

Systematic Selection of the Next Generation Martian Rotorcraft Configurations

Vishal Youhanna^{a*}, Leonard Felicetti^b, Dmitry Ignatyev^c

Faculty of Engineering and Applied Sciences, Cranfield University, College Rd, Cranfield, UK. MK430HP

^a vishal.youhanna@cranfield.ac.uk, ^b leonard.felicetti@cranfield.ac.uk, ^c d.ignatyev@cranfield.ac.uk

*Corresponding Author

Abstract

The successful deployment of NASA's Ingenuity Helicopter has paved the way for the development of advanced rotorcraft for Martian exploration. Despite Ingenuity's achievements, its limitations in endurance, payload, and range highlight the need for optimised designs for future Martian aerobot missions. This paper addresses these challenges by proposing and systematically analysing various rotorcraft configurations, including single rotors, coaxial designs, tandem rotors, quadcopters, and hexacopters, under Martian conditions. Through a detailed parametric analysis based on simplified momentum theory, power requirements are calculated for each configuration during hover, vertical climb, and forward flight. Special attention is given to coaxial multirotor designs, which offer improved performance in terms of power efficiency and payload capacity. The application of the Battery Mass Fraction (BMF) methodology further demonstrates the viability of electric-powered rotorcraft for extended Martian operations. The study identifies coaxial hexacopters as the most efficient configurations, providing a strong basis for the next generation of Martian aerial vehicles.

Keywords: Mars Exploration, Aerial Drones, Planetary UAV, Aerobots Conceptual Design

Nomenclature

d	horizontal distance between two consecutive rotor hubs (m)
D	rotor diameter (m)
D/q	component drag area(m ²)
e	Oswald's efficiency factor
E	known run time (hour or h)
f	adjustment for downwash on the fuselage
g	surface gravity acceleration on Mars used in this paper (m/s ²)
m	mass of the rotorcraft (kg)
M	figure of merit
N	number of rotors in a rotorcraft
P	power required (Watt or W)
q	dynamic pressure (Pa)
S	rotor disk area (m)
W	rotorcraft weight (N)
V	forward flight speed (m/s)
γ	climb path angle, =0 when levelled (Deg)
ρ	local air density on Mars (kg/m ³)
E _{sb}	battery-specific energy (Wh/kg)
K _{dw}	downwash factor
K _{ov}	overlapping interference factor, =1 when no overlapping
m ₀	total mass of the rotorcraft (kg)
m _b	battery mass (kg)
m _e	empty mass of the rotorcraft (kg)
M _{at}	rotor advancing tip Mach number (M)
P _{2 Iso}	required forward flight power of rotorcraft with

	2 isolated rotors (Watt or W)
P _{Fwd level}	power required during forward-levelled flight (Watt or W)
P _{Fwd climb}	power required during forward climb flight (Watt or W)
P _{used}	power required during a flight (Watt or W)
P _{Vert Climb}	power required during a vertical climb (Watt or W)
W ₀	total take-off weight of the rotorcraft (N)
W _b	battery weight (N)
V _{climb}	vertical climb velocity, =0 for hover (m/s)
η _{b2s}	total system efficiency from the battery to the motor output shaft
η _{mechanical}	mechanical losses adjustment due to driving of the tail rotor
η _p	propeller efficiency

Acronyms/Abbreviations

BMF	- Battery Mass Fraction
CAD	- Computer Aided Design
CFD	- Computational Fluid Dynamics
CNSA	- China National Space Administration
EDL	- Entry, Descent, and Landing
ESA	- European Space Agency
GIS	- Geographic Information System
JAXA	- Japan Aerospace Exploration Agency
LS	- Large Separation
MOLA	- Mars Orbiter Laser Altimeter
NASA	- National Aeronautics and Space Administration
RTG	- Radioisotope Thermoelectric Generator

UAV - Unmanned Aerial Vehicle
VTOL - Vertical Take-off and Landing

1. Introduction

The growing focus on Mars exploration has driven the development of specialised aerial robots, or aerobots, to support future missions in the planet's thin atmosphere. Before 2021, Mars exploration mainly relied on spacecraft, landers, and rovers. However, unmanned aerial vehicles (UAVs) have gained attention due to their advantages over rovers, such as higher speed, broader range, improved obstacle avoidance, and better visibility [1]. Historically, lighter-than-air airships or fixed-wing aircraft were preferred for planetary exploration because rotorcraft posed technical challenges. Nonetheless, recent advances in drone technology have reignited interest in rotorcraft for Mars.

Mars presents unique challenges for rotorcraft design. Despite its lower gravity, the atmospheric density on Mars is about 100 times lower than Earth's [2], leading to very low Reynolds numbers, especially for small helicopters. Additionally, rotor tip speeds must be higher to compensate for the thin atmosphere, while the reduced speed of sound on Mars (approximately 72% of Earth's) further complicates the design [3]. A key challenge for Martian drones is managing the heat generated by the propulsion system, which is essential for producing lift in such low-density conditions. Furthermore, the aeroshell used to transport aerobots to Mars has a maximum diameter of 4.5 m, adding to the design complexity [4]. Despite these challenges, NASA's successful deployment of the Ingenuity Helicopter in April 2021 disproved earlier scepticism regarding the practicality of rotorcraft on Mars.

1.1. Literature

Ingenuity, which completed 72 autonomous flights before its retirement in February 2024 [5], transitioned from a technology demonstration to an operational demonstration, showcasing the potential for future collaboration between rovers and aerial surveyors. The experience of designing and operating Ingenuity has provided valuable insights into the development of more advanced aerobots for Mars exploration. However, Ingenuity's small size and basic design limit its endurance, range, and payload capacity, preventing it from conducting longer-range missions or carrying larger scientific payloads, advanced communication systems, or robust propulsion for high-altitude flights.

To overcome these limitations, the authors proposed in their recent studies an enhanced design for Martian aerobots by establishing more ambitious mission requirements. This involves creating a new rotorcraft design that accounts for operational and design constraints, including a maximum aeroshell diameter of 4.5 m, with the assumption that launch and re-entry

technologies will remain stable over the coming decades. The selected mission site is the South-West (SW) Melas Basin within the Melas Chasma region of the Valles Marineris canyon system on Mars. Although the rugged terrain poses challenges, advances in planetary landing navigation and obstacle-avoidance technology in aerobots make this location a promising candidate for in-situ exploration [3]. An aerobot deployed here could produce high-resolution aerial maps and identify potential sample collection sites for future rover missions. The primary mission goal would be to capture detailed images of the region and successfully transmit the data to a rover or a ground control station on Earth.

One way to improve Ingenuity's capabilities is by increasing its size or adding fixed wings. Vertical takeoff and landing (VTOL) fixed-wing aircraft, both rigid and retractable, have been explored in several Mars mission plans [6]-[11]. Young et al. (2000) pioneered the concept of rotary VTOL planetary aerial vehicles, such as the Mars tiltrotor, which balances hover performance and cruise range—essential features for Mars exploration [6]. Other innovative designs include the Y-4 Tilt-Rotor VTOL Aerobot [7] and MIRAGE [8], which use different propulsion systems, such as tiltrotors, coaxial rotors, and embedded fans. Alternative approaches, like tailsitters [9] and hopper designs [10], also offer promising solutions for Mars exploration, with projects like VALKERIE incorporating inflatable wing technology for transport efficiency [11]. NASA's second-generation Mars helicopters, such as the Mars Science Helicopter (MSH) and Advanced Mars Helicopter (AMH), feature foldable designs with various rotor sizes and payload capacities [4].

1.2. Proposed Study

To meet the increasing demands of future Martian missions, new rotorcraft designs must be developed within practical limitations, particularly the maximum aeroshell diameter. Larger rotorcraft might need to be packaged with smaller spacecraft, transported separately, or fitted with an innovative folding mechanism to fit inside the aeroshell. A detailed parametric analysis of rotorcraft designs is crucial to assess the potential benefits of larger or winged rotorcraft and to propose suitable configurations for future research.

In a recent studies conducted by the authors, the performance of various battery-electric rotorcraft configurations, such as single, dual, quad [13] and hexa rotors [12], was analysed under defined parameters, including initial sizing estimates. This paper builds on that research by including coaxial quad and hexacopter configurations, broadening the scope of potential designs and performance outcomes.

The research article presents a generalised methodology (section 2) based on simplified momentum

theory to calculate the power requirements for different Martian rotorcraft configurations, including those with overlapping rotors. Additionally, an initial sizing method for battery-electric aircraft (section 3) estimates the required battery mass based on flight power, aiding in determining the total mass of the rotorcraft. The parametric analysis cases (section 4) cover conventional single-rotor helicopters, coaxial rotorcraft, three tandem rotorcraft configurations, and quadcopter and hexacopter setups. These parameters are defined and summarised (section 5). The results and analysis (section 6) concentrate on power demands for hovering, vertical climbing, and forward flight across the different configurations, helping to identify the most power-efficient designs. However, theoretical optima might face design constraints, requiring careful selection and refinement of the final configurations, which is discussed in section 7.

2. POWER REQUIREMENT ANALYSIS METHODOLOGY FOR ROTORCRAFT

Figure 1 depicts five rotorcraft configurations, which include single, dual, quad, and multi-rotor designs. Conventional rotary-wing aircraft typically use a single main rotor atop the fuselage to provide both lift and thrust, supplemented by a tail rotor to counteract torque. Coaxial rotorcraft, on the other hand, feature two rotors aligned on the same axis, rotating in opposite directions, eliminating the need for a tail rotor while enhancing stability. Tandem rotor configurations involve two main rotors placed one behind the other along the fuselage, increasing both lift capacity and payload potential. Side-by-side rotorcraft configurations, such as tiltrotors and tiltwings, position multiple rotors close together, allowing versatile operation in both hovering and forward flight modes.

Quadcopters, a type of multicopter, have four rotors arranged symmetrically and are valued for their simplicity, stability, and ease of control, making them popular for UAVs and drones. Hexacopters, which feature six rotors, offer superior stability and payload capacity compared to quadcopters, making them more suitable for demanding tasks requiring extra lift and redundancy. Additionally, coaxial quadcopters and coaxial hexacopters combine the advantages of both coaxial and multi-rotor designs by using two stacked rotors on each arm. These configurations further enhance lift, stability, and redundancy while potentially reducing the vehicle's footprint, making them ideal for space-constrained applications and more robust mission profiles. Each of these configurations presents unique aerodynamic characteristics and trade-offs, with the choice depending on specific mission requirements and design objectives.

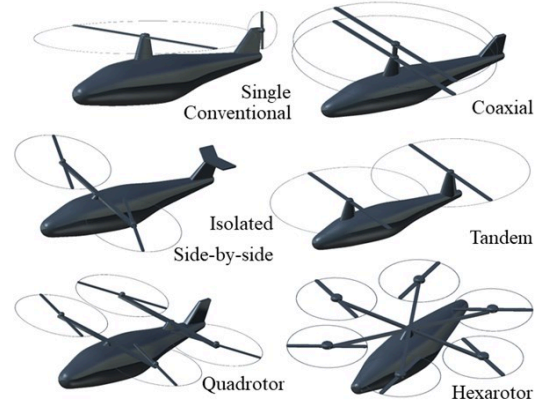


Fig. 1. Rotorcraft Configurations Illustration

2.1. Conventional Rotorcraft

The critical factor determining the operational success of a reusable Martian aerobot lies in its ability to perform vertical takeoff and landing (VTOL), given the lack of conventional runways on Mars. This capability is entirely dependent on the efficiency of the rotor propulsion system. Momentum theory is applied to estimate the rotor's power consumption during different flight phases, including hover, vertical climb, and forward flight. In this theoretical model, the rotor blades are treated as actuator disks with negligible thickness and a specific disk area (S). The model assumes uniform airflow across the rotor disk and immediate energy transfer to the airflow, neglecting factors such as airfoil drag losses, tip losses, and residual rotational velocities.

To account for these simplifications, the concept of the figure of merit is introduced. This figure of merit (M) represents the ratio of ideal power to actual power ($M = P_{\text{ideal}}/P_{\text{actual}}$) and serves as a measure of rotor efficiency. Equation (1) calculates the power required for the vertical (vert) climb or hover (when the climb velocity is zero), specifically for a conventional helicopter [14].

$$P_{\text{(Vert Climb or Hover)}} = \left[\left(\frac{fW}{M} \sqrt{\frac{fW/S}{2\rho}} \right) + \frac{WV_{\text{Climb}}}{2} \right] \left[\frac{(1 + P_{\text{tail rotor}}/P_{\text{main rotor}})}{\eta_{\text{mechanical}}} \right] \quad (1)$$

The total power calculated also includes the power needed for the tail rotor. The ratio of power required by the tail rotor to that required by the main rotor ($P_{\text{tail rotor}}/P_{\text{main rotor}}$) typically falls within the range of 0.14 to 0.22, as tail rotors typically have a diameter of about 15-20% of the main rotor's diameter [14].

V_{Climb} represents the vertical climb speed (which equals 0 for hover), and f is the adjustment factor for the

downwash effect on the fuselage, typically set to 1.03. $\eta_{\text{mechanical}}$ is mechanical losses adjustment due to driving of the tail rotor, typically of the value 0.97. During forward flight, the rotor behaves similarly to a circular wing with an aspect ratio of $4/\pi$. Empirical data suggests an equivalent Oswald efficiency factor ranging between 0.5 and 0.8 for such wings [14]. The Oswald efficiency factor, defined at a particular lift coefficient, is the ratio of the induced drag coefficient of the wing to that of an elliptic wing with the same aspect ratio, operating at the same lift coefficient. Parasitic drag can be expressed in terms of drag area (D/q), where q represents the dynamic pressure. Equation (2), integrating these elements, facilitates the estimation of the required power for forward climb or level flights [14].

$$P_{(\text{Fwd}_{\text{climb}} \text{ or } \text{Fwd}_{\text{level}})} = \left[\frac{V}{\eta_p} \left\{ q(D/q) + \frac{W^2}{4eqS} + W \sin(\gamma) \right\} \right] \left[\frac{(1 + P_{\text{tail rotor}}/P_{\text{main rotor}})}{\eta_{\text{mechanical}}} \right] \quad (2)$$

In the equation, $W \sin(\gamma)$ represents the climb component based on the climb path angle γ (0 for level flight). The rotor provides both lift and forward propulsion, acting like a propeller. To account for this, the propeller efficiency factor η_p is included to more accurately estimate the rotor's forward thrust performance.

2.2. Multirotor Rotorcraft Configurations

The following equations, described briefly, are used in this study for calculating power requirements across different rotorcraft configurations have been adjusted and explained in detail in the authors previous work [12], which are sourced from [15] and [16].

Equation (3) describes the power required for vertical climb or hover in a coaxial rotorcraft, which includes the overlapping interference factor (K_{ov}). This factor adjusts the power requirement due to the rotor wake interference when the rotors overlap.

$$P_{(\text{Vert Climb or Hover})} = \left[\left(\frac{fW}{(2\sqrt{2})M} \sqrt{\frac{fW/S}{2\rho}} \right) + \frac{WV_{\text{Climb}}}{4} \right] \left[\frac{2}{\eta_{\text{mechanical}}} \right] [K_{ov}] \quad (3)$$

In cases where the rotors are fully overlapped (zero vertical gap), K_{ov} increases power consumption by approximately $\sqrt{2}$ or about 41%. In scenarios with large separation (LS) between the rotors, typically around 10% of the rotor diameter, K_{ov} decreases to 1.281, assuming uniform disk loading [15][16]. In this configuration,

there is no tail rotor, but instead, a second rotor is used. Consequently, the ratio of power required by the two equal-sized rotors ($P_{\text{second rotor}}/P_{\text{main rotor}}$) becomes equal to 1. Equation (4) extends the power calculation to forward flight for coaxial rotorcraft. considered.

$$P_{(\text{Fwd}_{\text{climb}} \text{ or } \text{Fwd}_{\text{level}})} = \left[\frac{V}{\eta_p} \left\{ q(D/q) + \frac{W^2}{16eqS} + \frac{W \sin(\gamma)}{2} \right\} \right] \left[\frac{2}{\eta_{\text{mechanical}}} \right] [K_{ov}] \quad (4)$$

Equation (5) generalises the vertical climb or hover power calculation for isolate or non-overlapping multirotor systems, distributing the total thrust among 'N' rotors. In this case, the rotors operate without overlapping interference, and the total power is shared equally across the rotors, making it applicable for quadcopters and other multirotor systems. Equation (6) adapts the forward flight power calculation for multirotor systems, distributing the power requirements among N rotors and adjusting for parasitic drag and propeller efficiency.

$$P_{(\text{Vert Climb or Hover})} = \left[\left(\frac{fW}{(N\sqrt{N})M} \sqrt{\frac{fW/S}{2\rho}} \right) + \frac{WV_{\text{Climb}}}{2N} \right] \left[\frac{N}{\eta_{\text{mechanical}}} \right] \quad (5)$$

$$P_{(\text{Fwd}_{\text{climb}} \text{ or } \text{Fwd}_{\text{level}})} = \left[\frac{V}{\eta_p} \left\{ q(D/q) + \frac{W^2}{(N^2)4eqS} + \frac{W \sin(\gamma)}{N} \right\} \right] \left[\frac{N}{\eta_{\text{mechanical}}} \right] \quad (6)$$

In forward flight configurations where rotors are aligned in front of one another, an additional downwash factor is produced by the front rotor onto the rear rotor. To accurately estimate the required power, this downwash effect must be considered and incorporated into the calculations for the rear rotor(s), as detailed in the subsequent subsection on tandem configurations. The updated equation substitutes [N] for the segment $[1 + (P_{\text{tail rotor}}/P_{\text{main rotor}})]$ to indicate the number of rotors involved, as there is no tail rotor in this design but all equal-sized rotors.

Equation (7) defines the overlapping interference factor K_{ov} for tandem rotorcraft, based on the ratio of the horizontal distance between rotor axes to the rotor diameter (d/D). For maximum overlap, when one rotor's blade tip touches the hub of the other, K_{ov} increases, and this equation is used to quantify the effect.

$$K_{ov} = \left[\sqrt{2} - \frac{\sqrt{2}}{2} \left(\frac{d}{D} \right) + \left(1 - \frac{\sqrt{2}}{2} \right) \left(\frac{d}{D} \right)^2 \right] \quad (7)$$

When rotors are situated in distinct planes and the lower rotor functions within the contracting wake of the upper rotor, the calculation of the overlapping area necessitates numerical integration to determine a solution for K_{ov} .

Equations (8) and (9) calculate the total power required for forward flight in tandem rotorcraft, factoring in the downwash effect (K_{dw}) from the front rotor to the rear rotor. At maximum tandem overlap, K_{dw} is assumed as 1.134, representing the influence of the front rotor's downwash on the rear rotor. The total power for forward flight is adjusted accordingly. Also, if there exists an overlap between the two rotors, the overlapping interference factor (K_{ov}) is incorporated into the expression to calculate the total forward power.

$$P_{(Forward)} = P_{Front\ Rotor} + P_{Rear\ Rotor}(K_{dw}) \quad (8)$$

$$P_{(Forward)} = (1 + K_{dw}) \frac{1}{2} P_{2\ Iso} K_{ov} \quad (9)$$

In non-overlapping tandem rotor setups, K_{ov} is either excluded or set to 1 in equations (3) and (9), as Equation (7) for K_{ov} becomes invalid without rotor overlap.

The following equation can be used for coaxial multirotor rotorcrafts with no sideways overlapping, such as coaxial quadcopter or coaxial hexacopter, to calculate the power required for vertical climb or hover. P_{total} can be determined by applying Eq. (5).

$$P_{(Vert\ Climb\ or\ Hover)} = \frac{1}{2} P_{total} + \frac{1}{2} P_{total}(K_{ov}) \quad (10)$$

3. Initial Sizing Methods for Battery-Electric Aircraft

The total aircraft mass at take-off includes the empty mass, payload, and battery mass (m_b). Unlike fuel-powered aircraft, where mass decreases during flight, electric aircraft have a constant battery mass. The following equation calculates the Battery Mass Fraction (BMF), the ratio of battery mass to total mass [14].

$$BMF = \frac{m_b}{m_0} = \frac{W_b}{W_0} = \frac{EP_{used}}{E_{sb} \eta_{b2s} m} \quad (11)$$

The above equation considers factors such as the known run-time endurance (E) and the power consumed during different flight segments, encompassing vertical climb, hover, and forward flight for rotorcraft. η_{b2s} is the total system efficiency from the battery to the motor output shaft, typically equal to 0.9. The total BMF is the sum of BMFs for each flight segment.

Equation (11) gives the total take-off mass:

$$m_0 = m_e + m_b + m_{payload} \quad (12)$$

Equation (12) undergoes modification to formulate Eq. (13) for battery electric aircraft sizing, to calculate the total mass based on BMF and empty mass ratio.

$$m_0 = \frac{m_{payload}}{1 - BMF_{total} - \frac{m_e}{m_0}} \quad (13)$$

These equations help estimate total mass and payload capacity. The sizing process is iterative, requiring adjustments until the desired design parameters are met [12].

4. Definition of Rotorcraft Configurations

4.1. Tandem Rotorcraft Cases

The arrangement of tandem rotorcraft depends on how the rotors are positioned along the length of the fuselage. For the power consumption analysis, three different scenarios are examined, considering the structural limitations of the aeroshell (as discussed in [13] and [17]). In these cases, two equal-sized rotors are symmetrically spaced at distances of 2.25 m, 1.125 m, and 0.75 m from the centre for Cases 1, 2, and 3, respectively. This assumes the fuselage length matches the maximum aeroshell size of 4.5 m. Fig. 2 illustrates the placement of these rotors on the aerobot within the aeroshell dome. These configurations represent extreme cases for parametric study (Fig. 3): Case 1 places foldable rotors at the ends of the fuselage, allowing for a maximum rotor diameter of 9 m; Case 3 positions rotors within the aeroshell boundary, limiting the diameter to 3 m; and Case 2 falls between these, allowing for a maximum rotor diameter of 4.5 m. It is important to note that in practical applications, rotor blades must be positioned at a distance from the inner walls of the aeroshell and rotor hubs, although such spacing is not considered in this theoretical analysis.

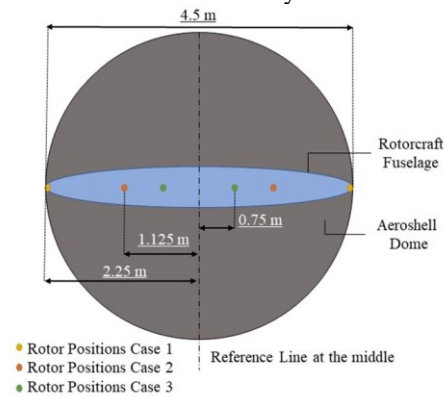


Fig. 2. Schema of the positioning of rotor hubs of tandem rotorcraft Cases 1, 2, and 3, on the fuselage placed inside an aeroshell [17]. (Not to scale)

In Case 1, a folding mechanism and potentially an articulated rotor hub system are required to ensure the rotors fit within the aeroshell for storage. If the rotor diameter exceeds 2.25 m, Case 2 would also necessitate the use of folding mechanisms and possibly an articulated rotor hub system. On the other hand, Case 3 allows for a rigid rotor hub system without the need for folding linkages. Table 1 provides a summary of the parameters established for each of the three tandem rotorcraft configurations, as well as the quadcopter and hexacopter study cases, which are discussed next.

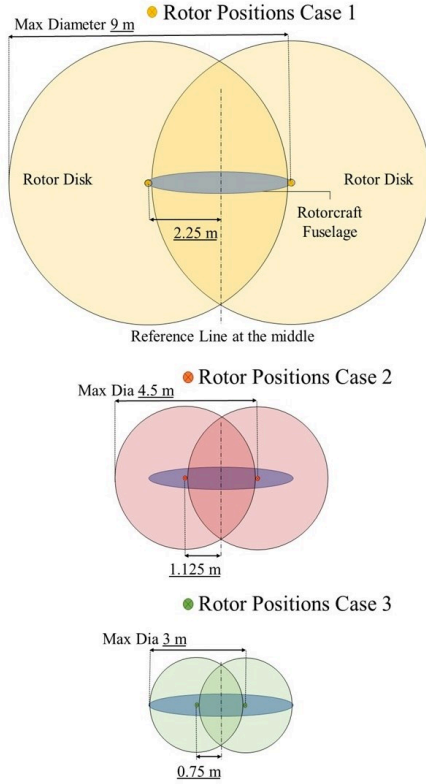


Fig. 3. Schematic illustration of the rotor positioning of tandem rotorcraft Cases 1, 2, and 3 in operational mode [12]. (Not to scale)

4.2. Quadcopter and Hexacopter Cases

The configurations for both the quadcopter and hexacopter vary based on the placement of the rotor hub support frames along the fuselage, similar to the tandem rotorcraft configurations mentioned earlier. However, since these multicopters typically have non-overlapping rotors, only non-overlapping designs are considered in this study. For the quadcopter, the parametric analysis involves two equal-sized, non-overlapping rotors positioned 1.125 m from the midpoint on each side. Fig. 4 outlines the parameters for this configuration. Likewise, the hexacopter setup for parametric analysis involves six equal-sized, non-overlapping rotors arranged 1.5 m from the centre, spaced 60° apart from each other. The parameters for the hexacopter

configuration are shown in Fig. 5.

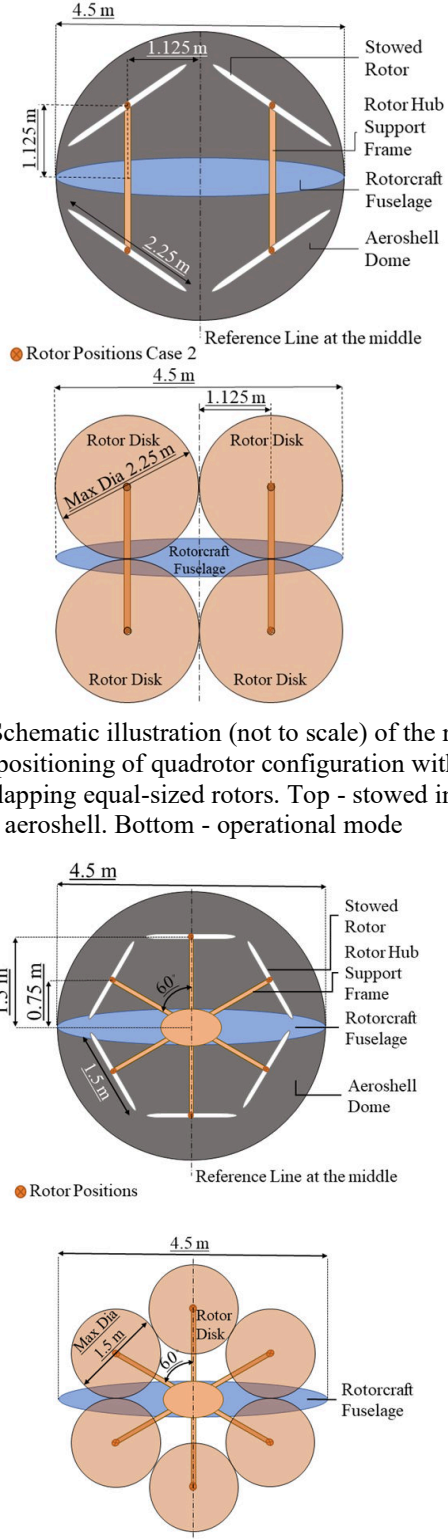


Fig. 4. Schematic illustration (not to scale) of the rotor hub positioning of quadcopter configuration with nonoverlapping equal-sized rotors. Top - stowed inside aeroshell. Bottom - operational mode

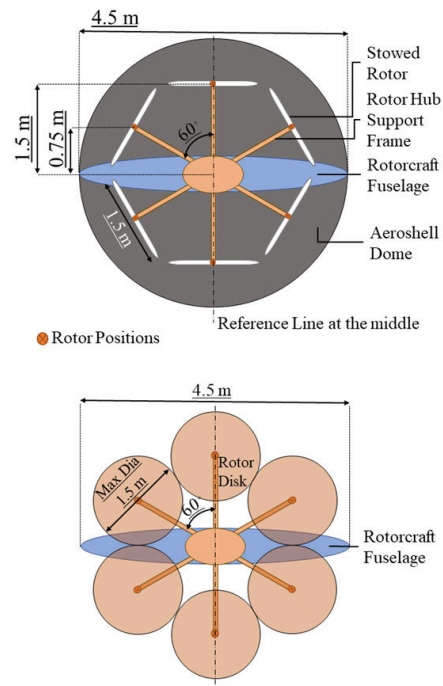


Fig. 5 Rotor hub positioning of hexarotor configuration with nonoverlapping equal-sized rotors. Top - stowed inside aeroshell. Bottom - operational mode

The defined quadcopter and hexacopter configurations ensure the maximum rotor diameter remains within allowable limits to avoid overlap during operation or storage inside the aeroshell dome. For the quadrotor, the rotor diameter is capped at 2.25 m, while for the hexarotor, it is limited to 1.5 m. Both configurations can employ a rigid rotor hub system. More detailed information is available in Table 1.

Table 1 Summary of Tandem, Quad & Hexa Rotorcraft Cases

Case No.	Rotor System Type	Folding Mechanism	Maximum Diameter	Rotor Position*	Isolated Rotor behaviour
Tandem 1	Articulated	Yes	9 m	2.25 m	$D \leq 4.5$ m
Tandem 2	Articulated**	Yes**	4.5 m	1.125 m	$D \leq 2.25$ m
Tandem 3	Rigid	No	3 m	0.75 m	$D \leq 1.5$ m
Quad	Rigid	No	1.25	1.125 m	$D \leq 2.25$ m
Hexa	Rigid	No	1.5	1.5 m***	$D \leq 1.5$ m

* Rotor hub position from the center of the fuselage

** When rotor D is > 2.25 m

***Radial position from the centre

4.3. Coaxial Quadcopter and Coaxial Hexacopter Cases

The configurations for both the coaxial quadcopter and coaxial hexacopter are based on the quadcopter and hexacopter with single/independent rotors discussed in the previous subsection. Fig. 6 and Fig. 7 illustrate these configurations in operational mode, respectively.

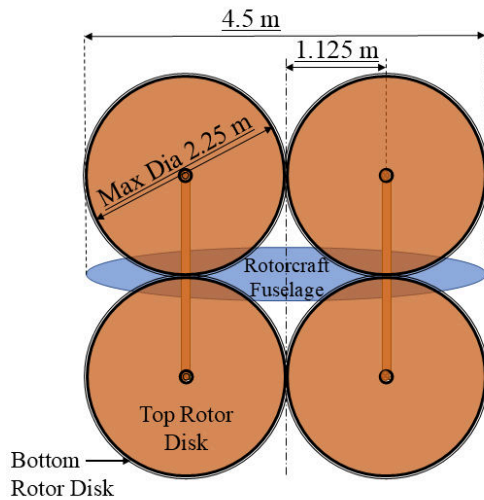


Fig. 6. Schematic illustration (not to scale) of the rotor hub positioning of coaxial quadrotor configuration with nonoverlapping equal-sized rotors in operational mode.

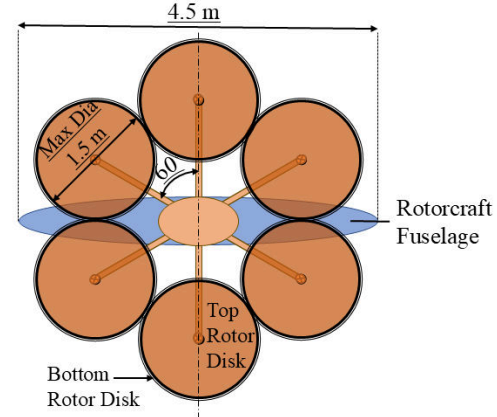


Fig. 7 Schematic illustration (not to scale) of the rotor hub positioning of coaxial hexarotor configuration with nonoverlapping equal-sized rotors in operational mode.

5. Definition of Parameters for Performance Analysis

Air density is a crucial factor in determining the initial power requirements for rotorcraft flight. On Mars, the average surface air density is around 0.02 kg/m^3 [18], but it can vary depending on factors such as location, altitude, and seasonal or diurnal changes. For the primary mission in SW Melas Chasma, located approximately 2 km below the datum, the Mars Climate Database (Version 6.1) [19] was used to estimate local air density at a flight time corresponding to the 11th hour of local solar time [20]. This analysis produced an average air density estimate of 0.016 kg/m^3 . The maximum allowable size of the aerobot is constrained by the aeroshell, with a diameter of 4.5 m and a height of roughly 2.2 m, limiting the design and assessment of Martian aerobot configurations. For the parametric performance study, the rotor disk size range spans from 5% to 100% of the aeroshell diameter (0.23 m to 4.5 m), except for tandem rotorcraft Case 1, which allows for a rotor diameter of up to 9 m.

On Mars, rotor tip speed and forward velocity are constrained to avoid transonic compression waves, with the local sound speed being around 240 m/s [14]. The advancing rotor blade tip speed is capped at about 0.75 Mach (180 m/s) to maintain lift on the retreating blade, which requires the advancing blade to move nearly three times faster than that of a helicopter on Earth [14]. This limits the recommended maximum forward speed to 60 m/s: one-third of the rotor tip speed and one-quarter of Mars' sound speed. Rotorcraft sizing focuses on range, cruising speed, takeoff, and ascent, assuming continuous high-power operation, while descent and landing are excluded for simplicity [14]. The flight profile (shown in Fig. 8) involves a 2-minute ascent to 1 km at 8.33 m/s, followed by a 3-minute, 10 km traverse at 55.56 m/s, ending with a vertical descent. Theoretical results align with experimental data when the advance ratio (the ratio

of forward speed to rotor tip speed) is between 0.1 and 0.3 [15].

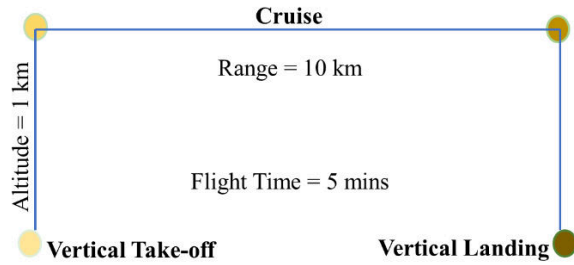


Fig. 8. Flight profile for the performance analysis

Table 2 outlines the parameters used in the power analysis for various rotorcraft configurations during forward flight, vertical climb, and hover. The aerobot's Maximum Take-Off Gross (MTOG) mass is fixed at 20

kg for the mission. A figure of merit (M) of 0.6 is assumed, within its typical range of 0.6 to 0.8 [14]. Additionally, based on a JPL technological projection, the battery's specific energy (E_{sb}), which is utilised to calculate the Battery Mass Fraction (BMF) for flights, is anticipated to be 230 Wh/kg [4].

Several additional parameters are crucial for forward flight analysis, including the frontal area of the aircraft body. The fuselage size, landing legs, and unfaired rotor hub remain constant across configurations. Helicopter drag data from D. Raymer [14] provide drag area (D/q) per unit frontal area, which is used to calculate component drag. The calculated total parasitic drag is then integrated into the conventional helicopter's Eq. (2) and, correspondingly, into the forward flight equations for other type of rotorcrafts. Although not precise, this method is sufficient for initial rotorcraft sizing until more detailed design analysis is possible.

Table 2 Parameters used in the forward flight, vertical climb and hover power analysis of various configurations of rotorcrafts

Parameter	Values			Unit
Mars Mean Air Density at SW Melas Basin	0.016			kg/m ³
Speed of Sound	240			m/s
Surface Gravity Acceleration on Mars	3.73			m/s ²
Aircraft MTOG Mass	20			kg
Aircraft MTOG Weight, W	74.60			N
Allowable Max Rotor Advancing Tip Mach Number, M_{at}	0.75			Mach
Air Speed at Max M_{at} on Mars	180			m/s
Traverse Range as per Flight Mission	10			km
Cruise Flight Endurance, E	3.0			min
Cruise Flight Velocity, V	55.56			m/s
Dynamic Pressure at the Cruise Velocity, q	24.69			Pa
Flight Altitude as per Flight Mission	1			km
Vertical Climb Endurance, E	2.00			min
Average Vertical Climb Velocity, V_{climb}	8.33			m/s
Rotor Blade Diameter, Blade D	0.23	to	9.0	m
Rotor Disk Area, S	0.04	to	63.6	m ²
Battery Specific Energy, E_{sb}	230.00			Wh/kg
Figure of Merit, M	0.6			
Mechanical efficiency factor, $\eta_{mechanical}$	0.97			
Fuselage downwash adjustment, f	1.06			
Helicopter Power ratio ($P_{tail\ rotor}/P_{rotor}$)	0.18			
Coaxial Power ratio ($P_{second\ rotor}/P_{main\ rotor}$)	1			
System efficiency battery to motor (η_{b2s})	0.9			
Propeller Efficiency, η_p	0.8			
Oswald Efficiency, e	0.5			
Parasitic Drag Area, D/q (Front Area x Drag data)	Front Area	Drag Data	D/q	
D/q Fuselage (radius 0.15 m)	7.1E-02	0.09	6.0E-03	m ²
D/q Tubular Landing 4 legs (0.002m x 0.03m, each)	2.4E-04	1.01	2.4E-04	m ²
D/q Unfaired Single Rotor Hub (0.005m x 0.003m)	1.5E-05	1.20	1.8E-05	m ²
Downwash Interference Drag Fuselage	7.1E-02	0.02	1.4E-03	m ²
Leakage & Protuberance Drag (15% Total D/q)				1.2E-03 m ²

6. RESULTS AND ANALYSIS

6.1. Hover and Vertical Climb Analysis

In Fig. 9, the power required for a conventional Martian helicopter is plotted against rotor disk diameter. As the diameter increases, the rotor disk area expands, resulting in a decrease in disk loading (W/S , weight divided by disk area). Lower disk loading reduces the battery power needed for hovering or ascent, improving power loading (W/P), which is the ratio of weight to engine power. However, larger rotors also increase weight, drag in forward flight, and the risk of shocks on the advancing blade [14], which are not addressed in this study.

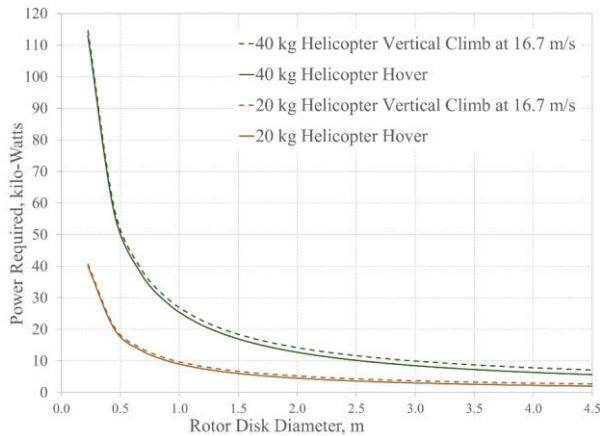


Fig. 9. Power Required vs Rotor Disk Diameter - 20 kg & 40 kg Martian Conventional Helicopter

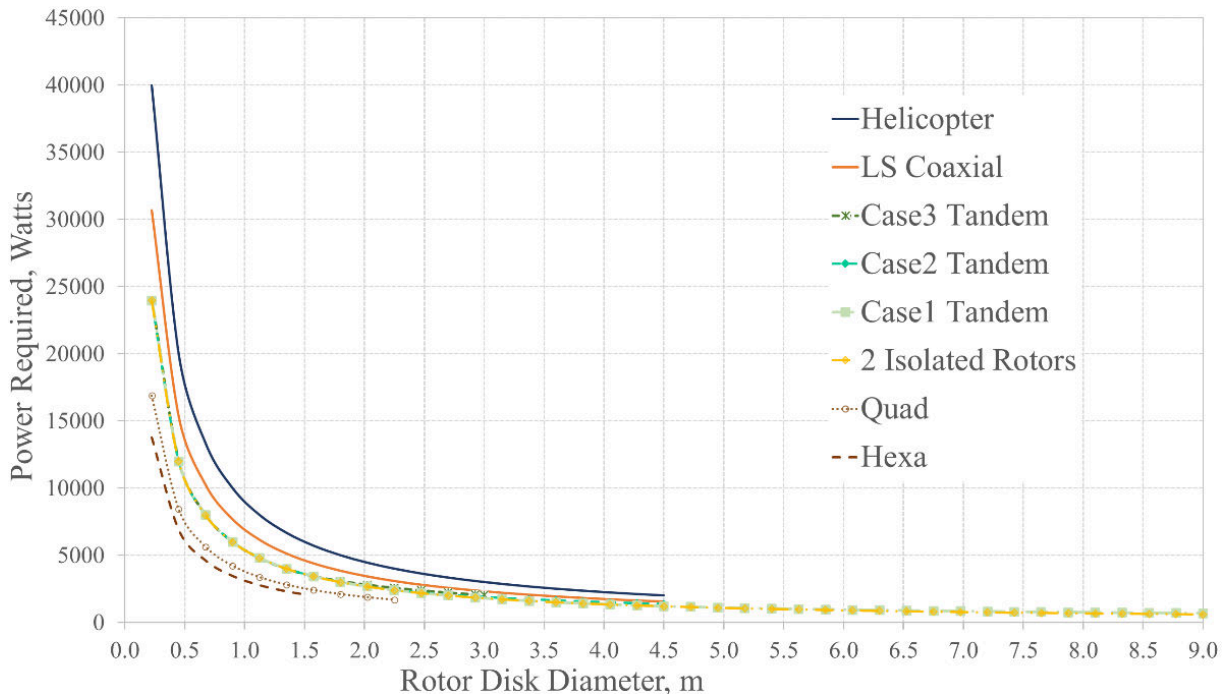


Fig. 10. Hover Power Required vs Rotor Disk Diameter – Comparison between various 20 kg rotorcraft configurations (Helicopter, Coaxial, Tandem Cases, 2 Isolated Rotors, Quadcopter, Hexa)

The graph shows that smaller rotors consume significantly more power, with power decreasing as rotor diameter increases (as also noted in [17]). Additionally, as the aerobot's mass increases, power demands for smaller rotors rise sharply, while larger rotors show minimal increases. This contrast is evident in the 40 kg vs. 20 kg helicopter comparison in Fig. 9. Vertical ascent requires slightly more power than hovering, a difference that grows as rotor size increases.

Fig. 10 and Fig. 11 display hover and vertical climb (at 8.33 m/s) power across various rotorcraft designs relative to rotor disk diameter. These configurations include conventional helicopters, coaxial rotorcraft, tandem rotorcraft, isolated rotors, quadcopters, and hexacopters. As discussed in the paper [12], all designs require more power for vertical climbing than hovering, with this gap increasing as rotor size grows. The conventional helicopter consumes the most power. Coaxial, tandem, quadcopter, and hexacopter configurations use significantly less power, particularly at smaller rotor sizes. For example, at a rotor diameter of 0.23 m, coaxial rotorcraft consumes 9,000 Watts less, tandem rotorcraft 16,000 Watts less, and quadcopters 23,000 Watts less compared to the conventional helicopter. At the maximum rotor diameter (4.5 m), power requirements for all designs remain below 2,500 Watts. Power needs decrease and stabilise with larger rotors, and differences between configurations become negligible for rotor sizes between 4.5 and 9 m, with quadcopters and hexacopters showing the lowest power consumption.

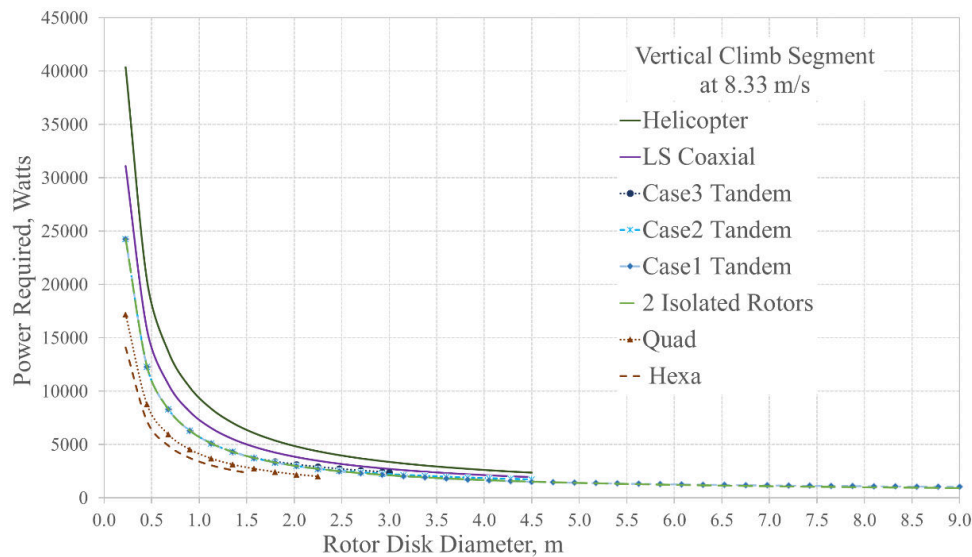


Fig. 11. Vertical Climb Power Required (at 8.33 m/s) vs Rotor Disk Diameter – Comparison between various 20 kg rotorcraft configurations (Helicopter, Coaxial, Tandem Cases, 2 Isolated Rotors, Quadcopter, Hexa)

6.2. Forward Flight Analysis

The power needed for both forward level flight and forward climb at a 20-degree incline was evaluated for each rotorcraft configuration, using a forward speed of 55.56 m/s. Fig. 12 displays how the power requirements for a Martian conventional helicopter vary as the rotor disk size increases. The graph shows that forward climb requires more power than level flight, but with smaller rotor disk diameters, power consumption for both modes is nearly the same. The difference becomes noticeable only when the rotor disk diameter exceeds 0.5 m. As the rotor disk size increases, the power reduction for forward climb is less significant than for level flight.

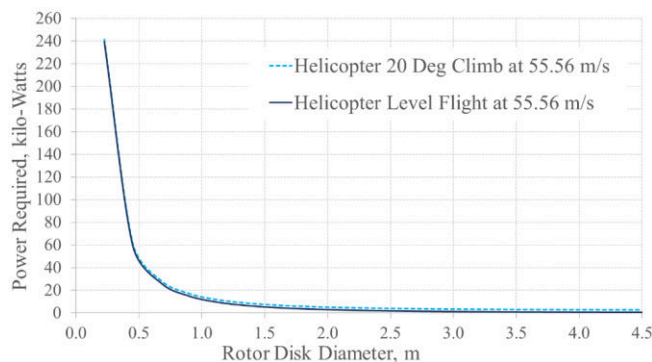


Fig. 12. Forward Flight Power Required (at 55.56 m/s) vs Rotor Disk Diameter - 20 kg Martian Conventional Helicopter

Fig. 13 highlights power demands for forward level flight across rotorcraft types with disk diameters up to 9 m. Conventional helicopters have the highest power demand at smaller rotor sizes, followed by coaxial, tandem, isolated rotors, quadcopters, and hexacopters. Power demand decreases rapidly with larger rotor disks, and beyond 2 m, the differences between configurations become minimal.

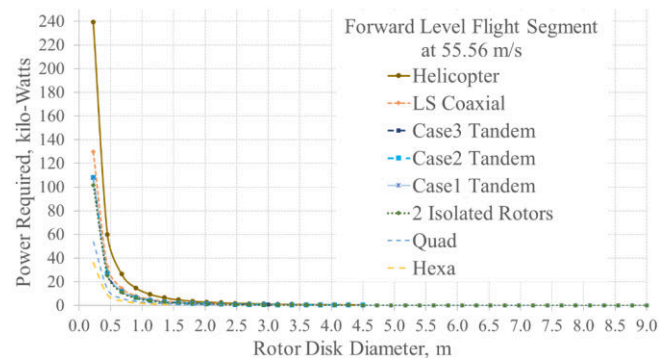


Fig. 13. Forward Level Flight Power Required (at 55.56 m/s) vs Rotor Disk Diameter - 20 kg Martian Various Rotorcraft Configurations

Fig. 14 focuses on the power variations for forward level and climb flights across different rotorcraft configurations, starting from a rotor disk diameter of 1 m. Notably, in tandem rotorcraft Case 1, the power required for forward climb exceeds a minimum value at a specific rotor size due to overlapping interference. This increase occurs when the rotors overlap, becoming apparent beyond a 4.5 m diameter for Case 1, as a result of the overlapping interference factor (K_{ov}) combined with the downwash factor (K_{dw}). Case 2 shows a similar trend but at a larger rotor diameter.

While climbing during forward flight requires more power than level flight, it remains more energy efficient than hovering ascent. Flying at lower altitudes benefits from ground effects, reducing energy loss and allowing optimal speed before ascent. To avoid air shocks at rotor tip speed, this analysis is conducted below the maximum allowable forward speed. Increasing forward speed or reducing the climb path angle could further lower power requirements for forward climb.

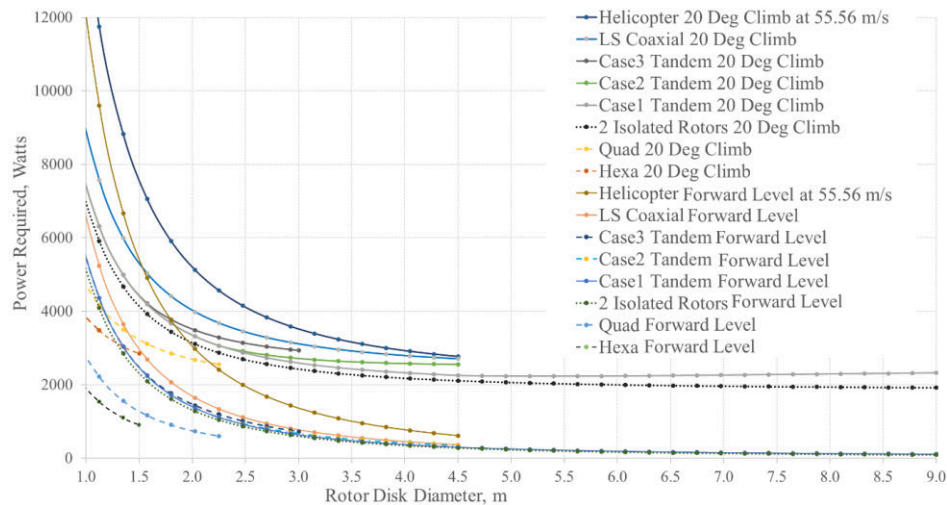


Fig. 14. Forward Flight Power Required (at 55.56 m/s) vs Rotor Disk Diameter (Rotor Diameter Limits – 1 m to 9m) – Comparison between various 20 kg rotorcraft configurations (Helicopter, Coaxial, Tandem Cases, 2 Isolated Rotors, Quadcopter, Hexa)

6.3. Efficient Rotor Configuration

Fig. 15 and Fig. 16 presents analytical graphs showing the power requirements for various rotorcraft configurations, including the conventional helicopter, LS (Large Separation) coaxial rotorcraft, three tandem rotorcraft cases, quadcopter, and hexacopter, in relation to rotor disk diameter for vertical climb and forward level flight, respectively. The graphs indicate that hexarotor configurations require the least power compared to single and dual-rotor designs, especially for rotor sizes up to 1.5 m. Based on the simplified formulas used, quadrotor and hexarotor operate independently without overlapping interference, except for the downwash caused by frontal rotors during forward flight. This downwash can be reduced in quadrotors by switching from a square to a diamond configuration, improving power efficiency [21]. When comparing single and dual-rotor systems, tandem rotorcraft have the lowest power consumption. Among the three tandem rotorcraft cases, Tandem Case 3 stands out for its simpler, lighter design and improved power efficiency, as highlighted in [17].

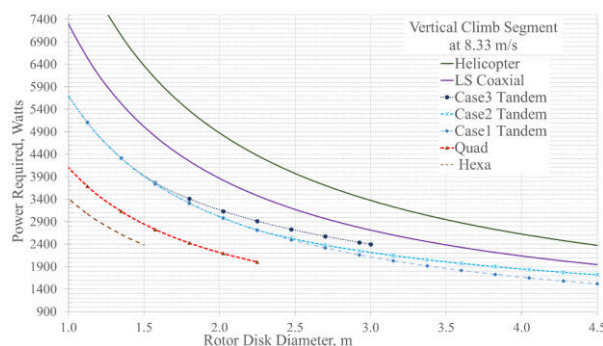


Fig. 15. Power Required (Vertical Climb at 8.33 m/s) vs Rotor Disk Diameter (Rotor Diameter Limits – 1 m to 4.5m) – Comparison between various 20 kg rotorcraft configurations

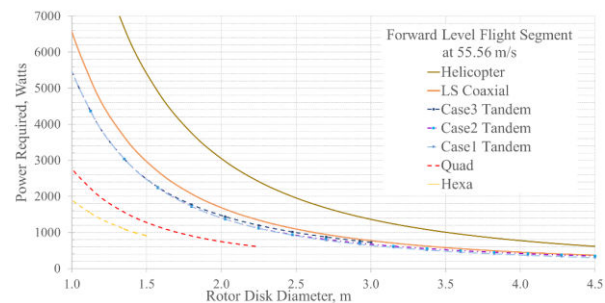


Fig. 16. Power Required (Forward Level at 55.56 m/s) vs Rotor Disk Diameter (Rotor Diameter Limits – 1 m to 4.5m) – Comparison between various 20 kg rotorcraft configurations

6.4. Coaxial Quadcopter and Coaxial Hexacopter Configurations

Once it is established the hexacopter and quadcopter configurations are among the most power efficient configurations, these can be further compared to coaxial quad and coaxial hexarotors. Fig. 17 graph compares power requirements for vertical climb across Quadrotor, Hexacopter, Coaxial Quadrotor, and Coaxial Hexacopter configurations. At smaller rotor diameters, the Quadrotor consumes the most power, while the Coaxial Hexacopter is the most efficient. As rotor diameter increases, power demands decrease, and differences between configurations narrow, though the Coaxial Hexacopter remains the most efficient overall. the Coaxial Quadrotor and Hexacopter configurations consume similar amounts of power up to a rotor disk diameter of 1.5 m. Beyond this diameter, the Coaxial Quadrotor begins to require slightly more power, while the Hexacopter continues to operate more efficiently, maintaining lower power consumption compared to the Coaxial Quad.

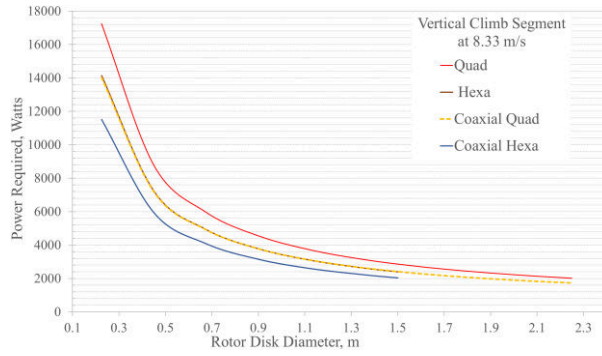


Fig. 17. Power Required (Vertical Climb at 8.33 m/s) vs Rotor Disk Diameter – Comparison between 20 kg coaxial and independent multi-rotor configurations

Fig. 18 illustrates the power required for forward level flight at 55.56 m/s across Quadrotor, Hexacopter, Coaxial Quadrotor, and Coaxial Hexacopter configurations as rotor disk diameter increases. Similar to previous analysis, power demand decreases significantly as rotor disk diameter increases, particularly between 0.1 and 0.5 m, due to reduced disk loading. Beyond 0.7 m, power requirements stabilise across all configurations. The Quad configuration exhibits the highest power consumption, while both coaxial quad and coaxial hexa configurations consistently require less power, especially at smaller diameters. This suggests that coaxial designs, with counter-rotating rotors, improve power efficiency and reduce drag, aligning well with the low-density Martian atmosphere.

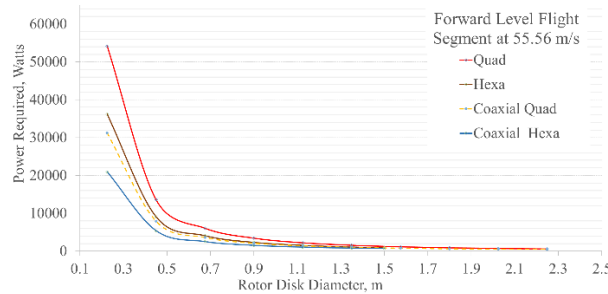


Fig. 18. Power Required (Forward Level at 55.56 m/s) vs Rotor Disk Diameter – Comparison between 20 kg coaxial and independent multi-rotor configurations

6.5. Comparative BMF Analysis of the Rotor Configurations

Fig. 19 illustrates the Battery Mass Fraction (BMF) for vertical climb by plotting power requirements against increasing rotor disk diameter for each rotorcraft

configuration. In calculating BMF using Eq. (11), factors such as a 2-minute runtime (E), an 8.33 m/s climb speed, and a constant total mass of 20 kg are considered.

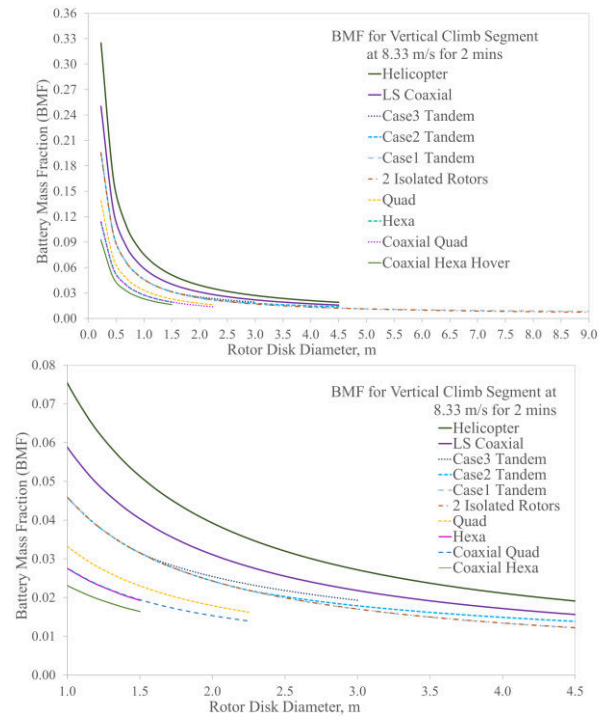


Fig. 19. Vertical Climb (at 8.33 m/s for 2 mins) BMF vs Rotor Disk Diameter - 20 kg Martian rotorcrafts. Top - BMF for rotor diameters from 0 to 9 m. Bottom - Close-up view, focusing on BMF for rotor diameters from 1 m to 4.5 m on the x-axis for clarity

The BMF trend mirrors that of Fig. 11, where higher power demands lead to higher BMF values, reflecting the required battery weight for vertical climb. Similarly, Fig. 20 shows the BMF trend for forward level flight, corresponding to the power requirements depicted in Fig. 13.

The battery mass is determined by multiplying the BMF by the aircraft's total mass. For example, a BMF of 0.05 results in a battery mass of 1 kg (0.05×20 kg). It is important to combine the BMF for each flight segment, as discussed in Section 3, to calculate the total BMF and overall battery mass needed for the mission. Additionally, the BMF calculated for flight does not account for battery mass required for avionics or electronic payloads, which would need separate calculations unless they use independent batteries.

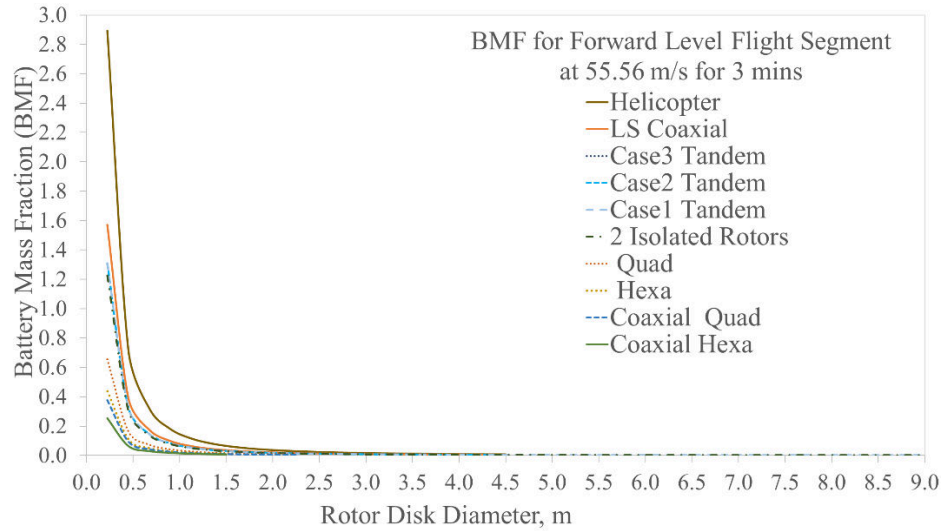


Fig. 20. Forward Levelled Flight (at 55.56 m/s for 3 mins) BMF vs Rotor Disk Diameter - 20 kg Martian rotorcrafts

7. Initial Sizing Application and Discussion

This parametric study establishes a theoretical baseline for estimating power consumption in various rotorcraft configurations under Martian conditions, using helicopter momentum theory. It explores both overlapping and non-overlapping rotors, aiming to identify the most power-efficient designs for aerobot missions, with a focus on simplicity to minimize the risk of malfunctions, as maintenance on Mars is not feasible. The analysis includes single, dual, and multi-rotor designs, with specific attention to coaxial multirotor configurations. Coaxial designs, which use two rotors on the same axis rotating in opposite directions, offer significant power efficiency due to their compact form, particularly at smaller rotor sizes. However, they introduce complexities in rotor wake interference and stability, which need to be carefully managed. These configurations are more efficient at reducing power requirements compared to single rotor systems, particularly in cases where space constraints are critical. For instance, in Case 1 of the Tandem rotorcraft with a 9 m rotor diameter, certain theoretically optimal configurations are excluded due to added complexity, such as the need for heavier materials, folding mechanisms, and control challenges. Similarly, smaller coaxial multirotor configurations are advantageous if they remain light and mechanically simple, as adding more motors and hubs increases the aircraft's weight and reduces payload capacity.

7.1. Applying Initial Sizing to Shortlisted Configuration

A hexacopter configuration with a 1.5 m rotor disk size is chosen for the initial sizing process. The power required for the vertical climb segment (at 8.33 m/s for 2 mins) is 2400 Watts, and for the cruise segment (at 55.56 m/s for 3 mins), it is 915 Watts. The corresponding

Battery Mass Fraction (BMF) values are 0.019 for vertical climb and 0.011 for cruise, resulting in a total BMF of 0.03. Using a predetermined aerobot mass of 20 kg, Eq. (11) calculates the required battery mass for the 5-minute flight mission, yielding 0.6 kg. With a science payload of 2 kg, Eq. (12) determines the aircraft's empty mass ($m_e = m_0 - m_b - m_{\text{payload}}$) as 17.4 kg, representing 87% of the total mass.

Similarly, for a coaxial hexacopter configuration with a 1.5 m rotor disk size is also analysed. The power required for the vertical climb segment is 2040 Watts, and for the cruise segment, it is 700 Watts. The corresponding Battery Mass Fraction (BMF) values are 0.016 for vertical climb and 0.008 for cruise, resulting in a total BMF of 0.024 which equals 0.48 kg battery mass. This results in 17.52 kg empty mass, representing 87.6% of the total mass.

7.1.1. Insights from Comparison

The initial sizing results for both the hexacopter and coaxial hexacopter configurations provide a strong foundation for further design exploration. The coaxial hexacopter shows a lower power requirement for both vertical climb and forward flight compared to the hexacopter, making it more flight efficient. Despite these differences, the total Battery Mass Fraction (BMF) remains quite similar for both configurations with medium to large rotor sizes, indicating that either option would require nearly the similar battery mass for short range/endurance mission.

The hexacopter's slight edge in carrying lesser number of motors and related propulsion system, make it preferable for short missions, whereas the coaxial hexacopter's better performance overall could prove advantageous for long range missions. Both configurations, with empty masses around 87% of the total aerobot mass, offer flexibility for payloads and

system integration, providing a good starting point for further analysis.

7.2. Future Work

The analysis highlights the importance of balancing the power demands for different flight segments to optimise overall mission performance. Further refinement of these designs can be achieved through iterative adjustments, especially in rotor size and system efficiency. The initial empty mass estimates include the rotorcraft's materials and components, which, in early stages, can be sourced from Commercially Off-The-Shelf (COTS) parts or similar aircraft. As the design progresses, adjustments to these components can refine the rotorcraft sizing and further develop the preliminary design phase.

This framework serves as a foundational step in validating Martian rotorcraft designs, recognizing that testing in Mars-like environment is costly and logistically challenging. Future studies will refine the estimates using advanced modelling techniques such as Computational Fluid Dynamics (CFD) and vortex wake models. These techniques will focus on improving rotor efficiency at high advance ratios, where compressibility effects become more prominent, playing a critical role in enhancing the reliability and performance of rotorcraft for Mars exploration.

8. Conclusion

The development of rotorcraft for Martian exploration, highlighted by NASA's Ingenuity helicopter, has opened new possibilities for planetary aerial missions. This study systematically examines a range of rotorcraft configurations, including conventional helicopters, coaxial designs, tandem rotors, quadcopters, and hexacopters, under Martian atmospheric conditions. Using simplified momentum theory, the analysis identifies hexacopters and coaxial hexacopters as the most efficient configurations, offering an optimal balance of low power consumption, higher payload capacity, and enhanced flight stability. These designs are particularly suitable for Martian exploration, providing a more efficient alternative to conventional rotorcraft while accommodating mission-specific constraints such as aeroshell size. The application of the Battery Mass Fraction (BMF) methodology further supports the practicality of electric-powered rotorcraft for Mars, showing that these designs are capable of meeting the energy demands of extended operations. Overall, this study contributes a robust framework for selecting and designing rotorcraft configurations capable of supporting the next generation of Martian exploration missions.

References

- [1] Hassanalani, M., Rice, D., & Abdelkefi, A. Evolution of space drones for planetary exploration:

A review. *Progress in Aerospace Sciences*, 97, 2018. 61–105.

- <https://doi.org/10.1016/J.PAEROSCI.2018.01.003>
- [2] NASA. Overview | Mars – NASA Solar System Exploration. Retrieved April 22, 2024, from <https://solarsystem.nasa.gov/planets/mars/overview/>
- [3] Radotich, M., Withrow-Maser, S., deSouza, Z., Gelhar, S., & Gallagher, H. (2021, January). A study of past, present, and future Mars rotorcraft. In 9th Biennial Autonomous VTOL Technical Meeting.
- [4] Johnson, W., Withrow-Maser, S., Young, L., Malpica, C., Koning, W. J. F., Kuang, W., Fehler, M., Tuano, A., Chan, A., Datta, A., Chi, C., Lumba, R., Escobar, D., Balaram, J., Tzanetos, T., & Fjaer Grip, H. (2020). Mars Science Helicopter Conceptual Design. <http://www.sti.nasa.gov>
- [5] NASA. (2023) Mars Helicopter - NASA Mars. Retrieved April 22, 2024, from <https://mars.nasa.gov/technology/helicopter/#Flight-Log>
- [6] Young, L. A., Chen, R. T. N., Aiken, E. W., Briggs, G. A., "Design Opportunities and Challenges in the Development of Vertical Lift Planetary Aerial Vehicles," Proceedings of the American Helicopter Society International Vertical Lift Aircraft Design Specialist's Meeting, January 2000.
- [7] Underwood, C., & Collins, N. (2017). Design and Control of a Y-4 Tilt-Rotor VTOL Aerobot for Flight on Mars. Proceedings of the 68th International Astronautical Congress (IAC), 25–29. <https://openresearch.surrey.ac.uk/esploro/outputs/conferencePresentation/Design-and-Control-of-a-Y-4-Tilt-Rotor-VTOL-Aerobot-for-Flight-on-Mars/99511131102346>
- [8] Aguirre, J., Casado, V., Chamie, N., & Zha, G. (2007). Mars Intelligent Reconnaissance Aerial and Ground Explorer (MIRAGE) AIAA 2007-244, Reno, Nevada. <https://doi.org/10.2514/6.2007-244>
- [9] Forshaw, J., & Lappas, V. (2012). Architecture and Systems Design of a Reusable Martian Twin Rotor Tailsitter. *Acta Astronautica*, 80(0), 166–180. <https://doi.org/10.1016/J.ACTAASTRO.2012.05.008>
- [10] RM Zubrin. (2012). The Mars Gashopper. *Concepts and Approaches for Mars 2012*. June 12-14, 2012 in Houston, Texas. <https://ui.adsabs.harvard.edu/abs/2012LPICo1679.4069Z/abstract>
- [11] Fathepure, M., Booker, A. L., Abouzahr, O., Wang, N., & Tikalsy, D. (2021). Design and Construction of an Inflatable-Winged VTOL Mars Electric Flyer. In AIAA AVIATION 2021 FORUM (p. 2578) <https://doi.org/10.2514/6.2021-2578>
- [12] Youhanna V, Felicetti L & Ignatyev D (2024). Preliminary Design Exploration of Prospective

- Multicopter Aerobots for Mars. In: 34th Congress of the International Council of the Aeronautical Sciences (ICAS 2024), Florence, Italy, September 9-13, 2024.
- [13] Youhanna V, Felicetti L & Ignatyev D (2024). Preliminary Investigation into Future Martian Multicopter Configurations. In: Vertical Flight Society's 80th Annual Forum & Technology Display, Montréal, Québec, Canada, May 7-9, 2024. <https://doi.org/10.4050/F-0080-2024-1266>
- [14] D. Raymer. *Aircraft design: A conceptual approach*, 6. Ed., AIAA education series, Reston, Va., 2018, Chaps. 20.11, 21.3.
- [15] Leishman, J. Gordon. *Principles of Helicopter Aerodynamics*, 2nd Ed., United Kingdom, Cambridge University Press, 2006. Chaps. 2.15, 5.5.11.
- [16] Johnson, W. *Rotorcraft Aeromechanics*. Cambridge University Press. 2013. Chaps. 4.6, 5.3. <https://doi.org/10.1017/CBO9781139235655>
- [17] Youhanna V, Felicetti L & Ignatyev D (2023). Conceptual Design Study based on Defined Parameters for Next Generation Martian Rotorcrafts. In: IEEE Aeroconf 2024, Montana, US, 2-9 March 2024. DOI: <https://doi.org/10.1109/AERO58975.2024.1052144>
- [1](#)
- [18] NASA. (2023) Mars Fact Sheet. *NASA Goddard Space Flight Center*. Retrieved April 22, 2024, from <https://nssdc.gsfc.nasa.gov/planetary/factsheet/marsfact.html>
- [19] Millour, E., Forget, F., Spiga, A., Pierron, T., Bierjon, A., Montabone, L., Vals, M., Lefèvre, F., Chaufray, J.-Y., Lopez-Valverde, M., Gonzalez-Galindo, F., Lewis, S., Read, P., Desjean, M.-C., and Cipriani, F. and the MCD Team: The Mars Climate Database (Version 6.1), Europlanet Science Congress 2022, Granada, Spain, 18–23 Sep 2022, EPSC2022-786, <https://doi.org/10.5194/epsc2022-786>
- [20] Balaram, J., Aung, M. & Golombek, M.P. The Ingenuity Helicopter on the Perseverance Rover. *Space Sci Rev* 217, 56 (2021). <https://doi.org/10.1007/s11214-021-00815-w>
- [21] Han, D., & Barakos, G. N. (2020). Aerodynamic interference model for multirotors in forward flight. *Journal of Aircraft*, 57(6), 1220–1223. https://doi.org/10.2514/1.C035978/ASSET/IMAGE_S/LARGE/FIGURE3.JPEG



DSPACE

<https://dspace.org/>

Systematic selection of the next generation Martian rotorcraft configurations

Youhanna, Vishal; Felicetti, Leonard; Ignatyev, Dmitry

2024-10-16

International Astronautical Federation (IAF)

<https://iafastro.directory/iac/paper/id/85796/summary/>

Youhanna V, Felicetti L, Ignatyev D. (2024) Systematic selection of the next generation Martian rotorcraft configurations. In: Proceedings of the 75th International Astronautical Congress IAC-2024, 14-18 Oct 2024, Milan, Italy, Paper number 85796