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Parametric Analysis of Rotary VTOL Aerobot Design Configurations to Fly on Titan

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Abstract

The exploration of Titan, Saturn's largest moon, presents significant aerodynamic challenges due to its dense atmosphere and low gravity, necessitating specialised rotorcraft designs. This study conducts a parametric analysis of multiple rotary Vertical Takeoff and Landing (VTOL) aerobot configurations, including conventional helicopters, coaxial systems, tandem rotorcraft, quadcopters, and hexacopters, with a focus on performance in Titan's environment. Using simplified momentum theory, the power consumption and operational efficiency of these rotorcraft are evaluated across key flight phases such as vertical climb, hover, and forward flight. The analysis highlights that hexacopter configurations are the most power-efficient during vertical ascent and hover for smaller rotor diameters, whereas conventional helicopter designs excel in forward flight for larger rotor sizes. The study also utilises Battery Mass Fraction (BMF) calculations to assess the energy requirements for various flight segments, offering valuable insights into the energy-efficient design of rotorcraft for Titan exploration. This research establishes a foundational framework for optimising rotorcraft design in extraterrestrial environments, providing critical data for future missions aimed at exploring Titan's surface and atmosphere.

Keywords: Titanian Aerial Drones, Planetary UAV, Rotorcraft 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 Titan 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 Titan (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-leveled 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
$\eta_{mechanical}$	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
EDL - Entry, Descent, and Landing
NASA - National Aeronautics and Space Administration
RTG - Radioisotope Thermoelectric Generator
UAV - Unmanned Aerial Vehicle
VTOL - Vertical Take-off and Landing

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1. Introduction

Titan, Saturn's moon, shares similarities with Earth and Mars in various fields like hydrology, sedimentology, and weather, offering valuable insights into universal processes and the formation of life. Huygens probe is the only spacecraft that explored the surface of Titan (2005), but some variants of unmanned aerial vehicles such as hot air balloons, winged and rotary-wing aircrafts have been proposed by researchers as the most attractive choice for some obvious reasons [1]. Titan offers a few aerodynamic advantages for rotorcraft design, mainly because its atmospheric density is about 4.4 times higher, and the surface gravity acceleration is about 7 times lower than that of Earth [2]. Moreover, the kinematic viscosity is 12 times lower, leading the rotors to operate comparatively at higher Reynolds numbers on Titan. This implies that the power required to fly a vehicle of a given mass on Titan will be significantly lower than on Earth. However, the speed of sound is 1.7 times lower on Titan, meaning if the rotors are spun at a higher rate the blades' tip speed can reach transonic Mach number quickly, though this can be considered as not to be the driving factor in the design. Operating on Titan presents some challenges due to its cryogenic conditions, which impose significant constraints on materials, lubricants, and vibration isolation for operations. The low solar flux on Titan makes radioisotope power systems the most viable option for long-term spacecraft, albeit with added weight.

1.1. Literature

In 2008, NASA and the European Space Agency (ESA) developed an initial concept to explore Titan using a Montgolfiere-style balloon as a flagship mission, with a pathfinder to study Titan's surface [1]. One proposal, developed by Global Aerospace Corporation in 2016, involved the Titan Winged Aerobot, which combined a helium-filled balloon with a glider to enable ascent and entry without propulsion or control surfaces, leveraging the efficiency of slower helium diffusion in Titan's atmosphere [3]. Additionally, in 2012, another UAV concept, the Aerial Vehicle for In-situ and Airborne Titan Reconnaissance (AVIATR), was put forward, focusing on the study of Titan's geology, hydrology, and lower atmosphere [3] [1]. Another concept called, Never-EVER Land 2 (NEL2), involves an inflatable-winged UAV designed for long-endurance atmospheric exploration on Titan, offering compact stowage and enhanced durability in its dense atmosphere [4]. Over time, the concept has shifted toward a rotary drone-based approach, leading to the Dragonfly mission proposal in February 2017 by NASA's Johns Hopkins University Applied Physics Laboratory [1] [2]. Meanwhile, the original balloon idea continued to inspire research. The Dragonfly concept features an eight-rotor vertical takeoff and landing (VTOL) design, capable of exploring Titan's surface and atmosphere. It is bound to be launched in June 2028 [5].

1.2. Proposed Study

The next generation of Titanian rotorcrafts face more ambitious requirements, necessitating the development of new designs within practical constraints. It may be necessary to package a large rotorcraft with a smaller ground spacecraft, transport it separately, or use an innovative folding mechanism within the aeroshell to accommodate it. A comprehensive parametric analysis of rotorcraft designs is necessary to determine the overall benefits of larger or winged Titanian rotorcraft and propose suitable configurations for further research. In this paper performance analysis of various battery-electric rotorcraft configurations with single, and multi rotors is conducted within defined parameters, including initial sizing estimation.

The research article outlines a generalised methodology (section 2) based on simplified momentum theory for calculating the flight power of various Titanian rotorcraft configurations, including those with overlapping rotors. Additionally, a method for initial sizing of battery-electric aircraft (section 3) estimates required battery mass based on flight power, aiding in determining the total rotorcraft mass. Study cases for parametric analysis (section 4) are established, involving single conventional helicopters, coaxial rotorcraft, three tandem rotorcraft configurations, quadcopter and hexacopter configuration. Then all the parameters are defined and summarised (section 5). Results and analysis (section 6) focus on power demands for hover, vertical climb, and forward flight across these configurations, informing the identification of the most power-efficient designs. However, theoretical optima may introduce complexities due to design constraints, necessitating careful configuration selection and refinement, as discussed in the penultimate section 7.

2. Power Requirement Analysis Methodology for Rotorcraft

Fig. 1 illustrates six rotorcraft configurations, including single, dual, quad, and hexarotor designs. Conventional rotary-wing aircraft typically is equipped with a single main rotor atop the fuselage to generate both lift and thrust, with a tail rotor used to counteract torque. Coaxial rotorcraft, featuring two rotors on the same axis rotating in opposite directions, eliminate the need for a tail rotor and provide greater stability and operational efficiency. Tandem rotor designs, with two main rotors positioned sequentially along the fuselage, offer increased lift capacity and enhanced payload potential. Side-by-side rotorcraft, such as tiltrotors and tiltwings, incorporate multiple rotors placed closely together, allowing operational flexibility in both hover and forward flight modes. Quadcopters, a multicopter

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subtype with four rotors, are noted for their simplicity, stability, and ease of control, making them a preferred choice for UAVs and drones. Hexacopters, equipped with six rotors, provide improved stability and greater payload capacity compared to quadcopters, making them particularly suited for more demanding applications requiring higher lift and redundancy. These various rotorcraft configurations each have their unique characteristics and aerodynamic considerations, and the choice between them depends on specific mission requirements and design objectives.

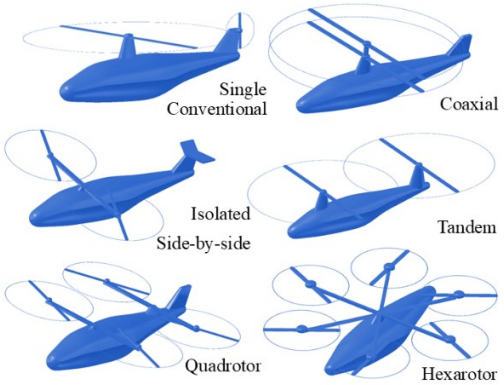


Fig. 1. Rotorcraft Configurations Illustration

2.1. *Conventional Rotorcraft*

The operational success of a reusable aerobot on Titan fundamentally depends on its ability to perform vertical takeoff and landing (VTOL), as conventional runways are absent. This capability is entirely reliant on the effectiveness of the rotor propulsion system. Momentum theory is applied to estimate rotor power consumption during various flight phases, including hover, vertical climb, and forward flight. Within this theoretical framework, rotor blades are modelled as actuator disks with infinitesimal thickness and a defined disk area (S). The assumptions include uniform airflow distribution across the rotor disc and instantaneous energy transfer, while factors like airfoil profile drag losses, tip losses, and residual rotational velocities are disregarded. 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 ($M=P_{ideal}/P_{actual}$) 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 [6].

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

The total power estimate 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 [6]. V_{Climb} is vertical climb speed (=0 for hover) and f is the adjustment for downwash on the fuselage (typically f=1.03). $\eta_{mechanical}$ is mechanical losses adjustment due to driving of the tail rotor, typically of the value 0.97.

During forward flight, the rotor assumes characteristics similar to those of a circular wing, with an aspect ratio of $4/\pi$. Empirical data indicates an equivalent Oswald efficiency factor (e) ranging between 0.5 and 0.8 for such wings [6]. The Oswald efficiency factor is defined at a given lift coefficient as the ratio between the wing's induced drag coefficient and that of an elliptical wing with the same aspect ratio. Parasitic drag is expressed through the 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 [6].

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

In the equation, $W\sin(\gamma)$ represents the climb component which depends on the climb path angle γ (0 for leveled flight). The rotor serves a dual purpose during forward flight, acting as a propeller to generate thrust while also maintaining lift. Therefore, the propellor efficiency factor η_p is added to the calculation to give a reasonable estimate of the rotor in forward thrust.

2.2. *Coaxial Rotorcraft*

In a conventional helicopter, the tail rotor counteracts the torque generated by the main rotor by producing an opposing thrust. An alternative way to manage this torque is to replace the tail rotor with an additional rotor of the same size, rotating in the opposite direction, which also provides additional lift. This approach is exemplified in coaxial rotorcraft, where two rotors are mounted to the same shaft within a complex hub structure. However, the proximity of the rotors can result in some lift loss due to airflow interference.

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Theoretically, when the two rotors perfectly overlap, which is a 100 percent overlapping case with a zero vertical gap, the overlapping interference factor (K_{ov}) increases power consumption by approximately $\sqrt{2}$ or about a 41% increase compared to two isolated rotors that are not influenced by the wake of the upper rotor [7]. In cases where there is no vertical separation between the rotors in a coaxial configuration, it is referred to as an equivalent single rotor system. This equivalent single rotor is analogous to a system comprising smaller twin rotors with identical total thrust and total projected area (disk loading), as they share similar rotor solidity [8]. Disk loading is the ratio of the total weight of the helicopter to the area of the rotor disk (W/S), and rotor solidity is the ratio of total blade area to total disk area.

In practical applications, coaxial rotors are usually spaced apart vertically. As the vertical distance increases, the wake from the upper rotor affects less of the lower rotor, reducing the overlapping interference factor (K_{ov}). For example, with a large separation (LS), typically around 10% of the rotor diameter, the K_{ov} becomes 1.281 when assuming uniform disk loading [7],[8]. Consequently, Eq.(1), to calculate vertical climb and hover power for a coaxial rotor system with two equal-sized rotors equally sharing the total rotorcraft weight (thrust), is adjusted by multiplying it by the overlapping interference factor (K_{ov}) to form Eq. (3). Similarly, Eq. (2) for the forward flight of a conventional helicopter is adjusted to form Eq. (4) for a coaxial helicopter [7].

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

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

In this setup, there is no tail rotor, but instead, a second rotor is used. Consequently, the ratio of power required by the two equal-sized rotors ($P_{second\ rotor}/P_{main\ rotor}$) becomes equal to 1.

2.3. *Isolated Rotors: rotorcraft having non-overlapping rotors*

The K_{ov} factor, which represents the degree of overlapping interference between equally sized rotors, decreases from $\sqrt{2}$ to 1 as the shared rotor area shifts from fully overlapping to no overlap within the same plane. When there is zero overlap, the rotors essentially operate as isolated units. However, even with vertical rotor separation and no overlap, residual interference, whether advantageous or detrimental, may still occur, though it is typically negligible in preliminary analyses [7],[8]. A subtype of side-by-side rotors, known as transverse rotorcraft (e.g., tiltrotors and tiltwings), features smaller rotors mounted horizontally on the tips of wings or an extended fuselage frame. These rotors are typically positioned to avoid overlap and thus behave more like isolated rotors. During cruise flight, they transition into functioning as forward propellers. For configurations involving multiple non-overlapping rotors, such as side-by-side rotors or quadrotors, Equations (1) and (2) can be adapted to account for a multirotor system comprising 'N' equal-sized rotors. In such an arrangement, the total thrust required for the rotorcraft is evenly distributed among all the rotors, expressed in Equations (5) and (6).

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

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

In configurations with rotors aligned in front of one another, an additional downwash factor is produced by the front rotor onto the rear rotor during forward flight. To ensure accurate power estimation, this downwash effect must be accounted for in the power calculations of the rear rotor(s) [7], as detailed in the subsequent subsection on tandem configurations. The updated equation substitutes [N] for the segment $[1 + (P_{tail\ rotor}/P_{main\ rotor})]$ to indicate the number of rotors involved, as there is no tail rotor in this design but all equal-sized rotors.

2.4. *Rotorcraft with Partial Overlapping Rotors (e.g., Tandem Rotorcraft)*

Tandem rotorcraft configurations consist of two equally sized rotors positioned longitudinally along the fuselage, with one rotor placed ahead of the other. Theoretical analysis of this configuration is similar to coaxial rotors, where the degree of rotor disk overlap is determined by the horizontal distance between them. Maximum tandem overlap occurs when one rotor's blade tip touches the hub center of the other rotor. As a result, the initial power analysis for vertical climb or hover in tandem rotors follows the same approach used for coaxial

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rotors, as detailed in Eq. (3). However, the calculation of the overlapping interference factor (K_{ov}) in a tandem configuration is influenced by the ratio (d/D), which represents the horizontal distance (d) between the two rotor axes to the rotor diameter (D). When the rotors are in the same plane (i.e., no vertical gap between rotors), K_{ov} can be approximated using Eq. (7) [7].

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

In settings where rotors are positioned in distinct planes and the lower rotor functions within the contracting wake of the upper rotor, the calculation of the overlapping area requires numerical integration to determine a solution for K_{ov} [7]. Similarly, side-by-side rotor configurations with overlapping rotors can use a comparable approach to estimate overall power demand.

For tandem rotorcraft, calculating the power required for forward flight must account for the downwash effect experienced by the rear rotor due to the front rotor. This downwash, which affects power loss, must be quantified and included in the calculations. For initial theoretical analysis, this downwash (dw) is assumed to be the maximum value of the overlapping interference factor (max $K_{ov} = K_{dw}$) [7], which is 1.134 when calculated using Eq. (7) at maximum tandem overlap. Thus, total power (P) required for forward flight is represented by Eq. (8) [7].

This preliminary analysis assumes that both rotors produce equal thrust, resulting in equal power consumption. Hence, this expression is represented in Eq.(9), where the total power for a forward flight of 2 isolated rotors (calculated using Eq. (6)) is divided by two and subsequently multiplied by the downwash factor. If overlap between the rotors is present, the overlapping interference factor (K_{ov}) is also included to refine the total forward power calculation.

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

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

In cases where there is no overlap between the rotors, for instance in non-overlapping same-plane tandem rotor setups, the K_{ov} is either excluded or its value is fixed at 1 in equations (3) and (9). This adjustment is essential as the application of Eq. (7) for K_{ov} estimation becomes invalid in the absence of rotor overlap.

3. Initial Sizing Methods for Battery-Electric Aircraft

At maximum take-off weight, the total mass of an aircraft is composed of its empty mass, payload, and fuel components. In fuel-powered aircraft, this mass decreases during flight due to fuel consumption across different flight stages: taxiing, take-off, ascent, cruising, and descent. This reduction in mass affects both the aircraft's performance and its drag characteristics, requiring detailed calculations for each flight phase during initial sizing. However, electric aircraft experience no change in battery mass throughout the flight, eliminating the need for such segment-by-segment integration. Instead, the fuel component of total aircraft mass is substituted with the mass of the battery (m_b). The required battery mass for each mission segment is determined using Eq. (10), which expresses it as a ratio of the battery mass to the total aircraft mass (m_b/m_0), known as the Battery Mass Fraction (BMF) [6].

$$BMF = \frac{m_b}{m_0} = \frac{W_b}{W_0} = \frac{EP_{used}}{E_{sb}\eta_{b2s}m} \quad (10)$$

The equation takes into account factors such as the known run-time endurance (E) and the power consumption during different flight segments, including 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 cumulative aircraft Battery Mass Fraction (BMF) is then determined by summing the individual BMFs for each flight segment [6]. This methodology enables a comprehensive assessment of the battery mass required for the various stages of the aircraft's mission. Equation (11) is used to determine the total aircraft take-off mass (m_0), by showing that it is equal to the empty mass, the battery mass, and the payload mass [6].

$$m_0 = m_e + m_b + m_{payload} \quad (11)$$

Eq. (11) undergoes adjustment to formulate Eq. (12) for battery electric aircraft sizing [6].

$$m_0 = \frac{m_{payload}}{1 - BMF_{total} - \frac{m_e}{m_0}} \quad (12)$$

This modification involves factoring in the total Battery Mass Fraction and the ratio of empty mass (m_e) to total mass [6]. For unmanned aircraft, the payload typically consists of instruments or items for delivery. Conversely, m_e encompasses all components excluding the payload or operational batteries, encompassing the propulsion system, aircraft structure, avionics, navigation equipment, and other critical systems.

A preliminary estimation of aircraft parameters can be made by utilising the initial sizing equation, drawing upon factors like the empty mass ratio, payload mass and the calculated Battery Mass Fraction (BMF) requirement. These inputs allow for calculating the total mass of the aircraft. Alternatively, known parameters can be used to estimate unknowns, such as total mass or empty mass, and subsequently determine the required BMF to assess payload capacity. This process often requires iterative

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calculations and adjustments until a reliable estimate is achieved, supporting the early stages of design exploration.

4. Definition of Rotorcraft Configurations

4.1. Tandem Rotorcraft Cases

The layout of tandem rotorcraft can differ depending on the longitudinal arrangement of the rotors atop the fuselage. For the power consumption analysis, three specific scenarios are considered, based on the structural limits of the aeroshell (similar to the case studies performed on Martian Aerobot in [9]). The two equal-sized rotors are positioned at equal displacements from the mid-point, resulting in displacements of 2.25 m, 1.125 m, and 0.75 m for Cases 1, 2, and 3, respectively, assuming the fuselage length equals the size of the maximum aeroshell, which is 4.5 m. Fig. 2 illustrates the positioning of the rotors on the aerobot fuselage within an aeroshell dome. These configurations represent extreme cases for parametric analysis, as depicted in Fig. 3. In Case 1, foldable rotors are positioned at the ends of the fuselage, allowing for a maximum diameter of 9 m. Case 3 places the rotors in a configuration where they can reach a maximum diameter of 3 m, fitting within the aeroshell boundary. Case 2 lies between these extremes, with rotors capable of reaching a maximum diameter of 4.5 m. It is important to note that, in practical applications, rotor blades must be spaced away from the inner walls of the aeroshell and rotor hubs. However, this theoretical study does not account for such clearances.

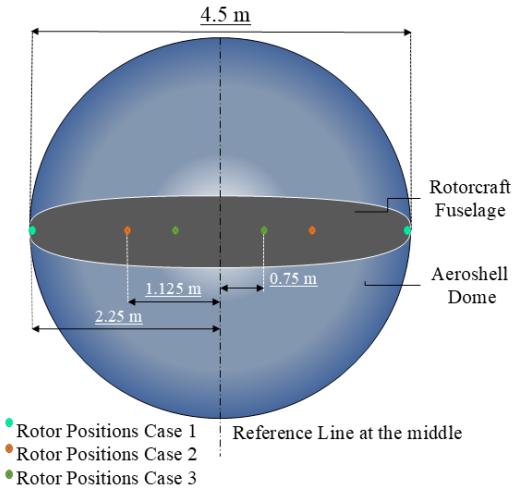


Fig. 2. Diagram of the positioning of rotor hubs of tandem rotorcraft Cases 1, 2, and 3, on the fuselage placed inside an aeroshell. (Not to scale)

Case 1 necessitates a folding mechanism, and possibly an articulated rotor hub system, to ensure the rotors fit within the aeroshell for storage. Similarly, in Case 2, if the rotor diameter exceeds 2.25 m, identical folding mechanisms and potentially an articulated rotor hub system would be required. In contrast, Case 3 allows for the use of a rigid rotor hub system without the need for linkages. Table 1 provides an overview of the parameters established for each of the three tandem rotorcraft cases, as well as the quadcopter and hexacopter study cases, which will be discussed next.

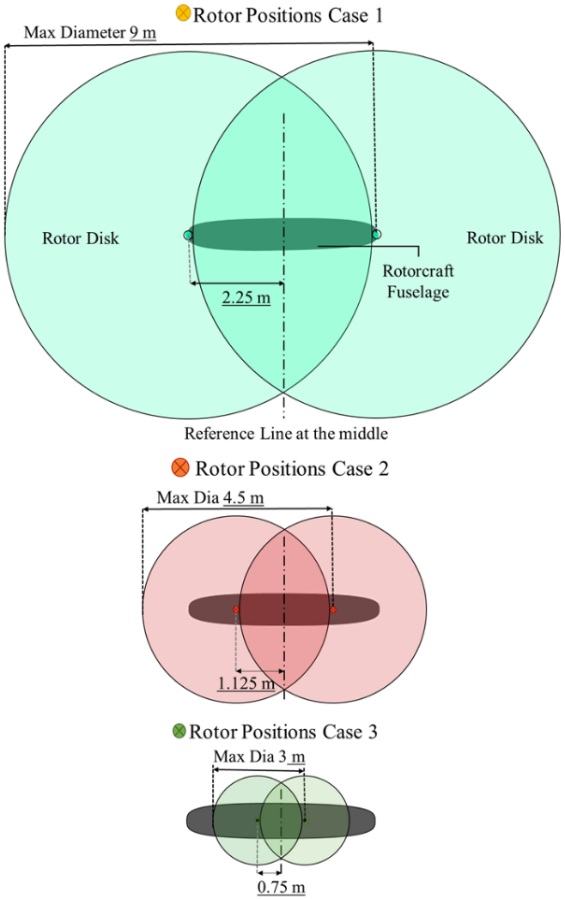


Fig. 3. Schematic illustration of the rotor positioning of tandem rotorcraft Cases 1, 2, and 3 in operational mode. (Not to scale)

4.2. Quadcopter and Hexacopter Cases

In both quadcopter and hexacopter configurations, the placement of rotor hub support frames along the fuselage can vary, similarly to the tandem rotorcraft configurations previously mentioned. Since these multicopters typically use non-overlapping rotors, only this layout is examined in the study. The quadcopter design positions two equal-sized, non-overlapping rotors 1.125 m from the midpoint on each side, as illustrated in Fig. 4. For the hexacopter, six equal-sized, non-overlapping rotors are arranged 1.5 m from the centre, spaced 60° apart, as shown in Fig. 5. These configurations serve as the basis for parametric analysis.

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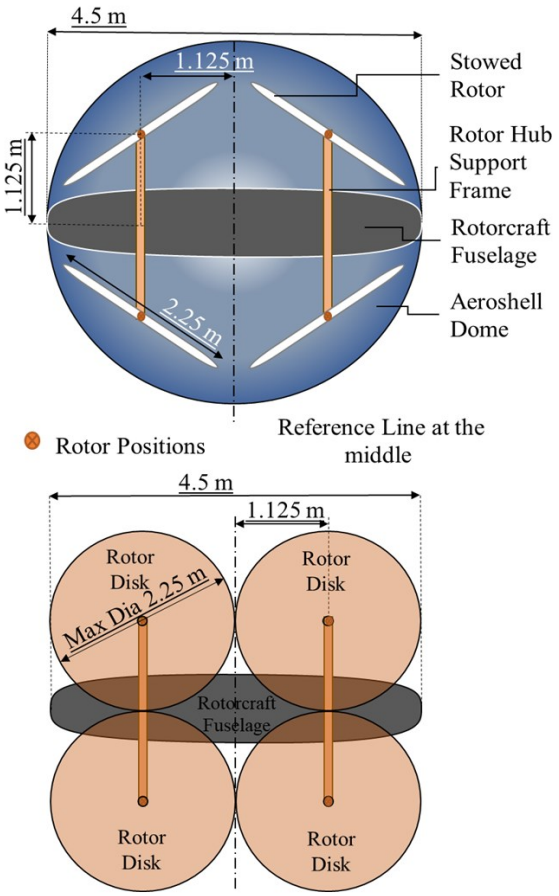


Fig. 4. Schematic illustration (not to scale) of the rotor hub positioning of Quadrotor configuration with nonoverlapping equal-sized rotors. Top - stowed inside aeroshell. Bottom - operational mode

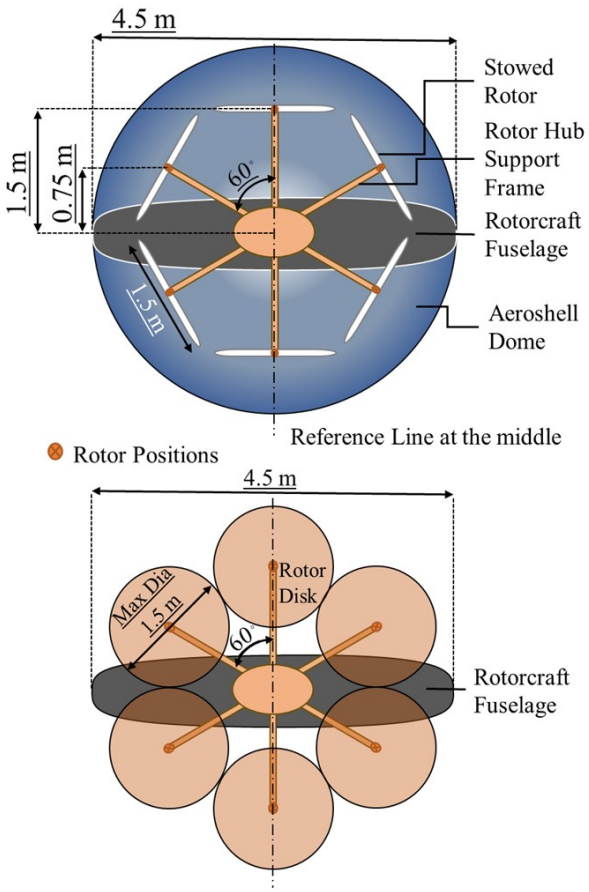


Fig. 5 Schematic illustration (not to scale) of the rotor hub positioning of hexarotor configuration with nonoverlapping equal-sized rotors. Top - stowed inside aeroshell. Bottom - operational mode

The defined quadcopter and hexacopter configurations allow for the maximum rotor diameter without overlap, both during operation and stowage within the aeroshell dome. The rotor diameter is capped at 2.25 m for the quadcopter and 1.5 m for the hexacopter to prevent overlap. These configurations can utilise a rigid rotor hub system. Detailed information is provided 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 ≤ 4.5 m
Tandem 2	Articulated**	Yes**	4.5 m	1.125 m	D ≤ 2.25 m
Tandem 3	Rigid	No	3 m	0.75 m	D ≤ 1.5 m
Quad	Rigid	No	1.25	1.125 m	D ≤ 2.25 m
Hexa	Rigid	No	1.5	1.5 m***	D ≤ 1.5 m

* Rotor hub position from the center of the fuselage

** When rotor D is > 2.25 m

***Radial position from the centre

5. Definition of Parameters for Performance Analysis

Air density is a key factor when determining initial power requirements during rotorcraft flight. On Titan, the average surface air density is roughly 5.4 kg/m³ [2]. The design and evaluation of Titanian aerobot configurations are restricted by the size of the aeroshell, with a maximum diameter of 4.5 m and a height of approximately 2.2 m. In the parametric performance study, rotor disk sizes range from 1% to 100% of the aeroshell diameter (0.05 m to 4.5 m), except for tandem rotorcraft case 1, where the rotor diameter can extend up to 9 m.

On Titan, operational restrictions are imposed on rotor tip speed and forward velocity to prevent the formation of transonic compression waves, given the sound speed of approximately 195 m/s [2]. The advancing rotor blade tip speed is typically capped at 0.75 Mach (146 m/s) to maintain sufficient lift on the retreating blade during forward flight, which necessitates an advancing blade speed nearly three times that of a

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helicopter [6]. As a result, the recommended maximum forward speed is 49 m/s, which is one-third of the maximum rotor tip speed and one-quarter of Titan's average 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 [6]. The flight profile in this study (depicted in Fig. 6) entails a 2-minute ascent to 1 km (at an average vertical climb velocity of 8.33 m/s), followed by a 15-minute traverse of 20 km (with an average cruising velocity of 22.22 m/s), culminating in vertical descent. The results of this theoretical model align well with experimental data when the rotorcraft's advance ratio is between 0.1 and 0.3 [7]. The advance ratio of a rotorcraft denotes the ratio of its forward flight speed to its rotor tip speed. Table 2 summarises the parameters discussed in this subsection that are utilised in the power analysis for various rotorcraft configurations during forward flight, vertical climb, and hover phases.

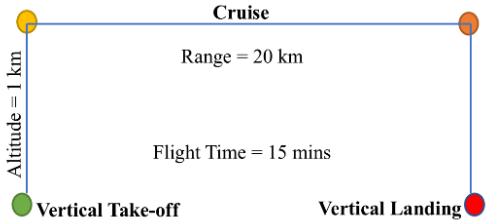


Fig. 6 Flight profile for the performance analysis

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

Parameter		Values		Unit
Titan Mean Air Density		5.4		kg/m^3
Speed of Sound		195		m/s
Surface Gravity Acceleration on Titan		1.35		m/s^2
Aircraft MTOG Mass		500		kg
Aircraft MTOG Weight, W		675		N
Allowable Max Rotor Advancing Tip Mach Number, M_{at}		0.75		Mach
Air Speed at Max M_{at} on Titan		146		m/s
Traverse Range as per Flight Mission		20		km
Cruise Flight Endurance, E		15		min
Cruise Flight Velocity, V		22.22		m/s
Dynamic Pressure at the Cruise Velocity, q		1333		Pa
Flight Altitude as per Flight Mission		1		km
Vertical Climb Endurance, E		2		min
Average Vertical Climb Velocity,V_{climb}		8.33		m/s
Rotor Blade Diameter, Blade D	0.05	to	9.0	m
Rotor Disk Area, S	0.002	to	63.6	m^2
Battery Specific Energy, E_{s2b}		230		Wh/kg
Measure (or figure) of Merit, M		0.7		
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 Efficicency, 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 0.3 m)	5.0E-01	0.09	4.3E-02	m^2
D/q Tubular Landing 4 legs with Skid (0.015m x 0.5m, eac	3.0E-02	1.01	3.0E-02	m^2
D/q Unfaired Single Rotor Hub (0.05m x 0.03m)	1.5E-03	1.20	1.8E-03	m^2
Downwash Interference Drag Fuselage	5.0E-01	0.02	1.0E-02	m^2
Leakage & Protuberance Drag (15% Total D/q)			1.3E-02	m^2

For the mission, the aerobot's Maximum Take-Off Gross (MTOG) mass is fixed at 500 kg. An average value of 0.7 for the figure of merit, M, is used, considering its typical range from 0.6 to 0.8 [6]. 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 [10].

Several other parameters are critical for forward flight analysis, such as the frontal area of the aircraft body. The dimensions of the fuselage's frontal area, landing legs, and the unfaired rotor hub are consistent across all variants for

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this analysis. Helicopter-specific drag statistics published by D. Raymer [6] provide the drag area (D⁄q) per unit frontal area, which can be multiplied by the helicopter's frontal area to derive specific values for each component's drag area. 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 drag data may not precisely determine parasitic drag, it provides a reasonable approximation for initial rotorcraft sizing until more detailed design explorations can be conducted.

6. RESULTS AND ANALYSIS

6.1. Hover and Vertical Climb Analysis

Fig. 7 presents a plot of the power required for a conventional Titanian helicopter as the rotor disk diameter increases. As the rotor diameter expands, the rotor disk area also grows, leading to a reduction in disk loading (W/S, where total weight is divided by disk area). Lower disk loading reduces the battery power needed for hovering or ascent, thereby increasing power loading (W/P). However, it is important to note that lower disk loading also results in larger rotor blades, which can increase the overall weight, cause greater drag during forward flight, and raise the risk of shocks on the advancing blade [6], factors that are not covered in this study.

The graph indicates that smaller rotors consume significantly more power than larger ones, with power decreasing sharply as the rotor disk diameter increases. Additionally, as the aerobot's total mass increases, the power demand for smaller rotor disks rises dramatically, whereas the increase in power required for larger rotor disk diameters is comparatively minimal. The 1000 kg versus 500 kg Helicopter graph in Fig. 7 illustrates this discrepancy. It is apparent from observing the power requirements that the helicopter needs slightly greater power to climb vertically than to hover. This is to be anticipated given the energy required to provide vertical forward propulsion. Nevertheless, over time, the gap between the two power requirements is more noticeable as the size of the rotor disk expands.

Hover power and vertical climb power (at a velocity of 8.33 m/s) are graphically represented for several rotorcraft designs in relationship to the rotor disk diameter in Fig. 8 and Fig. 9, respectively. The conventional helicopter, LS (large separation) coaxial rotorcraft, three tandem rotorcraft cases, two isolated rotorcraft cases, quadcopter and hexacopter cases are among these variants. The purpose of including the power data of two isolated rotors is not for practical application, but rather for analytical comparison with tandem rotor Case 1. Similar to the pattern in the helicopter power requirements graph, all these configurations have higher power demands for vertical climbing than hovering, and this difference steadily grows with rotor disk diameter. Of all these configurations, the conventional helicopter uses the most amount of power.

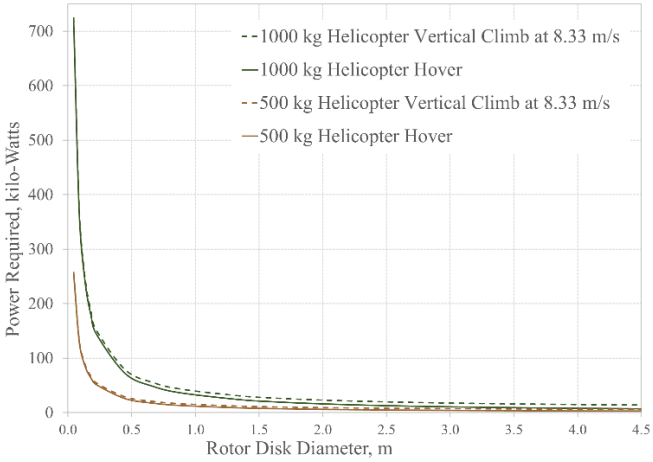


Fig. 7. Power Required vs Rotor Disk Diameter - 500 kg & 1000 kg Titanian Conventional Helicopter

In contrast to a conventional helicopter, the power consumption of two equal-sized coaxial rotors is substantially lower, particularly at smaller-sized rotors. For instance, the coaxial rotorcraft uses roughly 12000 Watts less power at a rotor size of about 0.2 m in diameter, while Tandem rotorcraft configurations use about 20500 Watts less power than the conventional helicopter for both hovering and vertical climbing, whereas quadrotor and hexarotor require about 29500 and 33500 Watts less power, respectively. At the maximum aeroshell size (corresponding to a rotor diameter of 4.5 m), hover and vertical climb power requirements range under 3000 and 6000 Watts for all configurations, respectively. It is evident for all three tandem rotorcraft situations that the power consumption of the tandem rotorcraft system is equal to that of the two isolated rotors prior to any overlapping between the rotors. The power requirements for all variants reduce inversely and become relatively steady as the rotor diameter increases. As seen in tandem rotorcraft Case 1, the difference becomes minor for rotor disk size values between 4.5 and 9 m. Notably, when using lower rotor diameters, quadcopter utilise far less power than all other rotorcraft types combined.

6.2. Forward Flight Analysis

The analysis in this section, examines forward level flight and forward climb flight at a 20-degree climb path angle, for each of the rotorcraft configurations at a forward flying speed of 22.2 m/s. The power required for a Titanian conventional helicopter to fly forward against its increasing rotor disk size is demonstrated in Fig. 10. The graphs illustrate how climbing up while flying forward consumes more power than a straight-forward flight. However, for smaller rotor disk diameters, the power consumption of both flights has closer values, and the difference between the two power requirements does not become apparent until and beyond the rotor disk diameter of approximately 0.5 m. As the rotor disk size increases, the power requirements for forward climb flight do not reduce as much as those for level flight.

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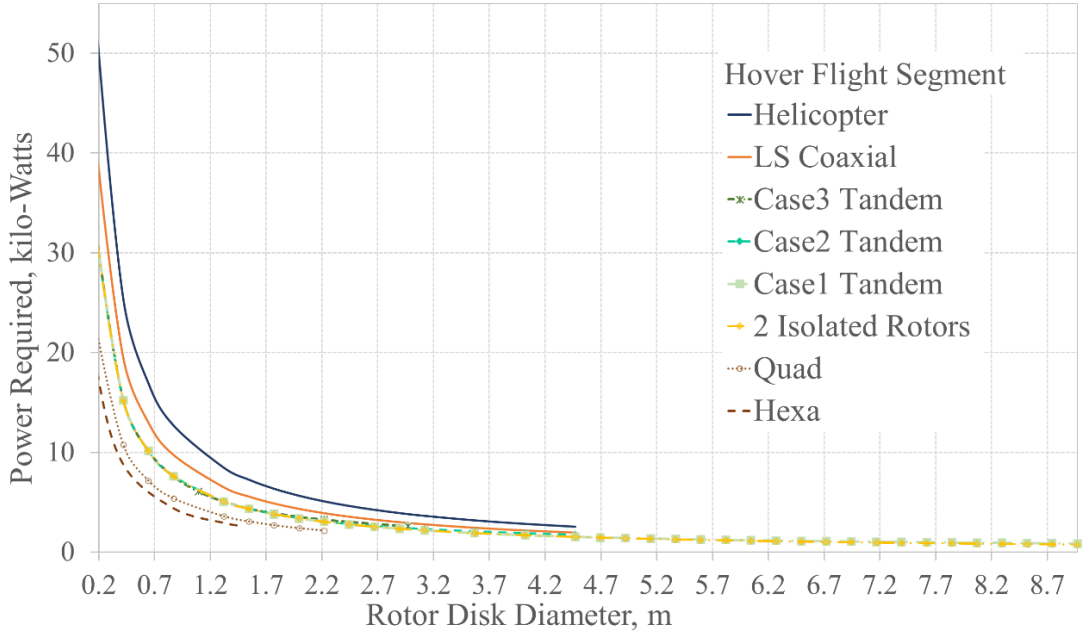


Fig. 8. Hover Power Required vs Rotor Disk Diameter (0.2 m to 9 m)– Comparison between various 500 kg rotorcraft configurations (Helicopter, Coaxial, Tandem Cases, 2 Isolated Rotors, Quadcopter)

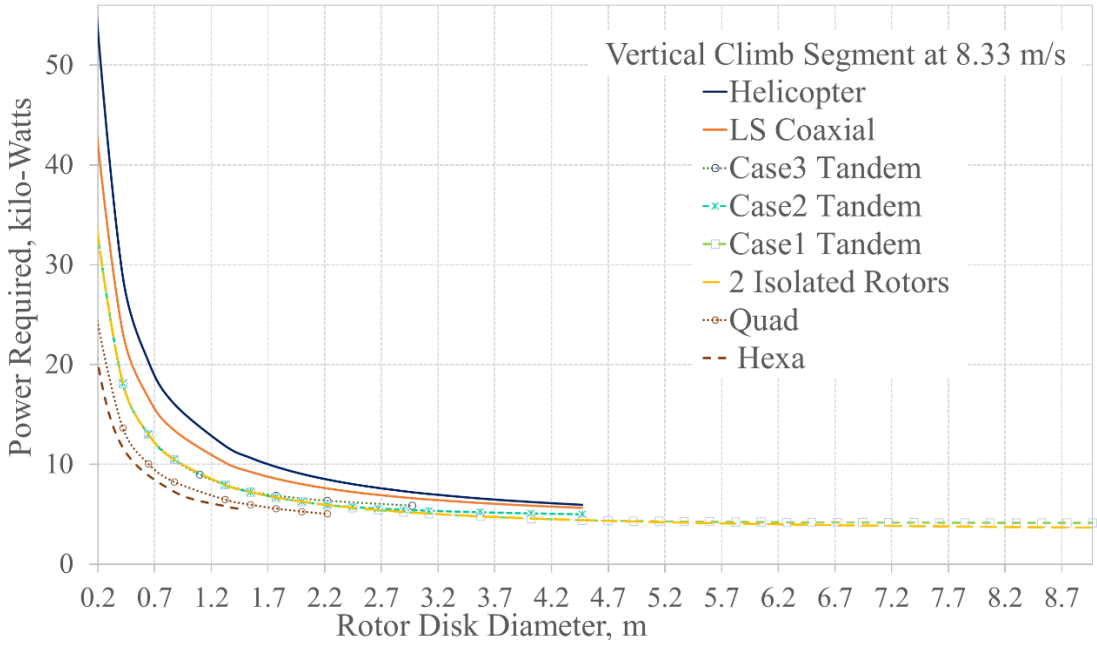


Fig. 9. Vertical Climb Power Required (at 8.33 m/s) vs Rotor Disk Diameter (0.2 m to 9 m)– Comparison between various 500 kg rotorcraft configurations (Helicopter, Coaxial, Tandem Cases, 2 Isolated Rotors, Quadcopter)

Fig. 11 illustrates a snapshot of the power requirements for the forward level flight of all the selected rotorcraft types against rotor disk diameters of up to 9 m. It is noteworthy that at the lowest rotor disk size, conventional helicopter power has the greatest and most unreasonable power requirement, following which are coaxial rotorcraft, tandem rotorcraft cases, two isolated rotors and finally quad and hexa rotor cases. Whereas with a modest increase in rotor disk size, the power demand decreases rapidly, till the difference in power becomes asymptotic for all except tandem cases. Finally, it is noted that after certain rotor sizes, the rotorcrafts with the fewer number of rotors become more efficient than the ones with greater number of rotors. At 1.5 m rotor disk size, hexacopter consumes the highest power, followed by quad, coaxial, tandem cases, 2 isolated rotors and the conventional helicopter.

Starting with a rotor disk diameter of 0.5 m on the horizontal axis, Fig. 12 provides a detailed view of the power variations required for both forward level and climbing flights across various rotorcraft configurations. An interesting behaviour is observed in tandem rotorcraft cases during forward climb, where the power required increases

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above a minimum value at a certain rotor disk size. This occurs when the tandem rotors start to overlap, which, for Case 1, happens beyond a rotor diameter of 4.5 m, for Case 2 and 3 it happens at 2.5 m and 1.5 m, respectively. The increase in power is due to the additional overlapping interference factor (K_{ov}) along the downwash factor (K_{dw}).

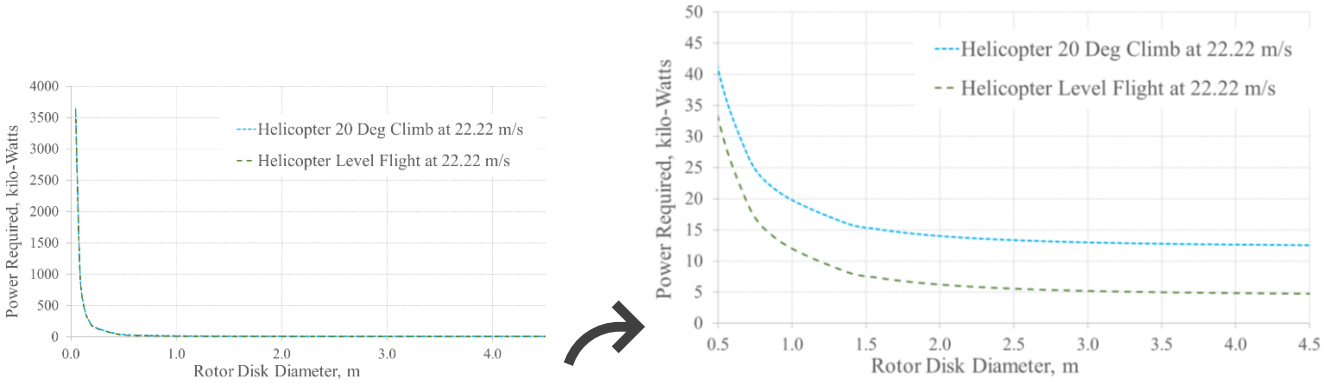


Fig. 10. Forward Flight Power Required (at 22.22 m/s) vs Rotor Disk Diameter - 500 kg Titanian Conventional Helicopter. Graph on the right side is the zoomed in view of the graph on left side, with rotor disk starting from 0.5 m.

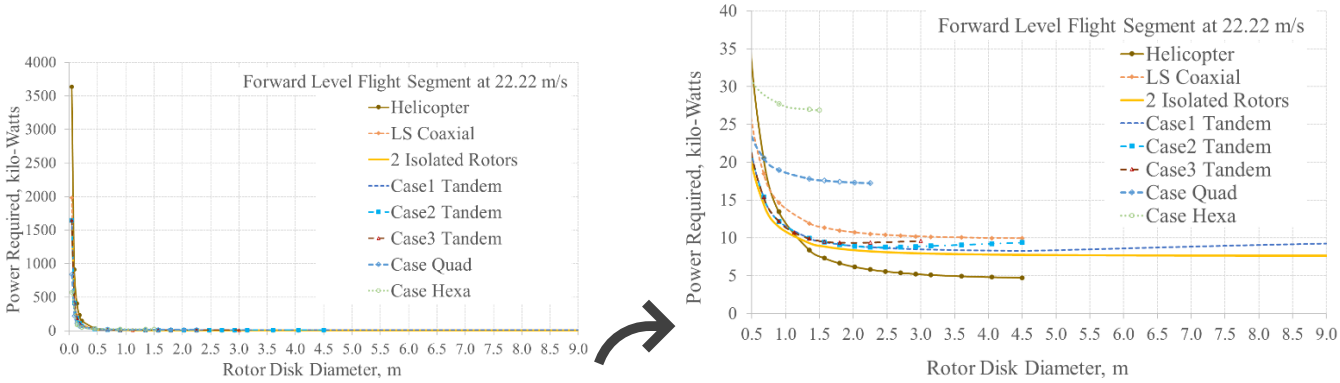


Fig. 11. Forward Level Flight Power Required (at 22.22 m/s) vs Rotor Disk Diameter - 500 kg Titanian Various Rotorcraft Configurations. Right-side graph is the zoomed in view of the left-side graph with rotor disk starting from 0.5 m.

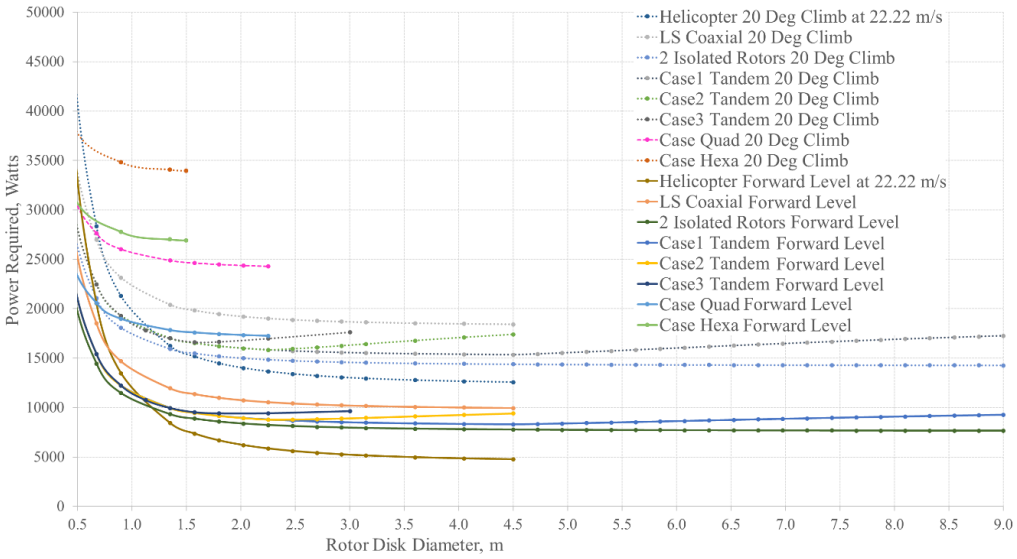


Fig. 12. Forward Flight Power Required (at 22.22 m/s) vs Rotor Disk Diameter (Rotor Diameter Limits – 0.5 m to 9 m) – Comparison between various 500 kg rotorcraft configurations (Helicopter, Coaxial, Tandem Cases, 2 Isolated Rotors, Quadcopter, Hexacopter)

Although climbing during a forward flight requires more effort than level flight, gaining altitude while flying forward is more energy efficient than a levelled flight. Maintaining a lower altitude while flying forward

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minimises energy losses because it generates an air cushion beneath the aircraft, a phenomenon known as ground effect, which aids in reaching the ideal flying speed before ascending. To prevent air shocks from building up at the rotor tip speed, this analysis is performed below the maximum forward flying speed permitted. It is possible to vary the amount of power required for each rotorcraft type by experimenting with a various forward speed such that at lower speeds the quad and hexacopter consume lesser power than single and dual rotors. Likewise, the amount of forward climb flight power required will decrease with decreasing climb path angle.

6.3. Comparative BMF Analysis of the Rotor Configurations

Fig. 13 illustrates the Battery Mass Fraction (BMF) for vertical climb segment by plotting the power required against with increasing rotor disk diameter for each rotorcraft configuration. A 2-minute run time (E), an 8.33 m/s climb speed, and a fixed total mass of 500 kg is taken into account while calculating the BMF using Eq. (10). The vertical climb power dependency observed in Fig. 9 is reflected in the trend of the vertical climb BMF lines.

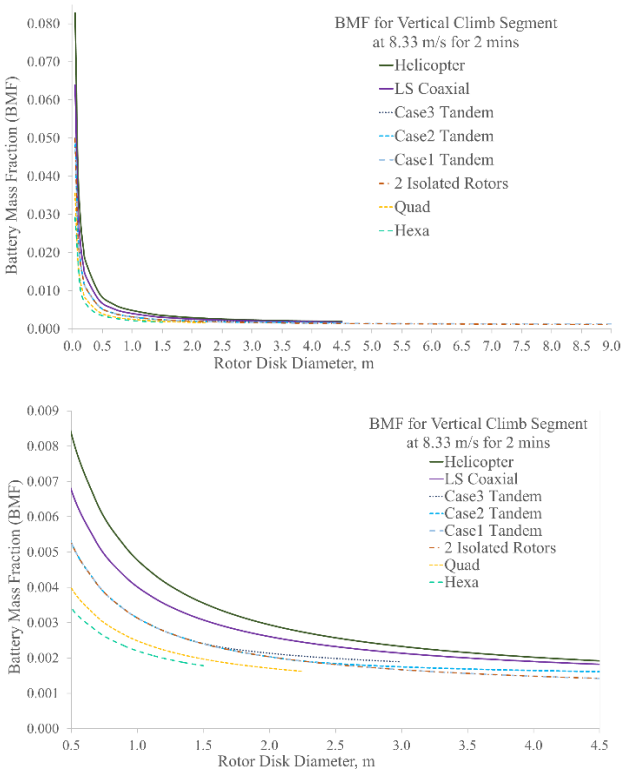


Fig. 13. Vertical Climb (at 8.33 m/s for 2 mins) BMF vs Rotor Disk Diameter - 500 kg Titanian rotorcrafts. Top - BMF for rotor sizes from 0.05 to 9 m. Bottom – Close-up view, focusing on BMF for rotor diameters from 0.5 m to 4.5 m on the x-axis for clarity

Essentially, as the required power increases, so does the BMF, reflecting the battery mass required for this specific flight segment. For the forward level flight segments displayed in Fig. 14, a comparable BMF trend is noted, which represents the power demand of the forward level flight depicted in Fig. 11.

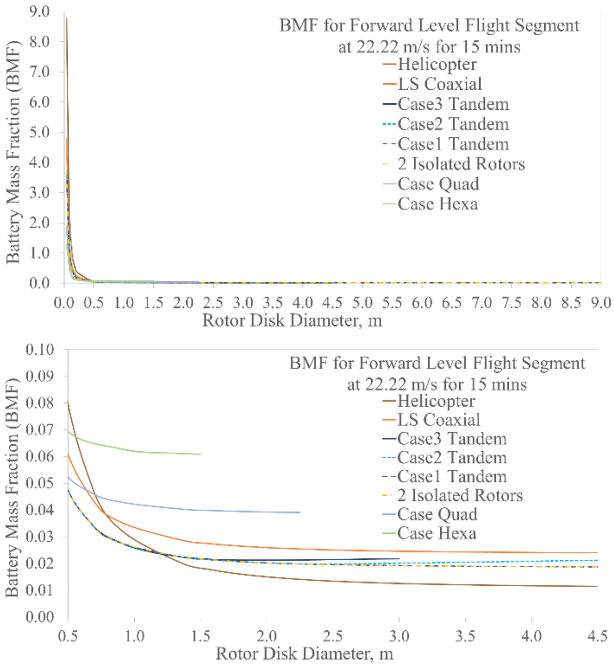


Fig. 14. Forward Levelled Flight (at 22.22 m/s for 15 mins) BMF vs Rotor Disk Diameter - 500 kg Titanian rotorcrafts. Top - BMF for rotor diameters from 0.05 to 9 m. Bottom – Close-up view, focusing on BMF for rotor diameters from 0.5 m to 4.5 m on the x-axis for clarity

The battery mass is calculated by simply multiplying the BMF by the aircraft's overall mass. For example, a 0.04 BMF would result in a battery mass of 20 kg (0.04 x 500 kg). It is vital to remember that the BMF of each segment must be combined with the BMF of other flight segments, as discussed in section 3, in order to establish the total BMF and the overall battery mass necessary for a specific flight regime. Additionally, the BMF calculated for the mission excludes the battery mass needed for avionics and electronic payload instrumentation, which would require separate calculations unless powered by independent batteries.

7. Initial Sizing Application and Discussion

The most power-efficient rotorcraft configurations may be selected for the aerobot design based on the power demand analysis of rotorcrafts with single, dual, quad and hexa rotors. However, when designing robots for extraterrestrial applications, simplicity in operational capability is essential to minimise the risk of malfunction, as physical maintenance or error correction

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is not feasible. For instance, the Case 1 Tandem rotorcraft, with its 9 m rotor diameter, highlights how specific design constraints are applied to exclude certain theoretical configurations that, although optimal in theory, introduce significant complexities. These challenges include the need for heavier, more robust materials, folding and stowing mechanisms, and addressing control and stability issues. Similarly, smaller rotors are more effective in small to medium-sized multicopters, but only when they are lighter and mechanically simpler. Otherwise, the increased number of motors and hub systems adds to the aircraft's empty weight, reducing its payload capacity.

7.1. Efficient Rotor Configuration

Fig. 15 and Fig. 16, present a view of the analytical graphs comprising power required by rotorcraft configurations such as conventional helicopter, LS (Large Separation between rotors) coaxial rotorcraft, three cases of tandem rotorcraft, quadcopter and hexacopter for vertical climb and forward level flight against the rotor disk diameter, respectively.

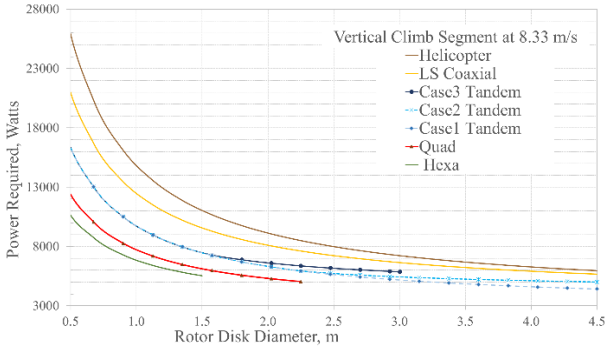


Fig. 15. Power Required (Vertical Climb at 8.33 m/s) vs Rotor Disk Diameter (Rotor Diameter Limits – 0.5 m to 4.5m) – Comparison between various 500 kg rotorcraft configurations

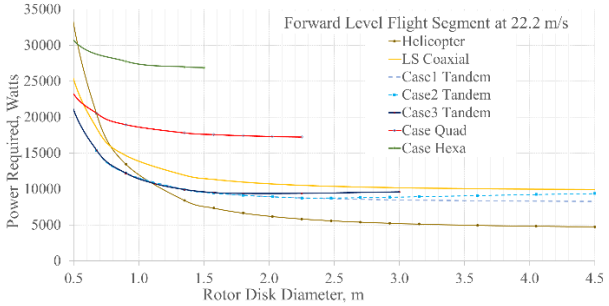


Fig. 16. Power Required (Forward Level at 22.22 m/s) vs Rotor Disk Diameter (Rotor Diameter Limits – 0.5 m to 4.5m) – Comparison between various 500 kg rotorcraft configurations

It is revealed from the data in these graphs that for hover and vertical flight the hexarotor configuration when compared to rotorcrafts with single, dual and quad rotors, requires the lowest power in the defined parameters for the rotor size of up to 1.5 m. Whereas, during forward flight hexacopter consumes the most power than all other configuration for the rotor disk sizes of about 0.5 m and beyond. This is likely due to increased drag from multiple rotors, especially in Titan's dense atmosphere, where aerodynamic drag is amplified. It is followed by quadrotor, which starts consuming the most power than the dual and single rotors at rotor disk size of about 0.7 m and beyond. According to the formulae used for this simplified method, hexarotor and quadrotor act as isolated units and do not have overlapping interference, except for the downwash from frontal rotors during forward flight. For quadrotor, this downwash from front rotors can be minimised and hence the power requirement can be improved if the quad setting is changed from square to diamond [11].

When comparing the power requirements between single and dual rotors, the conventional helicopter demonstrates the highest power requirements for hover and vertical flight for all disk sizes, and during the forward flight for rotor sizes smaller than 0.5 m (approx.). However, this single rotor configuration consumes the lowest power than all other configuration beyond the disk sizes of around 1 m. This indicates that the helicopter's single rotor faces less drag in forward motion compared to multicopters, making it an optimal choice for sustained forward flight on Titan. Coaxial rotorcraft apparently consumes most power than the tandem cases for all flight segments.

Overall, if the mission prioritises vertical climb, the hexacopter is the best option for smaller rotor sizes. For forward flight efficiency, the conventional helicopter becomes a preferred choice, particularly for larger rotor diameters. However, for a balanced approach between vertical climb and forward flight efficiency, tandem Case 1 is the most efficient configuration for larger rotor sizes, while Tandem Case 3 is better suited for smaller rotors. The coaxial rotorcraft, in contrast, consumes considerably higher power than most configurations but is consistent in power requirement trend in all the flight segments, while offering the advantage of a compact design.

7.2. Applying Initial Sizing to Shortlisted Configuration

A hexacopter case with a 1.5 m rotor disk size is selected to perform initial sizing. The power required at a vertical climb segment (at 8.33 m/s for 2 mins) is 5530 Watts and at a cruise segment (at 22.22 m/s for 15 mins) is 26900 Watts, and the Battery Mass Fraction (BMF) is 0.002 and 0.06, respectively. The total BMF sums up to 0.062. As it is predetermined, the total aerobot mass is aimed at 500 kg. So, using Eq. (10) the battery mass (m_b) required for this 15-minute flight mission is calculated to be 31 kg. Also, it is predetermined that the aerobot must be capable

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of carrying a science payload of 100 kg. Using Eq. (11) in terms of Mass, the available aircraft's empty mass ($m_e=m_0-m_b-m_{payload}$) is determined to be 369 kg, representing 74% of the total aircraft mass.

Similarly, for a conventional helicopter configuration with a 1.5 m rotor disk size is also analysed. The power required for the vertical climb segment is 11000 Watts, and for the cruise segment, it is 7660 Watts. The corresponding Battery Mass Fraction (BMF) values are 0.003 for vertical climb and 0.02 for cruise, resulting in a total BMF of 0.023 which equals 11.5 kg battery mass. This results in 388.5 kg empty mass, representing 78% of the total mass.

7.2.1. Insights from Comparison

The initial sizing results for both the hexacopter and conventional hexacopter configurations provide a strong basis for further design exploration. The conventional helicopter shows a lower overall power requirement compared to the hexacopter, saving it about a 4% (20 kg) of the total mass for the analysed flight regime. The helicopter's slight edge in cruise efficiency might make it preferable for longer missions at such required speeds, whereas the hexacopter's better performance in vertical climb could prove advantageous for missions that require frequent ascents and descents. For instance, instead of covering a ground range of 20 km, if 1 km range is targeted, then a multirotor configuration provides power efficiency along with simplicity in aeromechanics. Both configurations, offer flexibility for payloads and system integration, providing a solid starting point for further analysis.

7.3. Future Work

The analysis underscores the need to balance power requirements across various flight segments to optimise mission performance. Further refinement of rotorcraft designs can be achieved through iterative modifications, particularly in rotor size and system efficiency. The initial empty mass estimates account for the rotorcraft's materials and components, which, in the early design stages, can be sourced from Commercially Off-The-Shelf (COTS) parts or similar aircraft systems. As the design evolves, these components can be adjusted to fine-tune the rotorcraft's sizing and advance the preliminary design phase.

This framework provides a crucial foundation for validating Titanian rotorcraft designs, acknowledging the high costs and logistical challenges of conducting tests in Titan-like conditions. Future research will refine these estimates by utilising advanced modelling techniques like Computational Fluid Dynamics (CFD) and vortex wake models. These methods focus on enhancing rotor efficiency at high advance ratios, where compressibility effects become significant, ultimately improving the reliability and performance of rotorcraft for Titan exploration.

8. Conclusion

As interest in Titan continues to grow with missions like NASA's upcoming Dragonfly, which is set to explore the moon's diverse landscapes, understanding the performance of rotorcraft in Titan's unique environment has become more critical than ever. This study has provided a comprehensive analysis of rotorcraft configurations designed to Titan's unique atmospheric and gravitational conditions. Through the application of momentum theory and detailed parametric analysis, the power consumption and operational efficiency of single, dual, and multi-rotor systems were evaluated across critical flight phases, including vertical climb, hover, and forward flight. The results demonstrate that the hexacopter configuration offers the highest power efficiency for vertical ascent, particularly for rotor diameters up to 1.5 metres, making it a strong candidate for operations involving frequent vertical take-offs and landings. For forward flight, the conventional helicopter configuration exhibits superior efficiency, especially at larger rotor diameters and at speeds over 20 m/s, making it optimal for extended horizontal travel and surface exploration. Among the other rotorcraft configurations, tandem and coaxial cases showed a balanced performance, optimising power consumption across both hover and forward flight, particularly for larger rotor diameters. These findings underscore the importance of selecting rotorcraft configurations based on specific mission requirements, with a focus on balancing power efficiency, structural complexity, and operational performance. This analysis provides a critical foundation for the design and optimisation of rotorcraft systems, supporting future exploration missions on Titan.

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Parametric analysis of rotary VTOL aerobot design configurations to fly on Titan

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