Martian atmospheric conditions have a great impact on the aerodynamics, consequently shaping the overall performance of the UAV. The dynamic viscosity at reference ground level on Mars is $\mu = 1.2286 \times 10^{-5}\text{Pas}$. The combination of the extremely low atmospheric density and moderate dynamic viscosity, contributes to the operation of small fixed-wing UAVs on Mars within the low Reynolds number regime. In fact, considering the same reference length, freestream velocity and altitude, the Reynolds number associated to the mean aerodynamic chord of the UAV in the Martian atmosphere is estimated to be approximately 55 times lower than its counterpart in Earth's atmosphere. Operating within the low Reynolds-number regime typically results in a notable degradation of aerodynamic performance, characterized by elevated drag coefficients ($C_D$), diminished maximum lift-to-drag ratios $\left(\frac{L}{D}\right)_{\max}$, and reduced maximum lift coefficients ($C_{L\,\max}$). The modest maximum lift coefficient necessitates an oversize of the UAV's wing surface. Furthermore, the moderate maximum lift-to-drag ratio adversely impacts the mission range. In addition, the Martian atmosphere is characterised by low speeds of sound, $c = 244.39\frac{m}{s}$ at 0 metres altitude, when compared to the terrestrial atmosphere. Compressibility introduces non-trivial effects in the low-Reynolds regime, occasionally exhibiting behaviors contrary to those observed at high Reynolds numbers.

## 4. Innovative technologies

The atmospheric flight on Mars requires the use of innovative battery technology, characterised by high specific energy $e^*_{\text{spec}}$ and high specific power $p^*_{\text{spec}}$. This project proposes the use of Licerion batteries, a Lithium-Metal Oxide rechargeable battery [3]. This technology exhibits enhanced performance in terms of both specific energy $e^*_{\text{spec}}$ and specific power $p^*_{\text{spec}}$, outperforming traditional Li-Ion technology. Licerion batteries are designed to undergo more than 500 cycles with minimal performance degradation. This kind of battery is supposed to operate always at a temperature greater than $T \geq -25°\text{C}$, otherwise a heater must activate.
In the design of the Mars UAV, a hypothetical cell, modeled after those developed by Licerion, has been employed, featuring the characteristics reported by table 1. To enable self-recharging capabilities of the Martian drone, the integration of flexible solar cells has been explored. The cells are supposed to be mounted on the upper side of the wing surface of the

| Parameter | Value |
|---|---|
| Specific energy | $e^* = 450 \frac{\text{Wh}}{\text{kg}}$ |
| Specific power | $p^* = 1000 \frac{W}{\text{kg}}$ |
| Nominal capacity | $Q_{\text{nom}} = 17.5$ Ah |
| Minimum state of charge | $SOC_{\text{min}} = 10$ % |
| Cell mass | $M_{\text{cell}} = 0.166$ kg |
| Cell weight factor | $\omega_f = 0.85$ |

Table 1: Battery specifications

Mars UAV. The demanding environmental conditions on Mars necessitate the utilization of advanced materials designed for extreme applications. Consequently, the exploration of ultra-thin carbon fiber-reinforced materials has been undertaken to minimise the structural mass of the UAV. In addition, a combination of thin-film heaters and a metallised Kapton insulation layers are required, to withstand the glacial temperatures of Mars, maximizing the absorption of solar heat while simultaneously minimizing heat loss from inside the box to the Martian atmosphere. This configuration is coherent with what adopted by Ingenuity.

## 5. Mars UAV

Mars represents an extreme environment, in many respects. The Martian surface presents harsh terrain characteristics that require that the drone disposes of VTOL capabilities. Moreover, solar energy emerges as the most abundant and economically viable energy source on Mars. Therefore, a viable option for the Martian environment could involve the deployment of electric VTOL UAVs equipped with wing-mounted solar panels. To ensure practicality, a maximum recharge time limit has been established, $t_{\text{recharge}} \leq 2$sols. The Mars UAV is equipped with a payload consisting of a miniaturized gas chromatograph and a mass spectrometer. Assuming the adoption of the next-generation miniaturised gas chromatograph and mass spectrometer proposed by [4], projected to be operational in 5 to 10 years, the estimated payload mass has been set equal to $M_{\text{payload}} = 2.0$kg.

This project aims to propose the preliminary design a fixed-wing UAV for the aerial exploration of the Red Planet at a large scale. Therefore, the primary objective is to enhance as maximum as possible the mission range, with a minimum target of 200 km. To facilitate the exploration of the majority of the Red Planet while avoiding regions with extremely low atmospheric density, a cruising altitude of $h = 1000$m have been established. Moreover, due to economical and storage constraints, the maximum take-off mass (MTOM) of the Martian drone has been constrained to 20 kilograms. Several constraints regarding the target aerodynamic performance and the performance of the UAV have been set. Anticipating operation in the low Reynolds regime, the Martian drone is subjected to requirements ensuring relatively modest aerodynamic performance, including $C_{L\,\text{max}} \geq 0.8$, $E_{\text{cruise}} \geq 10$ and $F_{\text{max}} \geq 7$. In the conceptual design phase, the optimal combination of wing loading and power loading was determined using the Sizing Matrix Plot. The vertical take-off constraint has been consider based on Blade Element Momentum Theory, resulting from a trade-off study involving the number of rotors and rotor diameter. This approach was aimed at limiting the required power while maintaining a moderate level of configuration complexity. The Mars UAV adopts the use of six rotors, each with a diameter of 20 inches. Results of the sizing matrix plot sugegst a wing loading of $\frac{W}{S} = 29.2 \frac{\text{N}}{\text{m}^2}$ and a power loading of $\frac{W}{P_b} = 0.0165 \frac{\text{N}}{\text{W}}$; which correspond to a wing surface of $S = 2.53$ m$^2$, and a maximum shaft power equal to $P_b = 4.5$ $k$W. In the preliminary design phase, the primary objective was to enhance the mission range. This involved operating the cruise phase at maximum lift-to-drag ratio $\left(\frac{L}{D}\right)$ and maximising the battery mass fraction $\left(\frac{M_{\text{battery}}}{\text{MTOM}}\right)$. Consequently, to optimize the mission range, the cruising phase must be executed at $Re = 92000$ and $M = 0.38$, which correspond to $C_L = 0.50$ and $v_{\text{cruise}} = 92\frac{\text{m}}{\text{s}}$. Operating within the Low-Reynolds regime, the Martian drone employs the Ishii airfoil for its wing. Ishii airfoil presents enhanced aerodynamic performance, when compared to traditional airfoils, in that regime. As this project focuses on the conceptual and preliminary design phases of the Mars UAV, aerodynamic characteristics have been assessed using low-fidelity methods, specifically through Vortex Lattice Method simulations (VLM) conducted on OpenVSP. Results revealed a modest maximum lift-to-drag ratio,

$\left(\frac{L}{D}\right)_{\max} = 11$. The UAV features a maximum take-off mass of 20 kg, including a 2 kg payload, and a battery package with a mass of 4.68 kg. These characteristics ultimately led to an estimated mission range of $R = 375$ km.

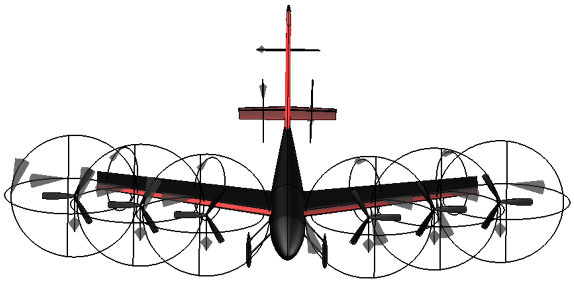

Figure 1: Mars UAV: Front view

## 6. Earth UAV

The terrestrial drone was conceived to replicate on Earth the baseline mission profile of the Mars UAV. The cruising altitude was maintained identical to the Martian case, equal to $h_{\text{cruise}} = 1000$ m. The Earth UAV is conceived to accommodate an identical payload as the Martian drone, it incorporates electric propulsion, wing-mounted solar panels, and employs identical battery technology to that utilized by the Mars UAV. The terrestrial drone is expected to have more compact dimensions with respect to the Martian one. Nevertheless, it will operate at larger Reynolds. The avoidance of the low Reynolds regime allows to demand enhanced aerodynamic performance, when compared to the Martian case. Consequently, more severe constraints have been set $C_{L\,\max} \geq 1.0$, $E_{\text{cruise}} \geq 16$ and $F_{\max} \geq 15$. In the conceptual design phase, the results of the sizing matrix plot provided a wing loading of $\frac{W}{S} = 311.98\ \frac{N}{m^2}$, and a power loading equal to $\frac{W}{P_b} = 0.0432\ \frac{N}{W}$. In the preliminary design phase, the main goal was to minimise the maximum take-off mass of the UAV while ensuring that the mission range of the terrestrial drone equaled or exceeded that of the Mars UAV. Results indicate a maximum take-off mass equal to MTOM = 7.50 kg a wing surface around $S = 0.2352$ m$^2$ and a maximum shaft power of $P_b = 1.67\ k$W. A tilt-rotor configuration, featuring four propellers with a diameter of 10 inches, has been selected. In order to enhance the mission range, the cruising phase must be carried out at a Reynolds number of $Re = 340000$ and a Mach number of $M = 0.09$, which correspond to $C_L = 0.60$ and $v_{\text{cruise}} = 31\frac{\text{m}}{\text{s}}$.

In the wing airfoil selection process, various airfoils were evaluated, and their polars were generated using Xfoil at cruising Reynolds and Mach numbers. The optimal airfoil was chosen based on a scoring system that considered parameters such as $C_{l\ max}$, $E_{max}$, $F_{max}$, $C_{d\ min}$, and $C_{m\ at\ E_{max}}$. The NACA 2408 airfoil has been awarded as the most promising, and it has been considered for the wing airfoil of the Earth UAV. Vortex Lattice Method simulations (VLM) on OpenVSP have been carried out also for the terrestrial drone. Results indicated a maximum lift-to-drag ratio, $\left(\frac{L}{D}\right) = 18.7$. The UAV is characterised by a maximum take-off mass of 7.5 kg, including a 2 kg payload, and a battery package of 3.12 kg. These features ultimately led to an estimated mission range of $R = 495$ km.

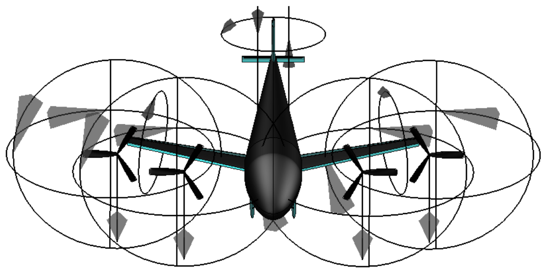

Figure 2: Earth UAV: Front view

## 7. Results

Both UAVs share identical payloads; however, the maximum take-off mass of the Mars UAV is nearly three times greater than the MTOM of the Earth UAV. This substantial difference is primarily attributable to a significantly greater structural mass ($M_s$), encompassing the combined mass of the wings, horizontal and vertical tail, fuselage, and skid. Specifically, the structural mass of the Martian drone is $M_s = 9.96\ kg$, significantly higher than the $M_s = 1.21\ kg$ of the terrestrial drone. Additionally, the wing surface of the Mars UAV is approximately 10.8 times larger than that of the Earth UAV. This is a consequence of the low wing loading observed in the Martian atmospheric conditions, persisting even at higher speeds. The maximum shaft power needed for the vertical take-off of the Martian drone is approximately 2.7 times higher than that required by the terrestrial UAV. The Mars UAV operates at a much lower Reynolds number and higher Mach number compared to the Earth UAV. Consequently, the maximum lift-to-drag ratio of the Mars drone is approximately 58% of its terrestrial counterpart. Even though the atmospheric density at 1000 metres altitude on Mars is roughly 81 times lower than the density at the same altitude on Earth, the power required for the Mars UAV during the cruising phase is significantly higher. The Mars UAV necessitates about four times more power, with a required power of $P_{r,\text{Mars}} = 634.8$ W in contrast to $P_{r,\text{Earth}} = 127.0$ W. Despite operating at a larger gravitational acceleration, by combining an higher battery mass fraction $\left(\frac{M_{battery}}{MTOM}\right)$ with an higher lift-to-drag ratio $\left(\frac{L}{D}\right)$, the mission range of the terrestrial UAV is about 32% higher ($R_{\text{Earth}} = 495$ km), when compared to its Martian counterpart ($R_{\text{Mars}} = 375$ km).

## 8. Conclusions

This thesis delves into the exploration of the potential application of fixed-wing UAVs for large-scale aerial exploration of the Red Planet. An examination of Martian atmospheric conditions and a comparative analysis with the terrestrial ones have been conducted in order to evaluate the influence of planetary environmental conditions on the design of fixed-wing Unmanned Aerial Vehicles. The preliminary design of an electric vertical take-off and landing UAV has been presented, conceived for the purpose of executing long-range missions on the Red Planet. Afterwards, it has been presented a different eVTOL UAV conceived to accomplish a similar mission in the terrestrial environment. The objective was to evaluate the effects of the diverse planetary conditions on various aspects of the design, with a particular focus on aerodynamics.

There is considerable potential for enhancement in various facets of this project. This thesis evaluates the conceptual and preliminary design phases of the Martian and terrestrial UAVs, therefore low-fidelity methods have been employed, when referring to aerodynamics. It is recommended to employ high-fidelity methods to more effectively assess the impact of planetary environmental conditions on the design and aerodynamic performance of the two drones. Structural and aeroelastic analyses are recommended to validate and enhance the hypotheses formulated, regarding the structural design of the two UAVs. In addition, the development of propellers specifically tailored for the Martian environmental conditions is expected to yield more accurate results than those presented in this thesis, potentially leading to improved outcomes for the Mars scenario. Further investigations on the future applicability of fixed-wing UAVs in other extra-terrestrial atmospheres is suggested, in particular referring to potential operability in the atmosphere of Titan.

## 9. Bibliography

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