

Design of NOMAAD (Nimble Observant Mars Aerial Autonomous Drone)

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ABSTRACT

NOMAAD

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This paper explores the conceptualization of a scientific quadcopter designed to investigate the lava tubes and caves of Mars, specifically in the Dao Vallis region. With Ingenuity's successful flight on the Martian surface, alongside the Perseverance rover, this design aims to outperform its predecessors and open the possibility of conducting science missions on extraterrestrial planets. Weight estimates and performance calculations will be calculated and evaluated with the aid of other conceptualized Martian and Earth-based rotorcraft. This quadcopter will then be compared to the rotorcraft to determine its feasibility and identify the steps that need to be taken to improve its overall design.

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Symbols

Symbol	Definition	Units (SI)
A	Area	m ² (ft ²)
AR	Aspect Ratio	-----
a	Speed of Sound	m/s (ft/s)
BL	Blade Loading	-----
c	cord	m (ft)
C	Coefficient	-----
D/q	Frontal Area	m ² (ft ²)
DL	Disk Loading	kg/m ² (lb/ft ²)
e	Oswald Efficiency Factor	-----
E	Energy	Wh
FM	Figure of Merit	-----
k	Induced Drag Factor	-----
M	Mach Number	-----
n	Number of	-----
P	Power	W (hp)
q	Dynamic Pressure	Pa (psi)
R	Rotor Radius	m (ft)
r	Blade Radial Coordinate	m (ft)
T	Thrust	kg (lb)
t	Time	s
V	Velocity	m/s (ft/s)
W	Weight	kg (lb)
Subscripts		
O _{blade}	Blade	-----
O _{climb}	Climb Phase	-----
O _{cruise}	Cruise Phase	-----
O _d	Drag	-----
O _{disk}	Disk	-----
O _{eff}	Effective	-----
O _{ffcruise}	Cruise Phase in Forward Flight	-----
O _{hover}	Hover Phase	-----
O _{ideal}	Ideal	-----
O _i	Induced	-----
O _l	Lift	-----
O _{lo}	Zero-Lift	-----
O _{local}	Local	-----
O _o	Initial	-----
O _{rotor}	Per Rotor	-----
O _t	Thrust	-----

O_{tip}	Blade Tip	-----
Greek Symbols		
α	Angle of Attack	Deg (rad)
ρ	Air Density	kg/m ³ (slugs/ft ³)
σ	Solidity	-----
γ	Climb Path Angle	Deg (rad)
ϕ	Blade Twist Angle	Deg (rad)
Acronyms		
CFD	Computational Fluid Dynamics	-----
MARV	Martian Autonomous Rotary-Wing Vehicle	-----
MOLA	Mars Orbital Laser Altimeter	-----
MSH	Mars Science Helicopter	-----
NOMAAD	Nimble Observant Mars Autonomous Aerial Drone	-----
PEM	Proton Exchange Membrane	-----
PYTHIA	PlanetarY Telemetric Helicopter for Investigation and Analysis	-----

1. Introduction

1.1 Motivation

On February 18, 2021, after nearly seven months of traveling from Cape Canaveral, Florida, to the Martian surface, the Perseverance rover landed in Jezero Crater [1]. With a small coaxial helicopter, known as Ingenuity, on board, NASA scientists began conducting a technical test to determine if controlled flight on an extraterrestrial planet was possible. This dream soon became a reality when Ingenuity conducted its first flight on April 19, 2021. Ingenuity was the first to ever achieve such a feat. However, despite this successful excursion, Ingenuity did not carry any payload like the various Martian rovers, which are used for scientific experiments [2].

The idea of conducting scientific experiments via rotorcraft was almost impossible to ignore. Even before Ingenuity touched the surface of Mars, students and engineers alike conceptualized various renditions of rotorcraft to fly on Mars and conduct these missions. Fortunately, now that controlled flight on Mars is possible, these conceptualizations have a window of opportunity that has never been more open. NOMAAD is a rotorcraft that will aim to seize this prime opportunity for efficient exploration of the Martian surface. To be more specific, this quadcopter will conduct missions similar to those undertaken by the rovers that have come before, such as Sojourner and Perseverance.

NASA scientists have been searching for potential signs of life, whether currently living on the planet or having existed at some point in the red planet's past, for decades. Unfortunately, as of the writing of this report, no significant evidence has been found to draw such a conclusion. Such evidence could allow humans to make Mars a habitable environment or enable scientists to draw other conclusions that have the potential to benefit humanity. NOMAAD will be able to investigate areas of the Martian surface that would be too difficult for rovers to access, specifically lava tubes that are known to be quite large on Mars and have a high potential for signs of life.

1.2 Earth Versus Martian Design

Designing a rotorcraft for Martian exploration is much easier said than done, as the Martian atmosphere is drastically different from our own. Not only does it have an extremely low air density, but its atmosphere is also composed mostly of carbon dioxide. The table below expresses these differences in atmospheric properties.

Table 1.1 – Atmospheric comparison [3 - 5]

Parameter	Earth (N ₂ + O ₂)		Mars' (CO ₂)	
Units	Metric	Imperial	Metric	Imperial
Pressure (K-Pa) (psi)	101.325	14.696	0.748	0.108
Temperature (K) (F)	288.150	59.000	223.150	-58.000
Density (kg/m ³) (lb/ft ³)	1.225	0.076	0.017	0.001
Speed of Sound (m/s) (mph)	340.300	761.229	233.100	521.430
Viscosity (Ns/m ²) (Poise)	0.175×10^{-4}	0.175×10^{-3}	0.113×10^{-4}	0.113×10^{-3}

Most of the data given was from the sources themselves. However, the atmospheric pressure on Mars had to be determined using the MOLA (Mars Orbital Laser Altimeter) data and NASA's Martian atmospheric model.

As shown in the table above, all of the major atmospheric properties are significantly lower than Earth's by a considerable margin. One of the most critical factors, air density, can pose unique challenges for rotor design. Due to such low density and viscosity, this can result in low Reynolds numbers. As a result, this can greatly hinder a rotorcraft's ability to generate lift. To combat this issue, rotor blades must be given a larger surface area and must operate at higher speeds to gain the lift necessary for flight [6]. However, these blades cannot operate above Mach 1, as this can generate shock waves at the tips of the blade, thus generating unnecessary drag and therefore decreasing rotorcraft performance. Typically, Martian rotorcraft will have a blade tip speed between a Mach number of 0.7 to 0.95 at its highest, but most conceptual designs stay within the range of 0.8 to 0.9 to be safe.

Not only do the rotor blades require these parameters and operating conditions to fly on Mars effectively, but the rotor blades' airfoil also requires a new design to gain the maximum amount of lift. Due to such low Reynolds numbers on the Martian surface, which is about 19,100, a much thinner airfoil is required. Flat and cambered airfoils are better for a Martian atmosphere, as opposed to conventional airfoils, because they avoid laminar separation and maintain higher, more reliable lift-to-drag performance [7]. One such airfoil in particular was utilized by Ingenuity for its design, which was known as the clf5605 airfoil.

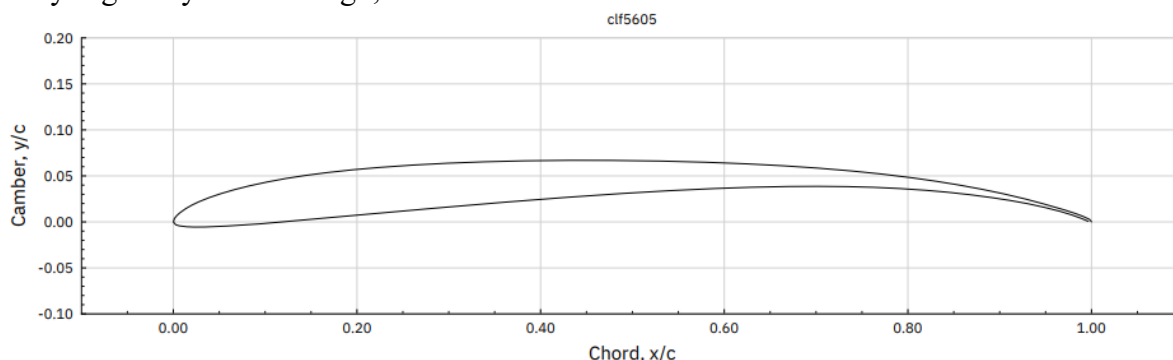


Figure 1.1 – Clf5605 airfoil [8]

1.3 Similar Aircraft Study

Due to the infancy of extraterrestrial rotorcraft, only one such rotorcraft has been manufactured and tested to fly on the Martian surface, being the Ingenuity coaxial helicopter. However, numerous conceptual designs have been created by extremely reputable NASA engineers that can aid in creating a baseline for the initial design of NOMAAD. The following rotorcraft were employed for further study:

1. Ingenuity
2. Mars Science Helicopter (MSH)
3. Planetary Telemetric Helicopter for Investigation and Analysis (PYTHIA)
4. Martian Autonomous Rotary-Wing Vehicle (MARV)
5. Freefly Alta X

Each of these rotorcrafts was handpicked based on the thoroughness of the design as well as the individuals who were behind its creation. One might recognize that most of the designs are

conceptualized rotorcraft for Mars, except for the very last one. This decision was purposefully made with the intent of utilizing an Earth-based analog quadcopter that would serve as a comparison to the other Martian rotorcraft. Additionally, the Freefly Alta X would aid the overall design of NOMAAD as it can carry a payload.

Ingenuity was an obvious choice as the first rotorcraft to study in comparison to NOMAAD. Even though Ingenuity did not carry any payload, it is still considered the only helicopter to have flown on the Martian surface. This fact alone justifies its reason for being one of the top rotorcraft for study in the design of NOMAAD. Not only does it have a fully tested design, but it also includes flight logs, which would prove useful for performance analysis. With an initial plan to conduct only five test flights in thirty days, Ingenuity managed to complete a total of seventy-two flights within three years [1]. Rather than being just a technology demonstration, it evolved into an aerial scout for NASA scientists, as various cameras were mounted to its underbelly [1]. Unfortunately, after a rough landing, the rotor blades of Ingenuity were damaged, rendering the rotorcraft incapable of further flight tests [1].



Figure 1.2 – Ingenuity mars helicopter [1]

Regardless of its current situation, Ingenuity broke ground within the rotorcraft community, demonstrating that flight on neighboring planets could be achieved. This revelation led NASA engineers to begin exploring the idea of designing rotorcraft for scientific missions, similar to the various rovers that have preceded them. Rotorcraft engineers at NASA Ames Research Center decided to spearhead this challenge with a hexacopter, known as MSH.

The Mars Science Helicopter is a solar-powered hexacopter that was theorized amid Ingenuity's mission to Mars in 2020 [7]. At the time of writing this report, MSH has not been manufactured and is considered a conceptual design. Nonetheless, this helicopter has some of the most influential and notable engineers in the rotorcraft industry who contributed to its design. Two engineers in particular, Larry Young, an experienced rotorcraft design engineer at NASA Ames, and Wayne Johnson, who authored the book "Helicopter Theory", have worked in the rotorcraft industry for quite some time and have significant authority on the subject matter [3]. Additionally,

this multi-rotor design was created to conduct scientific missions with a payload on board. This makes MSH a strong model to base the design of NOMAAD on.



Figure 1.3 – MSH conceptual design [7]

Once the design of MSH was completed, it inspired other NASA engineers to develop additional scientific rotorcraft to explore different regions of the Martian surface. MSH was created to study Jezero Crater, the same area where Ingenuity first flew [7]. However, Jezero Crater is not the only worthwhile location on Mars. Another team of NASA engineers focused on a much higher region on the planet's surface, known as Arsia Mons, a mountainous area with significantly lower air density than the Mars “sea level,” which is also home to numerous lava tubes and caves [9]. This spot would be ideal for searching for signs of ancient microbial life or water. The name chosen for this rotorcraft to carry out that mission is PYTHIA (Planetary Telemetric Helicopter for Investigation and Analysis).

PYTHIA is a solar-powered quadcopter that aims to conduct a mission similar to that of NOMAAD. This makes PYTHIA an excellent benchmark for comparison and further study, as the mission parameters are similar. This quadcopter aims to conduct its scientific research in two distinct phases, which are a short mapping phase and an exploration phase [9]. This is a mission profile that could potentially be utilized for the design of NOMAAD, as its mission will be to investigate lava tubes and caves as well. Unfortunately, as opposed to MSH, PYTHIA still has a long way to go in its design process, as its model is still in its infancy, and more iterations will need to be completed before a robust design can be established. Regardless of its infancy, PYTHIA has invaluable data that can and will contribute well to the creation of NOMAAD.



Figure 1.4 – PYTHIA conceptual design [9]

Both MSH and PYTHIA were designed amid Ingenuity's first flight on Mars, but interestingly enough, even engineers outside of NASA were working on their conceptualization of a scientific helicopter. Students at the University of Maryland published a report for a design competition back in 2000 that detailed a conceptual design that was shockingly similar to the design of Ingenuity. MARV (Martian Autonomous Rotary-Wing Vehicle) is a coaxial helicopter that was designed to conduct scientific missions on the Martian surface [10]. Not only did it have two blades for each rotor, but it also had the same landing gear, being a fixed quadrupedal set of stilts. However, this design can carry a massive payload, being 10.8 kilograms, as opposed to Ingenuity, which did not carry any payload. Unconventionally, this design did not entail the use of solar power for its power supply. Instead, it relied on the use of Proton Exchange Membrane (PEM) fuel cells [10]. This power option was briefly considered for use but was quickly scrapped due to the necessity of refueling. With this fuel option, NOMAAD would have a fixed timeline of operation before becoming obsolete.

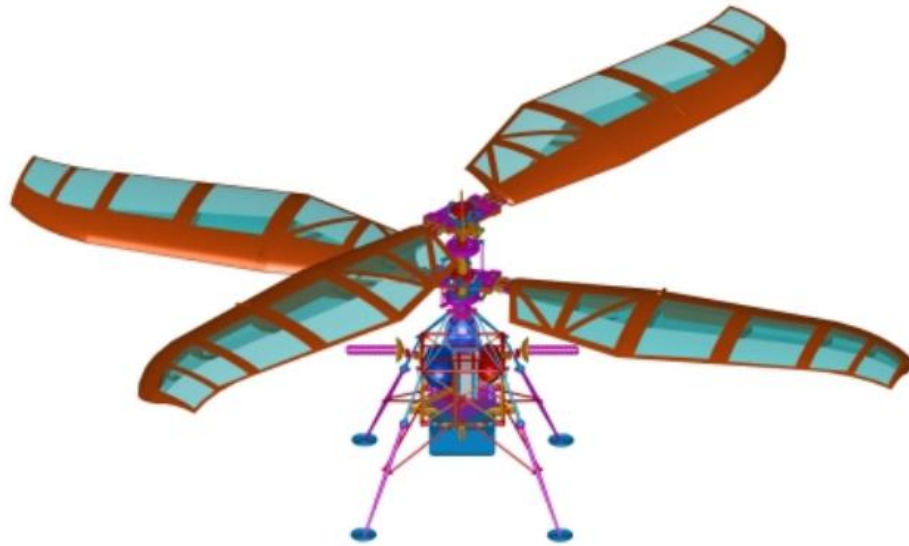


Figure 1.5 – MARV conceptual design [10]

Unfortunately, other than Ingenuity, all the models have been conceptual designs and have not been field-tested. Thus, another concrete, already manufactured and field-tested model would need to be considered to create a robust set of similar aircraft for NOMAAD to be compared to. Since no other Martian rotorcraft has been created, an Earth-based analog rotorcraft would be beneficial in creating a cohesive model for Mars. Not only would this help in comparing the Earth-based model to a Martian model, but it would also keep sizing and performance numbers within a reasonable range, as the conceptual models may have idealized values.

The rotorcraft of choice is the Freefly Alta X quadcopter. It is a battery-powered helicopter designed to carry heavy payloads such as various cameras and LiDAR sensors for efficient mapping [11]. Additionally, it can carry heavy payloads for a considerable amount of time. The Freefly Alta X has been well designed to operate in Earth's atmosphere, and considering that it has the same configuration that NOMAAD will have, it will be a suitable choice for comparison. Even with such significant differences between Earth and Martian atmospheres, the Freefly Alta X will be an excellent Earth-based analog to keep other metrics from becoming too idealized.



Figure 1.6 – Freefly Alta X quadcopter [11]

Table 1.2 – Configuration comparison [1 - 2, 7, 9 - 11]

	Ingenuity	PYTHIA	MSH	MARV	Freefly Alta X
Overall Configuration	Coaxial	Quadcopter	Hexacopter	Coaxial	Quadcopter
Landing Gear Configuration	Quadrupedal Fixed Landing Gear	Skid-Type Landing Gear	None	Quadrupedal Fixed Landing Gear	Tripod Fixed Landing Gear
Propulsion Type	Electric Solar Cells	Electric Solar Cells	Electric Solar Cells	PEM Fuel Cell Stack	Electric
# of Engines	2	4	6	2	4
Propulsion Configuration	Center of Rotor	Center of Rotors	Center of Rotors	Center of Rotor	Center of Rotors

Table 1.3 – Weight comparison [1 - 2, 7, 9 - 11]

	Ingenuity	PYTHIA	MSH	MARV	Freefly Alta X
Design Gross Weight	4.00 lbs 1.81 kg	66.27 lbs 30.06 kg	38.93 lbs 17.66 kg	110.23 lbs 50.00 kg	76.85 lbs 34.86 kg
Empty Weight	Unknown	Unknown	34.50 lbs 15.65 kg	63.27 lbs 28.7 kg	23.94 lbs 10.86 kg
Battery Weight	Unknown	Unknown	3.35 lbs 1.52 kg	23.37 lbs 10.60 kg	19.71 lbs 8.94 kg
Payload Weight	0 lbs 0 kg	5.51 lbs 2.50 kg	4.45 lbs 2.02 kg	23.81 lbs 10.80 kg	33.20 lbs 15.06 kg

Table 1.4 – Propulsion comparison [1 - 2, 7, 9 - 11]

	Ingenuity	PYTHIA	MSH	MARV	Freefly Alta X
Disk Loading (kg/m ²)	0.80	1.71	2.29	29.18	5.67
# of Engines	2	4	6	2	4
Maximum Thrust Per Engine in Hover	3.46 N	28.72 N	11.25 N	95.53 N	33.30 N
Maximum Total Thrust in Hover (All Engines)	6.92 N	114.87 N	67.48 N	191.07 N	133.21 N
Weight Per Engine	Unknown	Unknown	1.63 lbs 0.74 kg	4.41 lbs 2.00 kg	Unknown
Rotor Radius	2.00 ft 0.61 m	3.94 ft 1.20 m	2.10 ft 0.64 m	1.74 ft 0.53 m	2.33 ft 0.71 m
# of Propeller Blades per Rotor	2	8	4	2	2

Table 1.5 – Performance comparison [1 - 2, 7, 9 - 11]

	Ingenuity	PYTHIA	MSH	MARV	Freefly Alta X
Range	0.1 nmi 0.18 km	2.83 nmi 5.25 km	1.08 nmi 2.00 km	13.50 nmi 25.00 km	5.40 nmi 10 km
Endurance	1.5 min	Unknown	4.5 min	39 min	10.8 min
Cruise Velocity	3.89 kt 2.00 m/s	19.44 kt 10.00 m/s	58.32 kt 30.00 m/s	22.35 kt 11.5 m/s	38.88 kt 20.00 m/s
Climb Rate	Unknown	590.55 ft/min 3.00 m/s	1988.19 ft/min 10.10 m/s	492.13 ft/min 2.5 m/s	1181.10 ft/min 6.00 m/s

Table 1.6 – Geometry comparison [1 - 2, 7, 9 - 11]

	Ingenuity	PYTHIA	MSH	MARV	Freefly Alta X
Total Disk Area (S_{disk})	25.19 ft ² 2.34 m ²	194.83 ft ² 18.10 m ²	83.10 ft ² 7.72 m ²	18.94 ft ² 1.76 m ²	68.14 ft ² 6.33 m ²
Blade Area (S_{blade})	Unknown	10.33 ft ² 0.96 m ²	2.76 ft ² 0.26 m ²	0.46 ft ² 0.04 m ²	Unknown
Blade Span (b)	1.97 ft 0.61 m	3.94 ft 1.20 m	2.10 ft 0.64 m	1.74 ft 0.53 m	2.33 ft 0.71 m
Mean Chord (c)	Unknown	0.33 ft 0.1 m	0.33 ft 0.1 m	0.13 ft 0.04 m	Unknown
Blade Aspect Ratio	Unknown	12	6.4	13.25	Unknown

1.4 Power Considerations

Numerous types of power systems have been considered over the years for exploration of our neighboring planets. Rovers, such as Perseverance and Sojourner, relied on solar power and large battery packs to sustain them on their respective missions. All satellites have largely relied on a solar power system to operate. To nobody's surprise, this translated over to the rotorcraft scene as Ingenuity utilized lithium-ion batteries and solar cells to power its 90-second flight [1]. Even conceptual designs like PYTHIA and MSH also planned on using solar cells to charge their journey. Even though these designs were published recently, battery power has continued to evolve since Ingenuity's launch from Cape Canaveral back in 2020.

Many different battery types are noted in Daniel P. Raymer's book, "Aircraft Design: A Conceptual Approach," with their respective specific battery energy and densities. Lithium-ion batteries have about 100 – 265 Watt-hours per kilogram of battery density [12]. However, for electric aircraft to be able to maintain flight for an extended period, a higher battery density must be sought. However, Sion Power has been making moves to bring a battery pack that can push the

boundary of being able to allow extended flight times for rotorcraft. The Licerion® battery is a lithium metal battery that has a battery density of 500 Watt-hours per kilogram.

It has the largest battery density out of all the other types and was created just after Ingenuity left Earth to fly to Mars. It comes equipped with a protected lithium anode, which allows for higher energy storage than most other lithium batteries [13]. Additionally, it focuses on minimizing weight while maximizing energy, cycle life, and safety, thus making this battery an ideal choice for aerospace applications such as Martian rotorcraft. However, this doesn't mean that other forms of power systems have not been considered for Martian rotorcraft.

As mentioned earlier, MARV is the only rotorcraft, out of all the other Martian helicopters, that uses PEM fuel cells for its design. Just because it is the only one that considered the option for its design doesn't mean that it was walking down the wrong path. PEM fuel cells are highly capable of carrying out scientific missions on Mars, especially with a rotorcraft that is as heavy as MARV.



Figure 1.7 – PEM fuel cell diagram [14]

These fuel cell stacks intake hydrogen and oxygen and mix them. This reaction creates energy that the rotorcraft can then utilize for flight. The waste that proceeds to leave the stack is water, which is then transferred to a storage tank.

PEM fuel cells offer a low mass alternative to some batteries, and even some cars have begun playing with the idea of utilizing PEM fuel cells instead of internal combustion engines [14]. Additionally, they even claim to have a higher specific energy compared to the current batteries of today.

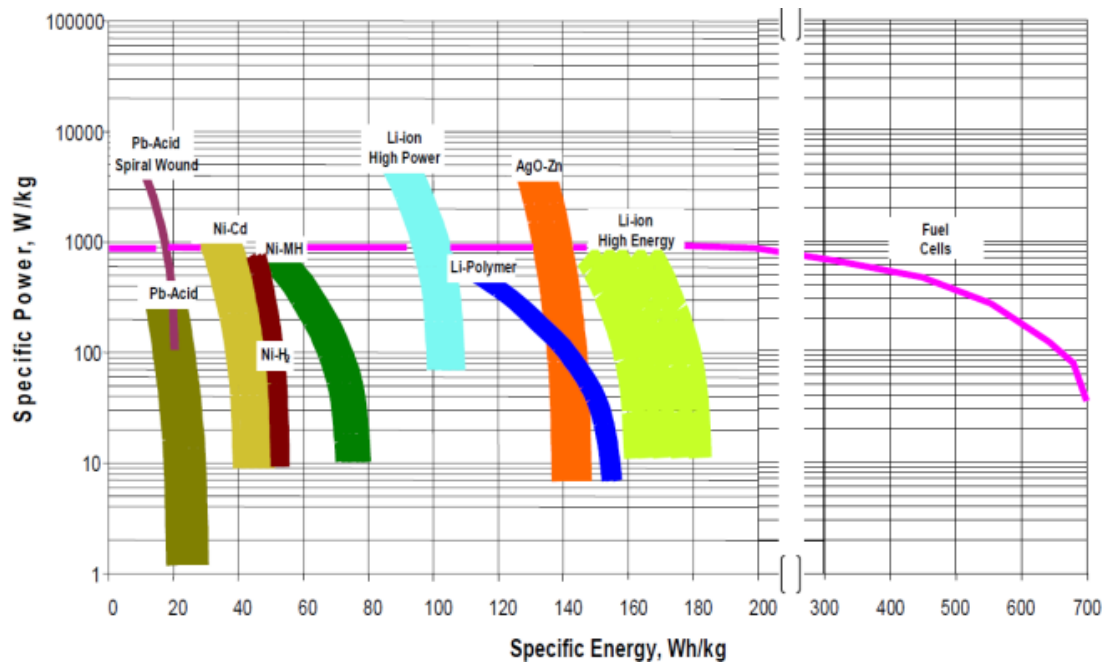


Figure 1.8 – Specific energy power system comparison [15]

Unfortunately, as battery technology continues to improve, fuel cell technology becomes increasingly less desirable for aerospace applications on extraterrestrial planets. The largest elephant in the room is that PEM fuel cells require refueling as they have a finite amount of hydrogen. This could mean that rotorcraft operating on Mars would have a limited operating period before becoming obsolete. The only way to keep the fuel stack fueled would have to be through In-Situ Resource Utilization, where the rotorcraft would have to find its source of hydrogen. Whether this occurs through water deposits on the planet or via some other method, which has yet to be discovered in the location that NOMAAD intends to investigate.

2. Mission Requirements

2.1 Mission Description

The location in question, where NOMAAD aims to explore, is a small valley that is just northeast of Hellas Planitia. Dao Vallis is a valley that was possibly formed by the runoff of an ancient volcano, known as Hadriacus Mons. This runoff drained into Hellas Planitia, which is considered the lowest flat region on the Martian surface, which is about 8 kilometers below the Martian “sea level” [4].

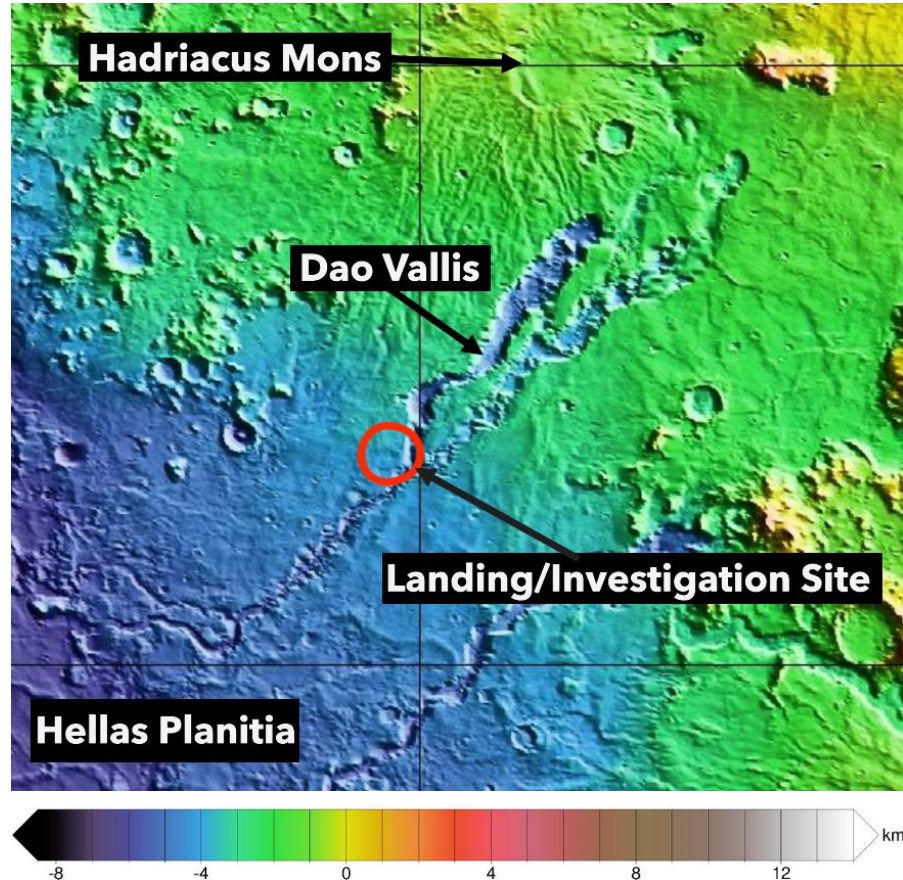


Figure 2.1 – Dao Vallis landing site [4]

For starters, Dao Vallis is a massive valley. Despite its image above, it is quite large in width and length. Exploring all of it would not only be inefficient but also too much work for one rotorcraft to complete. Dao Vallis has numerous locations that are excellent candidates for scientific research, considering its proximity to Hadriacus Mons. Numerous large systems of lava tubes and caves have been exposed due to the structural collapse of the ceilings of the caves and lava tubes surrounding the valley. One cave was of particular interest for exploration. The area circled above expresses the exact location of interest. A photo was taken of this cave, which is shown below.

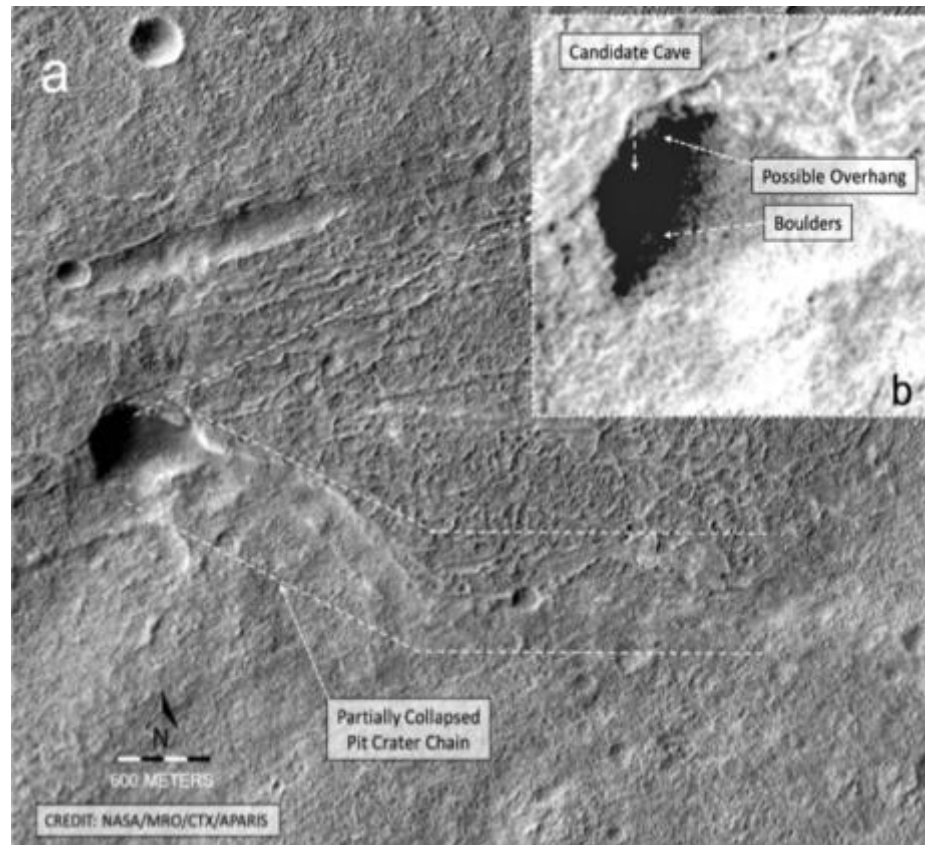


Figure 2.2 – Dao Vallis candidate cave [16]

The circled area from the MOLA data expresses the exact location of this cave. As opposed to Jezero Crater, where Ingenuity flew, this cave is not only deeper but has the potential to have a much higher density than Jezero. The significance of this could mean that NOMAAD could gain lift much more easily than Ingenuity did, thus making power requirements not as high. The table below expresses the atmospheric conditions between the two locations.

Table 2.1 – Jezero Crater versus Dao Vallis atmospheric conditions [4, 5]

Parameter	Jezero Crater (~ -3.2 km)		Dao Vallis Cave (~ -4 km)	
Units	Metric	Imperial	Metric	Imperial
Pressure (K-Pa) (psi)	0.93	0.13	1.00	0.15
Temperature (K) (F)	245.34	-18.06	246.14	-16.62
Density (kg/m ³) (lb/ft ³)	0.02	0.12×10^{-2}	0.02	0.12×10^{-2}

Note that the atmospheric conditions taken for the cave at Dao Vallis are at the supposed surface of the cave before NOMAAD even enters the area of investigation. This means that this is considered the lightest air density that NOMAAD will experience. As it goes deeper into the cave, the ability for the quadcopter to gain lift will only improve.

2.2 Mission Profile

The procedure that NOMAAD will take will consist of two distinct phases. The first, being the mapping phase, will have NOMAAD enter the chosen cave and utilize a LiDAR sensor to map out the interior of the cave itself. Once its mapping duration is complete, the quadcopter will return to the surface to recharge. Once recharged, the quadcopter will then descend back into the cave to investigate the mapped-out area. This process may repeat itself depending on the depth of the cave, in which case, the rotorcraft will map out sections at a time.

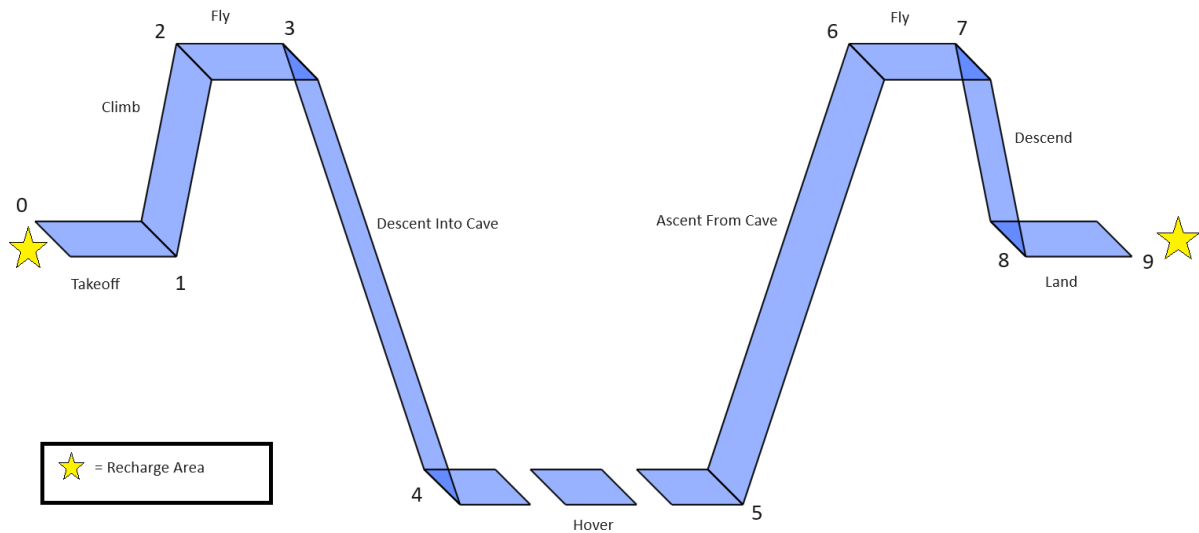


Figure 2.3 – Mapping phase

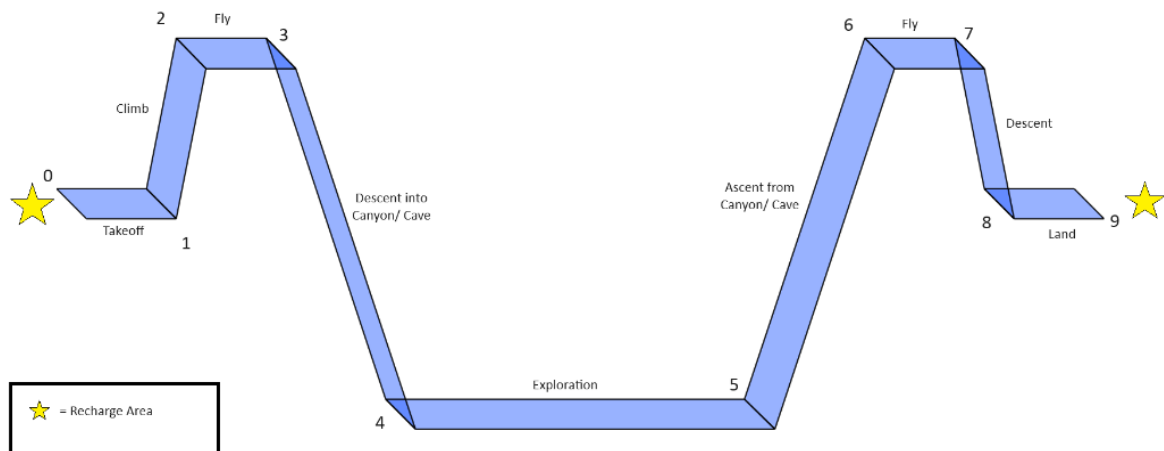


Figure 2.4 – Investigation phase

2.3 Mission Requirements

The table below expresses the criteria required to not only complete the mission, but to outperform its predecessors.

Table 2.2 – Mission requirements [7]

Payload Requirements		kg	lbs		
	Payload weight	5	11		
	Total payload weight (crew + passengers + cargo)	5	11		
			Metric Units		English Units
Performance Requirements	Range	5	km	3	nmi
	Endurance	6	minutes		
	Cruise altitude	200	m	656	ft
	Service ceiling	3,000	m	9,843	ft
	Cruise speed	36	km/h	19	kts
	Maximum speed (if applicable)	108	km/h	58	kts
	Climb rate	3	m/s	1,969	ft/min
	Charging time	24	hours		
Additional Requirements	Must fit inside the Mars Pathfinder Aeroshell (Max Diameter = 2.5 meters)				

To keep the NOMAAD mission cost-effective, the rotorcraft must fit within the design limits of the Pathfinder aeroshell. This aeroshell was used to carry the Sojourner rover and enable communication with Earth. Sending the results of NOMAAD's investigation back to Earth will require this aeroshell. Additionally, it is a field-tested design, which will save money compared to creating a new one specifically for this mission. It is important to note that many of these requirements are purely desired outcomes in terms of performance and payload. However, a select few are critical to ensure mission success.

2.4 Critical Mission Requirements

As mentioned above, NOMAAD will fit inside the Pathfinder aeroshell to reduce the overall cost of the mission. Creating a new one for this mission will not only prove to be impractical but also inefficient in terms of cost. Fortunately, this will greatly aid in the design of this quadcopter as it will have to fit within the defined set of dimensions. The only difficulty that will follow is

that NOMAAD will have to have some sort of folded design to fit properly inside. Once the rotorcraft reaches Dao Vallis, its performance, specifically its battery efficiency, will be critical to explore as much of the cave as possible.

Since the actual depth of the cave is unknown, the battery will need to keep the quadcopter in the air for as long as possible to scan and conduct its research within the cave. Scientists will need as much data as they can receive from NOMAAD's investigation to determine if life can exist on Mars or if there has ever been life before. The battery will be the most crucial factor, as NOMAAD will depend on it to have a successful mission. The amount of flight time that the battery can provide will also determine how much payload is possible for NOMAAD.

2.5 Measures of Merit

Considering these factors, a few of these requirements will be considered measures of merit that can be compared to other conceptualized rotorcraft, such as MSH and Ingenuity. Primarily, flight time will be an excellent comparison. NOMAAD needs to stay up in the air for as long as it can before needing to return to the surface. The coaxial helicopter, Ingenuity, could only fly in Jezero Crater for 90 seconds before requiring a recharge. Even MSH could only operate for about 4.5 minutes, theoretically, before needing a recharge. However, with NOMAAD, the aim is to have the quadcopter be able to operate for 6 minutes to gain the most scientific data. However, Ingenuity did not carry any payload, whereas MSH did. This leads to the next figure of merit that all Martian rotorcraft have been pushing.

Most aircraft on Earth, whether fixed-wing or helicopters, aim to create the lightest possible aircraft to improve fuel efficiency. For Mars, this is not just a performance desire, but a necessity for flight, as the Martian atmosphere is significantly lighter compared to Earth. Therefore, the empty weight of these rotorcraft has to be equipped with the lightest, yet strongest, material possible. Payload weight, however, has been the most difficult to add to Martian rotorcraft. The greater the payload that can be supported, the more scientific data can be retrieved. If Ingenuity could only fly for 90 seconds, without any payload, how long could a rotorcraft, like MSH, last? MSH is conceptualized and has yet to be field-tested. MARV has the same issue. Regardless, the payload weight can be compared to these previous designs to see if NOMAAD can outperform them, and it will be an excellent figure of merit.

2.6 Mission Requirements Discussion

The mission design of NOMAAD is well defined and based on other various mission profiles, like PYTHIA and MSH. Some of the performance values have also been based on these conceptualized rotorcraft. Not all of these mission requirements need to be followed exactly. The only requirement that is an absolute must is the ability for the quadcopter to fit within the specified dimensions of the Pathfinder aeroshell. Other requirements, like the battery and payload weight, are given a little wiggle room but should be expected to improve rather than decrease in weight or battery size.

The rest of the values within the mission requirements are given free range to move around as necessary to complete the mission and to keep the more rigid requirements in place. Whether it be the cruise speed or endurance of the rotorcraft, as long as the design of NOMAAD can fit within the aeroshell and the battery can keep the rotorcraft sustained for cave investigation, these requirements can move in any direction.

3. Weight Sizing

3.1 Weight Sizing Summary

The similar rotorcrafts that were studied were also used for initial weight sizing of NOMAAD. Each weight was obtained from its respective source. Their weight fractions were calculated based on payload weight, empty weight, and battery weight. Once these fractions were determined, the inverse of the payload fraction was multiplied by a 5-kilogram payload to find the new design gross weight. Essentially, each of the studied rotorcraft had its weights adjusted as if they were to carry a 5-kilogram payload. Once each rotorcraft was adjusted, they were then graphed to see how the design gross weight was a function of rotor radius.

Then, the various design gross weights were employed in MATLAB to sweep each design gross weight with a varying rotor radius. A total of four distinct sweeps were conducted, varying air density, tip speed Mach number, number of blades, and payload weight. The code would not only conduct these sweeps to find these factors, but would also calculate important performance numbers, such as thrust disk loading, solidity, and power calculations for hover and forward flight. This, in turn, would calculate the battery weight required for such a mission with a given specific battery energy.

3.2 Weight Sizing Details

3.2.1 Weight Sizing Assumptions

Many of these calculations borrowed numerous formulas from Daniel P. Raymer's book, "Aircraft Design: A Conceptual Approach," and Wayne Johnson's book, "Helicopter Theory". As much as these formulas aided in determining the design gross weight of NOMAAD, many of these formulas also came with variables that could not be determined based on previous rotorcraft. Rather, these variables had to be chosen based on experience with rotorcraft as well as some guidance from the authors of these texts. The first variable that needed to be determined was the specific battery energy.

With the idea of an electric rotorcraft in mind and the extreme isolation that NOMAAD would endure, a strong and reliable battery would be required with a high specific energy. Thus, the Licerion battery was chosen as it is a lithium sulfur battery with a specific energy of 500 watt-hours per kilogram [12]. This could not only result in a lighter battery for NOMAAD but also allow for longer flight times. Additionally, considering the lighter atmosphere, more power would be needed to help keep NOMAAD airborne.

Due to these atmospheric conditions, additional values would also be altered as the rotorcraft would not be able to perform as efficiently as rotorcraft on Earth. Assumed values like the Oswald Efficiency Factor, Figure of Merit, and propulsive efficiency would need to be downsized. The Oswald Efficiency Factor and propulsive efficiency values determine how well the rotors will perform under certain atmospheric conditions. This can also apply to the Figure of Merit, but this performance metric can only be used for rotorcraft of Vertical Takeoff and Landing (VTOL). Typically, all three of these metrics could achieve a value of 0.8 to 0.9 on Earth. A value of 0.9 would be considered a state-of-the-art design. Therefore, for Martian purposes, a value of 0.6 will be utilized for the Figure of Merit and Oswald Efficiency Factor, while a value of 0.7 will be employed for propulsive efficiency.

3.2.2 Similar Aircraft Design Gross Weight Plot

Before we can plug in these values, a graph was generated to see how the rotor radius changed with the design gross weights of each studied rotorcraft that was adjusted to the 5-kilogram payload.

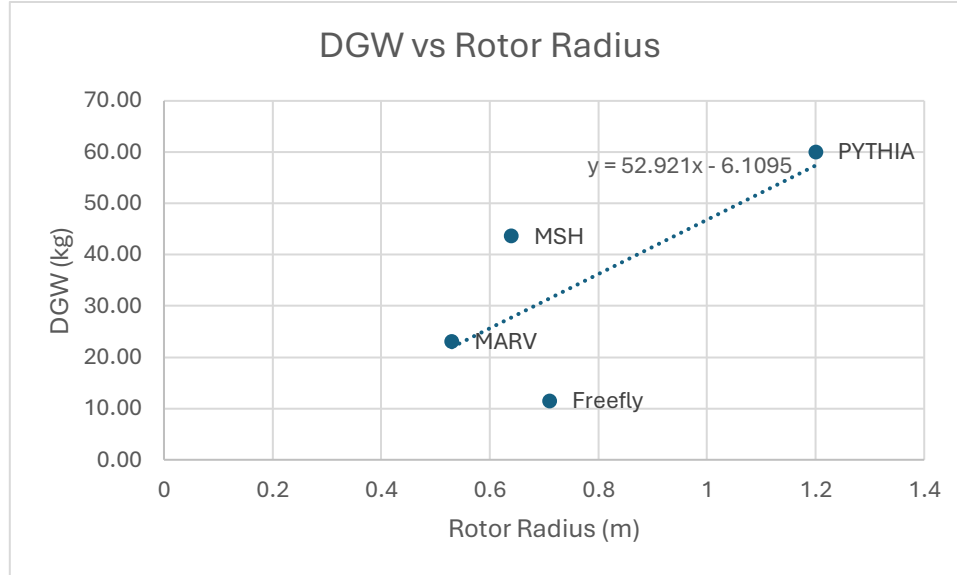


Figure 3.1 – Design gross weight graph

One might wonder why Ingenuity was not included in this figure. The four rotorcraft above were all known to carry a payload for scientific purposes, while Ingenuity did not. Since Ingenuity flew “payload-less”, the rotorcraft would not have a payload fraction, thus making it impossible to adjust Ingenuity to a 5-kilogram payload.

Following the rotorcraft data being inputted, a trendline was generated, alongside its respective equation. Each rotor radius was then placed in an Excel spreadsheet to see how the design gross weight changed with rotor radius. Each of these design gross weights was then input to the MATLAB code for testing.

3.2.3 Rotorcraft Sizing Calculations

A matrix of design gross weights was tested to find out which set of parameters would be the best fit for carrying such a payload. The following formulas were employed, as outlined in Raymer (equations 8, 13–16) and Johnson (equations 1–7, 9–11).

$$A_{disk} = \pi R^2 \quad (1)$$

$$A_{blade} = n_{blade} c R \quad (2)$$

$$AR = \frac{R}{c} \quad (3)$$

$$V_{tip} = aM \quad (4)$$

$$q = \frac{1}{2} \rho V_{tip}^2 \quad (5)$$

$$W_{rotor} = \frac{W_o}{n_{rotor}} \quad (6)$$

$$T_{rotor} = W_{rotor} \quad (7)$$

$$DL_{rotor} = \frac{T_{rotor}}{A_{disk}} = 1.03 \left(\frac{W_{rotor}}{A_{disk}} \right) \quad (8)$$

$$C_{t_{rotor}} = \frac{T_{rotor}}{\rho A_{disk} V_{tip}^2} \quad (9)$$

$$\sigma = \frac{n_{blade} C}{\pi R} \quad (10)$$

$$BL_{rotor} = \frac{C_{t_{rotor}}}{\sigma} \quad (11)$$

The next couple of formulas were utilized specifically for the hover case.

$$P_{ideal_{rotor}} = T_{rotor} \sqrt{\frac{DL_{rotor}}{2\rho}} \quad (13)$$

$$P_{hover_{rotor}} = \left[\frac{1.03 W_{rotor}}{FM} \sqrt{\frac{1.03 \left(\frac{W_{rotor}}{A_{disk}} \right)}{2\rho}} \right] \left(\frac{1}{0.97} \right) \quad (14)$$

$$P_{climb_{rotor}} = \left[\left(\frac{1.03 W_{rotor}}{FM} \sqrt{\frac{1.03 \left(\frac{W_{rotor}}{A_{disk}} \right)}{2\rho}} \right) + \frac{W_{rotor} V_{climb}}{2} \right] \left(\frac{1}{0.97} \right) \quad (16)$$

The next equations were utilized to determine the power calculations for forward flight.

$$P_{cruise_{rotor}} = \frac{V_{cruise}}{\eta_p} \left(q \left(\frac{D}{q} \right) + \frac{W_{rotor}^2}{4eqA_{disk}} \right) \left(\frac{1}{0.97} \right) \quad (15)$$

$$P_{ffclimb_{rotor}} = \frac{V_{cruise}}{\eta_p} \left(q \left(\frac{D}{q} \right) + \frac{W_{rotor}^2}{4eqA_{disk}} + W_{rotor} \sin \gamma \right) \left(\frac{1}{0.97} \right) \quad (16)$$

The rest of the formulas used were to find power loading and energy calculations.

$$\frac{W}{P_{rotor}} = \frac{W_{rotor}}{(P_{hover_{rotor}} + P_{cruise_{rotor}} + P_{climb_{rotor}} + P_{ffclimb_{rotor}})} \quad (17)$$

$$E_{climb} = \left((P_{climb_{rotor}})(n_{rotor}) \right) \left(\frac{t_{climb}}{3600} \right) \quad (18)$$

$$E_{cruise} = \left((P_{cruise_{rotor}})(n_{rotor}) \right) \left(\frac{t_{cruise}}{3600} \right) \quad (19)$$

$$E_{hover} = \left((P_{hover_{rotor}})(n_{rotor}) \right) \left(\frac{t_{hover}}{3600} \right) \quad (20)$$

$$E_{ffclimb} = \left((P_{ffclimb_{rotor}})(n_{rotor}) \right) \left(\frac{t_{climb}}{3600} \right) \quad (21)$$

Each of the calculations with a rotor subscript is solved with a single rotor. Therefore, the values of these equations can simply be multiplied by the number of rotors that will be in use, which would be four in this case.

3.3 Weight Sizing Results

Utilizing Equations 1–21, the MATLAB code iterated through each design gross weight to be tested, varying the rotor radius at each sweep. These results were then exported to an Excel spreadsheet for further analysis. The following results were chosen through a combination of similar aircraft, serving as a base for narrowing down my choices, as well as performance data, such as solidity, to further refine the selection. The remaining choices were eliminated based on preference to arrive at the following values.

Table 3.1 – Weight sizing results

Parameter	Calculated Value (MATLAB)	
	Metric	Imperial
Total Payload Weight (passengers + crew + cargo)	5.00 kg	11.02 lb
Empty Weight	36.78 kg	81.09 lb
Battery Weight	4.24 kg	9.35 lb
Maximum Takeoff Weight ($W_p + W_e + W_b$)	41.52 kg	91.54 lb
Payload Weight Fraction (W_p/W_o)	0.12	
Empty Weight Fraction (W_e/W_o)	0.89	
Battery Weight Fraction (W_b/W_o)	0.10	
Blade Aspect Ratio	9.94	
Oswald Efficiency Factor (e) (estimated)	0.6	
Propeller Efficiency (estimated)	0.7	
Range	5 km	3 nmi
Power Required for Cruise	5.86 kW	
Power Required for Climb in Forward Flight	7.46 kW	
Power Required for Climb	58.37 kW	
Power Required for Hover	5.38 kW	
Battery Specific Energy Density	500 Wh/kg	
Battery Total Energy (Wh)	2,120.00 Wh	

Additionally, the sizing results for NOMAAD, specifically the design gross weight, can be shown in the figure below to illustrate where the quadcopter compares to other rotorcraft from Figure 3.1. Keep in mind that these rotorcraft data points are adjusted to carry a 5-kilogram payload as opposed to their originally designed payload weight to create a more accurate comparison.

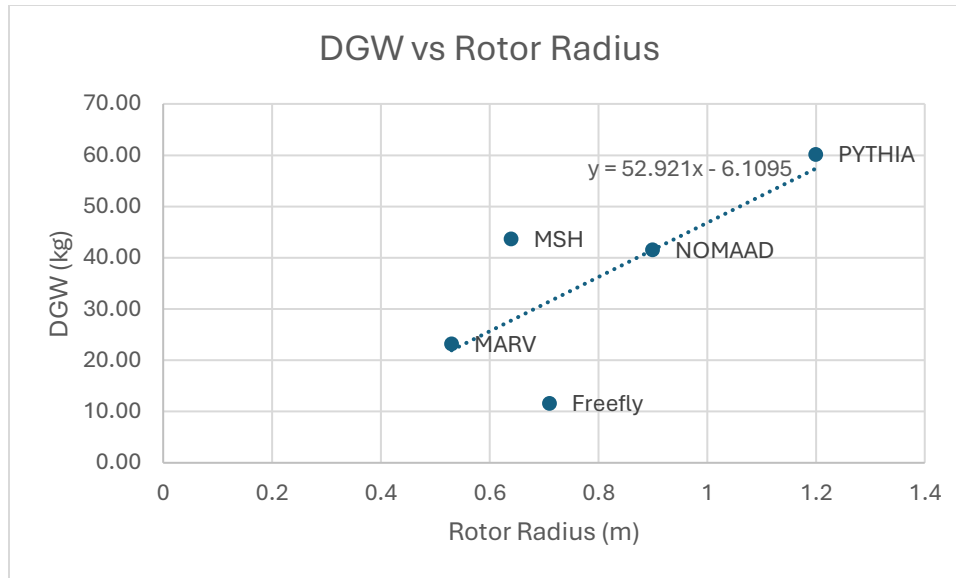


Figure 3.2 – Design gross weight graph with NOMAAD

3.4 Weight Sizing Discussion

Once all the design gross weights were evaluated with each sweep, the final weights were determined for NOMAAD. Each of the values that were calculated for NOMAAD was also calculated for each studied rotorcraft. These calculations aided in determining the most reasonable values for a quadcopter carrying a 5-kilogram payload. This method helped narrow down many of the various options that could be chosen for such a mission. Eventually, the choices came to be narrowed down to two, which at that point were determined based on preference. The rotor radius chosen, being 0.9 meters, was chosen as not only did the solidity match closely with PYTHIA and MSH, but it would best fit within the Pathfinder Aeroshell.

These parameters for NOMAAD turned out to be reasonable, as MARV carried a 10.8-kilogram payload with a design gross weight of 50 kilograms. Additionally, the rotor radius is long enough to generate enough lift while lessening the power requirements. However, the possibility of resizing in the future is not out of the question. Even with these values being within a reasonable range, performance metrics still need to be evaluated to determine if NOMAAD will even be able to lift off the ground with this payload and battery.

4. Configuration

4.1 Overall Configuration

NOMAAD will be an autonomous quadcopter with a fixed quadrupedal landing gear. Its rotor blades will be made of a carbon fiber polymer, and its geometry will be based on Ingenuity's blades. Ingenuity was the primary inspiration for its design. Similar rotorcraft also played various roles in its design, such as the MSH and the Freefly AltaX. Shown below are the different views of this rotorcraft.

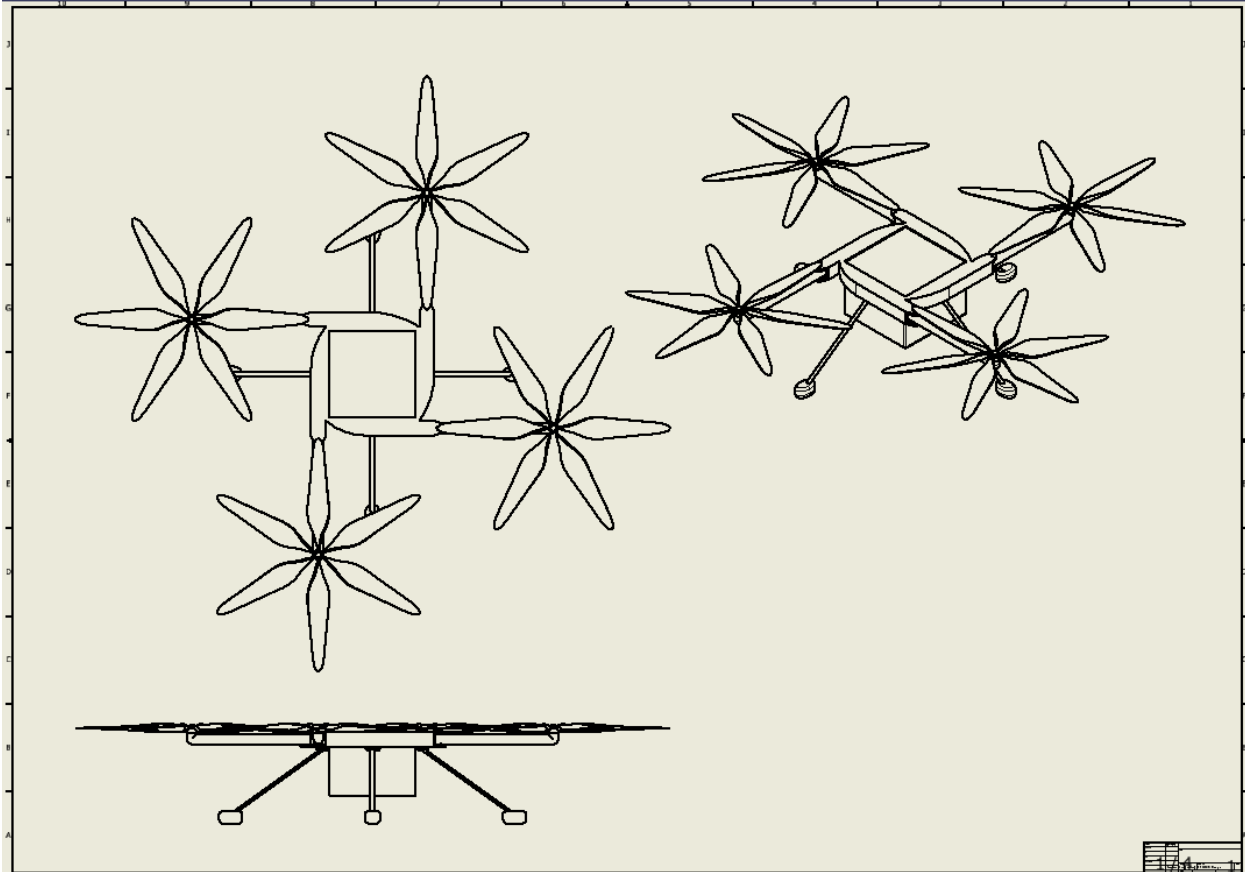


Figure 4.1 – NOMAAD views

4.2 Rotorcraft Center Configuration

For instance, the design of the center of NOMAAD was inspired by the Freefly AltaX quadcopter. Its retractable arm design aided in the design of its arms. This was desirable, not only for compactability, but also to lessen the rotor span to fit well inside the Pathfinder Aeroshell. This would allow for the mission to Dao Vallis to be far more cost-effective. Additionally, similar to MSH, the rotorcraft would also have a square solar panel in the middle of the rotorcraft, thus allowing for quick and easy power storage.

4.3 Propulsion Configuration

NOMAAD will require four different rotors, all powered by a single electric battery at the rotorcraft's center. The reasoning behind this choice was that the four-rotor configuration would increase stability for lava tube investigation as opposed to a coaxial configuration. Additionally, this was also chosen based on personal preference. The battery itself will be a lithium-sulfur battery created by Sion Power. Due to the Licerion battery's high specific energy as opposed to most other lithium batteries, it was the ideal choice for keeping the endurance of NOMAAD high.

4.4 Rotor Configuration

Ingenuity was the first and only helicopter to date that had flown on the Martian surface. After 72 successful flights, one of its blades got damaged, which resulted in the obsolescence of the rotorcraft altogether. Regardless of its accident, as one might say, "If it isn't broken, don't fix it". Considering how many successful flights Ingenuity has completed, NOMAAD will be employing the same blades. However, as opposed to Ingenuity's 0.64 rotor radius, these blades will conform to a 0.9 rotor radius that NOMAAD will have.

4.5 Folded Configuration

At NOMAAD's current configuration, it would be unable to fit within the Pathfinder Lander. Thus, the quadcopter would have to be slightly downsized to get it to Dao Vallis. Inspired by the Freefly AltaX, the rotorcraft's arms would fold in, as well as the blades themselves. This would create a temporary compact design to get it to Mars. It is important to note as well that NOMAAD will only be folded like this for its journey there. Once it makes landfall, it will unfold and will never refold itself again. This will also make things much easier for the rotorcraft's manufacturing.

4.6 Landing Gear Configuration

Taking inspiration, once again, from Ingenuity, its landing gear will consist of four fixed stilts that will be bolted to the undercarriage of NOMAAD. The feet at the bottom will be made of polymer or an elastic material that would aid in cushioning the rotorcraft's landings. This configuration will be simple and effective, thus continuing to save the overall cost of the mission.

4.7 Configuration Selection Discussion

Given the field-tested design of Ingenuity's blades and the overall simplicity of the configuration, NOMAAD will be well prepared to carry out scientific missions on Mars. Before a rotorcraft can even land on the Martian surface, the design must be cost-effective enough to make such a mission feasible. Ultimately, funding presents the biggest obstacle, but if the mission can be proven to cost as little as possible, securing the necessary funds will be much more achievable. The simplicity of NOMAAD's design supports this goal. Additionally, its foldable design allows it to fit within an already tested and manufactured aeroshell. However, that doesn't necessarily mean that this configuration or design is perfect in all respects.

This is NOMAAD's first iteration, meaning that plenty more iterations will be required to determine the validity of these configurations and parameters. One important thing to note is that the folded design of NOMAAD may be mechanically complex. The quadcopter will have to

undergo a few folding procedures to get it into its folded state. Determining the complexity of this design is difficult to measure, but considering that it will only need to be folded once, it may be worthwhile.

5. Propulsion System Design

5.1 Motor Selection

For NOMAAD to operate properly on Mars, the quadcopter will employ solar power to allow for the mission to last as long as possible. Solar energy will power four different rotors. Two of the rotors will spin in the opposite direction from the other two. To be more specific, the rotor that is diagonally opposite the other will spin counterclockwise, while the others will spin clockwise. The reason behind this is to counteract the natural force of torque that the rotors create while spinning. This power system will be similar to other rotorcraft, such as Ingenuity and MSH.

5.2 Propeller Design

After the initial weight estimates had concluded, the Excel spreadsheet that was created from the MATLAB code aided in determining the number of blades and the rotor radius for the design. MSH also offered some help in determining the weight of these blades, as their weight fractions were multiplied by the design gross weight. The result of this work is expressed in the table below.

Table 5.1 – Rotor blade results via weight sizing

	Imperial Units	Metric Units
Number of Blades	6	
Rotor Radius	2.95 ft	0.90 m
Rotor Pitch	Variable	
Propeller Cruise Efficiency	0.7	
Propeller Weight	8.91 lb	4.04 kg

5.3 Electric Propulsion System

Due to NOMAAD's dependency on its battery for mission success, as mentioned earlier, the Licerion battery will be utilized for NOMAAD's mission. This will ensure longer flight times, giving the quadcopter more than enough time to conduct its investigation of the lava tubes and caves within the area. Ingenuity utilized lithium-ion batteries to complete its 90-second flights. However, Ingenuity was meant to fly alone and not for investigation; thus, its batteries were not considered for NOMAAD. The specifications for the Licerion battery are listed below.

Table 5.2 – Battery specifications [13]

Battery Specs	Metric Units
Battery Chemistry Type	Lithium-Sulfur
Battery Specific Energy (Wh/kg)	500
Battery Pack Nominal Voltage	3.82
Operating Temperature (K)	243.15 – 318.15
Pulse Discharge Rate (60 s) (A)	360 (5C Rate)
Battery Capacity	72 Ah
Battery Weight	635 g

Since the weight of the battery is known, the battery capacity can be calculated. This battery can not only last longer than the ones that are currently in use for such rotorcraft, but it can also operate at low temperatures. Of course, a thermal blanket will be required to keep the electrical systems warm.

5.4 Propulsion System Design Discussion

With the help of MSH and the thoroughness of its design, the propulsion system of NOMAAD was determined to be well suited for such a mission. Its solidity and thrust disk loading were similar to those of MSH and PYTHIA, confirming the appropriateness of the rotor radius. Additionally, considering the payload weight, the rotor radius and blade weight were reasonable for carrying such a load. The power calculations appeared realistic and reasonable as well, as it was reflected in the weight of the battery itself.

Using MSH's weight breakdown for its battery and converting it to a weight fraction, created a battery weight that was different from that of the one calculated from the MATLAB code. Fortunately, this discrepancy proved to be useful in that it created a ballpark area for what the battery weight should roughly be. The table for this will be shown later. Keep in mind that this is an initial iteration where the battery weight calculated from MATLAB had a small difference from MSH's weight fraction calculation. MSH's mission profile is different from opposed to NOMAAD, which could make up for the discrepancy. Future iterations will be needed to determine this change.

6. Center Design of the Quadcopter

6.1 Rotorcraft Center Layout

The center design of NOMAAD drew heavy inspiration from the Freefly AltaX quadcopter. The primary reason for this design choice was for the benefit of compactability. To ensure that NOMAAD would be able to downsize itself significantly to fit within the parameters of the aeroshell, the arms would have to be retractable. This would only be one of the mechanisms to make this rotorcraft smaller. However, the Freefly AltaX wasn't the only rotorcraft that NOMAAD drew inspiration from.

Ingenuity would also play a significant role in the center design. The square area at the top of the quadcopter will be where the solar panel is located to recharge the rotorcraft. Additionally, the cube that is just below the rotor arms will be the location of all NOMAAD's necessary equipment to complete its mission. Components such as the Licerion battery and the LiDAR sensor will be integrated within this part of the rotorcraft. This section will be covered with a thermal blanket to prevent all the electrical components from freezing.

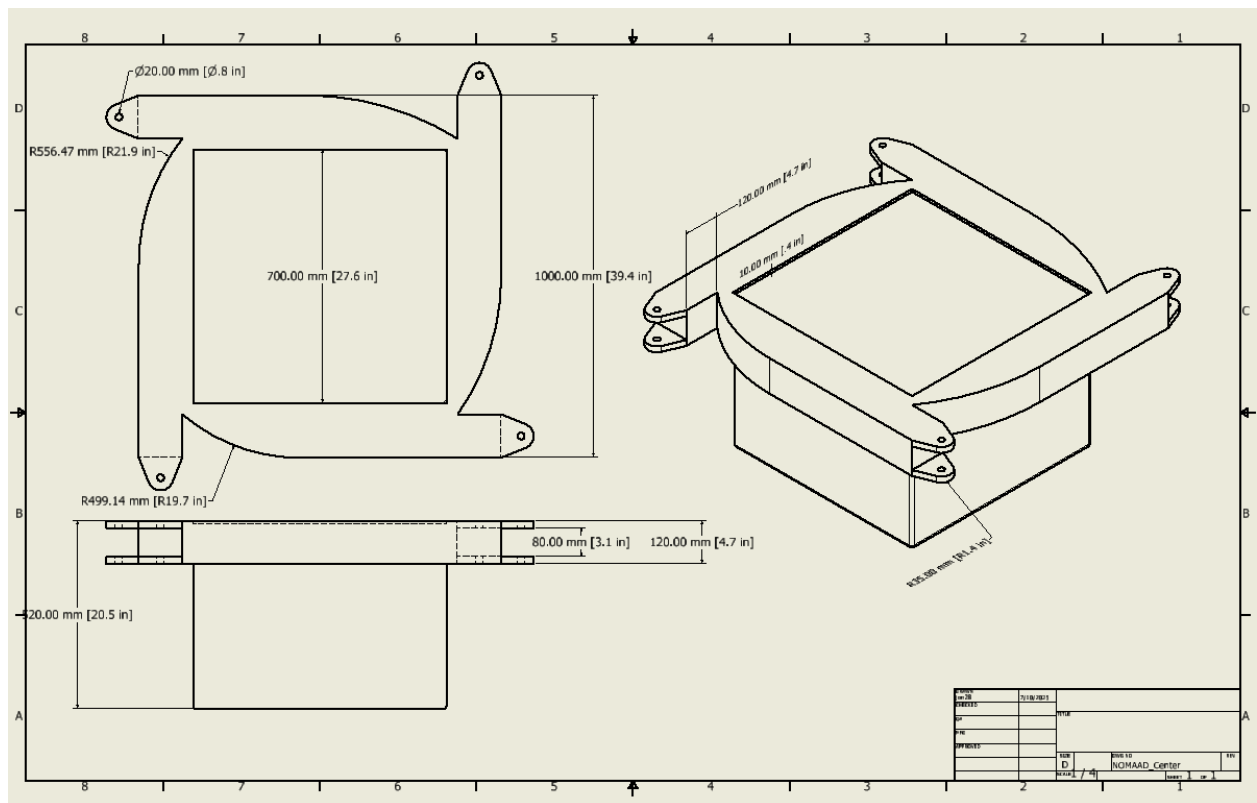


Figure 6.1 – NOMAAD center design

6.2 Rotorcraft Center Design Discussion

The primary goal of this design was with the Pathfinder Lander in mind. Considering how crucial this requirement is to meet, this goal was considered a top priority. Fortunately, along with some other mechanisms and folding techniques which will be discussed later, this design works

perfectly for NOMAAD's purposes. This design was also created with the intent of keeping everything symmetrical. This would not only keep the center of gravity in the middle of the xy-plane but would ensure proper stability for the rotorcraft during flight. It is important to note that some creative liberties were taken in designing the solar panel area as well as the cube beneath the rotors. The box should have more than enough space to hold all of the scientific instruments necessary, and the solar panel should be large enough to charge the battery quickly.

7. Rotor Design

7.1 Rotor Design

7.1.1 Rotor Design Criteria

Due to the thin atmosphere on Mars, typical helicopter blades used on Earth would struggle to gain lift effectively. Thus, entirely new and unconventional helicopter blades would be required to gain the lift needed for extraterrestrial flights. As mentioned earlier, blades with a wider surface area must be used to compensate for the reduced air density. Rotorcraft like MSH also ensured that the blade would be thin as well to have the best chance of attaining the required lift. With some of these ideas in mind, and after deep research, a well-researched and effective airfoil was determined for NOMAAD's potential use.

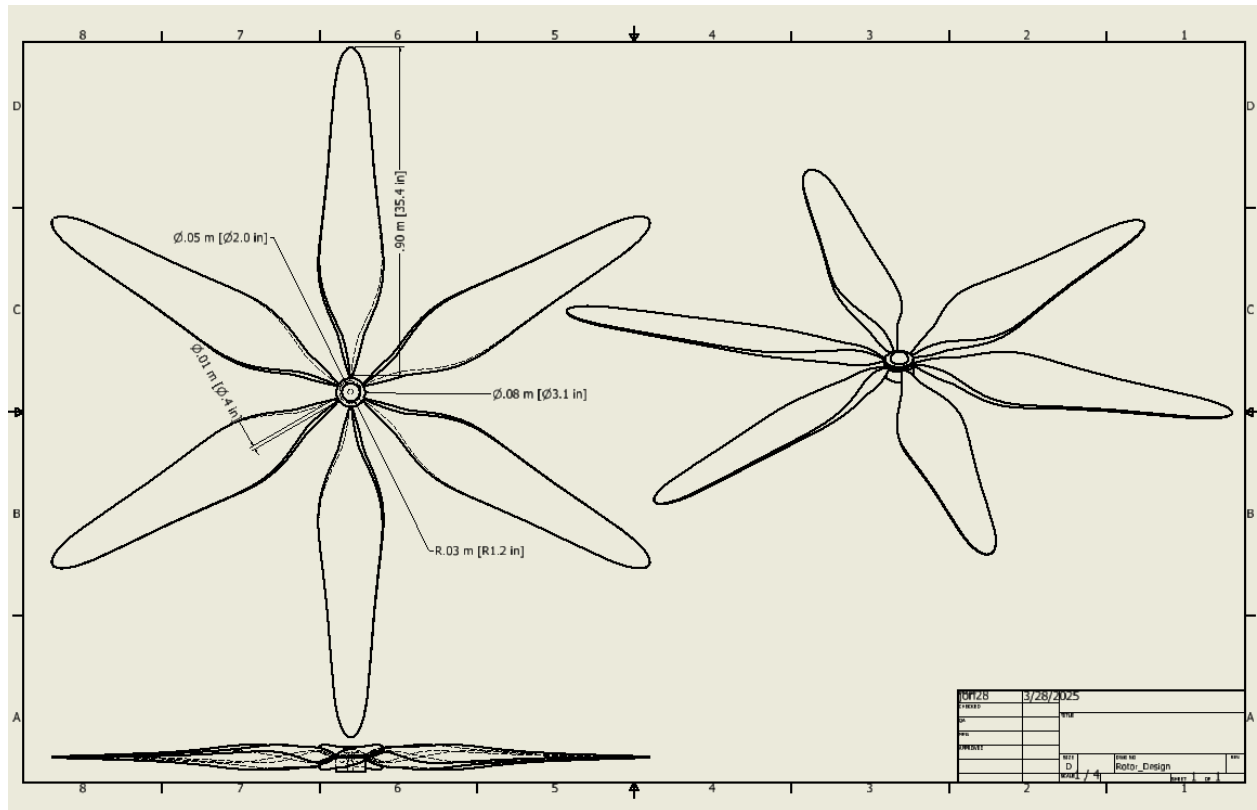
7.1.2 Rotor Blade Design

Since Ingenuity has been the only rotorcraft to fly within the Martian atmosphere successfully, it only made sense to follow in its footsteps. The blades utilized by Ingenuity were manufactured by AeroVironment Incorporated, in collaboration with NASA [8]. They were designed specifically for this mission and were made to perform particularly well within the Martian atmosphere. Furthermore, these blades operate at a maximum speed of 3 meters per second vertically and 10 meters per second horizontally [8]. Not only are these blades well-researched and field-tested, but they also allow the coordinates of these blades to be altered to fit within any range of rotor radii. The table below expresses the original fractions of Ingenuity's blades. These fractions were then fitted with the determined rotor radius of 0.9 meters.

Table 7.1 – Ingenuity rotor blade data [8]

Blade Twist (Θ) (deg)	Ingenuity Data			NOMAAD Fit ($R = 0.9$ m)		
	Radial Coordinate Fraction (r/R)	Chord Fraction (c/R)	Thickness Fraction (t/c)	Radial Coordinate (r) (m)	Chord (c) (m)	Thickness (t) (m)
16.326	0.0908	0.0506	0.973	0.08172	0.04554	0.04431
16.716	0.1158	0.0631	0.707	0.10422	0.05679	0.040151
17.316	0.1551	0.0967	0.391	0.13959	0.08703	0.034029
17.616	0.2	0.1407	0.22	0.18	0.12663	0.027859
17.216	0.2472	0.1758	0.14	0.22248	0.15822	0.022151
15.916	0.295	0.1968	0.098	0.2655	0.17712	0.017358
14.142	0.3429	0.2021	0.074	0.30861	0.18189	0.01346
12.067	0.3903	0.1968	0.06	0.35127	0.17712	0.010627
10.703	0.4369	0.1863	0.052	0.39321	0.16767	0.008719
9.495	0.4826	0.1743	0.05	0.43434	0.15687	0.007844
8.433	0.5271	0.1627	0.05	0.47439	0.14643	0.007322
7.486	0.5704	0.153	0.05	0.51336	0.1377	0.006885
6.632	0.6121	0.1446	0.05	0.55089	0.13014	0.006507
5.858	0.6523	0.1375	0.05	0.58707	0.12375	0.006188
5.156	0.6908	0.1314	0.05	0.62172	0.11826	0.005913
4.512	0.7274	0.1259	0.05	0.65466	0.11331	0.005666
3.926	0.7621	0.1209	0.05	0.68589	0.10881	0.005441
3.388	0.7947	0.116	0.05	0.71523	0.1044	0.00522
2.901	0.8252	0.1111	0.05	0.74268	0.09999	0.005
2.461	0.8535	0.1058	0.05	0.76815	0.09522	0.004761
2.061	0.8794	0.1001	0.05	0.79146	0.09009	0.004505
1.706	0.903	0.0935	0.05	0.8127	0.08415	0.004208
1.39	0.9241	0.086	0.05	0.83169	0.0774	0.00387
1.117	0.9427	0.0775	0.05	0.84843	0.06975	0.003488
0.881	0.9588	0.0679	0.05	0.86292	0.06111	0.003056
0.543	0.9722	0.0573	0.05	0.87498	0.05157	0.002579
0.179	0.983	0.046	0.05	0.8847	0.0414	0.00207
0.057	0.9912	0.0341	0.05	0.89208	0.03069	0.001535
0.019	0.9966	0.0223	0.05	0.89694	0.02007	0.001004
0	1	0.0123	0.05	0.9	0.01107	0.000554

With each of these values found, they were then input into Autodesk Inventor. Starting at the rotor hub, each radial coordinate came with a set of chord lengths and thicknesses. Along each radial coordinate, a rectangle was formed along with its respective twist angles. Of course, each rectangle would come with the corresponding airfoil, but the image below shows a version that was able to be constructed in a simplified manner.



Once the rectangles were drawn out, the figure was then lofted to go through each rectangle along the radial coordinates until it reached the rotor radius of 0.9 meters. A mirrored design was also created, with the twist angle going in the opposite direction. Out of the four rotors in total, two of them would be mirrored. These opposite ones would spin in a counterclockwise direction, while the other two would spin in a clockwise direction. The reason for this would be to balance out the natural torque that would be generated from the other two rotors. Once these rotors were finalized, the following parameters were identified.

Table 7.2 – Blade parameters

Parameter	Metric Units	Imperial Units
Reference Blade Area (A_{blade})	0.103 m ²	160.3 in ²
Aspect Ratio (AR)	9.945	
Rotor Radius (R)	0.9 m	35.4 in
Number of Blades per Rotor	6	
Geometric Twist Angle	16.33 deg	

7.2 Airfoil Selection

7.2.1 Airfoil Criteria

To make the blade work as efficiently as possible within the thin Martian atmospheric conditions, not only was a large surface area for the blades needed, but the airfoil itself needed to be as thin as possible. As opposed to most airfoils used for flight on Earth, such as the Clark Y, flatter, cambered airfoils tend to outperform these conventional airfoils. These thinner airfoils, surprisingly, work better at low Reynolds numbers.

7.2.2 Airfoil Selection

The airfoil in question is the clf5605 airfoil. AeroVironment utilized this airfoil for Ingenuity's blades as well. Since they were already field-tested to work well in Martian conditions, it only made sense to utilize these blades again for NOMAAD. The airfoil is very thin and has a minimum thickness of 5%. The airfoil geometry is shown below.

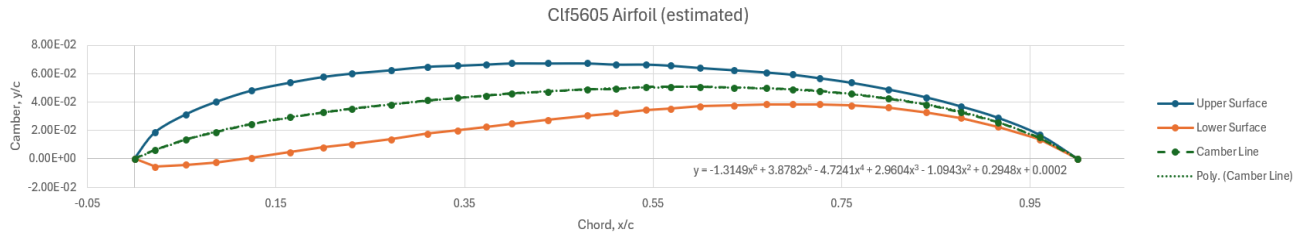


Figure 7.2 – Clf5605 airfoil geometry

The airfoil was also employed for MSH's blades as well, thus making this choice a no-brainer for NOMAAD to use for its mission.

7.2.3 Airfoil Analysis

Due to the thinness of the airfoil and the low Reynolds numbers, this benefits the analysis. In order to determine the coefficient of lift at each radial coordinate, thin airfoil theory was employed. The following equation of the camber line was used.

$$z = -1.3149x^6 + 3.8782x^5 - 4.7241x^4 + 2.9604x^3 - 1.0943x^2 + 0.2948x - 0.0002 \quad (22)$$

Once the derivative of this equation was determined and then converted to polar coordinates, the equation was then plugged into the following equations.

$$\alpha_{lo} = -\frac{1}{\pi} \int_0^\pi \frac{dz}{dx} (\cos\theta - 1) d\theta \quad (23)$$

$$x = \frac{c}{2} (1 - \cos\theta) \quad (24)$$

$$\alpha_{local} = \tan^{-1} \left(\frac{\Omega r}{V_i} \right) \quad (25)$$

$$\alpha_{eff} = \alpha_{local} - \varphi \quad (26)$$

$$C_l = 2\pi[\alpha_{eff} - \alpha_{lo}] \quad (27)$$

$$C_d = C_{d_{lo}} + kC_l^2 \quad (28)$$

Once the calculations were completed for each section, the following parameters were identified.

Table 7.3 – Airfoil analysis results

C_{root}	0.04554 m (0.14941 ft)
C_{tip}	0.01107 m (0.03632 ft)
Root Airfoil Reynolds Number	1,399
Tip Airfoil Reynolds Number	3,745
Average Airfoil Reynolds Number	19,561
Airfoil Name	Clf5605
Airfoil C_{lmax}	10.2

Additionally, the coefficient of lift was plotted along the blade span as well as against the coefficient of drag.

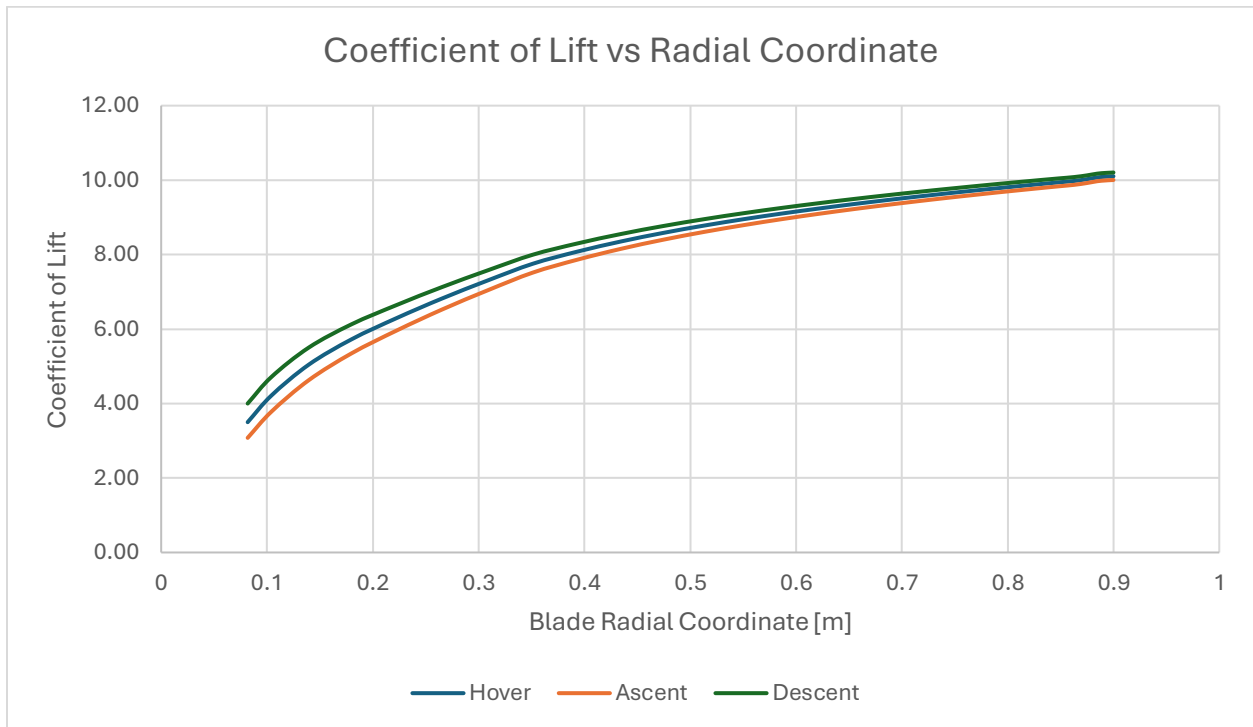


Figure 7.3 – Clf5605 coefficient of lift along the blade span

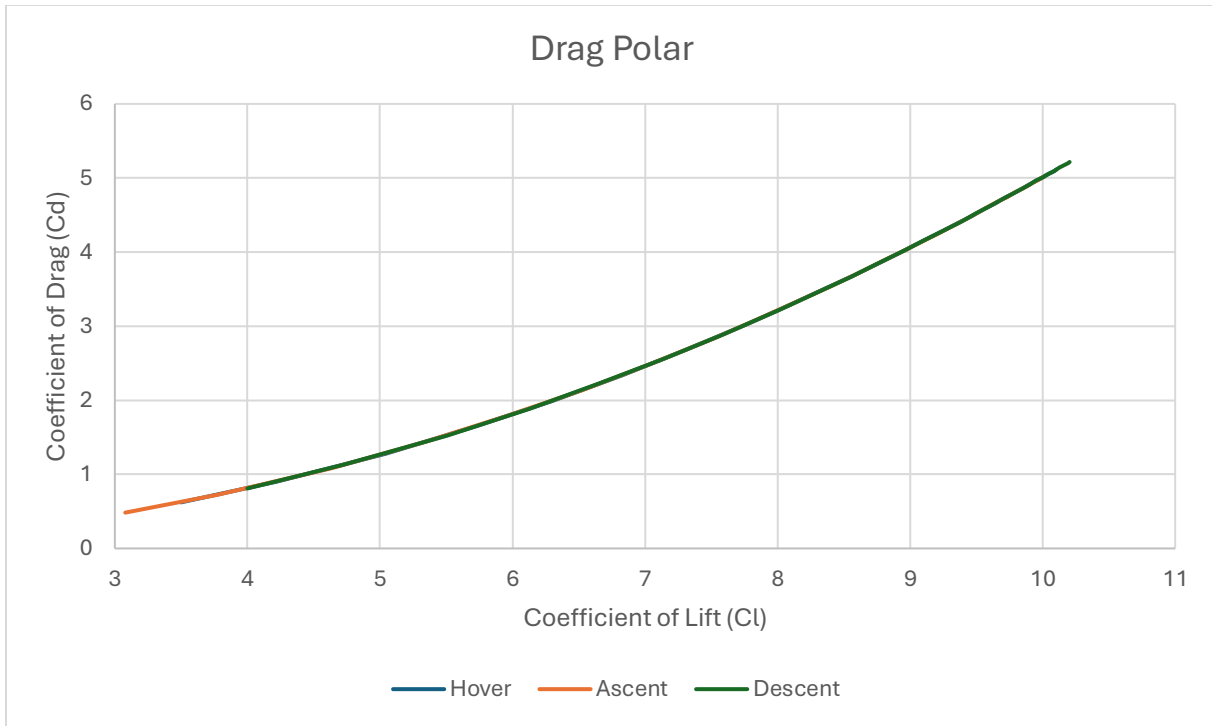


Figure 7.4 – Clf5605 drag polar

7.3 Rotor Design Analysis

The Clf5606 airfoil was specifically designed for the Martian atmosphere, and the airfoil analysis confirms this. The lift coefficient, approximately 10.2, is typically too high for most rotorcraft on Earth. However, due to the significantly lower air density and Reynolds numbers, this is expected. Additionally, the descent exhibits a slightly higher coefficient of lift along the blade span, which is also likely as the inflow would be reversed when descending. Overall, the coefficient of lift increases steadily towards the tip of the blade, even with a high blade twist at the root, making this airfoil an excellent choice for NOMAAD's mission.

7.4 Rotor Design Discussion

Due to the infancy of rotorcraft on extraterrestrial planets, branching out to other types of airfoils or blades would not be beneficial nor practical. At this moment in time, going with what has been field-tested and known to work was the obvious choice. The blade geometry for Ingenuity was easily accessible thanks to the Aeromechanics Branch at NASA Ames. Unfortunately, the airfoil had no coordinate system for the airfoil itself. Thus, an estimated coordinate system had to be created to conduct the thin airfoil theory analysis. This may have caused inaccuracies in the determination of the coefficient of lift at each radial coordinate, but the coefficient of lift seems reasonable for such a mission for NOMAAD.

Fortunately, the average Reynolds number matches the reports found for MSH, noting that the Reynolds number for MSH's mission, with a Mach of 0.5, has a value of 19,100. This aligned nicely, revealing it to be 19,561, particularly because NOMAAD's mission operates in a higher

air density compared to MSH. Overall, the rotor design is robust and a safe bet for a Martian scientific mission.

8. Folded Design

8.1 Folded Design

Before any project can get off the ground, funding will be a necessity. If the federal government doesn't fund it, as NASA is, then it would need funding from investors or some other means. To receive such funding, the mission would not only need to be well researched and proven to be beneficial to science but would also have to be as cost-effective as possible. To keep the price of NOMAAD's mission to a minimum, an already designed and field-tested lander would be a huge step in the right direction. Thus, the Pathfinder Lander was chosen as the lander that would house NOMAAD.

This lander was host to the Sojourner rover that was also set for Martian exploration. The lander did not just provide a safe way for the rover to land on Mars, but it was also a base of operations. Communications back to Earth were one of its key features, which will be extremely useful as NOMAAD will need to send back its findings to Earth for further analysis by scientists. However, as useful as this aeroshell is, it has limited space. To be specific, a diameter of 2.5 meters is the maximum space that NOMAAD would have to fit inside the lander. To ensure a snug and safe trip, the quadcopter would need a folded design to fit within the lander.

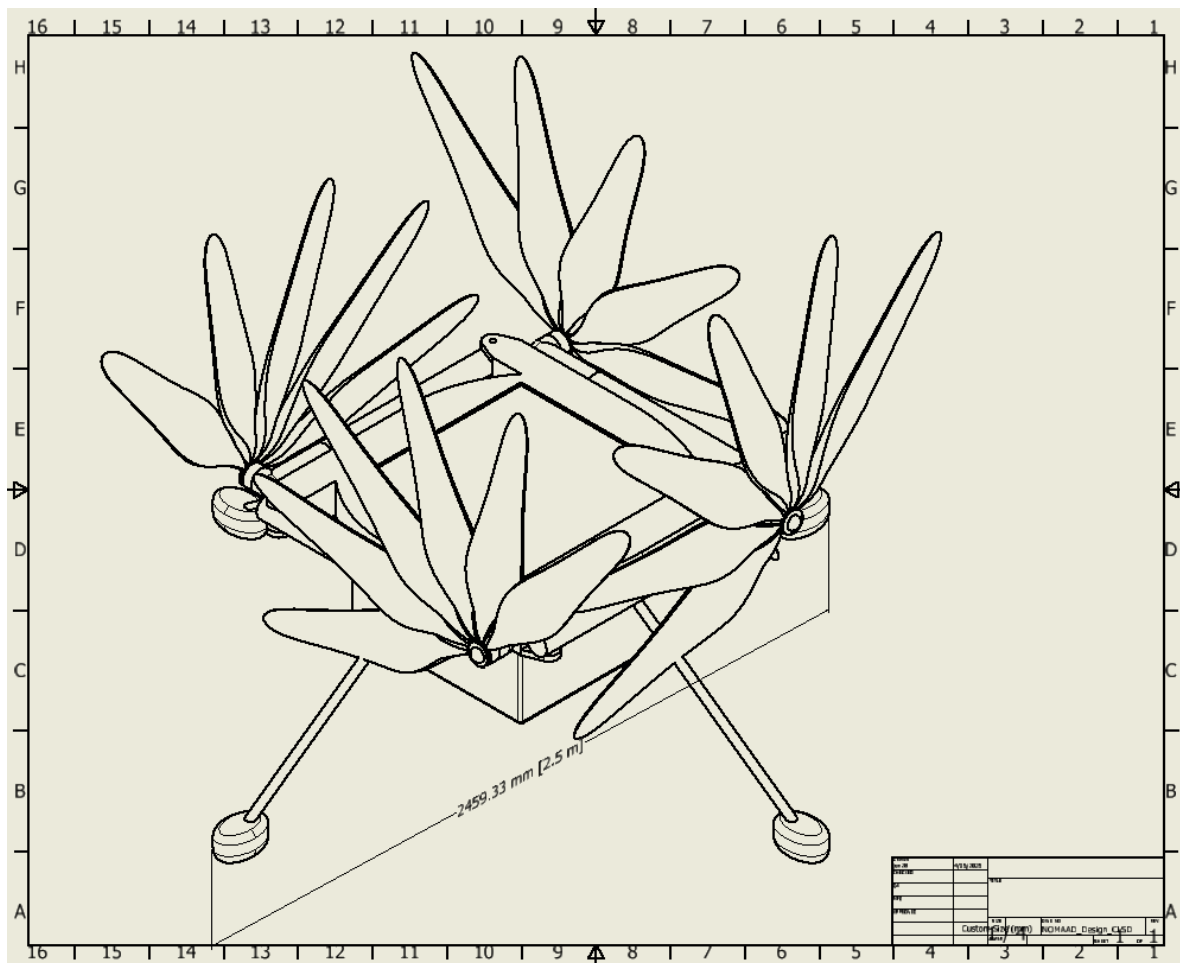


Figure 8.1 – NOMAAD folded design

8.2 Folded Design Discussion

As shown in the figure above, the landing gear has an exact width of 2.5 meters, which would give NOMAAD a snug fit into the Pathfinder Lander. However, the biggest challenge was to downsize the blades and rotors realistically, as the blades themselves have a large surface area. This made the folding method far more difficult. As mentioned earlier, the folding method was loosely inspired by the Freefly Alta X as the rods fold inward. Mechanically, the folding design is not only possible, but feasible as well. Unfortunately, the lander has a diameter of 2.5 meters, meaning that the landing gear might be stepping outside its bounds. To ensure the rotorcraft fits within the lander, the landing gear may need to be retractable in some way to keep everything close together. One suggestion may be to where some sort of spring system may be put in place to where the landing gear rods collapse in on themselves. Once the quadcopter lands on Mars, the springs will release, allowing for an easy deployment as well as aiding in shock absorption. Additionally, this will be mechanically simple as well.

9. Weight and Balance

9.1 Component Weight Breakdown

The weights of each component were determined based on MSH's weight breakdown, as it was considered the most complete out of all the other similar aircraft. Additionally, the reputation of the engineers behind the hexacopter design was also considered. Hence, the weights of each component of MSH were then divided by the design gross weight to create a weight fraction. The design gross weight fraction would have a fraction of 1. Therefore, the weight fractions were then taken and multiplied by the design gross weight of 41.52 kilograms, which was taken from the initial sizing estimates by MATLAB. The following table expresses the weight breakdown below.

Table 9.1 – Component weight breakdown with MSH [7]

NOMAAD			
Number of Rotors	4		
Weight	Weight Fractions from MSH (Value/DGW)	Weight	
Units	Unitless	kg	lb
DESIGN GROSS WEIGHT	1.00	41.52	91.54
EMPTY WEIGHT	0.89	36.78	81.09
STRUCTURE	0.36	15.06	33.19
rotor group	0.19	7.81	17.22
blade	0.10	4.04	8.91
hub	0.05	2.08	4.58
shaft	4.87×10^{-3}	0.20	0.45
rotor support	0.04	1.49	3.29
fuselage group	0.11	4.46	9.84
alighting gear	0.07	2.78	6.13
PROPULSION	0.20	8.13	17.93
motor	0.04	1.74	3.84
solar cell	0.07	2.81	6.20
battery	0.10	4.24	9.35
SYSTEMS & EQUIPMENT	0.15	6.22	13.70
flight controls	0.08	3.39	7.48
avionics	0.07	2.82	6.22
CONTINGENCY	0.18	7.35	16.21
PAYLOAD	0.12	5.00	11.02

9.2 Center of Gravity Location

Since NOMAAD will be operating autonomously on the Martian surface as well as utilizing an electric battery, the weight of the quadcopter will not change over time. Thus, the center of gravity will not change either. To make things even simpler, the symmetrical nature of NOMAAD makes finding the center of gravity easier on the xy-plane. Although the center of gravity on the xy-plane will be located in the exact center of the quadcopter, the location of the center of gravity

on the yz-plane will need to be determined. Assuming the yz-plane's origin is in the bottom-center of the figure below, the following measurements are displayed.

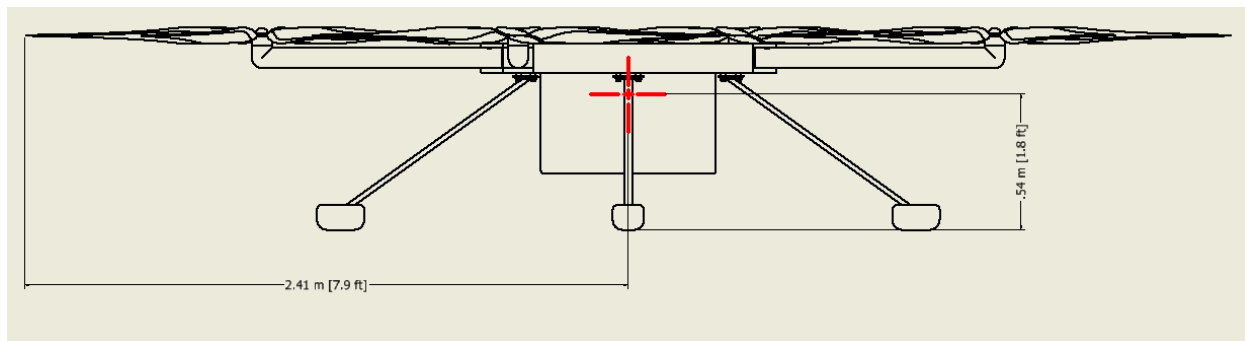


Figure 9.1 – NOMAAD center of gravity

9.3 Weight and Balance Discussion

Due to the reliability of the engineers behind MSH, many of the weight fractions were beneficial to the breakdown, as many of them aligned with NOMAAD's design and mission. One may ask why the other similar rotorcraft were not considered for this analysis. Aside from MARV, which wasn't as complete as MSH, the rest were only able to break down into payload and empty weight fractions. The rest of the weights could not be found, considering that they were conceptual designs and not fully manufactured. Thus, the Mars Science Helicopter was the ideal choice for providing the most detail. It's important to note that some of the fractions, like the battery and payload fractions, were altered to fit with NOMAAD's initial sizing. However, the initial sizing was only slightly higher than that which was determined with the original MSH weight fractions for battery and payload. The weight breakdown is not only backed by a well-designed rotorcraft but is within a reasonable range of values for such a mission.

The center of gravity of the rotorcraft was also reasonably determined with the aid of AutoDesk Inventor. It was expected that the center of gravity would be in the center of the quadcopter, as was the design's intention. However, the exact height of the center of gravity may change as the payload weight, where the box is located beneath the rotors, was not taken into account. Nonetheless, the fact that the center of gravity is in the middle of the rotorcraft on the xy-plane is the most important. If it weren't, it would affect the weight distribution for the rotors, which would cause problems in the instance of turbulence or other disturbances in flight.

10. Stability Analysis

10.1 Modal Analysis

To assess the stability of the rotor blades and the rotor design for Martian conditions, modal analysis was used to identify the rotor's natural frequencies. The oscillations these blades may experience are known as flutter. This can lead to either plastic deformation or complete structural failure. A simulation was conducted in Autodesk Inventor to determine these natural frequencies. The blades were tested with carbon-fiber polymer material, as this is the most likely material to be used.

Table 10.1 – Simulation parameters

Parameter	Value
Material	Carbon Fiber Reinforced Polymer (CFRP)
Rotor Mass (FEA)	11.33 kg
Volume	$7.9 \times 10^6 \text{ mm}^3$ (7.9 L)
Constraints	Pinned in radial/axial directions
Operating Frequency	~33 Hz (based on tip speed)

Table 10.2 – Frequencies tested

Mode #	Frequency (Hz)
F1	0.00 (rigid body)
F2–F12	19 – 22 (near operating frequency)
F13–F18	97 – 114

Table 10.3 – Material properties

Property	Value
Density	1.43 g/cm ³
Young's Modulus	133 GPa
Yield Strength	300 MPa
Ultimate Tensile Strength	577 MPa
Shear Modulus	47.8 GPa

Table 10.4 – Mesh settings tested

Property	Value
Avg. Element Size (fraction of model diameter)	0.03 – 0.12
Min. Element Size (fraction of avg. size)	0.01 – 0.024
Grading Factor	1.5
Max. Turn Angle	25 deg
Create Curved Mesh Elements	Yes

A sample of the simulation run shows the rotor in its rigid body configuration.

F1 0.00 Hz Displacement

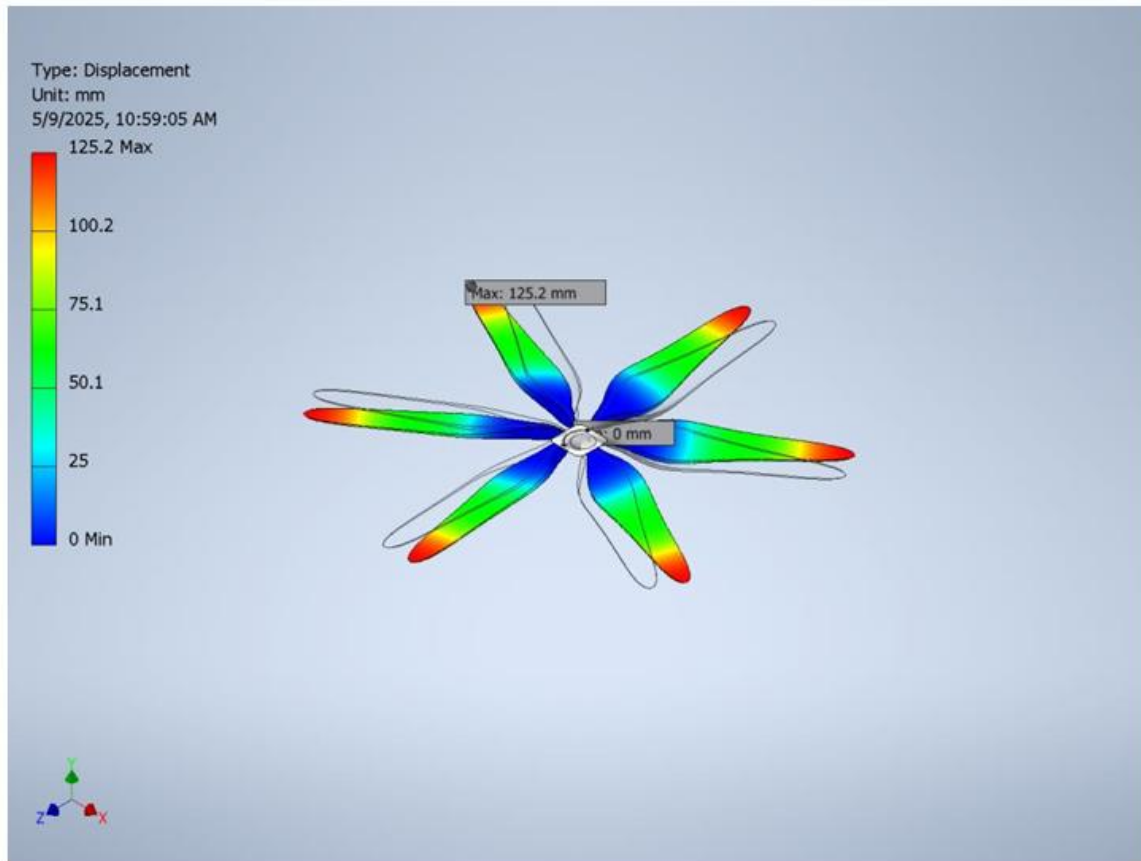


Figure 10.1 – Stability simulation for the rigid body

The first bending and twisting modes lie just below the operating frequency. This can cause a substantial risk of resonance, or flutter, if the blade frequency matches or harmonically excites these modes. Essentially, if the rotor speed doesn't match the natural frequencies of the rotor, then the rotor will operate safely without running the risk of damaging the blades. However, how can we ensure that these results are accurate? Numerous meshing sizes, shown in Table 10.4, were utilized to determine if the results come out similarly. The graphs and the table below display how the meshing changes these results.

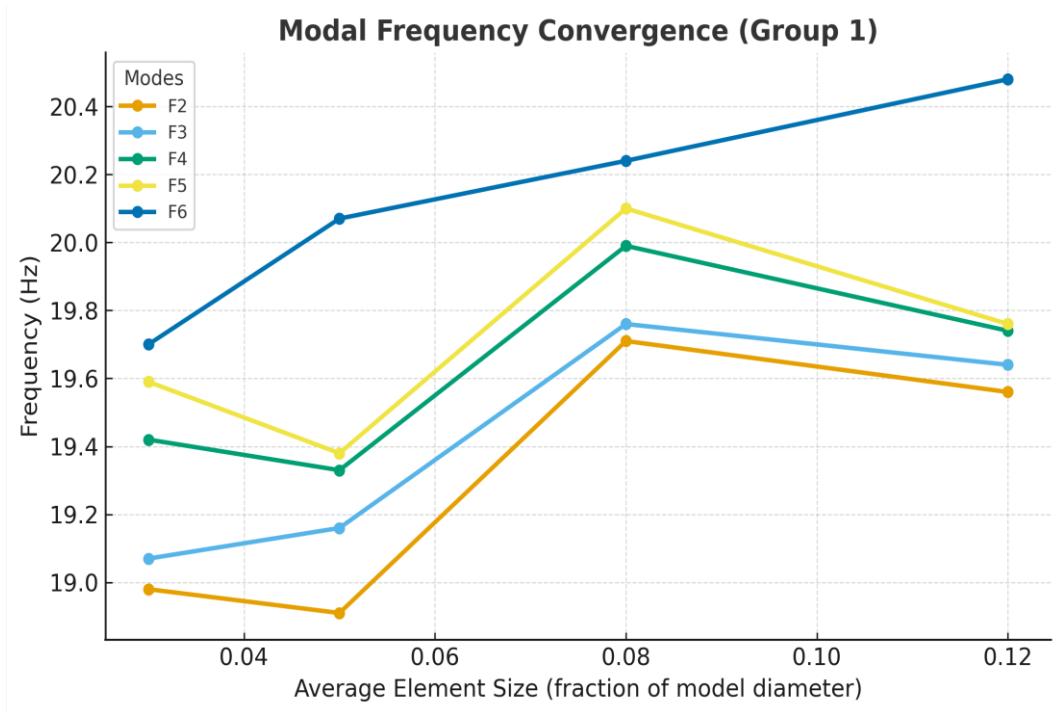


Figure 10.2 – Mesh size convergence comparison group 1

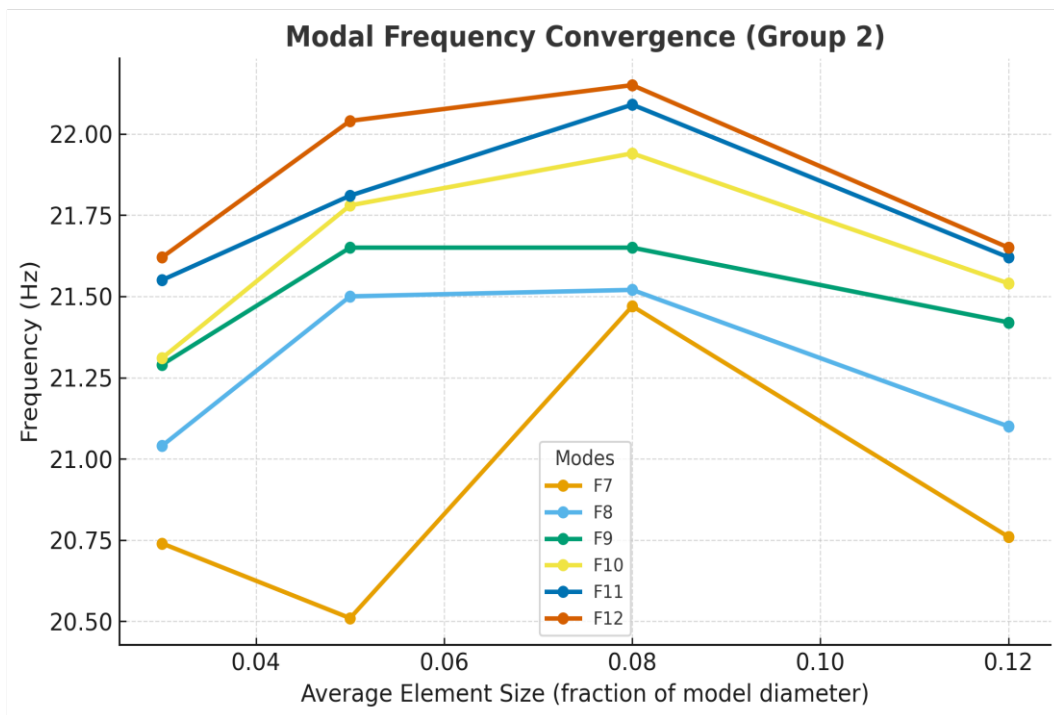


Figure 10.3 – Mesh size convergence comparison group 2

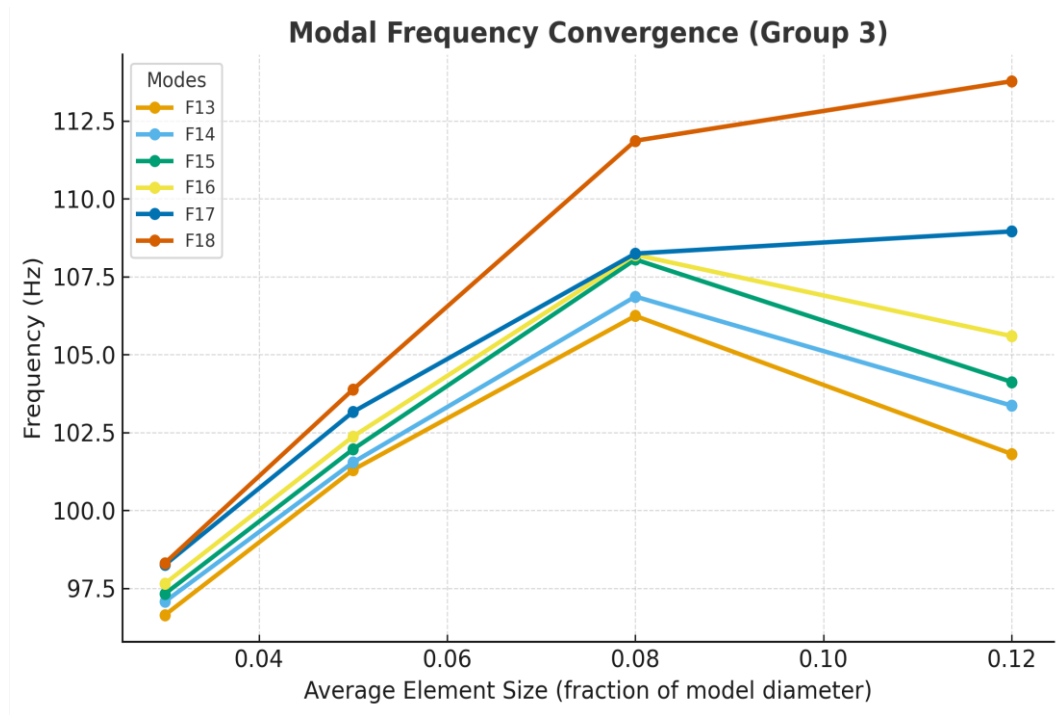


Figure 10.4 – Mesh size convergence comparison group 3

Table 10.5 – Mesh results

Mode	Average Element Size (fraction of model diameter)			
	0.12	0.08	0.05	0.03
	Frequency (Hz)			
F1	0.00	0.00 (0.00%)	0.00 (0.00%)	0.00 (0.00%)
F2	19.56	19.71 (+0.77%)	18.91 (−4.06%)	18.98 (+0.37%)
F3	19.64	19.76 (+0.61%)	19.16 (−3.04%)	19.07 (−0.47%)
F4	19.74	19.99 (+1.27%)	19.33 (−3.30%)	19.42 (+0.47%)
F5	19.76	20.10 (+1.72%)	19.38 (−3.58%)	19.59 (+1.08%)
F6	20.48	20.24 (−1.17%)	20.07 (−0.84%)	19.70 (−1.84%)
F7	20.76	21.47 (+3.42%)	20.51 (−4.47%)	20.74 (+1.12%)
F8	21.10	21.52 (+1.99%)	21.50 (−0.09%)	21.04 (−2.14%)
F9	21.42	21.65 (+1.07%)	21.65 (+0.00%)	21.29 (−1.66%)
F10	21.54	21.94 (+1.86%)	21.78 (−0.73%)	21.31 (−2.16%)
F11	21.62	22.09 (+2.17%)	21.81 (−1.27%)	21.55 (−1.19%)
F12	21.65	22.15 (+2.31%)	22.04 (−0.50%)	21.62 (−1.91%)
F13	101.81	106.24 (+4.35%)	101.30 (−4.65%)	96.64 (−4.60%)
F14	103.36	106.86 (+3.39%)	101.54 (−4.98%)	97.07 (−4.40%)
F15	104.12	108.05 (+3.77%)	101.96 (−5.64%)	97.32 (−4.55%)
F16	105.59	108.20 (+2.47%)	102.37 (−5.39%)	97.65 (−4.61%)
F17	108.95	108.24 (−0.65%)	103.16 (−4.69%)	98.25 (−4.76%)
F18	113.77	111.86 (−1.68%)	103.88 (−7.13%)	98.31 (−5.36%)

At modes F2 – F12, around 19 to 22 hertz, the values only shift by about 0.5 to 1.5 hertz. This shows that these modes are stable for the rotorcraft blades and thus converge well. Unfortunately, the same was not true for higher frequencies. The coarse meshes appeared to vary significantly. These values shifted by roughly 4 to 5 hertz but converged smoothly at the finer meshes, suggesting that higher modes are much more sensitive to mesh details. Overall, the first 10 – 12 modes below 25 hertz stabilized within 2–3% by the 0.05 element size mesh, indicating reliable convergence in the frequency band of most interest. Higher-frequency modes remain mesh-sensitive and would require further refinement to demonstrate convergence.

10.2 Campbell Diagram

The figure below represents these findings on a comprehensive graph. The gray lines represent these natural frequencies of the rotor, and each colored line represents the tested rotor speeds. The last dotted red line represents the operating frequency of the rotor. If the dotted red line intersects with the colored lines, on top of the natural frequencies, then that means that the rotor will be unstable at that speed. The goal is not to have the operating frequency intersect with the rotor speeds on top of the natural frequency.

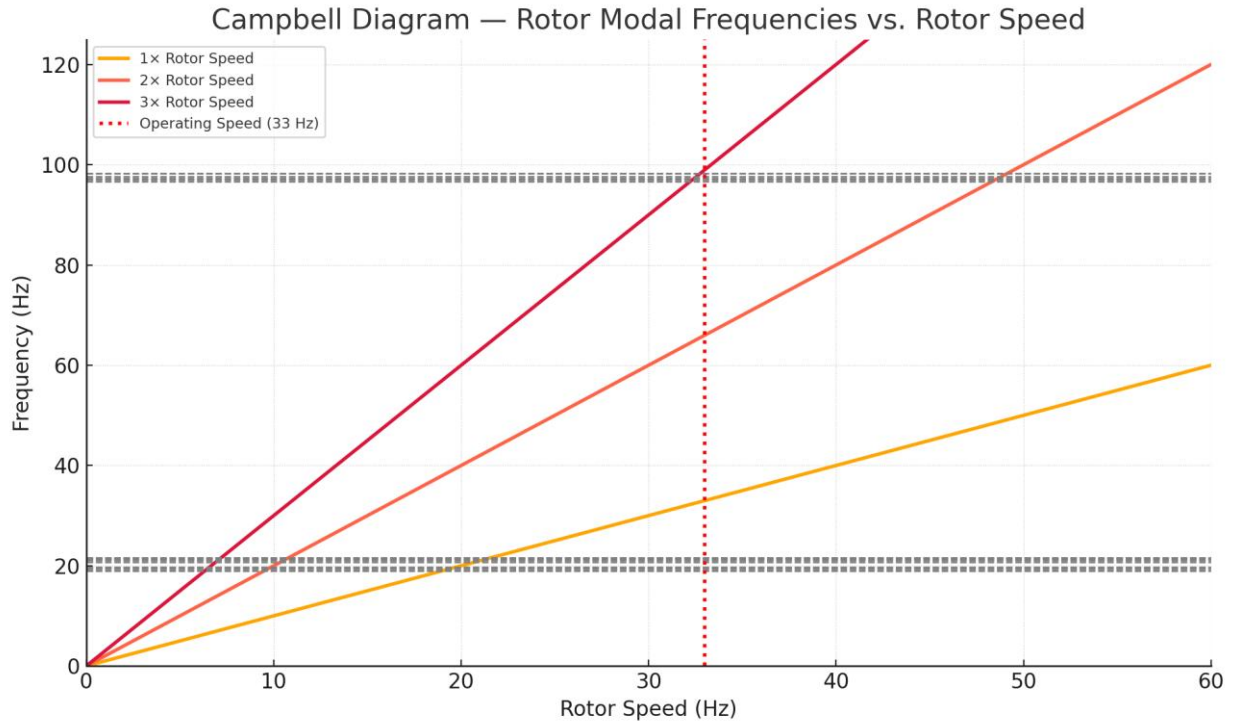


Figure 10.5 – Campbell diagram

The first dozen modes cluster between 19 – 22 hertz, well below the $1\times$ rotor harmonic and therefore not directly excited by the operating rotor speed. However, the higher-frequency modes around 96–98 hertz lie very close to the $3\times$ harmonic at 99 hertz, posing a potential resonance risk that could affect the rotor’s structural integrity.

10.3 Stability Analysis Discussion

The analysis of the rotor’s stability is well thought out, but it might have proven more beneficial to utilize computational fluid dynamics instead of modal analysis. The Campbell diagram provided some useful insights into the rotor's design and showed that the rotor would require some revision, as expected from a first iteration of NOMAHD’s design. Additionally, the tip speed of the blades may need to be tweaked slightly as the blades' frequency doesn’t quite intersect with the rotor’s natural frequencies, but still may be too close for comfort. In future iterations of this design, more sophisticated software will need to be employed to determine the robustness of the rotor itself. Adding in some Martian atmospheric conditions will be extremely useful as well to see how NOMAHD will perform once it reaches Dao Vallis.

10.4 Stability Analysis Conclusion

Overall, the rotor would best operate at $1\times$ or $2\times$ its rotor speed, as the operating frequency doesn’t intersect anywhere close to the natural frequencies of the rotor. This will ensure stability without causing flutter. However, to have the quadcopter operate at such speeds consistently would

be unrealistic. The rotor is dynamically stable in cruise but is vulnerable to resonance during its transitions.

11. Landing Gear Design

11.1 Design

NOMAHD's landing gear is greatly inspired by Ingenuity's design, not only for its simplicity but also for its practicality. The angle of the landing gear would not exceed 45 degrees, as higher angles could potentially cause NOMAHD to tip over during landing. A low-lying landing gear would offer maximum stability, especially in unpredictable weather conditions. The bottoms of the landing gear would also be fitted with some form of rubber-like material to soften landings. Four bolts would be installed into the center design, just below the rotor rods. Additionally, as mentioned earlier, the landing gear could include a spring system where the legs are collapsible, further reducing NOMAHD's size when integrated into the Pathfinder Lander. Once the quadcopter has landed on Mars, the springs would release, fully extending the legs and providing extra protection for the rotorcraft during landing, as the springs would serve as natural cushions.

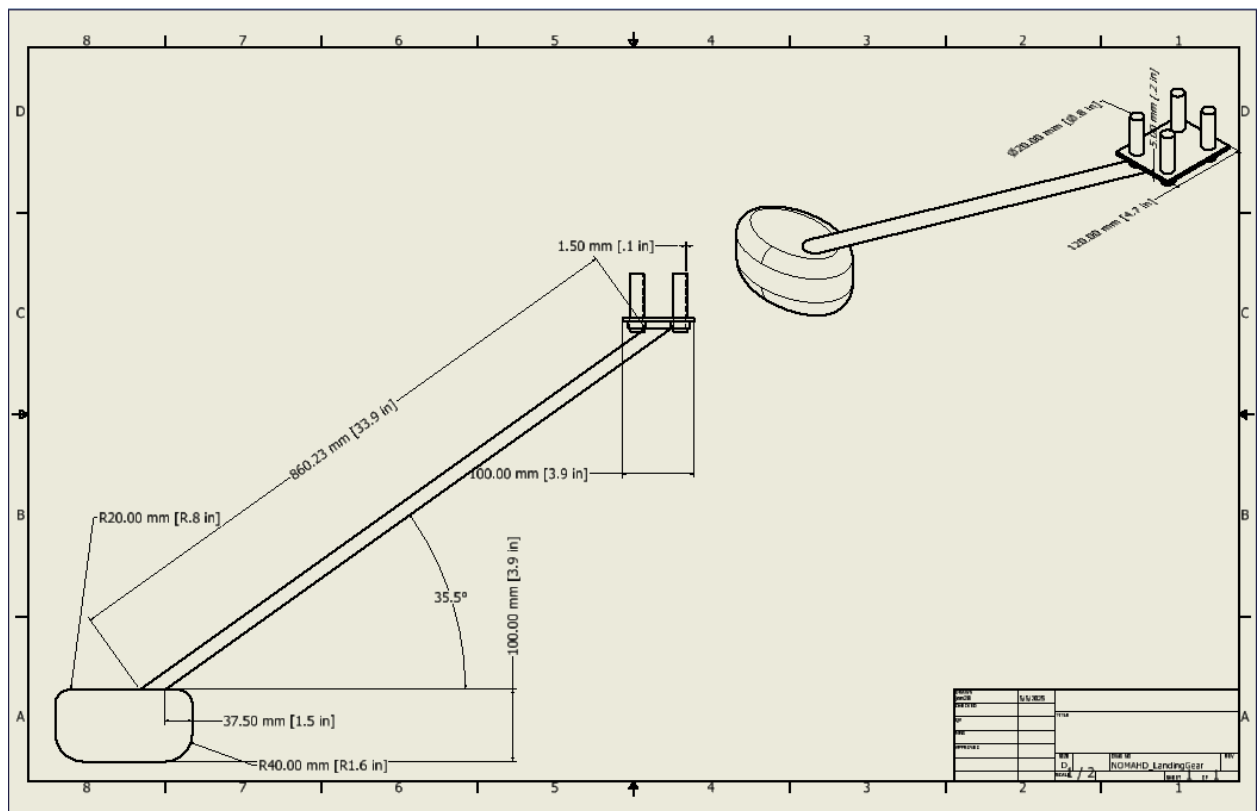


Figure 11.1 – Landing gear design

11.2 Landing Gear Design Discussion

This landing gear design will be extremely simple, which will lower costs and simplify manufacturing since it requires few mechanical parts. Ingenuity's design also follows this simplicity, as it is equipped with shocks on its legs to provide extra cushioning during landing. This makes the landing gear a robust design for NOMAHD to use in its mission. However, the placement of the landing gear will need some revision, as stability analysis will be necessary to

ensure proper placement and safe landings. This could potentially help create a more stable and durable overall design.

12. Considerations

12.1 Considerations Introduction

The purpose of this section is to evaluate the potential impacts of the NOMAAD mission across multiple societal domains, including economic, environmental, social, political, ethical, health, manufacturing, and sustainability aspects. While NOMAAD is primarily a scientific mission aimed at exploring Mars and collecting data, its development, deployment, and operation may have broader implications for society, industry, and future space exploration. By considering both the direct and indirect effects of sending an autonomous rotorcraft to another planet, we can assess the feasibility of its design as well as the broader effects across the industry if NOMAAD were to successfully find evidence of life on Mars.

12.2 Economic Considerations

The idea of extraterrestrial rotorcraft is still quite in its infancy. Even with the numerous conceptual designs being created well before Ingenuity took flight, only one has ever successfully flown on Mars. However, if this design were to also fly on Mars and conduct scientific missions as well, it could open the idea to other private companies, like SpaceX, to manufacture something similar. NOMAAD intends to be sent up to Mars and never return to Earth. Its main goal is to gather data for the scientific community. Once sent up, only a small group of scientists would need to monitor the data that NOMAAD sends back to Earth.

12.3 Environmental Considerations

No such considerations will be necessary as NOMAAD will be manufactured once. This quadcopter will then be sent to Mars, never to return home. Once it reaches Mars, it will continue to conduct its mission until it either completes its mission or gets damaged beyond operational capacity.

12.4 Social Considerations

The main goal of NOMAAD's mission isn't just to find ancient signs of water and microbial life for science. Discovering this evidence could suggest that humans might eventually live on Mars and that Mars was once a habitable planet. NASA, the National Aeronautics and Space Administration, might also start missions to send humans to Mars for colonization, which could have huge societal impacts. Of course, this all depends on whether such evidence is found. If the opposite is true, then NOMAAD will have little to no effect on society. It would be no more significant than Ingenuity.

12.5 Political Considerations

NOMAAD, like Ingenuity, will be a scientific quadcopter that would most likely be funded by NASA. Being that NASA is a government agency, its design will most likely be kept under wraps until its launch from Earth to Mars. Its sole destination will be the Dao Vallis region on Mars and nothing more. Once launched, its design might be publicly disclosed to the citizens of the United States of America, but limited to other countries, particularly countries that are

America's enemies. Outside of these concerns, NOMAAD will not have much other impact unless it makes an incredible discovery on the surface of Mars.

12.6 Ethical Considerations

There is no valid reason why NOMAAD shouldn't exist. This quadcopter would purely be utilized for the betterment of human understanding of our neighboring red planet. Whether it makes a discovery or not, this quadcopter will only work to serve the good of humankind.

12.7 Health and Safety Considerations

NOMAAD's design is somewhat simple, which will make it more reliable when it operates on the surface of Mars alone. Outside of this, no other safety or health considerations will be necessary. This quadcopter will not be able to be maintained.

12.8 Manufacturing Considerations

Due to the heavy inspiration of other rotorcrafts, like Ingenuity and the Freefly Alta X, NOMAAD will be simple to manufacture. Its blades are those of Ingenuity's rotor geometry. Its landing gear requires simple mechanical mechanisms to retract. Its folding design may be the most complex part, but considering that NOMAAD will only be folded once and not need to fold again, that may make the folding mechanisms more trivial. No new facilities will be required to make NOMAAD, nor will any custom components need to be made. Additionally, no new lander will have to be made as NOMAAD will be able to fit inside the Pathfinder Lander, which is an already designed and manufactured vehicle. Most of these components will have some background on other rotorcraft currently in use or have been made before.

12.9 Sustainability Considerations

Most materials required to make NOMAAD will be easy to obtain, such as the carbon fiber polymer used for the blades. Additionally, many components of this quadcopter will be made from lightweight materials like aluminum, which are readily accessible. Many of these materials can be easily sourced, particularly from places like SpaceX and NASA. Since only one quadcopter will be made for this mission, the materials needed will be minimal.

13. Conclusions

Considering how new the rotorcraft scene is for extraterrestrial planets, designing a quadcopter for Martian exploration was already a feat that would prove to be quite difficult. With most of the similar aircraft being conceptual designs rather than fully operational models, many of the performance and weight metrics had to be based upon numbers alone. Additionally, many of these designs are conceptualized given ideal conditions rather than actual performance tests. Ingenuity was the only one that had flown on Mars that could be compared based on actual performance, but even this was difficult since Ingenuity carried no payload. Consequently, this would make a direct comparison difficult.

MSH, however, was the primary template for NOMAAD, particularly given the considerable expertise behind its design. Out of all the conceptual designs, MSH aided in many of the weight estimates and performance metrics. Regardless of its predecessors, NOMAAD still came out to be a solid and robust iteration.

Its blades are well-suited for Martian atmospheric conditions, and it has a solid foundation of conceptualized rotorcraft to guide the design process. The simplicity of its landing gear is also advantageous, considering its inspiration from Ingenuity and the fact that its landing gear has been flight-tested. Additionally, the entire design being able to fit within the Pathfinder Lander is its major advantage. The weight sizing was also accurately calculated for the given payload, even though NOMAAD's predecessors had a largely varying payload weight. Although it may be beneficial to further analyze the weight calculations to ensure accuracy.

Of course, NOMAAD still has a long way to go before it can even touch the surface of Mars. More refinement of the current model may be necessary to ensure a successful mission. For starters, the use of more sophisticated software, such as computational fluid dynamics, will be utilized to obtain better drag polars and lift-to-drag ratios. This will determine the level of benefit the current blades will provide to NOMAAD's mission. One of the biggest advantages of using computational fluid dynamics would be its stability analysis capabilities. Modal analysis could only allow us to see snapshots of certain modes, but with CFD, we could see a far more detailed analysis. As mentioned earlier, the higher modes were more mesh sensitive and thus made it difficult to converge with the larger mesh sizes. This could be greatly improved with CFD.

If NOMAAD could reach Mars, it would be the first scientific helicopter to fly and conduct scientific missions. This quadcopter could not only carry out its research but also assist other rovers, like Perseverance, in their missions. It would be opening a door that was recently created, thus ushering in a new era of Mars scientific exploration.

References

- [1] NASA, "Ingenuity Mars Helicopter," NASA Science, retrieved 1 June. 2025.
<https://science.nasa.gov/mission/mars-2020-perseverance/ingenuity-mars-helicopter/>
- [2] Withrow-Maser, S., Johnson, W., Young, L., Cummings, H., Chan, A., Tzanetos, T., Balaram, J., and Bapst, J., "An Advanced Mars Helicopter Design," NASA Ames Research Center, Moffett Field, CA, and NASA Jet Propulsion Laboratory, Pasadena, CA, 2020.
- [3] Bensignor, I., Seth, D., and McCrink, M., "Rotor Propulsion Modeling for Low Reynolds Number Flow ($Re < 10^5$) for Martian Rotorcraft Flight," *AIAA Paper* 2022-3958, Aug. 2022.
<https://doi.org/10.2514/6.2022-3958>
- [4] NASA Goddard Space Flight Center, "Mercator Projection of Mars from MOLA Data," NASA, retrieved 1 Jul. 2025.
<https://attic.gsfc.nasa.gov/mola/images/mercat.jpg>
- [5] NASA Glenn Research Center, "Mars Atmosphere Model – Metric Units," NASA, accessed 1 July 2025.
<https://www.grc.nasa.gov/WWW/K-12/airplane/atmosmrm.html>
- [6] Radotich, M., Withrow-Maser, S., deSouza, Z., Gelhar, S., and Gallagher, H., "A Study of Past, Present, and Future Mars Rotorcraft," Presented at the Vertical Flight Society's 9th Biennial Autonomous VTOL Technical Meeting, Virtual, Jan. 26–28, 2021.
- [7] 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., and Grip, H. F., "Mars Science Helicopter Conceptual Design," NASA Technical Memorandum NASA/TM—2020–220485, Ames Research Center, Moffett Field, CA, March 2020.
- [8] Koning, W. J. F., and Dominguez, M., Mars Helicopter Ingenuity Rotor Geometry, NASA/TM-20240001510, NASA Ames Research Center, Moffett Field, CA, Feb. 2024.
<https://ntrs.nasa.gov/citations/20240001510>
- [9] Kallstrom, K., Shirazi, D., Weist, L., Dominguez, M., Schatzman, N., and Young, L., "Planetary Telemetric Helicopter for Investigation and Analysis (PYTHIA): A Rotorcraft for Martian Lava Tube Exploration," Presented at the Vertical Flight Society's 6th Decennial Aeromechanics Specialists' Conference, Santa Clara, CA, 6–8 Feb. 2024.

- [10] Datta, A., Bao, J., Gamard, O., Griffiths, D., Liu, L., Pugliese, G., Roget, B., Sitamaran, J., and Chopra, I., "The Martian Autonomous Rotary-wing Vehicle (MARV)," Alfred Gessow Rotorcraft Center, Department of Aerospace Engineering, University of Maryland, College Park, MD, 1 June 2000.
- [11] Freefly Systems, "Alta X Brochure," Version 2, retrieved 1 June. 2025.
<https://freefly-prod.s3-us-west-2.amazonaws.com/support/alta-x-brochure-v2.pdf>
- [12] Raymer, D. P., Aircraft Design: A Conceptual Approach, 6th ed., American Institute of Aeronautics and Astronautics, Reston, VA, 2018.
- [13] Sion Power Corporation, "Licerion® Products," Sion Power, Tucson, AZ, 2024, retrieved June 23, 2025.
<https://sionpower.com/products/>
- [14] Burke, K. A., Small Portable PEM Fuel Cell Systems for NASA Exploration Missions, NASA/TM–2005-213994, NASA Glenn Research Center, Cleveland, OH, Dec. 2005. Presented at the 3rd International Energy Conversion Engineering Conference, San Francisco, CA, Aug. 15–18, 2005.
<https://ntrs.nasa.gov/citations/20050213994>
- [15] Jakupca, I., Status of Primary and Regenerative Fuel Cells for Space Applications, NASA Glenn Research Center, Cleveland, OH, 25 Sept. 2020.
- [16] Paris, A., Davies, E., Tognetti, L., & Zahniser, C. (2020). Prospective Lava Tubes at Hellas Planitia. arXiv: Earth and Planetary Astrophysics.

Appendices

```
%*****
% Mars Rotorcraft Sizing with Parameter Sweeps
% Author: Jonathan Sutton
% Johnson & Raymer Method for Controlled Flight (metric units)
% Last Updated: 2/26/2025
%*****

clear
clc

%*****
% Setting Up Parameters
%*****

% Atmospheric Conditions
gm = 3.71; % [m/s^2] Martian gravity
a = 233.1; % [m/s] Martian speed of sound

% Mission Profile
h_cruise = 200; % [m] Cruise altitude
V_cruise = 10; % [m/s] Cruise speed
V_climb = 3; % [m/s] Vertical climb speed
gamma_deg = 45; % [deg] Flight path angle for forward flight
gamma_rad = gamma_deg * (pi / 180); % [rad] Flight path angle in radians
range = 5000; % [m] Range
num_rotor = 4; % Number of rotors
t_climb = h_cruise / V_climb; % [s] Climb time
t_cruise = range / V_cruise; % [s] Cruise time
t_hover = 60; % [s] Hover time

% Initial Design Parameters
Esb = 500; % [Wh/kg] Specific energy of batteries
c = 0.0905; % [m] Chord Length
np = 0.7; % Propulsive efficiency [0.6 - 0.85]
e = 0.6; % Oswald efficiency factor [0.5 - 0.8]
FM = 0.6; % Figure of Merit [0.55 - 0.6 for martian rotorcraft]

% D/q Component Build-Up (Frontal Area)
Dq_fuselage = 0.09;
Dq_landing_gear = 1.01;
Dq_rotor_hub = 0.6;
Dq_downwash = 0.02;

Dq_base = Dq_fuselage + Dq_landing_gear + Dq_rotor_hub + Dq_downwash;
Dq_total = Dq_base * 1.10; % 10% for leakage and protuberance drag

% Estimate Frontal Area
S_ref = 0.15; % [m^2], estimated total frontal area

% Final D_q Used in Power Equation
D_q = Dq_total * S_ref; % [m^2]
```

```

% Default Values for Parameters
default_rho = 0.0205; % [kg/m^3] Air Density
default_tip_speed = 0.8; % Tip speed Mach number
default_payload = 5; % [kg] Payload weight
default_num_blades = 6; % Number of blades

% Sweep Ranges
rotor_radius_values = 0.4:0.05:2; % [m] Rotor Radius
rho_values = [0.02, 0.025, 0.03]; % [kg/m^3] Air Density
tip_speed_valuesM = [0.7, 0.8, 0.9]; % Tip speed Mach number
num_blades_values = [4, 6, 8]; % Number of blades
payload_weight_values = [3, 4, 5]; % [kg] Payload weight values

% Sweep Parameter Definitions
sweep_params = {rho_values, tip_speed_valuesM, num_blades_values,
payload_weight_values};
sweep_names = {'Density Sweep', 'Tip Speed Sweep', 'Number of Blades Sweep', 'Payload
Sweep'};
constant_values = {default_rho, default_tip_speed, default_num_blades,
default_payload};

% ADD FILE PATH HERE
filename = 'C:\Users\jon28\OneDrive\Desktop\Project NOMAAD FINAL\Sizing
Calculations\Mars_Rotorcraft_DGW_Sweep.xlsx';

if exist(filename, 'file')
    delete(filename); % Remove old file so it doesn't retain old sheets
    fprintf('Old file "%s" deleted.\n', filename);
end

%*****
% Initial User Input
%*****
% Input Design Gross Weights to Evaluate
DGW_guess = [41.5194]; % [kg]

%*****
% Begin Sweeping
%*****

for i = 1:length(DGW_guess)
    Wo_guess = DGW_guess(i);

    for sweep_idx = 1:length(sweep_params)
        sweep_vals = sweep_params{sweep_idx};
        sweep_name = sweep_names{sweep_idx};
        results = {};

        for sweep_val = sweep_vals
            for R = rotor_radius_values
                % Set defaults
                rho = default_rho;

```

```

tip_speed_M = default_tip_speed;
num_blades = default_num_blades;
payload_weight = default_payload;

switch sweep_idx
case 1, rho = sweep_val;
case 2, tip_speed_M = sweep_val;
case 3, num_blades = sweep_val;
case 4, payload_weight = sweep_val;
end

% Area Calculations
A_disk = pi * R^2; % [m^2] Disk area per rotor
S_rotors = num_rotor * A_disk; % [m^2] Total disk area
A_blade = num_blades * c * R; % [m^2] Blade area
tip_speed = a * tip_speed_M; % [m/s] Tip speed in m/s
q = (1/2) * rho * (tip_speed)^2; % [Pa] Dynamic pressure

% Aerodynamic Calculations
% Thrust Calculation
W_rotor_kg = Wo_guess / num_rotor; % [kg] Weight per rotor
W_rotor_F = (Wo_guess * gm) / num_rotor; % [N] Weight per rotor
T_hover_rotor = W_rotor_kg * gm; % [N] Thrust force per rotor for
hover

Wkg = W_rotor_kg * num_rotor; % [kg] Weight total
WF = W_rotor_F * num_rotor; % [N] Weight force total
T_hover = T_hover_rotor * num_rotor; % [N] Thrust force total for
hover

% Disk Loading Calculation
T_DL_rotor = 1.03 * (W_rotor_kg / A_disk); % [kg/m^2] Thrust disk
loading per rotor
T_DL_Frotor = 1.03 * (W_rotor_F / A_disk); % [N/m^2] Thrust disk
loading per rotor
T_DL_total = T_DL_rotor * num_rotor; % [kg/m^2] Thrust disk loading
total
T_DL_Ftotal = T_DL_Frotor * num_rotor; % [N/m^2] Thrust disk loading
total

% Rotorcraft Aerodynamic Properties
Ct_rotor = T_hover_rotor / (rho * A_disk * tip_speed^2); %
Coefficient of thrust per rotor
Ct = Ct_rotor * num_rotor; % Coefficient of thrust total
Sigma = (num_blades * c) / (pi * R); % Solidity
Blade_loading_rotor = Ct_rotor / Sigma; % Blade loading per rotor
Blade_loading = Blade_loading_rotor * num_rotor; % Blade Loading
total

AR = R / c; % Aspect ratio

%*****
% Power Calculations

```

```

%*****

% Induced and Downwash Velocity
V_induced_rotor = sqrt((T_DL_Frotor / (2 * rho))); % [m/s] Induced
velocity per rotor
V_downwash_rotor = 2 * V_induced_rotor; % [m/s] Downwash velocity per
rotor
V_induced_total = V_induced_rotor * num_rotor; % [m/s] Induced
velocity total
V_downwash_total = V_downwash_rotor * num_rotor; % [m/s] Downwash
velocity total

% Ideal and Actual Power Calculations for Hover (Estimated)
P_ideal_rotor = T_hover_rotor * sqrt(T_DL_Frotor / (2 * rho)); % [W]
Ideal power per rotor
P_actual_rotor = (T_hover_rotor / FM) * sqrt(T_DL_Frotor / (2 *
rho)); % [W] Actual power per rotor
P_ideal_total = P_ideal_rotor * num_rotor; % [W] Ideal power total
P_actual_total = P_actual_rotor * num_rotor; % [W] Actual power total

% Power Calculations for Hover (Realistic)
P_hover_rotor = (((1.03 * W_rotor_F) / FM) * sqrt((1.03 * (W_rotor_F
/ A_disk)) / (2 * rho))) * (1 / 0.97); % [W] Power for hover per rotor
P_climb_rotor = (((1.03 * W_rotor_F) / FM) * sqrt((1.03 * (W_rotor_F
/ A_disk)) + ((W_rotor_F * V_climb) / 2)) / (2 * rho))) * (1 / 0.97); % [W] Power for
vertical climb per rotor
P_hover_total = P_hover_rotor * num_rotor; % [W] Power for hover
total
P_climb_total = P_climb_rotor * num_rotor; % [W] Power for vertical
climb total

% Power Calculations for Forward Flight (Realistic)
P_cruise_rotor = ((V_cruise / np) * ((q * D_q) + (W_rotor_F^2 / (4 *
e * q * A_disk)))) * (1 / 0.97); % [W] Power for cruise per rotor
P_ffclimb_rotor = ((V_cruise / np) * ((q * D_q) + (W_rotor_F^2 / (4 *
e * q * A_disk)) + (W_rotor_F * sin(gamma_rad)))) * (1 / 0.97); % [W] Power for climb
in forward flight per rotor
P_cruise_total = P_cruise_rotor * num_rotor; % [W] Power for cruise
total
P_ffclimb_total = P_ffclimb_rotor * num_rotor; % [W] Power for climb
in forward flight total

% Power Calculations Total
P_total_rotor = (P_hover_rotor + P_climb_rotor + P_cruise_rotor +
P_ffclimb_rotor) / 0.97; % [W] Total power required per rotor
P_total = P_total_rotor * num_rotor; % [W] Total power required for
all rotors
Power_loading_rotor = Wo_guess / P_total_rotor; % [kg/W] Power
loading per rotor
Power_loading = Power_loading_rotor * num_rotor; % [kg/W] Power
loading total

```

```

        % Energy Calculations
        E_hover_rotor = P_hover_rotor * (t_hover / 3600); % [Wh] Energy for
hover per rotor
        E_climb_rotor = P_climb_rotor * (t_climb / 3600); % [Wh] Energy for
vertical climb per rotor
        E_cruise_rotor = P_cruise_rotor * (t_cruise / 3600); % [Wh] Energy
for cruise per rotor
        E_ffclimb_rotor = P_ffclimb_rotor * (t_climb / 3600); % [Wh] Energy
for climb in forward flight per rotor
        E_hover = E_hover_rotor * num_rotor; % [Wh] Total energy for hover
        E_climb = E_climb_rotor * num_rotor; % [Wh] Total energy for vertical
climb
        E_cruise = E_cruise_rotor * num_rotor; % [Wh] Total energy for cruise
        E_ffclimb = E_ffclimb_rotor * num_rotor; % [Wh] Total energy for
climb in forward flight

        Ener_tot = E_climb + E_cruise + E_hover + E_ffclimb; % [Wh] Total
mission energy required

        % Update Battery Weight Calculation
        Wb = Ener_tot / Esb; % Battery weight calculation (based on total
energy)

        % Store results
        results = [results; {payload_weight, Wb, R, AR, T_hover, Ct, rho,
num_blades, tip_speed_M, S_rotors, A_blade, Sigma, Blade_loading, T_DL_total,
Power_loading, P_ideal_total, P_hover_total, P_climb_total, P_cruise_total,
P_ffclimb_total, P_total}];
    end
end

    % Save each sweep per DGW
    % Write to Excel
    headers = {'Payload Weight (kg)', 'Battery Weight (kg)', 'Rotor Radius (m)',
'Aspect Ratio', 'Hover Thrust (N)', 'Ct', 'Density (kg/m^3)', 'Blades', 'Tip Speed
(Mach)', 'Disk Area (m^2)', 'Blade Area (m^2)', 'Solidity', 'Blade Loading (ratio)',
'Thrust Disk Loading (kg/m^2)', 'Power Loading (kg/W)', 'P_ideal (W)', 'P_hover (W)',
'P_climb (W)', 'P_cruise (W)', 'P_ffclimb (W)', 'P_total (W)'};
    try
        sheet_name = sprintf('%s_%.1fkg', strcmp(sweep_names{sweep_idx}, ' '),
' '), Wo_guess);
        writecell([headers; results], filename, 'Sheet', sheet_name);
        fprintf('Saved results for %.1f kg DGW in sheet: %s\n', Wo_guess,
sheet_name);
    catch
        warning('Could not write results for %.1f kg DGW. Check if the file is
open.', Wo_guess);
    end
end
end

disp('All sweeps completed and saved!')

```