

# Advancements and Challenges of Unmanned Aerial Vehicles in Mars Exploration: A Comprehensive Review

Shalini Ravi, Abhijeet Shreyas, Hana Shahir, Hitika Ranparia, Bharath Sreekumar,  
Duvvuru Suhitha Reddy

Amrita Vishwa Vidyapeetham, Coimbatore, India

**ABSTRACT:** The initial phase of Mars exploration primarily relied on rovers, landers and orbiters. The potential advantages of UAVs over other conventional exploration methods make them a suitable candidate to lead us into the future of Martian expeditions. UAVs are also known for their ability to traverse challenging terrains, manoeuvrability and ability to survey large areas. This paper presents a comprehensive survey of proposed UAV configurations for Mars exploration. It reviews the trends of Martian UAV designs while discussing the unique challenges posed by the Martian environment.

**KEYWORDS:** Mars UAV ; Martian Atmosphere; Space Exploration; Autonomous vehicles

## I. INTRODUCTION

Exploring the Red Planet has always been one of the major aims of humankind from the day we stepped foot on the Moon. The rovers Opportunity, Spirit and Perseverance have been the trailblazers for developing technology required to send vigorous systems that can conduct experiments on Mars. On the other hand, orbiters have mapped the local terrain with great precision which further expand the boundaries of our knowledge. The more scientists learn about Mars, the better they can define future mission objectives. NASA's Ingenuity became the first UAV to achieve powered flight on another planet. The rocky terrain and dust storms and the lack of technology to mitigate them prove to be significant hurdles in ground exploration. This technological gap may be addressed with the use of Unmanned Aerial Vehicles (UAVs) on the surface of Mars which are capable of traversing long distances and flying close to the surface to obtain precise measurements whilst complementing the use of Landers, Orbiters, and Rovers. UAVs' observations can provide insights to a new perspective for scientific discovery which would have the ability to survey regions scientifically inaccessible or hazardous to Rovers and Landers.

## II. MARTIAN ATMOSPHERE

The Martian Atmosphere is very thin, comparable to the Earth's atmosphere at an altitude of 33.5 km (110,000 ft). Standard Reynolds numbers are in the orders of 100,000 to 200,000, while on Earth it is in the order of millions. The Atmosphere on Mars is primarily composed of CO<sub>2</sub> (95%) with small amounts of Argon (2%) and O<sub>2</sub> (0.1%). Traces of water vapour are present, in addition to copious amounts of dust. The atmospheric pressure on Mars ranges from 0.4 - 0.87 kPa, which is about 1% of Earth's atmospheric pressure at sea level. It's thin atmosphere and greater distance from the sun result in highly fluctuating temperatures throughout the day. It drops to as low as -140°C in winters and up to 20°C in summers. The temperatures also vary throughout the day.

Table 1.1 - Different atmospheric parameters compared (Earth and Mars)

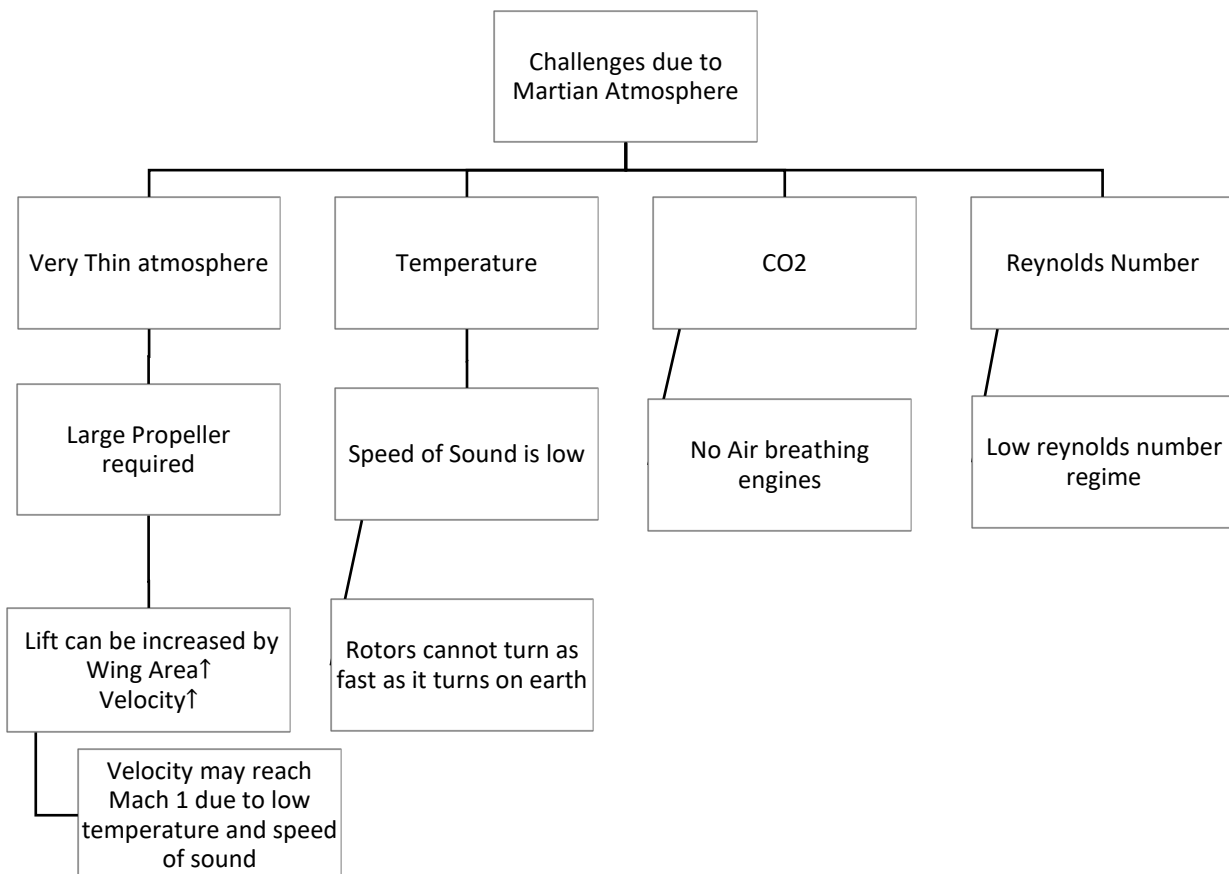
Parameter	Value on Earth	Value on Mars
Atmospheric Density (kg/m <sup>3</sup> )	1.225	0.01 - 0.02
Reynolds Number	In millions	100,000 – 200,000

Temperature Range (°C)	-25 to 40	-140 to 20
Average Surface Pressure (kPa)	101	0.636
Atmospheric Composition	0.03% CO <sub>2</sub> + 21% O <sub>2</sub>	95% CO <sub>2</sub> + 0.1% O <sub>2</sub>
Speed of Sound (m/s)	343	238.2
Acceleration due to gravity (m <sup>2</sup> /s)	9.81	3.72

### III. CHALLENGES OF MARTIAN ATMOSPHERE

The thinness of the Martian atmosphere proves to be the greatest challenge, as revealed by Colloza’s investigations [1], which show that the low atmospheric density undercompensates the low gravity advantage on Mars. Thinner atmosphere means that sonic velocity is about 20% lower on Mars. Traditional aircrafts would need to fly at exceedingly high Mach Numbers, around 0.6, to generate sufficient dynamic lift to stay airborne. Such high speeds increase the complexity of take-off and landing manoeuvres. Fixed wing configurations would be useful only during cruise.

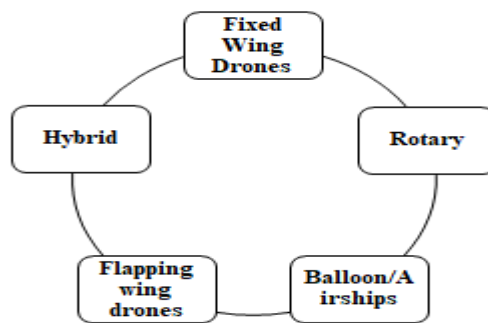
The Low Reynolds number coupled with such high speeds can increase the susceptibility of shock generation and airflow separation bubbles when using traditional rotors and propellers. Thus, airfoils designed for Earth cannot be plainly adopted for Martian missions [12]. The oxygen deficient atmosphere rules out the use of air breathing engines making electric, chemical and solar power the only possible solutions. [10] The Martian atmosphere resembles the Earth’s atmosphere at an altitude of 33.5 kms and hence, Earth drones designed for this altitude would be aerodynamically suited for Mars.[8]



A large wing area is necessary for flight on Mars making a foldable or inflatable wing the only option available. This creates packaging and stowage constraints which will lower the length and weight ceilings. The high-temperature fluctuations will influence materials, propellants and avionic components used. Thus, there is a need for the identification of features and configurations that are suitable for a UAV that is custom designed for operating in the atmosphere of Mars. Such a UAV must be enclosed in a aeroshell and stowed aboard an Orbiter or a Lander, and then deployed in-situ for its operation.

**Types of configurations**

Detailed analysis of UAVs proposed for Earth and Martian exploration was conducted by extensive literature survey. Based on operational capabilities and configurations of the UAVs, they can be classified into 5 categories.



**IV. FIXED WING UAV**

The simplest and most common configuration is Fixed wing UAVs. They have a simple structure and are ideal for long endurance missions due to their low power consumption [11]. The design of fixed wing UAVs for Martian exploration draws inspiration from the design of high-altitude UAVs since earth’s atmosphere at 30.5 km is similar to the Martian atmosphere. The first Mars drone designed and tested was NASA’s Mini Sniffer. The characteristics of different Martian fixed wing drones analysed are presented below[9].



Figure 1 – Fixed Wing Martian UAVS (Top left to right) – Mini Sniffer,Colozza [4] Solar UAV,Ames [5] Concept,Mage Drone,University of Colorado Mars drone,Mars Drone by Calvin,MarsFlyer,Kitty Hawk.[2]

Table 1.2 Martian Fixed Wing UAVs

Name	MTOW (Kg)	Wingspan (m)	AR	Year	Cruise Speed (m/s)	Features
Mini Sniffer	75.7	6.7	10.663	1975	33.33	First drone to meet Martian requirements (tested at an altitude like 30 km) [2]
Astroplane	300	21	22.05	1978	100	Serves as a scientific platform. Can conduct aerial surveys and collect samples. Resembles a competition glider on earth [3]
Colozza	1189.44	108	34.714	1990	29.71	Long endurance solar powered Mars aircraft [4]
Colozza	521.95	48.2	16.022	1990	43.54	Radio-Isotope powered Martian aircraft.[4]
Ames	203.8	12.44	12.643	1996		Has a total of 6 wing joints, 1 fuselage joint and a tail – boom release. Objective - to investigate the aerodynamics of fixed wing drones in Martian environment.[5][2]
MAGE(Mars Airborne Geophysical Explorer)	135	9.75		1998		Mars Airborne Geophysical Explorer designed to collect data regarding the formation and evolution of Valles Marineris [2]
Canyon Flyer	20	2.2	6.2857	1999	144	A compact drone featuring twin folding tail booms and four bladed folding propeller to explore the geological properties of Mars.[6]
MAP (Mars Airplane Package)				1999		Focused on imaging mars, designed for aerial reconnaissance and data collection [3][8]
Mars Flyer	12	1.562	3.87	1999	150	A rocket powered drone with a V- tail shape.
Calvin et al		2		2000	120	A small mars aircraft. Two prototypes were designed: Unpowered Glider and a solid rocket booster.[2]
Wichita state University	80.8625	30.5		2000	67	Solar powered drone. Developed retrieving and deploying system.[2]
Murray and Tartabini	18	1.06		2001		A lightweight drone with 4 – hinged line foldable wing [2]
Mother Goose				2001		A glider drone designed to perform aerial reconnaissance.[2]
BIG BLUE				2001		A drone with inflatable wings that harden when exposed to UV rays, designed for compact storage and ease of deployment[7]
ARES-I	175	6.33	5.64	2002	145	Rocket propelled drone. Employment of airfoils ss1e and ss1f was considered.[2]
ARES-2		6.25	5.58	2003		Improved aerodynamic performance and control margin of ARES –I [8]
HADD1/HADD2				2002		High altitude Deployment Demonstrator designed to prove concept of ARES-I and ARES-II
BIG BLUE I				2003		Continuation of Big Blue I project [ 2]
MATADOR		4		2004	180	Mars Advanced Technology Airplane for Deployment.A folding delta-wing drone.[9]
Sky Sailor	2.5	3.2	13.196	2004		A solar powered,lightweight drone with a V-tail configuration.[10]
M4- Minnerva Mars	141.5	6.18	5.7217	2005		A fixed wing design with twin boom inverted V tail.It is propelled by pulsed bi-propellant rockets.[2]
CRATER	63.88	4.107	5.9814	2005		Cranfield Remote Aircraft for Technical Evaluation and Research(CRATER),was built as

						a drop test vehicle.[2]
BIG BLUE III				2005		Continuation of the BIGBLUE 1 Project
ARMaDA	63	8		2006	60	Advanced Reconnaissance Martian Deployable Aircraft[11]
KLIMars	122	6			80	
MAREA	50	8.8		2006	40	Martial Aerial Research Euroavia Airplane [11]
MIRAGE						Blended wing body design and lift fan to achieve VTOL; powered by fuel cells.[2]
Argo VII	164	6.66	6.0430	2008	M0.65	Blended wing body design with constant airfoil section.[2]
Kozo et al				2009		High performance wing for low Reynolds number[12]
Koji Fujita et al	3.5	2.6	5.4	2011	50	A compact Mars fixed wing drone[15]
MISCAV	51.3	20	16		54.2	Mars Inflatable wing Solar Continuous Aerial Vehicle [13]
MAGGIE	-			2024	Mach 0.25	Solar Powered aircraft[14]

## V. MULTIROTOR UAV

A rotary wing UAV uses rotating blades to generate lift required for flight. It is capable of vertical take-off and landing, and can hover, making it ideal for a variety of applications, including surveillance, mapping, and inspection. The fast rotors make this configuration the most power consuming amongst all configurations.

Design of rotorcrafts for use in mars dates to the mid – 1990s with G.Savula’s Proposal [17]. Coaxial Rotor by Han has 4 blades with 2.2 m radius and a three-legged landing system.[2].

NASA proposed a rotary vehicle design in 2015 which has similarities with NASA’s Ingenuity. It is designed to accompany a six wheeled land vehicle. This design has counter rotating propellers and solar panels for recharging[2].MICOR is a micro coaxial rotorcraft which weighs approximately 100 grams. This vehicle is in order of magnitude smaller than previously developed systems and operates in low Reynolds number flow conditions.[18]

University of Maryland and Georgia tech designed rotorcrafts for 2002 American Helicopter Society student design competition.University of Maryland designed MARV,it is a coaxial helicopter powered by fuel cells.Airfoil AGRC 1506 is used[19].Mesicopter is a miniature rotorcraft concept.Mesicopters, are centimeter-scale devices with masses of 3 to 15g, powered by DC motors [20].

Eye On is a tilt rotor UAV designed by University of Surrey.The unique characteristics of EyeOn was,it was capable of independently performing both vertical and horizontal flights with commendable stability during transition[21]. University of Surrey unveiled next generation VTOL called Y4TR [16]. This UAV is equipped with a coaxially counter-rotating rotor system located within the central duct for vertical takeoff, while two sets of single rotors on either side of the UAV are employed for horizontal flight[21].ETH Zurich started the muFly project to develop intelligent micro unmanned aerial vehicles while imposing stringent requirement on the overall size and mass of UAV.They also developed spherical UAV to reduce the mass of the structural components while ensuring rigidity & dynamic stability[21].

MSH program (Mars Science Helicopter) has produced three vehicle conceptual designs to be used as references for planning future Mars missions namely Conceptual Advanced Mars Helicopter, Conceptual Mars Science Helicopter-Coaxial Design and Conceptual Mars Science - Hexacopter[32].Sample fetch helicopter is designed to assist Mars sample return mission by providing sample fetch capability.It has a manipulator arm and wheeled mobility system[26].Marsbird V is an octocopter with foldable rotor system and wheels for mobility. The MarsBird-V can perform sampling tasks in a cycle time of 2 to 5 days.[33]



Table 1.3 Mars Rotary UAV

Name	Year	MTOW	Rotor Diameter	Endurance
Coaxial Rotor by Han	2011	33.12	4.4	
NASA Rotary Vehicle	2015	1	1.1	0.05
Hexacopter - Pergola		6.52		0.46
MICOR	2001	0.103	0.1524	0.083
GTMARS	2002	10	1.84	
MARV	2003	50	4.26	0.65
Mesicopter1	2000	0.003		
Mesicopter2	2000	0.015		
Eye On	2012	15	1.4	0.63
Y4TR	2016	25	1	1
muFly 1	2010	95.84	0.15	
muFly 2	2011	80.31	0.15	
Spherical UAV	2016	0.59	0.226	
Japanese Mars Helicopter	2018	10.7	1.05	
TAMS 1	2002	3.5	0.982	0.1
TAMS 2	2002	4.6	1.25	0.1
Ingenuity	2021	1.8	1.2	0.03
Conceptual Advanced Mars Helicopter [15]		4.6	1.21	
		20	1.28	
Sample Fetch Helicopter	2022	2.2	1.21	
MarsBird-V	2023	6	1.4	

### Lighter – than – Air (Balloon/Airships)

These lightweight vehicles use the concept of buoyancy to generate lift force and can be deployed in the Martian atmosphere. The main advantage of using an LTA system is that it can be airborne for a longer endurance as it produces its lift from Buoyancy but difficult to control them. It can be stored in the launch vehicle and deployed once after entering the Martian atmosphere. In the end of 1997, JPL initiated a Mars Balloon Validation Program to develop and validate the technology required for Mars Balloon Mission.

The Lifting Balloon must be of a favourable material and shape. The material of the envelope should

- High resistance/mass ratio
- Low permeability
- Adaptability
- Wide temperature operating capability
- Radiation resistant

The aerostatic/lifting gas used is usually Hydrogen or Helium. Hydrogen is more effective for a particular volume and floated mass. But, it also poses challenges such as the embrittlement of titanium tanks and need for heavier steel tanks.

Balloons can be of various types

- Closed (Montgolfiere) – Balloon filled with superpressured aerostatic gas.
- Open – Inflated by an atmospheric gas which can be heated to provide buoyancy. It nearly empties at night and is sensitive to transverse winds.
- Canniballoon – closed and open balloon coupled together.
- Double – Montgolfiere + Gas/Canniballoon

- Single Balloon – filled with a quantity of Helium to provide bouyancy only for half the mass of the system. It is closed to emprison the gas.

Table 1.4 Balloons Designed for Mars

Name	Year	
Mars - 94	1994	Transparent polyester single balloon which fills up with Helium in 200 seconds [23]
Powered Aerostat - HASPA		High Altitude Superpressured Powered Aerostat
MABVAP – 1 <sup>st</sup> Generation	1997	Superpressure Mylar ‘Pumpkin’ Helium balloon [25]
MABVAP – 2 <sup>nd</sup> Generation		Zevlar® ‘Pumpkin’ Balloons with shock absorbing ripstitches [27]
Montgolfiere	1999	Kevlar Helium balloons that use solar heat for landing at the martian poles during summer or for shorter flights at lower latitudes [24]
Double balloon		Montgolfiere (closed solar balloon) with an open balloon filled with Martian CO <sub>2</sub>
Stratosail	2004	Helium Filled Balloon and a Gondola
Balloon Guidance System - Altadena	2005	Mars Exploration balloon which can be used to drop science packages

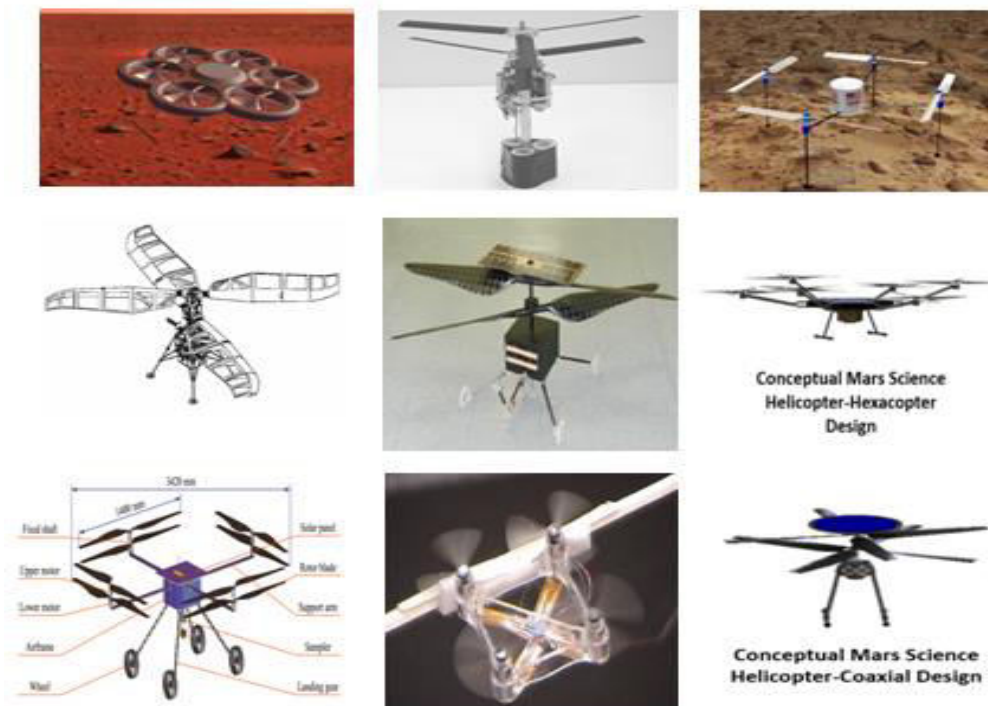


Figure 2 – (Top right to left) Hexacopter by Pergola[2], MICOR[18], GTMARS[19], MARV[19], Sample Fetch Helicopter[32], MSH – Hexacopter[32], Marsbird – V[33], Mesicopter[20], MSH – Coaxial[32]

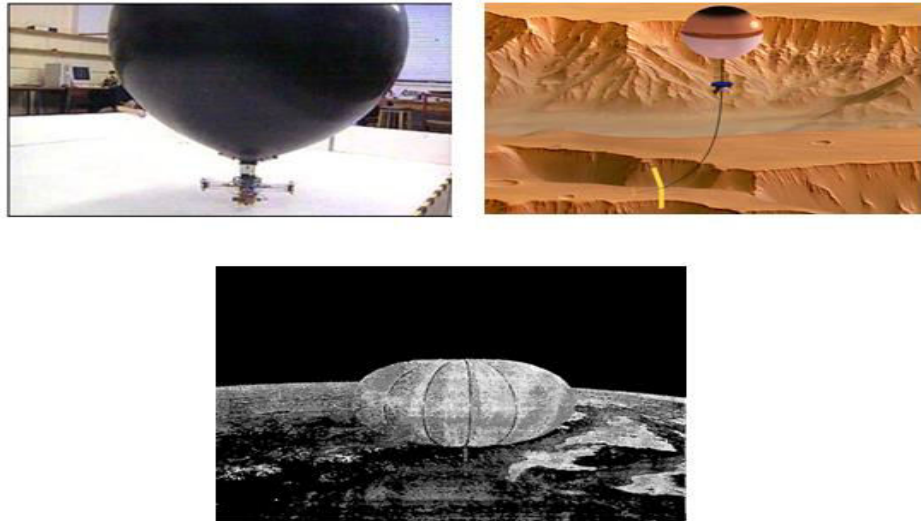


Figure 3 – (Top right to Left) Stratosail balloons [2], Balloon Guidance System[2], Pumpkin Balloon[27]

## VI. FLAPPING WING

Modelled upon insects (entomopters) and hummingbirds (ornithopters), these UAVs can generate high lift and is well suited to the low density, high viscosity Martian atmosphere.

Because of the low atmospheric density on Mars, a vehicle with a wingspan on the order of 1 m would be in the same flight Reynolds number regime as most insects are here on Earth. Because of this, it is conceivable to construct a vehicle that can fly near the surface of Mars (up to 100 s of m in altitude) and generate sufficient lift to allow it to fly slow, manoeuvre easily, and land. This realization is the genesis for the entomopter concept for Mars.

The entomopter consists of a central fuselage that houses the propulsion system, fuel, and all instrumentation. On top of the tubular fuselage are two sets of wings that oscillate 180° out of phase. These wings provide the flapping motion that generates the lift for the vehicle. Beneath the vehicle are spring-loaded legs that absorb energy during landing, assist in take-offs, and stabilize the vehicle while on the ground.

Table 1.5 Flapping wing Mars UAVs

Name	Year	Wingspan	Mass	Cruise time	Speed	Frequency (Hz)	
Entomopter	2002	1					Reciprocating Chemical Muscle
DeIFly II	2004/05	300 mm	15g	15 min			Tubular carbon fibre structure with Mylar foil wings [29]
ExoFly	2008	350 mm	<40 g	12 min	1.8 m/s	6	Solar cells are attached to the tail; missions can be envisaged using multiple ExoFlies [30]
Marsbee (nominal)	2019	20 cm	6g			20	Deployable swarm of bioinspired flapping wing UAVs [31]
Marsbee (small)		5 cm	0.21g			63	
Bumblebee			0.175		M0.3	155	



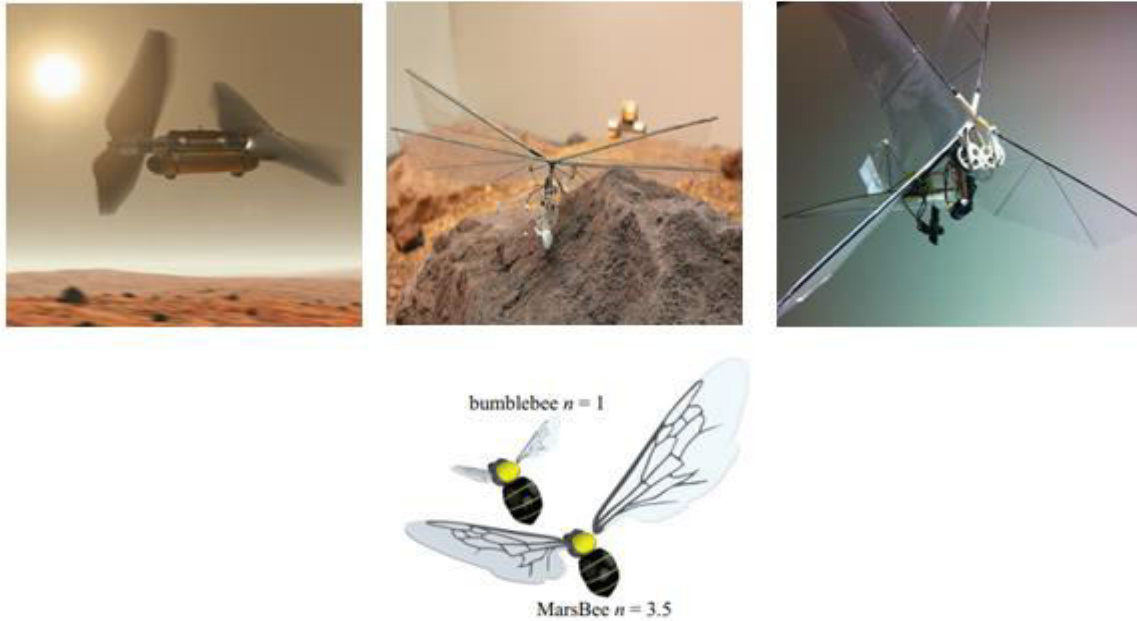


Figure 4 – (Top Right to Left) Entomopter[2],DelFly[29],ExoFly[30],Bumblebee[31]

### VII. HYBRIDS

The best of both worlds, Fixed wing-rotor hybrids are capable of VTOL and hover.

Balloon – drone hybrids have an inflatable wing/fuselage and can take away some of the strain away from the rotors by providing buoyant lift.

Table 1.6 – Hybrid Mars UAVs

Name	MTOW	Wingspan	AR	Year	Cruise Speed	Features
MIRAGE	490	4.8	3.84	2007	M0.45	Blended wing design with lift fan
MASSIVA	15	8.5	12.04167	2004	30	Introduced VTOL flying drones in Mars
Halcyon	25	8.56	8.903232	2008	50	Powered by Solar cells
Hyperion	25	8.56	8.903232	2013	50	This design attempted to reduce the mass by adding one large coaxial tilt rotor
UAV by Ishan Mishra et al		3.6	7.2	2021	16.66	
Bertani	20	3.5	4.8	2023	92	Electric drone[16]
ISPHA	49.7	12			23.9	HTA hybrid with inflatable structure [22]

Mars Electric Resusable Flyer		0.91				VTOL Electric drone developed by NASA
VITAS	14					X-wing style tailsitter



Figure 5 -(Right to left) UAV designed by Bertani[16],NASA Electric reusable Flyer[2],VITAS[19]

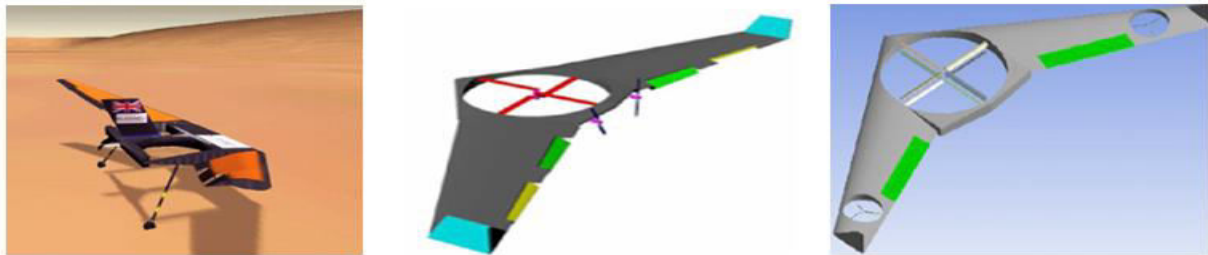


Figure 6 – (Right to left) Massiva[2],Halcyon[2],Hyperion[2]

VIII. ADVANTAGES AND DISADVANTAGES OF CONFIGURATIONS

Configuration	Advantages	Disadvantages
Fixed Wing	<ul style="list-style-type: none"> <li>• Can fly at higher altitudes</li> <li>• Simpler structure</li> <li>• Produces more lift</li> <li>• Ideal for stowing in aeroshell</li> <li>• Higher Range and Endurance</li> <li>• Higher speeds</li> </ul>	<ul style="list-style-type: none"> <li>• Greater take-off and landing areas</li> <li>• Cannot hover</li> <li>• Continuous translation required to generate lift</li> </ul>

<p><b>Multi Rotor UAVs</b></p>	<ul style="list-style-type: none"> <li>• Vertical take-off and landing</li> <li>• Can hover</li> <li>• Accessibility</li> <li>• Ease of use</li> </ul>	<ul style="list-style-type: none"> <li>• Low endurance</li> <li>• High power consumption</li> <li>• Low cruise velocity</li> <li>• Supersonic tip speed of advancing blade and stalling of the retreating blade at high angle of attack in thin air</li> <li>• Lower payload capacity</li> </ul>
<p><b>Balloons/Airships</b></p>	<ul style="list-style-type: none"> <li>• No power required for lift</li> <li>• Low power consumption</li> <li>• Uncomplicated design, technology, and manufacturing</li> </ul>	<ul style="list-style-type: none"> <li>• Lacks directional control</li> <li>• Vulnerable to weather</li> <li>• Low speed</li> <li>• Limited payload capacity</li> </ul>
<p><b>Flapping Wing</b></p>	<ul style="list-style-type: none"> <li>• Suitable for low-density, high-viscosity atmospheres</li> <li>• High coefficient of lift</li> </ul>	<ul style="list-style-type: none"> <li>• Low endurance</li> <li>• Complex design</li> <li>• Limited range</li> <li>• Limited payload capacity</li> </ul>
<p><b>Hybrid (VTOL/Tilt Rotor)</b></p>	<ul style="list-style-type: none"> <li>• VTOL</li> <li>• Hovering capability</li> </ul>	<ul style="list-style-type: none"> <li>• High Power consumption, albeit lower than pure rotor vehicles</li> </ul>
<p><b>Hybrid (Balloon-Drone Inflatable wing/fuselage)</b></p>	<ul style="list-style-type: none"> <li>• Low power consumption</li> </ul>	<ul style="list-style-type: none"> <li>• Vulnerable to weather</li> </ul>

### IX. CONCLUSION

Martian UAVs hold immense potential for revolutionizing Mars exploration. It offers enhanced mobility, increases coverage, and access to previously unreachable areas, supplementing both surface rovers and orbiters. Until 2010, fixed-wing Martian drones dominated research in the field. However, after this period, rotary Martian drones gained prominence, leading to significant advancements and breakthroughs in their development. Every configuration comes with its own advantages and disadvantages, and the selection of a specific configuration depends on the particular problem being addressed. Future research will focus on improving UAV autonomy and integrating these systems into larger Mars mission architectures, both for robotic and potential human exploration.

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