A review of Unmanned Aerial Vehicle configurations for exploration of Mars

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Abstract- This paper starts with a review of the existing projects related to UAVs which have been proposed to fly in the Martian atmosphere. A comparative analysis of various UAV configurations suitable for exploration of Mars is carried out. Desirable features of the likely UAV configurations suitable for meeting this requirement are brought out. International and National status of UAVs developed for this purpose are elaborated, with a special emphasis on the latest successful deployment of NASA's *Ingenuity* helicopter. Some details of an ongoing study to design a lightweight compact UAV for high endurance-loiter in the Martian atmosphere is provided, which aims to carry out a comparative analysis of differing configurations, ranging from a tethered aerostat, tethered quadcopter, large-span inflatable wing glider and a co-axial helicopter on the lines of *Ingenuity*.

Keywords —Mars Exploration, Unmanned Aerial Vehicles, Ingenuity

I. INTRODUCTION

Since the last five decades, various missions to explore Mars have been carried out by the USA [1], Europe [2] and recently by India [3]. Exploration of Mars using UAVs has evoked recent interest due to the successful deployment of *Ingenuity* by NASA.

A. Atmospheric properties of Mars

The surface atmospheric pressure on Mars varies from 0.4–0.87 kPa, which is about 1% of the value on Earth [4]. Even though Mars has low density compared to Earth, due to the importance of Martian research, the design of UAVs which can fly on this planet has attracted lots of attention globally. Due to its thin atmosphere and its greater distance from the Sun, surface temperatures on Mars range from -140^0C in Winter to $+20^0$C in Summer. The maximum ambient wind recorded in the Summer season on Mars are in the range of 7 to 25 km/h and in the winters of 18 to 36 km/h [5]. These atmospheric conditions pose a huge challenge for the design of UAVs that can operate in the atmosphere of Mars. At ~ 30.5 km above the Earth, the atmospheric conditions are seen to be quite similar to those prevailing on the atmosphere of Mars near its surface. Hence the design of UAVs for operation on Mars began in the early 1970s [1,6,7] with a study of high-altitude UAVs above Earth.

B. Features of UAVs for Mars

The launch vehicles for Mars exploration usually consist of a Lander which is launched from a Mother Ship and approaches the surface of Mars at an atmospheric entry speed of around 7.3 km/s [8]. If we launch the UAV from the Lander during the atmospheric entry phase, we will have to decelerate it to reach within subsonic speeds and during this time, the Lander would have moved far ahead of the UAV. It has an onboard gimbal mounted camera enabling the Lander to examine the region in the vicinity of the landing spot. After examining the surrounding area, the Lander chooses the optimal heading for Martian exploration.

This UAV has to be solar powered, built with light weight non-corrosive materials and carry a small camera for surveillance and RF link with the satellite. Its propellers should be adjustable to allow it to carry out forward flight, as well as vertical flight for hovering.

The next section outlines the current status (International as well as National) of UAVs that have been under development for exploration in the lower atmosphere of Mars.

II. INTERNATIONAL STATUS OF MARS UAVS

Mars is a promising planet for space exploration, and many probes have been sent to study its atmosphere. NASA's Mars Helicopter Scout is the first UAV which completed its first successful flight. This paper summarizes the chronological order of the advancements in Mars

Exploration using UAVs. Fig. 1 Shows the timeline of the International and National developments in the field of Martian UAVs over the years.

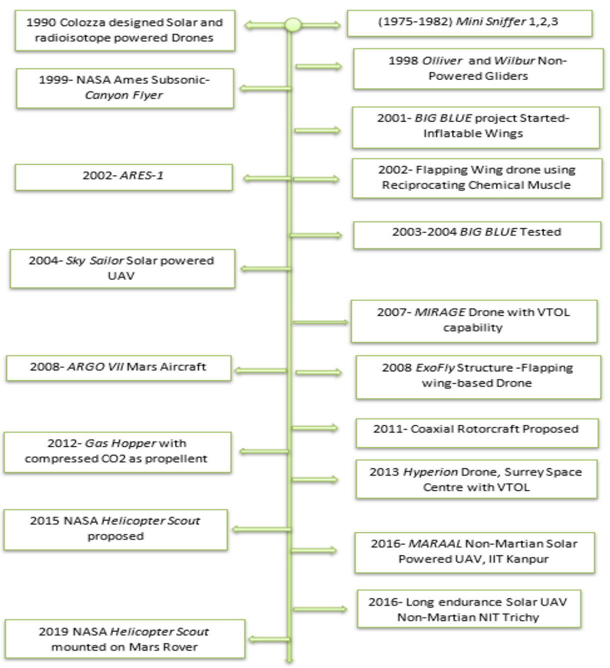

Fig. 1: Chronological Order of Key Technological Advancements in Mars Exploration using UAVs

A brief description of some of the projects listed in Fig. 1 is described in the sub-sections that follow.

A. NASA Mini-Sniffer [9] (I, II, III) 1970 -1982

The first UAV designed to meet the requirements for flying in Martian atmosphere was the *Mini-Sniffer* airplane developed by NASA [6,7]. Reed et al. [7] have described how NASA designed and built three different *Mini-Sniffer* models as small UAVs during 1975-1982. Their third model was able to fly at up to 30.5 km to conduct turbulence and atmospheric pollution measurements. This UAV was powered by a unique non-air-breathing hydrazine fuelled engine. A photograph of *Mini Sniffer-III* is shown in Fig. 2.

Fig. 2 : *Mini-Sniffer -III* UAV developed by NASA

B. Orville and Wilbur Gliders -1998

In 1998, the NASA Ames and JPL team proposed two new design of gliders for Mars exploration, named Kitty Hawk Glider prototypes *Orville* and *Wilbur* [10]. These concepts reduced the weight and design complexity due to the absence of a propulsion system. These two gliders are shown in Fig.3.

(a) (b)

Fig. 3 : Kitty Hawk Gliders prototypes (a) *Orville* and (b) *Wilbur*

C. Canyon Flyer-1999

Canyon Flyer was designed to explore the geological properties of the Martian surface [11]. This fixed wing had a propeller-driven propulsion system with twin folding tail booms and a folding four-bladed propeller. It had a wingspan of 2.2 m, mass of 20 Kg, wing chord of 0.35 m, wing area of 0.77 m^2, and endurance of 15 min [10,11]. A schematic view of *Canyon Flyer* is shown in Fig. 4.

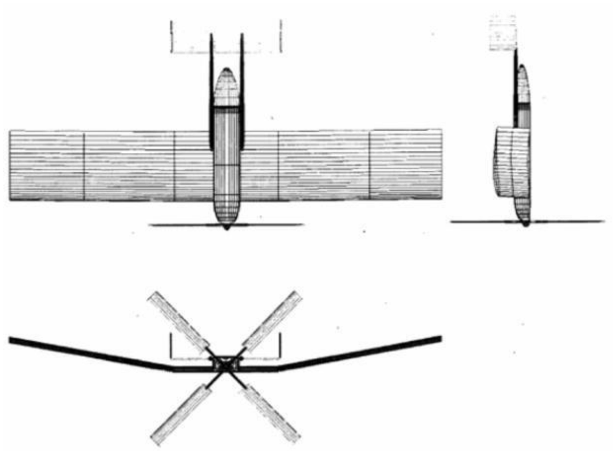

Fig. 4: Schematic View of *Canyon Flyer* Mars UAV

D. BIG BLUE (Baseline Inflatable Wing Glider) UAV (2001-2004)

This project was the first program which demonstrated the deployment of an Inflatable UAV through high altitude balloon deployments. The first Design *BIG BLUE-1* was successfully tested in 2004 at high altitudes, and several aspects of the technology were successfully determined, such as the first rigidization of an Inflatable wing at high altitudes [12,13]. Fig. 5 shows the Inflatable wing mounted on *Big Blue* UAV.

Fig. 5:*Big Blue* UAV designed at University of Kentucky [11]

E. Sky Sailor [14]- (2004-2008)

In 2004, the *Sky-Sailor* program began at the Autonomous Systems Laboratory of the Swiss Federal Institute of Technology, Lausanne via a contract with the European Space Agency (ESA) [14]. The *Sky-Sailor* project initiated the first design of a lightweight solar powered airplane for Mars exploration with weight under 3 kg. Fig. 6 shows the *Sky-sailor* UAV.

Fig. 6: *Sky Sailor*

The design parameters for the *Sky-Sailor* aircraft were to sustain a continuous flight of 10 hours, while carrying a 0.5 kg payload. It was required to be compact enough to fit within an aeroshell of 1 m diameter by 0.4 m. Research continued for the *Sky-Sailor* project until 2008 when the aircraft completed an autonomous flight lasting 27 hours [12].

F. VTOL Based UAVs - (2004-2013)

Since 2004, Surrey Space Centre has studied and designed an autonomous fixed-wing all electric vertical take-off and landing (VTOL) aircraft for the purpose of Martian exploration. The first design, known as *MASSIVA*, was developed in 2004 [15]. The UAV incorporated two side by side rotors for thrust, as shown in Fig.7 (a).

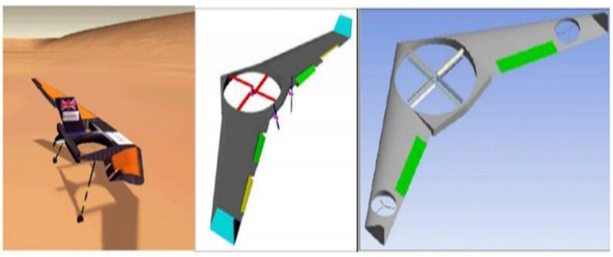

Fig. 7: *Mars* UAVs
(a) *MASSIVA*, (b) *Halcyon*, and (c) *Hyperion*

The next design, labelled *Halcyon* and shown in Fig.7 (b), was developed in 2008 [15]. *Halcyon* was larger than the previous design and was powered by solar cells. It used two variable pitch contra-rotating coaxial rotors to provide vertical thrust and two fixed pitch pusher propellers for horizontal thrust. The third iteration developed by Surrey Space Centre in 2013 was named *Hyperion* and is shown in Fig. 7 (c). The new design attempted to reduce the total mass by using a large coaxial tilt rotor in the wing for both vertical and horizontal flights.

The geometric characteristics of these three designs are compared in Table 1.

Table 1: Geometric Characteristics of *Hyperion*, *Halcyon* and *MASSIVA* UAVs

Parameter	*Hyperion*	*Halcyon*	*MASSIVA*
Wingspan (m)	8.56	8.56	8.5
Wing area (m^2)	8.23	8.23	6
Aspect ratio	6.6	6.6	12
Endurance (days)	10	10	10
Cruise speed (m/s)	50	50	30
Cruise altitude (Km)	1	1	70
Total mass (Kg)	25	25	8.5
Power Source	-	Solar Cells	-

G. MIRAGE [16] - 2007 VTOL

In 2007, a UAV labelled *MIRAGE* was designed and studied at the University of Miami for Martian exploration. *MIRAGE* implements a blended wing body design as well as a lift fan to achieve vertical take-off and landing (VTOL). At the nose of the UAV is a four-bladed propeller which generates horizontal thrust. All systems on the vehicle are powered by fuel cells [15]. Fig.8 shows the wing body design of *MIRAGE*.

Fig. 8: A schematic view of *MIRAGE* UAV

H. ExoFly Structure based DelFly II -2008

In 2008, Peeters et al. [17] proposed a flapping winged aerobot for autonomous flight in Mars atmosphere. This flapping wing design was well suited for the low atmospheric density of Mars. Since that time, the *ExoFly* technology has been developed by Delft University resulting in the *DelFly* aerobot for use in Mars atmosphere. In Mars conditions, initial studies have identified a potential mission with *ExoFly* mass of less than 20 g and range of 10–15 km with onboard solar cell recharging of the energy storage subsystem and a scientific payload. A demonstrator called *DelFly II*, shown in Fig. 9, was also designed and manufactured with a wingspan of 350 mm, length of 400 mm, mass of 17 g, flying speed of 1.8 m/s, and flight times of 12 min.

Fig.9: *DelFly II* from Delft University for use in Earth's atmosphere

I. NASA Mars Helicopter Scout (MHS) [18] 2021

Recently, NASA successfully launched this UAV on the surface of Mars on 19th April 2021. Fig. 10 shows the NASA's *Mars Helicopter Scout* (aka *Ingenuity*).

Fig. 10: NASA *Mars Helicopter Scout*

In the next section, we describe NASA's *Ingenuity* helicopter in more detail, with the latest updates.

III. NASA'S INGENUITY ROTORCRAFT

Ingenuity is a solar powered aircraft meant to operate in the Martian atmosphere. It travelled to Mars attached to the underside of the *Perseverance* Rover and landed on the surface of Mars on 18th February 2021. Fig. 11 shows *Ingenuity* separating from the underside of the Mars *Perseverance* Rover.

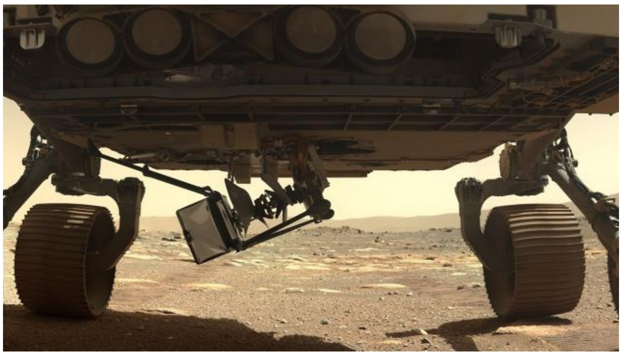

Fig. 11: *Ingenuity* separating from *Perseverance* rover

A. Mission objective of Ingenuity

Ingenuity is a technology demonstrator which opens up ways for future missions over Mars. Its main objective is to perform a powered controlled flight in the Martian atmosphere. It was planned for a 30-day mission (which has since been extended by another 30 days), in which it has to identify new rover paths and new landing sites for the scouting of future missions. It is also aimed to provide high-resolution aerial images of the Mars surface.

B. Specifications of Ingenuity

Ingenuity is a small helicopter weighs around 1.8 kg and having rotor blade diameter of 1.2 m. It can fly for a maximum duration of 90 seconds covering a range of 600 m and up to 5m above ground level [18]. It can perform forward flight as well as hover over a desired location. Its blades are made up of carbon fiber which allows it to produce lift in the thin Martian atmosphere. It has four legs also made up of carbon fiber to make them ultralight in weight which helps in safe landing. It has batteries to provide power to the helicopter and charged with the help of solar panels installed above it. *Ingenuity* has radio antennas to communicate with Earth via Mars *Perseverance* Rover. It is equipped with some sensors and cameras to carry out its mission and perform aerial surveillance over Mars. Fig. 12 shows the features of *Ingenuity*.

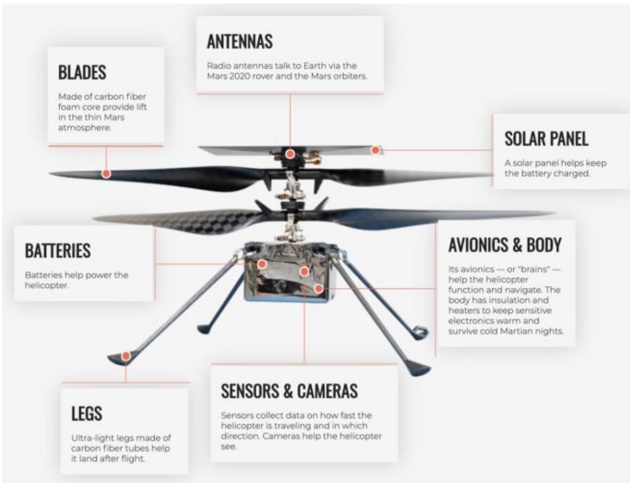

Fig. 12: Features of *Ingenuity*

Till date, Ingenuity has successfully completed four flights in the Martian atmosphere and the next flight is scheduled on 7th May 2021.

IV. NATIONAL STATUS OF MARS UAVS

Two attempts have been made to develop solar powered UAVs in India, one at IIT Kanpur [18] and the other at NIT Trichy [19]. The details of these projects are provided in the next sub-section.

A. MARAAL-2 [20] IIT Kanpur 2016

MARAAL-2 is the second version of the solar powered UAV designed and developed in the Aerospace Engineering Department of IIT Kanpur. It weighs 12 kg and can fly for

18 hours with max service ceiling at 1000 meters. The payload capacity is 7 kg. This UAV is not designed to fly in Martian atmosphere; however, it has been tested in Earth's atmosphere. Fig. 13 shows the *MARAAL-2* UAV during one of its test flights.

Fig. 13: *MARAAL-2*

B. Long Endurance Solar UAV [19] NIT Trichy 2016

This project was inspired by the *Solar Impulse- 2* [21] airplane which circumnavigated the globe. This UAV was the final year undergraduate project of Verma [19], carried out in the Mechanical Engineering Department of NIT Trichy in 2016. It had a wingspan of 3 m, total mass 4.5 kg with solar power to give an endurance of 4 hours with battery backup to extend it till 6 hours. The solar cells were able to produce the power required for cruise. Fig. 14 shows Verma standing with the UAV [19].

Fig. 14: Long Endurance Solar UAV–NIT Trichy [19]

C. Mars Project ISRO- IITB Cell 2021

Recently, ISRO has sponsored a research project at IIT Bombay to study and design a UAV which can perform high endurance loiter near the surface of Mars and scout for the interested locations for the exploration of Mars. The aim of this project to compare the several UAV configurations to meet these requirements.

The proposed solutions consist of an aerostat tethered to the lander, tethered quadcopter, large-span inflatable wing glider and a co-axial helicopter. A comparative study of these solutions will be carried out to suggest the configuration that is best suited to meet these requirements.

V. CONCLUSIONS

Several attempts have been made since the late 70s to create a UAV to explore Mars, which are described in this paper. Till date the only practical implementation has been in the form of NASA's *Ingenuity* helicopter that was recently launched. Operating a UAV on Mars poses many challenges due to the thin and cold atmosphere prevalent there. There is a need to carry out a comparative study of various configurations that can meet these challenging requirements, which is the aim of an ongoing research project being pursued by the authors in IIT Bombay.

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