Mars Aircraft Concept Exploration: a Literature Review

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Abstract

In this paper, we explored and analyzed how the design issues stemming from the Mars specific conditions have been addressed in previous studies. The design of a Martian aircraft is affected by the local low density, low speed of sound, low temperature, low Reynolds numbers, powerful dust storms, electrical phenomena, carbon dioxide carving. For a lander, Martian rugged terrain excludes the conventional take-off and landing option. The need to deliver the aircraft to Mars and expose it to the space radiation affects the aircraft aerodynamic layout, structural design, and weight specification. The target operating area, altitude, and season may significantly affect the design decisions in terms of aircraft configuration, geometry and total mass. The identified design trends, as well as the presented historical data on the previous Mars aircraft can be used as a basis for determining future Mars aircraft mission scenarios.

Keywords: Mars aircraft; Mars atmosphere; aircraft design; viscosity-compressibility coupling

1. Introduction

For several decades, scientists have been exploring Mars using orbiting spacecraft and rovers. Orbiters cover large areas and provide images of the planet surface with a resolution limited to a few meters, while rovers can analyze the composition of soil and rocks. The first in history powered flight on another planet of NASA Ingenuity copter opened a whole new chapter of planetary exploration. As a technology demonstrator, Ingenuity is intended to fly few meters above the ground and provide its mothership, the Preservence rover, with aerial reconnaissance of nearby terrain. In contrast, an aircraft flying at a low altitude above the surface of Mars will carry out a whole range of specific scientific research, mapping an area several orders of magnitude larger than a rover, with a resolution much higher than the resolution offered by modern satellites, as well as gathering valuable atmospheric data at different altitudes.

The earliest of Mars airplanes was Mini-Sniffer, an aircraft with a wingspan of 6.7 m and powered by a hydrazine engine [1]. Since then, significant improvements related to aerodynamic design, concepts of engines, energy storage and materials, have expanded the range of options for Martian unmanned aerial vehicles. Among the proposed projects, the most famous are ARES (Aerial Photography of the Environment on a Regional Scale) from the NASA Langley Research Center [2] and a Remotely Piloted Vehicle for Mars Exploration [3]. Other projects of Martian unmanned aerial vehicles with a wide variety of concepts are being studied, such as gliders [4], [5], [6], including those with inflatable wings [7], [8], helicopters [9], lighter flying insect robots [10], flapping-winged vehicles [11], etc.

The aims of the present paper are to:

- explore and analyze how the design issues stemming from the Mars specific conditions have been addressed by previous authors, and
- collect and analyze historical data on the previous Mars aircraft projects.

In contrast to the previous publications, the focus of the current investigation is to identify the relation between the Martian specific conditions and the design options adopted for exiting Martian aircraft projects. This will enable us to justify the design of a new fixed-wing Mars aircraft and to compose a set of relevant requirements to start the design process. Each new aircraft project starts with identifying the mission scenario and the corresponding payload options. The currently operating Martian rovers use a wide range of space-qualified instruments, including [12]:

- a Mössbauer spectrometer (it can determine the composition and abundance of iron-bearing minerals to a high degree of accuracy);
- a robotic arm with a rock abrasion tool;
- a microscopic imager: this miniature camera is held by the robotic arm very close to the surface of rocks or soils to take black-and-white pictures of features as small as 1/10 of a millimeter across;
- an alpha particle X-Ray spectrometer (it detects alpha particles and X-rays emitted by rocks and soils in order to detect the chemical composition of the sample).

These instruments are needed to fulfill the specific mission which can be accomplished by ground-based vehicles.

Possible missions of a Mars science aircraft include performing a climatic, mineralogical, thermophysical and magnetic study of Mars [13].

Climatic study may require a meteorological package (performing the measurements of temperature, pressure, wind and humidity), laser spectrometer (determining the atmospheric mass density and the thermal state of the lower atmosphere), camera (filming dust storm development).

Mineralogical, thermophysical and magnetic study of Mars may require an infrared reflectance spectrometer (studying the mineralogy and abundance of silicate, carbonate, and hydrated materials) and tri-axial fluxgate magnetometer, gravity gradiometer, camera (filming weathering, erosion, as well as evidence of volcanism) [13]. The Mars aircraft may perform either independent exploration of the planet, or operate 64 in conjunction with a fixed lander or a rover vehicle.

2. Mars Aircraft Concept Exploration

The basic advantage of an airplane over other airborne systems (e.g., balloons) is its maneuverability. A Mars aircraft as a maneuvering vehicle offers an enormous potential for Mars science.

The specific Mars environment affects the design approach, as well as the appearance of Mars aircraft. In subsequent sections, we discuss the effect of the Martian conditions on aircraft design options.

2.1. Mars Atmospheric Environment

Mars atmosphere is composed mainly of carbon dioxide (96% of CO_2). The average surface pressure of Mars atmosphere is about 1% of Earth sea level pressure. The surface temperatures on Mars vary from -140 C° to +20 C°. The temperature is eminently variable with 60 °C of diurnal near-surface range [49]. Furthermore, strong winds, up to 5 m/s during daytime, and turbulences can degrade aircraft efficiency and stability. The density at the surface of Mars is as low as that at the altitude of approximately 32 km above the Earth surface. Figure 1 shows the distribution of nominal atmospheric density with altitude for Mars as compared to the data of the Earth standard atmosphere.

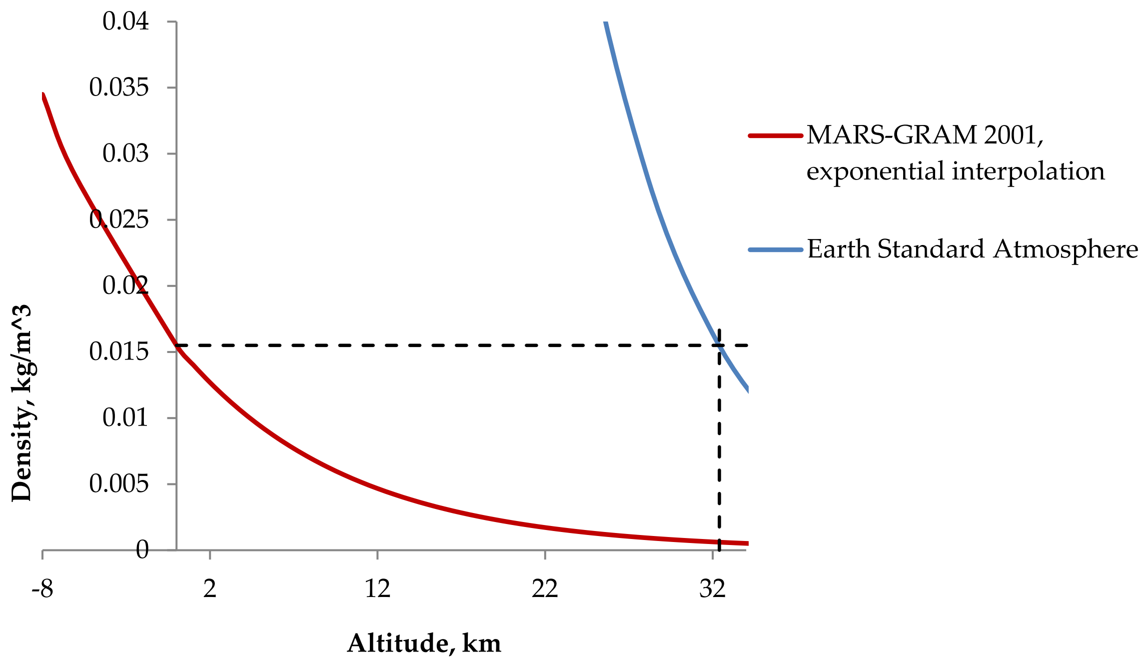

Figure 1. Mars Nominal Atmosphere [15] and Earth Standard Atmosphere [16]:

Density vs Altitude

Density on Mars is highly variable depending on seasonal and daily cycles. During daytime, it can fluctuate between 0.014 and 0.020 kg/m^3 [14].

The speed of sound on Mars is also lower than that on Earth due to low temperature and different atmosphere composition: therefore, compressibility effects are more easily triggered. Figure 2 shows the dependency of the speed of sound on the altitude for Mars and Earth.

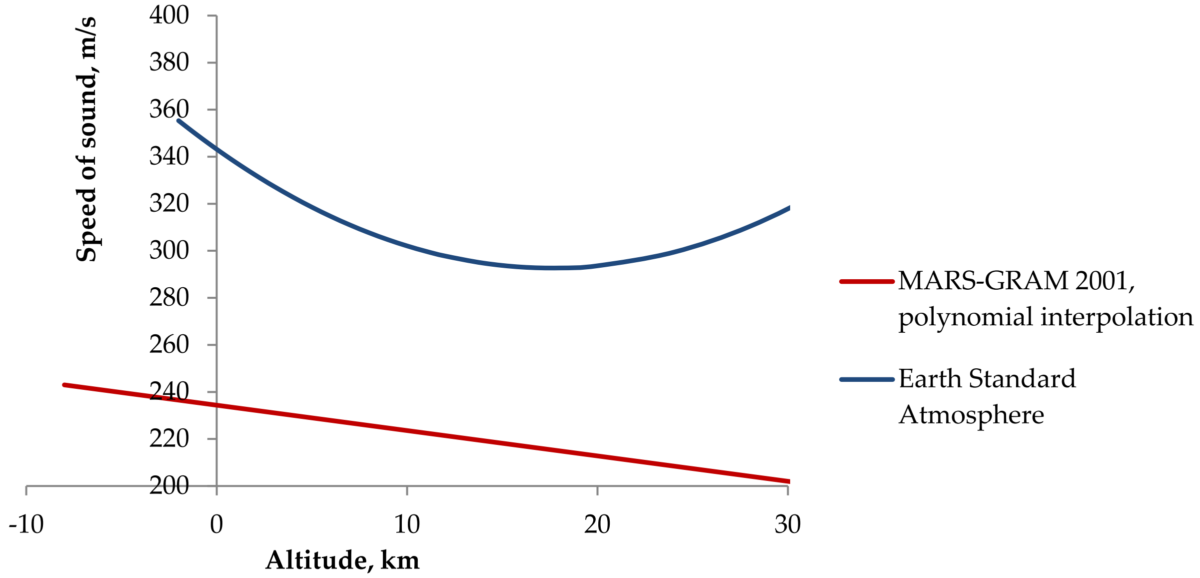

Figure 2. Mars Nominal Atmosphere [44] and Earth Standard Atmosphere [45]:

Speed of Sound vs Altitude

Due to these specific environmental conditions, as well as unknown terrain elevation, limited knowledge of wind speed, dust storm, and rugged terrain, a Mars flying vehicle should possess some features different from those of Earth aircraft. Over the past decades, numerous studies have investigated options for overcoming these challenges in designing a Martian flying vehicle.

2.1.1. Low Density, Low Reynolds Number, High Mach Number - Aerodynamic Design Options

In a thin atmosphere, wing loading has to be small. On the other side, on Mars, the airplane weight is only approximately 38% of what it would be on Earth due to the lower gravity. Nevertheless, for a Mars aircraft, the airframe and system masses must be as low as possible in order to achieve the required low wing loading at the least possible wing area.

For the given aircraft weight, the low atmospheric density is associated with a high cruise Mach number (greater than 0.5), but at low flight Reynolds number (of the order of 50 000, for the previous projects). Since the speed of sound on Mars is lower than on Earth, the aircraft will suffer transonic aerodynamic effects at a comparatively low speed. Therefore, the measures should be taken to ensure the kinetic energy level of the boundary layer high enough to resist premature separation; on the other side, the flow acceleration on the surface of the airframe should be limited to avoid shock waves.

Aerodynamic layout options for Mars aircraft proposed since 1970-s include:

- conventional wing-tail layout with a high aspect-ratio straight wing and winglets ([17];[18];[2]; [4]; [19]).
- flying wing with wingtip vertical stabilizers [20] and with the vertical stabilizer on the fuselage [21].

Flying wing layout is promising because of its potential of eliminating the tail parasite drag, thereby obtaining a gain in the aerodynamic efficiency. Also, it offers propulsion integration and folding simplicity (one fold for each wing). However, the trim drag of a flying wing should be relatively high. Probably, for this reason, most of Mars aircraft feature a conventional wing-tail layout.

Below, some historical data on the fixed-wing Mars aircraft projects is presented.

Table 1. Historical Data on the Existing Fixed-Wing Mars Aircraft Projects

	" Mini-Sniffer"	A Concept Study of a Remotely Piloted Vehicle for Mars Exploration	NASA Ames Mars Airborne Geophysical Explorer	Canyon Flyer	ARES (Aerial Regional-scale Environmental Survey of Mars)	SKY-SAILOR	Minerva
Take-off mass (kg)	75.7	490.0	204.0	20.0	175.0	2.5	141.5
Payload mass (kg)	11.3	100.0	25.0	8.7	N/A	0.5	10.0
Wing span (m)	6.7	21.0	12.4	2.2	6.3	3.2	6.2
Wing area (m^2)	4.2	20.0	12.2	0.7	7.0	0.8	6.7
Aspect ratio	10.7	22.0	12.6	6.3	5.6	13.0	5.7
Cruise velocity (m/s)	33.3	90.0	110.0	144.0	N/A	35.0	N/A
Wing loading (N/m^2)	66.9	55.0	62.0	96.6	93.0	12.0	78.9
Payload-take off mass ratio	0.15	0.20	0.12	0.44	N/A	0.20	0.07
Reynolds Number (based on chord length)	32223	131868	166510	77538	N/A	12896	N/A
Aspect ratio/weight (N^{-1})	0.04	0.01	0.02	N/A	0.08	1.40	0.01

Although Table 1 doesn't include the data on the aircraft with too few known parameters or extreme parameter values (like [22], [12]), the wing span, area, as well as the take-off and payload masses change in a wide range. This might be attributed to the variation in scientific mission, technical advances, as well as to the uncertainty in the input design data. The average value of non-dimensional design parameters, excluding too extreme values, are presented in Table 2.

Table 2

Parameter	Average value
Wing loading (N/m^2)	66.35
Payload-take off mass ratio	0.20
Reynolds Number (based on chord length)	84207
Aspect ratio/weight (N^{-1})	0.26
Aspect ratio	11

An alternative view on possible means of achieving flight in the Martian atmosphere includes flapping wings concept [11], [23], and even a Mars bee [24].

It has been suggested that flapping aerial vehicles may provide an attractive solution for the exploration of Mars, due to low gravity and low Reynolds numbers on Mars.

In [11], an Entomopter, a flying vehicle that generates lift like an insect with an extremely high potential lift generation capability (C_L=5.3), was developed. The lift generation capability of flapping animals is due to the continual formation and shedding of the wing vortex in flapping flight. For flapping wings, unlike fixed wings, there is no substantial reduction in lift after the wing exceeds its critical angle of attack. This may happen due to low Reynolds number and the high wing flap rate (10^{-1} to 10^{-2} seconds).

In [23], it was reported that the demonstrator with a total weight of 17 gr and capable of flying for 12 min with onboard energy storage and a pinhole camera payload was tested. In Mars conditions, the equivalent vehicle would have the mass of 20 gr and range of 10-15 km with onboard solar cell recharging of the energy storage subsystem and a similar scientific payload.

Example of balloon option is considered in [25]. Mars balloons can be helium-filled, carry a battery and infrared/ ultrasonic navigation system. Balloons can be steered in the right direction and can drop small science packages over the target sites.

2.1.2. Low Density, Low Reynolds Number, High Mach Number - Power Plant Options

Propulsion system capability is the key element in establishing the aircraft feasibility and reaching the desired flight envelope. This is especially true for an aircraft that is to fly on other planets, including Mars. The specific Mars environment, as well as the launch from Earth and transit in deep space, produce significant obstacles to airborne platform performance.

Without the ability to refuel, mission duration is to be limited by the amount of energy that can be carried onboard the aircraft. Therefore, the more efficient and lightweight the propulsion system is, the longer the mission.

Low atmospheric density assumes issues with generating thrust. The lower the atmospheric density, the less mass available for momentum transfer and the less thrust that can be generated for a given propulsion system.

Therefore, a propeller designed for Mars conditions would be larger than a typical Earth propeller to generate the same amount of thrust.

A lack of appreciable amounts of atmospheric oxygen presents another propulsion issue for a Martian aircraft [26]. Most Earth powered aircraft use air-breathing propulsion systems, relying on O_2 from incoming air as an oxidizer to release energy stored in the on-board fuel. This approach is not viable in the mainly carbon dioxide Martian atmosphere. Numerous concepts exist for non-airbreathing propulsion systems. The common drawback of the majority of these systems is that they have much higher fuel consumption and additional mass and complexity compared to conventional airplane propulsion systems.

Propulsion options potentially feasible for Martian conditions include:

- no propulsion (glider),
- rocket (liquid or solid), and
- propeller (driven by various power sources).

The technology for these systems is well understood and may require very little development. Because of this, the first generation of aircraft for Mars exploration will most likely be based on one of these kinds of propulsion systems.

A **glider** is attractive because for a Martian glider, the mass, cost, and risk associated with the propulsion system are eliminated. The obvious downside to a glider is related to the fact that its range is determined by the glide slope and the starting altitude. On the one side, the higher the starting altitude, the greater the range. On the other side, the operating altitude of the on-board scientific instruments may be limited.

The Mars glider design proposed in [27] was based on inflatable wings. The aircraft was designed to be stowed in aeroshell, released at a high altitude above the Martian surface where its wings would inflate and rigidize.

[28] reported the first program which demonstrated the deployment of an inflatable drone through high altitude balloon drop test**.**

Rocket propulsion is believed to be one of the lowest risk options for a powered Mars aircraft. Solid rocket motors are inherently simple. However, the need for controlled thrust over a comparatively long time period greatly increases the complexity of a solid rocket system. The applicability of the solid rocket propulsion to a Mars aircraft was considered in [2]. It was suggested that an alternative option might be a liquid rocked system.

Generally, rocket propulsion is inefficient for the demanding Martian environment and significantly limits the airplane range and endurance. Also, the rocket exhaust plume must be considered in determining the airplane layout since it can affect the accuracy of measurements made by the on-board scientific instruments.

In the Earth conditions, **a propeller** is a more efficient means of generating thrust than a rocket for a low-speed, high-altitude airplane. For Mars application, a number of propeller-based propulsion systems were considered as well.

Options considered for driving the propeller in Martian conditions included:

- an electric motor powered by batteries (consisting of batteries, propeller, gearbox, electric motor),
- an electric motor powered by a fuel cell, and
- the Akkerman type hydrazine engine (consisting of hydrazine engine, piston expander).

The thin Martian atmosphere makes heat rejection an important issue for these systems. None of these propeller-based propulsion systems are immediately available for the application at hand and would require design and development, which leads to significant cost and risk implications.

In [2], due to the lowest risk and cost system which enabled the science objectives to be met, a liquid rocket propulsion system was selected.

Propeller-based propulsion systems for a Martian aircraft were proposed, e.g., in [18], [29].

In [18], the Mars aircraft called Canyon Flyer was equipped with a folding four-blade propeller. The mission of the aircraft was set to explore the geology of Mars, and the estimated endurance of 15 min was provided by the battery-electric motor system or hydrazine engine. The propeller was designed using a free-wake linear-potential propeller model combined with 2-D propeller section drag data at several stations along the blade. The propeller diameter was constrained to approximately twice the diameter of the aeroshell since the folded propeller blades span the aeroshell. The design condition for the blade mid-section airfoil was Mach 0.7 and $C_l = 0.73$ at a chord Reynolds number of 16,000. The tip section design condition was Mach 0.8 and $C_l = 0.2$. The propeller was designed to operate with forced boundary layer transition at 20% chord.

In [29], a solar drone with four two-blade propellers and the range of 1000 km was reported. The radius of the propeller was r = 0.6 m. The chord length of the entire airfoil for the propeller was 0.1 m with a hub radius of 0.1 m. The limit tip speed of the propeller was set to 200 m/s.

As an alternative to propeller-electric motor and rocket-based power systems, in some papers, the option of **hydrazine fueled engine** was proposed ([30], [1]). This option would require the design and development of the power plant before it could be implemented on a Mars airplane.

The use of **radioisotope/heat engine** was proposed in [17]. The heat-source materials considered in the paper were plutonium (Pu) 238 and curium (Cm) 244. Pu 238 is the standard material used in all radioisotope generators. A Brayton cycle heat engine was chosen as a means to convert the heat energy to mechanical and electrical energy. This type of heat engine is capable of producing the power required by aircraft with 35 % efficiency (the ratio between the total energy contained in the fuel, and the amount of energy used to 227 perform useful work) and specific power (power-to-mass ratio) of 55 W/kg.

In [17], it was shown that the average cruising velocity for the various radioisotope powered aircraft was approximately 10 m/s greater than that of the equivalent solar powered aircraft.

A radioisotope aircraft is inherently more versatile than a solar-powered vehicle. It is capable of flying to all regions of Mars regardless of the season. Its size and weight may be less than that of the solar aircraft due to the low efficiencies of the existing solar arrays. On the other side, the high cost of producing the quantity of isotope needed for the radioisotope powered system would be far greater than the cost of an equivalent solar array.

A **solar power system** of a Mars aircraft may consist of solar PV array panels, a regenerative fuel cell for energy storage and electric motor [17]. The array panels can be located on the wings, tail and fuselage.

On Earth, the search for clean power systems has led to the development of alternatives to the traditional lead–acid battery. One of them is a **fuel cell**, which is a chemical and mechanical device to convert chemical energy stored in a source fuel into electrical energy without the need to burn the fuel. This is potentially highly efficient, has almost harmless emissions, and is quiet (which is of primary importance for Earth applications) [31]. While supplied with the two input gases, the fuel cell process is continuous. These devices have been successfully used in spacecraft and submarines for many years.

The fuel cell as a power source was considered in some Mars aircraft projects. It should be noted that hydrogen, one of the input gases, requires high storage pressure. Other elements of the propulsion system based on a fuel cell are a fuel cell stack, pressure regulators, check valves, filters, vent valves, flow and pressure sensors, a controller, and oxygen pressure tank [32]. The battery system tends to be much less complicated compared to the fuel cell system as it requires fewer active controls and no mechanical parts.

Nevertheless, in [12], it is reported that for the MIRAGE airplane, a Proton Exchange Membrane (PEM) type fuel cell was used. This choice was justified by its simplicity, compact size and lack of volatility. PEM fuel cells have a performance advantage of delivering high power density with a lower weight and volume than other fuel cell types. Also, it can operate at relatively lower temperatures (80 °C compared to more than 1000 °C typical for other types of cells), which is important for Martian atmosphere.

2.2. Dust Storms and Other Mars Special Atmospheric Processes

Mars special Atmospheric Properties and Processes that can drive Mars aircraft design include:

- dust storms, which are common during perihelion, when the planet receives 40 % more sunlight than during aphelion (when Mars is farthest from the Sun) [33];

- atmospheric electrical phenomena which may be related to dust storms. Dust grains are known to become electrically charged upon colliding with the ground or with other grains [34];
- carbon dioxide carving: Mars Reconnaissance Orbiter images suggest an unusual erosion effect occurs based on Mars' unique climate. Spring warming in certain areas leads to CO_2 ice subliming and flowing upwards [34].

These conditions can lead to a failure, as it happened, e.g., to the Opportunity (MER-B) NASA's Mars Exploration Rover after 5250 earth days of successful operation. It is reported that due to the planetary dust storm on Mars, Opportunity ceased communications on June 10, 2018 and entered hibernation on June 12, 2018. It was expected it would reboot once the weather cleared, but it did not, suggesting either a catastrophic failure or that a layer of dust had covered its solar panels [35]. This issue should be taken into account if the Mars aircraft is intended to use solar panels and operate at a low altitude.

2.3. Rugged Terrain

Due to the Mars uneven and rugged terrain, the fixed wing Mars airplane missions typically begin by deploying the airplane and end with an uncontrolled crash into the planet's surface. Therefore, the only option for a Mars aircraft lander is to be capable of performing vertical take-off and landing.

Although the low Reynolds Number and high subsonic Mach number environment of Mars poses some problems, the Earth-bound Pathfinder flight tests at a 30 km altitude have proved the feasibility of a VTOL propulsion system for the conditions similar to those of Mars [35].

For any VTOL aircraft, it is desirable to use the same propulsion system for both hovering and cruise. But normally, the power needed for hovering and cruise is very different. Therefore, there are various ways to realize the VTOL maneuver capability, basically from three categories [36]:

- augmented power plant for hover (ejector, ducted propeller/fan, rotor),
- same propulsion system for both hover and cruise (tilt shaft,tilt prop, tilt duct, tilt wing, tilt rotor, tilt jet, deflected slipstream, vectored thrust, tail sitter), and
- separate propulsion system for hover and cruise.

In [12] and [36], the authors adopted ducted rotors for VTOL maneuver and separate propellers for the forward flight.

2.4. Delivery

A Mars aircraft design is driven not only by the challenge of generating sufficient lift and thrust to fly through the Martian atmosphere, but also by the issues associated with getting the aircraft to Mars.

Since a Mars aircraft must be stowed and fit into an aeroshell capsule for transit and entry into the Martian atmosphere, its volume is important.

The geometric arrangement best suited for stable atmospheric flight should be balanced against that best suited for the launch and atmospheric entry.

The most straightforward packaging approach is to design the airplane **small enough** to fit inside the aeroshell in the flight configuration. This option is only viable if the aircraft size meets the requirements for payload.

To achieve a compromise betweeen delivery and performance, an efficient packaging of the aircraft should be contemplated from the very beginning of the project to provide sufficient wing area and space for the thruster within the geometric constraints of the given aeroshell. Upon reaching the Martian atmosphere, the airplane must be deployed into its flight configuration. During conversion from the stowed configuration to flight the airplane must unfold, orient itself, and execute a pullout maneuver.

In general, for a Mars aircraft, inflatable, foldable and morphing wings were considered.

Using a non-rigid wing takes most advantage of the available aeroshell volume. One possibility is a **Rogallo type parawing** [2].

Another concept is an **inflatable wing**. Flexible or inflatable structure could also be used to add wing area to a rigid structure [2]. The main issue with nonrigid wing concepts was the risk associated with the complexity of this unconventional structure and its performance when being exposed to a cold space environment and radiation during transit to Mars, as well as on Mars. Undoubtedly, any materials used for Mars aircraft structures must be space-qualified. This issue can be addressed, but the need for the development and qualification of appropriate materials increases the cost and the duration of the project.

In [7], a demonstration flight of an inflatable composite wing impregnated with a UV-curable resin is reported. A flight experiment on May 3, 2003 was the first-ever demonstration of inflatable/rigidizable wing technology. In the design of the wing, extreme flight loads were considered to specify the number of layers of the composite; the low-temperature, high-altitude environment was considered for resin selection and to develop the cure-time test protocol. The balloon-launched flight test article consisted of an unmanned aircraft including the folded wings, an inflation system, microprocessor control, sensors, cameras, GPS, and communications radios. The wings were successfully deployed at an altitude of 55,000 ft and cured while continuing ascent to a maximum altitude of 89,603 ft. The wings were fully cured on recovery, but were not symmetric.

A **conventional rigid structure** can exploit folding and telescoping mechanisms. In [2], spring-loaded folds were considered the simplest, lowest risk packaging approach.

The general guideline in design of folded wings is to minimize the number of folds, since folds increase technical complexity and risks.

2.5. Season and latitude impact on Mars aircraft design

In [17] it was shown that for a solar-powered Mars aircraft, the design requirements associated with the expected operating area, altitude, and season may affect significantly the design decisions in terms of aircraft configuration, aspect ratio, wing area and total mass. With a fixed value of payload mass, the take-off mass of the versions of the aircraft intended for different operating conditions varied between 1200 and 300 kg, with the span varying from 40 to 130 m, aspect ratio – from 14 to 40. The wing loading and cruise velocity varied between 11 and 14 N/m^2, 26 and 44 m/s, correspondingly.

In [37] it was suggested that for a Mars aircraft, from engineering point of view, it would be preferable to fly over the Northern plain on Mars so that it could take advantage of the relatively higher atmospheric density at a low altitude. For a lander, the plains of the northern hemisphere would also provide more suitable landing sites. If the aircraft uses solar panels, the flight path should not be too far away from the equator. The best season for the flight would be within the period of early spring until summer, when the day-to-day pressure variation and wind speed are small, with the prevailing west wind. Undoubtedly, besides the engineering considerations, the scientific significance of the operating area should also be estimated.

3. Mars Aircraft Design and Analysis

Due to the specific Mars environment, and due to the limited number of vehicles operating on Mars, Mars aircraft design process is likely to include a large variety of candidate configurations.

In [38], for three categories of aircraft (lighter-than-air, fixed-wing and rotary-wing) the authors present a method for evaluating which of these aerial platforms would deliver the maximum efficiency for a particular scientific mission on Mars. For each of the possible missions**, a measure of merit** was established. These measures of merit were used to compare the three candidate categories and identify their advantages and disadvantages within a specific application.

The measures of merit included some performance indicators (the required power and maneuverability), as well as the overall mass and complexity of each platform. Fort the scope of trade studies, these were converted to cost functions. A cost function is a product of, or a sum of, or some other mathematical combination of two or more parameters that yields a value that can be used to evaluate the quality of the combination [39].

In [38], the resultant **cost function** represented a weighted sum of the selected measures of merit, and varied between 0 and 10. By comparing the cost function of the different platforms for each mission, it was possible to determine which platform was best suited to a particular mission.

Besides typical aerodynamic layout options, and conventional procedures of aerodynamic, stability and control, performance analysis, some papers present the investigation of the relationship between the particular operating area and the corresponding feasible aircraft designs [17]. The type of solar panels (e.g, silicon and gallium arsenide solar cells in [13], as well as the type of the entire powerplant may be varied to ensure the achievement of the particular scientific goals.

In aircraft design**, scaling** as a design approach is sometimes used. The feasibility of scaling of the parameters of Terrestrial aircraft to Martian atmosphere was considered in [40]. The scaling relations between the performance parameters of Earth and Mars propeller-driven aircraft included the cruising velocity, cruising power, and propeller thrust. In the paper, a power ratio criterion for feasible cruising flight of propeller-driven aircraft on Mars was proposed, and the relevant design parameters were identified. This criterion was applied as a guideline to the preliminary design of a Mars aircraft. In addition, the constraints on the rotational speed of a propeller in cruising flight on Mars were identified.

In **airfoil selection** for a Martian aircraft, conventional approaches are typically being used. For example, in [2], the higher lift capability SS1F airfoil with high zero-lift pitching moment was applied only where it was necessary to increase the critical angle of attack. For other wing sections, a less cambered SS1E airfoil was used. In this study, a vortex lattice analysis of the planform shape was conducted to determine the section C_l distribution. The airfoils were defined at three span locations and a simple linear lofting between these stations was used. In order to maintain the elliptical spanloading, a linear geometric twist was exploited.

In [3], the issue of decreasing maximum lift coefficient and increasing drag with the reduction of operating Reynolds numbers for conventional airfoils was discussed. An example presented showed that the lift to drag ratio of a GA airfoil dropped from 140 at a typical light airplane cruise Reynolds number of 3×10^6 to 7 at a Reynolds number of 45,000 which is typical to Mars airplane flight at 10 km altitude above the surface of Mars. This would practically translate into 10 times reduction in maximum range of the airplane.

This drop in airfoil performance was a result of the flow separation on the upper surface of the wing due to steep adverse pressure gradients. This is why the thin airfoils intended for small aeromodels generate a big part of their lift on the highly undercambered lower surface where the separation is most improbable. The upper surface of this type of airfoils is moderately cambered and the lift coefficient for best lift to drag ratio is attained at a relatively low angle of attack. These two facts prevent the flow separation on the upper surface. Furthermore, tripping devices forcing the boundary layer transitions on the upper surface might have a beneficial effect on a UAV operating under low Reynolds numbers.

In [3], for the design of special airfoils for low Reynolds numbers, the Eppler code was used, implementing conformal mapping method.

In [41], a comparison between several low Reynolds number airfoils for the Mars Helicopter was presented. In the study, it was shown that at low Reynolds numbers, flat and cambered plates can outperform conventional airfoils, making them of interest for the Mars Helicopter rotor. The authors used free wake analysis, a Reynolds-Averaged Navier-Stokes based approach (OVERFLOW), and a rotor analysis code CAMRADII. The analysis indicated that the cambered flat plate airfoil produced 7% larger maximum rotor thrust versus the Mars Helicopter airfoils, and 5% larger Figure of Merit over the design thrust coefficient range.

Complicated flow phenomena including separation, transition and reattachment take place on the wing surface and strongly affect the flight performance of a Martian aircraft. Nevertheless, all the available tools for low and high fidelity aerodynamic analysis are being applied to Mars aircrafts. For preliminary design purposes, it is typical to use **potential flow assumption,** implemented, e.g., in a vortex-lattice method [30]. Potential flow models are not capable of capturing viscous effects, including maximum lift coefficient. Prediction of maximum lift coefficient and viscous drag requires methods which encompass the viscous flow effects. The conventional and well-proven semi-empirical equations used for these purposes are unlikely to be adequate to the unusual combination of high Mach number and low Reynolds number.

Due to low local Reynolds Numbers, laminar separation bubbles are likely to play an important role in determining pressure distributions on the wing and aerodynamic characteristics of a Martian aircraft. In addition, a Mars airplane flies at relatively high speed to produce a lift enough to sustain its weight as well as to ensure a stabile flight in gusty atmosphere. Therefore, the effects of the specific heat ratio are also important since its value is different in CO_2 and air [42]. Thus, it is expected that the flow field on a Mars airplane will be highly complicated with a strong interaction of viscous and compressibility effects. This makes the numerical simulation of aircraft operating in Martian atmosphere extremely challenging.

Actually, a new aerodynamic domain is to be explored: compressible ultra low Reynolds number flows [43]. So far, only a few depressurized experiments recreate compressible ultra-low Reynolds number conditions for airfoil [44] or rotor [45] performances measurement. However, neither studies except for [43] provide a validated computational tool for the simulation of a compressible ultra-low Reynolds number flow.

As it was mentioned, **the experimental data** of airfoils is very limited in low Reynolds number and high Mach number flow region.

In [46], the investigation conducted in the Mars Wind Tunnel (MWT) at Tohoku University was reported. The aerodynamic characteristics of a 5% flat plate and NACA0012-34 airfoil in low Reynolds number ($Re=0.43x10^4$ ~$4.1x10^4$) and high Mach number (M=0.1~0.6) were measured. It was shown that for the flat plate, Mach number effect does not have much effect on its aerodynamic performance, while Reynolds number affects the lift slope and the drag characteristics. On the contrary, for NACA0012-34 airfoil, both Reynolds and Mach number effects become more prominent. The lift curves were highly nonlinear and the drag polars were affected by laminar separation bubbles. A comparison of the results obtained at different Mach numbers has suggested that the compressibility has an effect to stabilize the separated shear layer.

In [42], a numerical and experimental investigation of airfoil shape and optimization on 2D and 3D compressible ultra-low Reynolds number flows was reported. The main conclusions included the following:

- optimal airfoils for 2D ultra-low Reynolds number flows are thin and highly cambered;
- 3D effects do not fully compensate nor stabilize the detached flow experienced by airfoils enhancing vortex shedding for lift production.

4. Discussion

The number of constraints shaping the feasible design area of a Martian aircraft is greater than that of an Earth aircraft. In addition to more typical constraints, the feasible design area for a Martian aircraft may be limited by:

- the aeroshell shape and size, with the consequence of rigid (folding, telescoping, spring-loaded) or inflatable unconventional structures with high risk;
- the coupling of viscosity and compressibility effects which is difficult to predict;
- the launch and entry g-load, with the consequence of increased structural weight;
- the low temperatures and radiation, with the added weight due to the protection and heating systems;
- the need to ensure the specific conditions for the onboard scientific instrumentation (this may limit, e.g., the flight altitude and speed); also, this implies that the combustion exhaust products must not contaminate scientific measurements;
- the aeroshell center-of-gravity constraint, which also may exert significant influence on the "big" decisions, like that of the aerodynamic layout selection.

In figure 3, the cruising Mach number as a function of the altitude is plotted for the Martian atmosphere for a number of existing Mars aircraft projects.

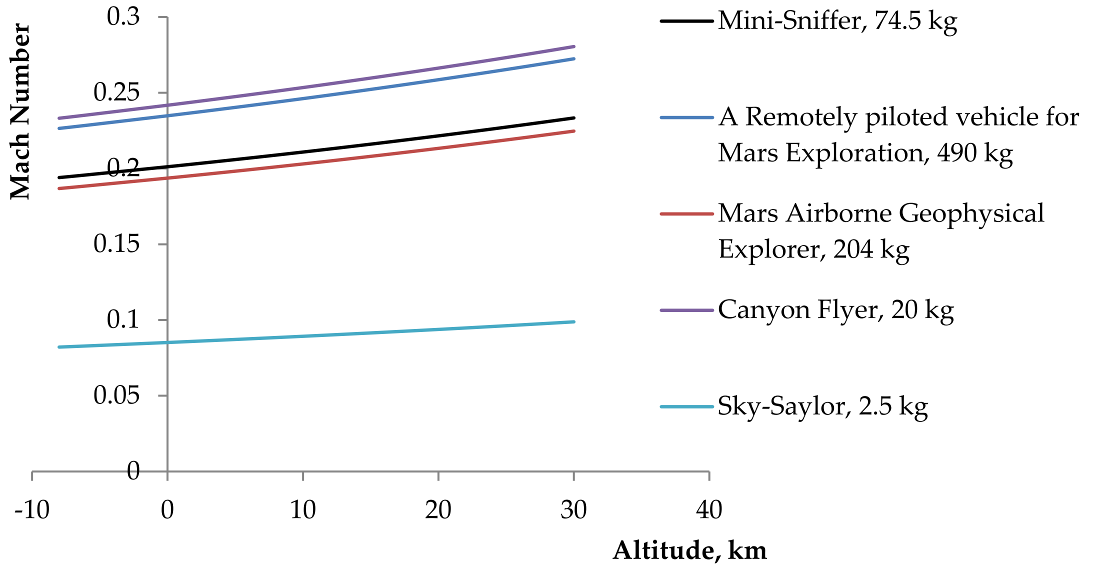

Figure 3. Cruising Mach number vs flight altitude for existing Mars aircraft projects

5. Conclusion

In this study, we explored and analyzed how the design issues stemming from the Mars specific conditions have been addressed by the previous authors. The identified design trends, as well as the presented historical data on the previous Mars aircraft projects can be used as a basis for determining a future Mars aircraft mission scenario.

The recent improvements related to aerodynamic design, concepts of engines, energy storage and materials, have expanded the range of options for Martian unmanned aerial vehicles.

Possible missions of a future Mars science aircraft include performing a climatic, mineralogical, thermophysical and magnetic study of Mars.

The design process will be guided by the specific Mars environmental conditions (density, speed of sound, temperature, Reynolds number, dust storms, electrical phenomena, carbon dioxide carving). For a lander, Martian rugged terrain will exclude the conventional take-off and landing option. The need to deliver the aircraft to Mars and expose it to the space radiation will affect the aircraft aerodynamic layout, structural design, weight specification. The expected operating area, altitude, and season may significantly affect the design decisions in terms of aircraft configuration, geometry and total mass.

Finally, the flow field on a Mars airplane is expected to be highly complicated with a strong interaction of viscous and compressibility effects. This makes the numerical simulation of the aircraft operating in Martian atmosphere extremely challenging.

Nevertheless, the concept of a long-endurance aircraft, either solar or radioisotope powered, featuring foldable or inflatable wings and capable of flying in the Martian atmosphere seems feasible and can be considered as an option for future Mars exploration missions.

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