Conceptual Design of an Unmanned Aerial Vehicle for Mars Exploration

Ishan Mishra, Aayush Kumar, and Vanshaj Malhotra

Abstract — Significant technology advances have enabled planetary exploration aircraft to be considered as a viable science platform. These systems fill in a unique planetary science measurement gap, that of the regional scale, near-surface observation while providing a new perspective for planetary discovery. Exploration of Mars using UAV (Unmanned Aerial Vehicle) has been planned for over 25 years by leading space organizations such as NASA. Recent efforts have been able to produce some mature mission and flight system concepts, ready for flight project implementation. There are however significant numbers of challenges associated with getting an airplane to fly through the thin, carbon dioxide-rich Martian atmosphere. Traditional aircraft design expertise does not always apply to this sort of vehicle, and geometric, aerodynamic, and mission restrictions result in a restricted viable design space. This paper presents the conceptual approach that was taken to design a UAV capable of performing a VTOL (Vertical Take-Off and Landing) in the atmosphere of Mars. The UAV was designed to participate in the International Planetary Aerial Systems Challenge 2021. The UAV could carry a science payload of up to 5 kg (weight on mars).

Key words — Mars Airplane; Science Payload; UAV; VTOL.

Abbreviations Used:

UAV – Unmanned Aerial Vehicle

VTOL – Vertical Take-Off and Landing

EP – Extreme Pressure

PFPE – Perfluoropolyether

PTFE – Polytetrafluoroethylene

FEA – Finite Element Analysis

NACA – National Advisory Committee for Aeronautics

TCS – Temperature Control System

RHU – Radioisotope Heating Units

CCD – Charge Coupled Device

I. INTRODUCTION

For at least 50 years, people have imagined winged spacecraft flying through the Martian atmosphere. The Mars Project, written by Wernher von Braun and originally published in the early 1950s. For almost 25 years, considerable attention has been given to the use of an unmanned aerial vehicle (UAV) as a research platform for exploring Mars. From its unique vantage point, a few kilometres above the Martian surface, an autonomous airplane could return unique science measurements over regional-scale distances. By traversing regional-scale distances at near-surface altitude, planetary airplane observations complement and extend orbital and landed

measurements while providing a fresh perspective for scientific discovery.

This paper presents the design of an Unmanned Aerial Vehicle capable of VTOL working under the Martian atmosphere. The UAV is a solar-powered wing body design having the main wingspan of 3.6m and a root chord of 0.5 m. Based on the DOS SAMARA [1] concept the main wing is divided into 2 sections i.e., the inner and outer sections. The outer section is 1 m long and rotates to generate sufficient thrust for VTOL operations. With a full payload of about 12 Kgs, the UAV is capable of traveling 10 Kms having a velocity of 16.66 m/s during the cruise while flying at a max altitude of 7 km from the ground. A propeller located at the back of the plane provides sufficient thrust to counteract the drag forces, putting the plane in steady and levelled flight conditions.

II. REQUIREMENTS AND CONSIDERATIONS

The first and foremost consideration is the nature of the Martian atmosphere. Atmospheric density near the surface of Mars is roughly equivalent to an altitude of 100,000 feet on Earth. It is difficult to create enough lift to maintain the airplane's weight in such a thin atmosphere, thus wing loading must be kept to a minimum.

Owing to the reduced gravity on Mars the weight of the airplane is roughly 38% of its weight on earth. Nonetheless, to attain a reduced wing loading, a considerable focus must be made on reducing airframe and system weight.

Because of the low air density, the cruise velocity is increased, but the flight Reynolds number is reduced. Because of the lower speed of sound on Mars than on Earth, transonic aerodynamic effects are encountered at lower flight speeds. To reduce significant lift losses and/or drag increases associated with low Reynolds number, high Mach number flying circumstances, special consideration was necessary for the aerodynamic design.

Thrust generation is further complicated by low atmospheric density. The lower the density, the less mass available for momentum transfer and the less thrust generated for a given size propulsion system.

III. MISSION LAYOUT

Extensive trade studies and design cycles were performed to develop a low-risk mission architecture. The resultant

architecture enabled the satisfaction of the mission requirements with the use of a basic, low-risk flying system design.

The UAV will fly a pre-planned 5 km route from a vantage point 7-8 km above the ground and then return to the base. The UAV could carry a science payload weighing roughly 5 Kgs and an additional payload of 2 kgs that could be connected at the base of the UAV. The science payload would analyse both the Martian atmosphere and surface during flight.

The detailed flight plan is shown in the image.

Fig. 1. Mission Architecture.

IV. MODES OF OPERATION

The hybrid UAV consists of three modes of operation concerning flight stages. VTOL mode for vertical take-off and landing along with the inclusion of loitering as well at a specific altitude and location. The fixed-wing aircraft mode for normal flight operations (horizontal translation).

The transition and tuning mode for switching between VTOL and Fixed Wing mode.

A. VTOL Mode

This phase has been intended for vertical take-off, landing, and hovering operations. During this phase, the outboard wing panels spin generating sufficient thrust to lift the UAV. To save power consumption, the UAV platform automatically switches to aircraft mode after reaching the appropriate height.

B. Transition Mode

The thruster-mounted shaft of the UAV starts and provides a forward thrust. The two outboard wing panels are halted synchronously which causes a halt to the vertical motion of

the UAV and the outboard panels now act as a fixed-wing. With an increase in horizontal speed, the fixed wings start to develop lift.

C. Aircraft Mode

During this phase, the UAV has reached a sufficient translational speed and is producing a sufficient lift force to offset its weight. Under these conditions, the platform performs like a typical airplane, with control surfaces such as ruddervators, ailerons, and flaps providing the necessary yaw, pitch, and roll motions. This phase is designed for energy-efficient operation throughout a large chunk of the mission.

V. DESIGN PROCESS

A systematic design approach has been used to design our UAV. The constraints have been analysed first followed by the selection of aerofoils for both wing and tail. A preliminary design of the fuselage, wing, and tail has been developed based on calculations and analysis which has been refined to minimize weight and optimize storage. The final design has undergone several analyses to ensure whether or not the design is adept enough to fly in the challenging Martian atmosphere. Structural and Thermal analyses have been carried out to prevent any kind of mechanical failure during operations. As shown in Fig 2.

VI. UAV MECHANICS

All of the materials used in the parts were chosen after careful consideration of different criteria such as weight, hardness, yield strength, tensile strength, and so on.

Owing to the property of gold to block radiation, the parts of the UAV have been gold plated to protect the UAV from extreme levels of UV Radiations.

After extensive investigation and testing of different alternatives, gear lubrication has been assured by a mixture of 50% 802 EP grease and 50% 815Z oil to ensure efficiency even at extremely low temperatures since these lubricants do not dry up quickly. Penzane-3 Pb Np oil and 601 EF have been produced from PFPE oil thickened with PTFE powder [2] for lubricating other components such as bearings, motors, and so on.

The aerodynamic and structural analysis of the UAV has been done considering several factors and the calculations have been made considering the weight of the UAV to be 10 Kgs on Mars.

Fig. 2. Design Process.

VII. GEOMETRY

Our plan has mixed the drifting capacity of a helicopter and rapidly expanded the perseverance flying of a fixed-wing airplane. This has helped our UAV to gain the benefits of both into one.

We have used outboard wing panels that are 1 m long and have a root and a tip chord of 0.3 m, that spin to generate thrust to lift the UAV in vertical flight. The wings rotate at 3000 RPM generating a maximum lift of 110 N making them capable of lifting the UAV from the ground. Both rotors rotate in opposite directions hence generating a contour torque preventing the UAV from spinning. During horizontal translation the outboard wing panels lock hence, acting as a fixed-wing. A pusher propeller is located aft of the UAV to provide thrust during the cruise. For deciding the wing geometry, possible planform shapes have been explored extensively, several trade studies between wing area and aspect ratio have been conducted, and the theoretical position of the wing aerodynamic centre has also been restricted to avoid excessive deviations from the needed aircraft centre of gravity. Based on the outcome of these studies, A baseline planform with a 17.4 aspect ratio and a wing size of 1.8 m² has been chosen.

Fig. 3. Dimensions.

On the ground, the plane is supported using a landing mechanism fabricated using Aluminium – 7079 at the front and on the Y-Tail at the aft position. The landing mechanism is connected to the plane using Heim joints providing flexibility to the structure making it capable of landing comfortably on uneven Martian terrain.

VIII. FUSELAGE

The Fuselage is an integral part of the UAV. It has been designed to maximize storage capacity while minimizing weight. The fuselage houses the Flight Electronics, Science Module, and everything that has to be incorporated in or on the UAV. The Fuselage is 1.5 m long and about 0.6 m wide making it adept to cache all the components appropriately, enabling a compact and efficient design. The Fuselage has been fabricated using Mylar and AS Graphite-Epoxy composite [3]. This material provides an excellent strength-to-weight ratio and could easily withstand both temperature extremes on Mars. Ease of Serviceability has been kept in mind while designing all the components making all

subsystems accessible to the astronaut during maintenance. Openings have been provided both under the fuselage as well as on the rear end which makes it easier to access the electronics without dismantling the wings.

Fig. 4. Lateral View.

IX. AEROFOIL SELECTION

Several Airfoils including Eppler 203, NACA 66(3)-418, RG-15[4], i.e., those capable of operating under Low Reynolds Number and High Mach Number (0.6-0.8) on the Martian atmosphere have been considered and after performing extensive analysis of those airfoils considering various key factors such as density, pressure, gravity, etc.

Fig. 5. Aerofoil Comparison.

RG-15 has been selected for our design. The aerofoil provides a minimum drag coefficient as well as a maximum lift coefficient, which means the highest lift-to-drag ratio; also, it provides a low pitching moment coefficient. These characteristics empower our UAV wing with noteworthy thrust and negligible drag, subsequently diminishing the power consumption and force utilization for an efficient flight. The aerofoil which has been selected for our UAV guarantees a positive Coefficient of Pressure enabling us to achieve a Lift Coefficient as high as possible. An angle of attack of 8 deg. has increased the aerodynamic force and has streamlined power, along with giving a positive moment about the Aerodynamic Centre.

Fig. 6. Pressure and Velocity Graph of RG-15.

X. RIB DESIGN

Morphed wing configuration has been for the UAVs fixed wings, which consists of three main components: aluminium profiles, low-temperature foam, and silicone elastomers.

A. Low-Temperature Foam

It has been used to fill the gap between the aluminum profiles. A protective layer of low-temperature silicone elastomers has been applied to aluminum profiles and foam [5].

B. Skin Material

Silica Elastomer has been used as the material for the skin hence making the morphed wing adaptable and flexible so that the material is handily twisted, while as yet having the solidarity to convey the streamlined loads of the UAV. Likewise, the material has been supplied with an abrasion-resistant coating so that the material is not harmed when liable to evolving conditions. After the material has been converted to an alternate wing shape, the material recuperates its original size. The "skin" of the wing additionally upgrades the construction's exhibition. It has been produced using covering portions of adaptable material, layered to some degree like quills or fish scales, taking into account the pieces to get across one another as the wing flexes, while as yet giving a smooth external surface.

Fig. 7. Rib Structure.

C. UAV Morphing Plan [6]

The plan will affect the flying performance of our UAV by the dramatic change of wing shapes. Such plans take out the requirement for various, costly, mission-explicit aerofoils. Morphing aerofoils can change their shape for various flying performances. Such changes can be either incremental change to facilitate flight control. The key to the successful morphing of our wing was geometric scaling to match a particular performance requirement. The morphing would be carried out using 4 servo motors placed within the fixed-wing and connected to the spars. These ensure precise morphing to facilitate the required aerodynamic characteristics.

Fig. 8. Skin.

XI. EMPENNAGE DESIGN

The Empennage provides for trim, stability, and control and is designed to operate normally at only a fraction of lift potential. Y- Tail configuration has been chosen for reducing drag interference, avoiding the complexities of ruddervators, and keeping the propeller off the ground when compared to conventional tail. The horizontal tail provides better stability and the vertical tail reduces aerodynamic sideslip and provides directional stability. NACA 0009, has been chosen for our UAVs tail which guarantees pitch control and longitudinal stability since it is an asymmetrical airfoil. This airfoil also provides a negative lift with an increased angle of attack, resulting in a negative moment, allowing the UAV to remain naturally stable.

TABLE I: EMPENNAGE DESIGN PARAMETERS

Parameters	Horizontal Tail	Vertical Tail
Root Chord	0.4188 m	0.25m
Tip Chord	0.1637m	0.15m
Total Surface Area	0.74 m ²	0.344m ²
Wing Span Length	2.5408m	0.3m
Wing Aspect Ratio	8.71	1.60

XII. PROPELLOR DESIGN

The propeller blade has been designed for the lowest weight possible. Mylar, a light plastic material, has been chosen as the primary component of the skin structure. Because of its excellent strength-to-weight ratio, graphite-epoxy composite [7] was chosen as the material for the skin-supporting structure. The baseline design consists of a single hollow spar with rib elements to support the Mylar skin. To avoid aeroelastic instabilities, the blade's centre of gravity has been restricted to be coincident with the quarter chord axis position. NACA 16-012 aerofoil has been selected for our propeller. With a 70° twist angle and desired minimum thickness of 12%, our propeller ensures a high turning rate with a motor of 3000 RPM. The blade design is inherently smoother with reduced tip speed and minimal noise. This design marks constant thrust along the entire length of blades thereby maintaining the pitch to diameter ratio of 1:1 and making it more efficient.

Fig. 9. Weight Distribution.

Fig. 10. Propellor.

Fig. 11. Heat Switch.

XIII. WEIGHT DISTRIBUTION AND BALANCING

The well-known Boeing-Vertol equations were used in preliminary investigations to determine the weight breakdown. This algorithm takes size, gross weight, and other basic parameters and compares them to historical patterns. The output of these equations includes more detailed weight information on UAV subsystems.

TABLE II: WEIGHT DIVISION

S.no	Sub-System	Weight (Kg)
1.	Structural	4.0
2.	Batteries and Propulsion	1.2
3.	Electrical	0.3
4.	Science Payload	4.7
TOTAL		10.2

The design has been optimized using the data obtained to have a maximum scientific payload capacity without exceeding our weight. Our final weight estimates slightly deviated from the traditional Boeing-Vertol formulae due to the following reasons:

- Our fuselage is lighter than anticipated since our plane is unmanned. Composite materials have also been used throughout instead of traditional heavier metals.
- Our wings and blades have been made using composite materials hence are lighter than traditional designs. Hence, they were lighter than predicted.

XIV. ENVIRONMENTAL CONTROLS

A. Temperature Management

To make our UAV adaptable to the fluctuations in Martian temperatures from 20 °C to a freezing -15 0°C we have introduced a wire meshing network in the main UAV body. The meshing is the primary heating system for the Electronics and Science subsystems. The network is connected to the centralized power system via a relay. The meshing is made of electrically insulating and thermally conductive diamond coating on copper coils [8] thus providing electrical safety to the components without compromising on thermal parameters of the devices used.

Fig. 12. RHU.

In addition to the meshing network, a robust Temperature Control System (TCS) has been incorporated. TCS is inclined towards sustainable temperature management without compromising any power consumption. It consists of 8 Radioisotope Heating Units (RHUs) [9] spread across the plane. RHUs have an excellent capability to produce heat and additionally provide the benefit of reduced electromagnetic interference to their electrical heating counterparts. It provides a constant supply of 1W heat without adding on a burden on the power cache as they provide heat through radioactive decay. The placements of RHUs have been criticized due to the difference in the amount of heat required by individual components.

Adequate temperature range for each component is maintained using heat switches and insulation as discussed below:

Maximum heat insulation has been provided for the UAV to ensure it withstands cold Martian. All electronic components are placed within this insulated box known as Heating Module. It has been further thermally regulated using graphene tubing [10] perforated through the box which conducts heat through it to the base of the payload carrying mechanism. It prevents our UAV from overheating during operations on warm Martian days.

The radiators have been designed such that, in the worst scenario of temperature variation they maintain the optimal working temperature in the Heating Module. To prevent heat loss during the night, the conduction tubes would be connected to the radiator plates through Shape Memory Heat Switches [11]. These are metallic materials that can return to a previous shape or size when subjected to the right thermal conditions. These switches can operate within a temperature range of roughly -200 C to +100 °C, making them suitable for the Martian atmosphere.

Fig. 13. Radiators.

To trap heat inside the UAV the inside of the UAV would be flushed with CO₂ gas. Also, a layer of solid silica aerogel [12] would be placed around the electronic box and the motors. Both carbon dioxide and silica aerogel are excellent insulators of heat. These prevent any unwanted heat loss from the plane's surface. Graphene has been employed as the material for making the tubes as it has an excellent conduction and convection potential, hence making it an ideal material for making the tubes. To allow efficient heat transfer between radiators and the Martian atmosphere the radiators are made of copper which is an excellent conductor of heat.

Fig. 14. Thermal Analysis of Fuselage.

B. Dust Protection

Mars is infamous for intense dust storms, which sometimes kick up enough dust to be seen by telescopes on Earth. Individual dust particles on Mars are very small and slightly electrostatic, so they stick to the surfaces they contact, and consequently, the possibility of dust settling on and in machinery is a challenge for the mission. To prevent this from happening the entire exposed surface of the UAV is covered with a dust repellent layer of CVD Nano-Coating [13] that

prevents the UAV surface from wear due to the bombardment of fast-moving dust particles. To protect the cameras and lenses from damage due to dust and wind, they are equipped with lens-protective covers.

XV. SCIENCE PAYLOAD

The science payload for the UAV comprises the following components:

A. Planetary Surface Analyzer (PSA)

It is a CCD Camera and electronics kit with a dual optic path and a single focal plane scope. It would be used for providing regular summary and low-goal imaging of Mars to examine the climatic changes.

B. Calorific Imaging Spectrometer (CIS)

It is a plane reflection spectrometer that would be used for the analysis of the Martian atmosphere and to measure the surface composition of CO₂, N₂, Ar, O₂, etc.

C. Atmospheric Data System (ADS)

It will provide a comprehensive measurement of the Martian near-surface atmosphere. Also, it would be used to measure the wind speed and direction.

D. Infra-Red Spectral Chemistry Suite (ISCS)

The primary goal of the ISCS instrument would be to detect minor atmospheric gases along with sensitive detection of minor gases and Isotopes to address global scientific issues related to Mars.

E. High Precision Neutron Detector (HPND)

It would help gather more information about the geology of Martian soil. It would also be used to create high-resolution maps of hydrogen-abundant regions on Mars.

F. Subsurface Sounding Radar and Altimeter (SSRA)

The primary goal of SSRA would be to map the distribution of water and ice in the upper layers of Martian Crust. It also acts as an altimeter.

G. Magnetometer

It will study Mars' magnetic and electric fields as well as its plasma environment.

XVI. CONCLUSION

We presented the conceptual aerodynamic design of a UAV in this article capable of performing a VTOL (Vertical Take-Off and Landing) in the atmosphere of Mars. The UAV is capable of traveling over a range of 10 km per flight at an altitude of 7-8 km above the surface. It is equipped with Cameras and Sensors that would be used to analyze the surface and atmosphere of Mars providing us with a better understanding of the Planet. It is capable of withstanding harsh Martian climate owing to its Temperature control and dust protection systems. Such UAVs will have a crucial role in future Mars missions as they provide us with a better overview of the Planet.

XVII. FUTURE SCOPE

A. Surface Mapping

The UAV could be used for mapping the surface of Mars. The data so obtained could be used for planning further rover missions or to find a suitable site for humans to settle.

B. Transportation

The UAV could be used to transport essential items over a larger range faster.

C. Exploration

The UAV could be used to Explore hard-to-reach places and provide the required data for further analysis.

D. Meteorology

The UAV could be used to monitor regular changes in climatic conditions. Providing a better understanding of the Martian atmosphere.

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