PlanetarY Telemetric Helicopter for Investigation and Analysis (PYTHIA): A Rotorcraft for Martian Lava Tube Exploration

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ABSTRACT

The PlanetarY Telemetric Helicopter for Investigation and Analysis (PYTHIA) project presents an early feasibility study into future Mars rotorcraft. With the success of Ingenuity and the current development of the Mars Sample Retrieval Helicopters, there is motivation to explore additional vehicle concepts for Mars exploration. This work presents an early conceptual design of a lava tube exploring quadrotor. The nominal mission for the PYTHIA quadrotor includes a two-phase in-depth exploration of one or mutliple lava tubes in the area of interest, Arsia Mons. A sizing analysis was completed using the NASA Design and Analysis of Rotorcraft (NDARC) tool. An eight-bladed quadrotor was selected based on the NDARC sizing sweeps. With preliminary vehicle and blade sizing completed, a flow visualization study was conducted. Two simulations were completed in Rotorcraft Computational Fluid Dynamics (RotCFD): one of the quadrotor alone and another in a lava tube. This paper introduces a baseline reference mission, preliminary vehicle design, and initial sizing analysis of a rotorcraft to explore Martian lava tubes.

NOTATION

C_T	coefficient of thrust
C_P	coefficient of power
FM	figure of merit
h	elevation (m)
P	pressure (Pa)
R	gas constant (J/kg K)
T	temperature (K)
γ	specific heat ratio
ρ	density (kg/m^3)
JPL	Jet Propulsion Laboratory
LTE	Long Traverse and Exploration
MSH	Mars Science Helicopter
MSR	Mars Sample Return
SM	Short Mapping
SRH	Sample Recovery Helicopter

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INTRODUCTION

The study and exploration of lava tube systems on Mars is of great interest to planetary scientists, as these regions may provide a rich source of information on the potential for life [1]. To explore such lava tubes, the PYTHIA project is proposed. The PYTHIA project seeks to define a mission concept for a Mars rotorcraft tailored to explore and better understand these Martian lava tube systems. The design and mission innovations proposed in this work – specifically, the use of rotorcraft to explore Martian lava tube systems – would yield capabilities beyond that provided by rovers alone [2].

Early feasibility studies of the vehicle and mission design space are presented for the development of a rotorcraft capable of conducting science-forward missions in Martian lava tubes. A rotorcraft enables unique maneuverability opportunities, including the capability of repeatedly entering and exiting one or multiple lava tubes aerially. This effort introduces a possible location for exploration, Arsia Mons, and the mission profile to explore the lava tubes there. The PYTHIA mission is a two phased exploration of a lava tube that could be used on multiple lava tubes in series, allowing for an in-depth exploration of the lava tubes across the Arsia Mons region. To support the proposed mission, the PYTHIA vehicle, a collective-controlled quadrotor, is introduced and conceptual design trade studies to select vehicle characteristics are conducted. The final effort of this paper is a computational flow visualization study to analyze the recirculation effects possible when flying in an enclosed lava tube.

BACKGROUND

The scientific goals of the PYTHIA vehicle and mission study are primarily to help understand the geographical history and composition of Martian terrain. The notional mission presented focuses on exploring lava tubes; however, this overall mission concept could also be applicable to other cave types as well. The primary mission objective of the PYTHIA project is to collect information on Martian lava tubes to assist planetary scientists in further understanding Mars's planetary formation and development, climate, and signs of previous or current life [3–5]. Future missions beyond the baseline missions discussed in this work could also explore caves and provide data on their viability as possible shelter locations for future astronauts and sensitive scientific equipment; in addition to their potential for life, cave and lava tube structures protect against surface radiation and weather events such as dust storms [6–8].

History of planetary rotorcraft research

In studies as early as 2000, Young et al. presented the possibility of rotorcraft flight on Mars and other planetary bodies in our solar system [9, 10]. The potential for flight on another planet in our solar system sparked research interests within industry, academia, and the government. The very first Mars quadrotor design proposal was submitted by undergraduate and graduate students at Georgia Tech in response to an American Helicopter Society (AHS) call for proposals for a student design competition sponsored by both NASA Ames Research Center and Sikorsky Aircraft [11]. In 2003, Datta et al. proposed a conceptual design vehicle named the Martian Autonomous Rotary-wing Vehicle (MARV). Datta et al. described the overall mission, rotor, and fuselage design, power plant, control system, and potential deployment methods [12].

Research endeavours such as these continued the dialogue on what is possible on Mars. In 2014, the Jet Propulsion Laboratory (JPL), NASA Ames Research Center, and NASA Langley Research Center partnered to develop a concept for a Mars Helicopter that solidified NASA's commitment to achieving the goal of first flight on the Martian surface, later accomplished by the technology demonstrator Ingenuity. Ingenuity landed with the Perseverance rover in the Jezero Crater region of Mars in March of 2021.

The success of the Ingenuity Mars Helicopter technology demonstrator, with more than 70 successful flights on the Martian surface, has opened up the exploration of Mars in a way that is revolutionizing planetary exploration [13, 14]. As a technology demonstrator, Ingenuity has proven that controlled, powered flight on Mars is indeed possible. With the success of Ingenuity (even before its proven long-term capability), there was renewed interest in flying rotorcraft on Mars with a science payload. Throughout the development of Ingenuity, JPL and NASA Ames Research Center worked together to conceptualize what future generation helicopters may look like and postulated on the science missions that could be accomplished. The Mars Science Helicopter (MSH) is another example of a next-generation rotorcraft concept pushing the boundaries of our current capabilities on the red planet. In 2020, Johnson et al. published a conceptual design detailing multiple vehicle configurations and a variety of possible science objectives for the Mars Science Helicopter, which would be larger in scale than its predecessor [15]. Multiple configurations were explored and a variety of possible science objectives, including mapping, polar science, non-intrusive investigation of recurring slope lineae regions, icy scarp mapping, atmospheric profiling, and subsurface geophysics exploration, were considered. Introduced in June 2022, the Sample Recovery Helicopters (SRH), supporting the Mars Sample Return (MSR) mission concept originally slated for 2028, are two Ingenuity-class helicopters that serve as the back-up option for soil sample tube retrieval and transfer to the ascent vehicle as part of the current MSR mission concept. It is hoped that SRH will soon show that rotorcraft on Mars are also capable of carrying a dedicated science payload [16]. Images of Ingenuity, MSH, and the SRH are provided in Figure 1. Table 1 contains the configurations for each of these rotorcraft. At this time, configuration and sizing for the MSH is subject to change based on mission selection and requirements.

Table 1. Ingenuity, MSH, and SRH configurations [15,16].

Rotorcraft	Ingenuity	MSH	SRH
Number of rotors	2	6	2
Number of blades	2	4	2
Blade radius (m)	0.600	0.640	0.705
Mass (kg)	1.80	31	2.50
Payload (kg)	0	2-5	0.15

NASA Ames Research Center has long been at the forefront of planetary rotorcraft research and was an early key partner with the Jet Propulsion Laboratory, along with NASA Langley Research Center, in the development of Ingenuity. Future missions beyond Ingenuity, SRH, and MSH are being notionally explored within Ames. Potential science payloads and regions of interest are continuous points of discussion. The SRH and MSH missions are leveraging the key heritage aspects of Ingenuity's design to achieve science driven missions on Mars. Ingenuity's continued flights provides the foundation for the success of rotorcraft flight on Mars. Furthermore, lessons learned pave the way for design improvements and continued growth in the evolution of Mars rotorcraft design.

Outside of Mars, there is also research to utilize rotorcraft on other planetary bodies, such as Titan, Saturn's largest moon. Selected in 2019 as the fourth New Frontiers mission, the Dragonfly project aims to use a rotorcraft to explore the surface of Titan. Recent research suggests that, similar to Mars, there may be caves on Titan [20]. With the ongoing development work on the Dragonfly multirotor vehicle, there might be future opportunities for cave exploration on Titan just like on Mars [21].

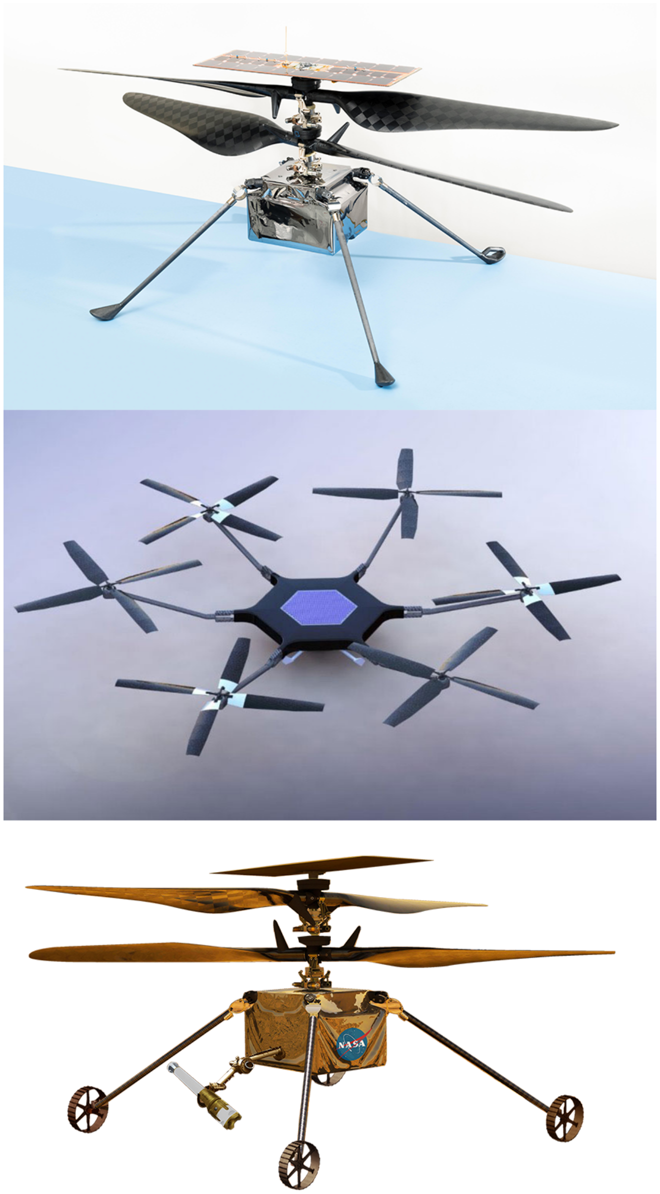

Figure 1. Ingenuity (top), SRH (center), and MSH (bottom) flight models [17–19].

Existing cave exploration concepts

Within the scientific and engineering communities, there is great interest in furthering science goals on Mars through the exploration of caves and lava tubes. In a 2011 NASA Innovative Advanced Concepts (NIAC) Phase I report, Whittaker proposed robotic exploration of Martian lava tubes and caves. The proposed concept, Spelunker, utilizes hopping robots, one such named "Cavehopper," to explore cave structures using LiDAR and communicate collected data to a lander. Many concepts are discussed in this proposal including tethered, hopping, and climbing robots [22]. In Whittaker et al.'s Phase II NIAC proposal, different methods for accessing lava tubes via skylights or pits are explored, including propulsive precision landing, hopping into the cave using a robot such as the Cavehopper, tethered descent, scree slope descent, and Tyrolean line descent [23].

Besides Whittaker, several other authors have proposed various Martian cave explorers. These authors proposed climbing robots, hopping tensegrity robots, and robotic flying swarms [24–26]. In addition to exploration robots, many rotorcraft concepts have been investigated. In 2018, Aoki et al. proposed a conceptual helicopter design for pit crater and cave exploration in the Elysium Mons region of Mars [27]. A later study by Sugiura et al. focused on the optimization of rotor blades specifically designed for exploring pit craters on Mars [28]. In 2020, Wiens et al. submitted an abstract proposing a drone equipped with an ultra-light payload to image regions of interest and detect potential organics in the environment [29].

In addition to the concepts discussed above, there are a multitude of rotorcraft projects that are currently being researched and designed for Martian exploration. The research referenced in this work does not encompass the entirety of research accomplished to date. For a more comprehensive document of proposed planetary rotorcraft designs and potential missions, see either Radotich [30] or Young [31].

LOCATION SELECTION

Several potential landing sites were considered for the PYTHIA mission. The first landing site, Jezero Crater, was looked at as a control location, as both Ingenuity and the Perseverance rover have successfully accomplished their missions there. Hellas Planitia is considered for its unique geological and atmospheric conditions and potential for liquid water. Arsia Mons is considered for its collection of caves and lava tubes that may be of interest to the scientific community.

Jezero Crater

Jezero Crater is the site where the previous 2020 Mars rover, Perseverance, and Mars helicopter, Ingenuity, landed. Perseverance's mission was to support Curiosity's discovery and focused on finding evidence of water and taking Martian soil and rock samples. Jezero Crater is a flat plain north of the Martian equator and has a width of 45 km [32]. This location was identified as a lake bed that existed about 3.5 million years ago. Curiosity, the 2011 Mars rover, previously found signs of possible past microbial life in the form of carbon, oxygen, nitrogen, sulfur, and phosphorus [33]. Jezero Crater has an atmospheric density of $\sim$0.0178 kg/m^3, an average temperature of about 244 K, and atmospheric pressure of $\sim$837 Pa. The presence of water millions of years ago in this region suggests the potential for signs of ancient life. Jezero Crater was selected for the 2020 mission because signs of past water makes it an ideal site for finding any signs of ancient life or fossils [34, 35]. Figure 2 shows the landing location of the previous Mars Rovers [36].

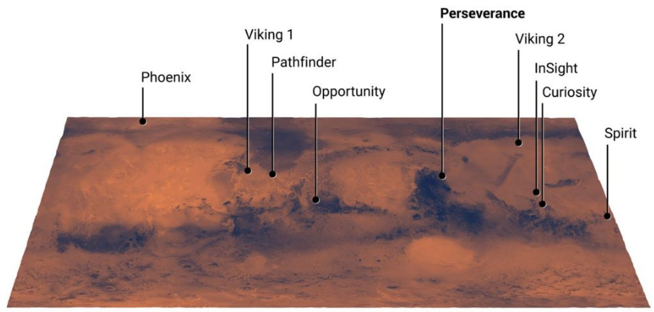

Figure 2. Location of landing site of previous Mars missions [36]).

Hellas Planitia

The second possibility for potential exploration is the Hellas Planitia region in the southern hemisphere of Mars. The region encompasses a ∼2,300 km diameter crater with a depth of ∼-7 km, created by an ancient meteor impact, making it the largest impact crater on Mars. It is difficult to determine exact diameter of this area because several volcanoes are located on the rim of this ancient region. Because of Hellas Planitia's depth, the air pressure and density are much greater than experienced elsewhere on the planet. The atmospheric pressure at the lowest elevations is as much as 1,310 Pa, and the air density is approximately 0.0274 kg/m^3. For context, the air density in this region is roughly equivalent to Earth air density at altitudes up to 35 km. The temperature in this region is slightly greater than conditions experienced in both Jezero Crater and Arsia Mons, and can reach upwards of approximately 283 K during the summer. The density, pressure, and temperature conditions experienced in Hellas Planitia could potentially enable the formation of liquid water [37]. Although, the atmospheric conditions are more hospitable to flight, the frequent occurrence of dust storms in the Hellas Planitia area renders it less conducive for aircraft operations.

Another factor to consider is that Mars does not have the same protective magnetosphere that is experienced on Earth, and as such, cannot effectively shield the surface from solar and cosmic radiation. Radiation levels are significant factors in the eventual human exploration of Mars, and impact not only human life, but the efficacy of electronics on the surface. In a 2019 journal article, Paris et al. describes possible lava tubes in Hellas Planitia and their potential for human habitation in future manned missions to Mars [38]. One of the most attractive features in the Hellas Planitia region is that the radiation levels experienced in the basin are significantly less than anywhere else on Mars [39]. These geographic phenomena would be well suited for exploration via a rotorcraft, but at this time only preliminary imaging exists of this region, so specific lava tubes can't be identified.

Arsia Mons

The final site considered for the PYTHIA mission is Arsia Mons, a part of the Tharsis volcanic region. The Arsia Mons region is 450 km in diameter, with the volcano's peak summit at an elevation of ∼11.7 km. Volcanic areas are of interest to planetary scientists for the scientific information in the volcanic remains on the formation, development, and history of the planet. Arsia Mons is one of four major volcanoes in the Tharsis volcanic region that could provide information on the geographical history of this area and is of great interest to astrobiologists. Every volcanic eruption in the Tharsis region contains differences in magma composition, that when compared allows planetary scientists to gain information on the differing conditions inside Mars. Additionally, existing survey images of Arsia Mons depict an area on the south side that was likely formed by a lava river and therefore may contain rich soil. This rich soil composition may lead to an increased chance of finding microorganisms or evidence of past life.

Additionally, the south side of Arsia Mons contains fumarole, which are vents that allow volcanoes to release gas and vapors, and once the lava cools, they remain in the form of skylights. Table 2 lists several skylights in the Arsia Mons region and their corresponding sizes, showing the location of several possible lava tubes that would be able to accommodate the PYTHIA rotorcraft [40].

Table 2. Possible skylight locations in Arsia Mons [40].

Name	Diameter (m)	Minimum depth (m)
Annie	225	101
Dena	162	80
Jeanne	165	75
Wendy	125	68
Chloe	252	N/A
Abby	100	N/A
Nikki	180	N/A

Existing images also suggest the possibility of finding caves near Arsia Mons. Figure 3 shows the Tharsis volcanic region with red dots indicating the possible locations of caves on Mars [6]. The quantity of caves present in this image adds credence that the Arsia Mons region would be a suitable place for a cave-exploring rotorcraft to conduct its mission.

In addition to the presence of caves, a water ice cloud with an approximate length of 1000 km forms every year above Arsia Mons. This cloud is generated from the vaporization of ice on the slopes of the volcano and reaches its peak during the summer when the sunlight is strong, and is an area of interest to scientists [41]. But, this cloud may also cause issues for solar charging, which needs to be considered. This phenomena makes Spring or early Summer an ideal time for landing while avoiding the Fall dust storm, which is a drawback of the Tharsis region. On the southwest side of Arsia Mons, the altitude is about 10-12 km, and the temperature during early summer is about 175 K, with a density of approximately 0.0065-0.0051 kg/m^3 and pressure of 284-215 Pa. The wind speed average is 5 m/s, providing an ideal site to land and the possibility of capturing valuable geographical and atmospheric data [42, 43].

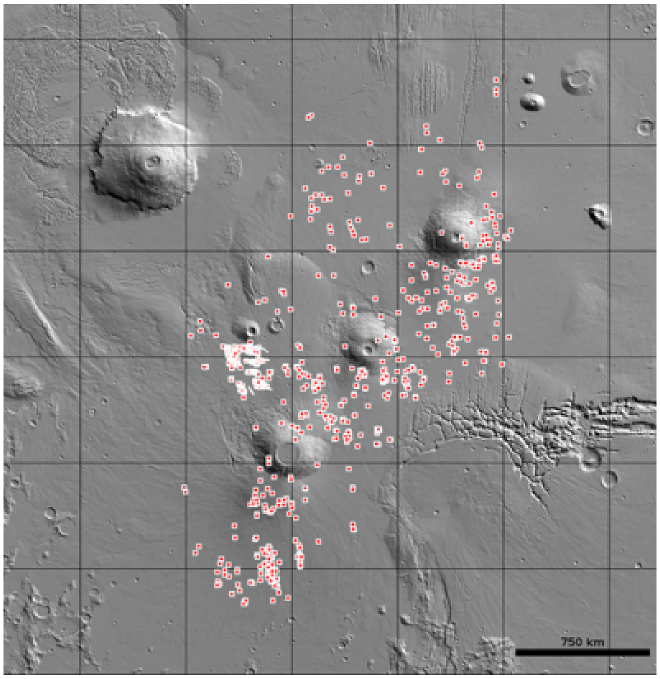

Figure 3. Tharsis volcano region on Mars and location of possible caves (Source: USGS.gov, Public Domain).

Final selection

A comparison of the atmospheric conditions in the three areas of interest are shown in Table 3. Although each location has its own benefits, the Arsia Mons region was selected as the PYTHIA mission location for a few reasons. At present, there are research efforts focusing on the collection of samples and further exploration of regions in Jezero Crater, as suggested by the current objectives for both MSH and MSR missions, reducing the need for additional studies at this time. At present, the Hellas Planitia region has less information available on its environment, including weather patterns, compared with regions of Mars at higher altitudes. Similarly, there is less information available on the sizing of lava tube and cave skylights in Hellas Planitia. These reasons make Arsia Mons a more attractive landing site over the other two locations discussed.

As stated previously, Arsia Mons has a large number of potential lava tube candidates identified in existing research. In addition, the approximate diameter of lava tube skylights in the Arsia Mons region provide more than adequate space for a rotorcraft to perform both short and long traversals into a lava tube to accomplish science objectives. It is important to emphasize, though, that this area has only been mapped by imaging. This means that all cave and lava tube data is approximate to what can be guessed from orbit. These approximations provide a good estimate for the caves, but until an exploration vehicle maps the caves, there is only so much detail that can be gained. Thus, the need to conduct an exploration mission to generate an accurate map of these lava tubes is highly justified. Additionally, the altitude of Arsia Mons provides the opportunity to challenge the existing flight capability of rotorcraft in a low density, low Reynolds number regime. The effect the large water ice cloud may have on solar efficiency will ultimately need to be investigated, but is not considered a selection factor in the preliminary design stage.

Table 3. Atmospheric conditions at Arsia Mons (AM), Jezero Crater (JC), and Hellas Planitia (HP) [42, 44].

	AM	JC	HP
h (m)	10,000	-2000	-7000
T (K)	228	244	249
ρ (kg/m^3)	6.5x10^{-3}	1.78x10^{-2}	2.74x10^{-2}
R (J/kg K)	191.8	191.8	191.8
γ	1.29	1.29	1.29
P (Pa)	2.84x10^2	8.37x10^2	1.31x10^3

REPRESENTATIVE BASELINE MISSION

The PYTHIA project based its vehicle design on two mission phases, defined as the Short Mapping (SM) phase and the Long Traverse and Exploration (LTE) phase. This mission profile was selected to be able to conduct the objectives of the PYTHIA project iteratively and was utilized in the conceptual design stage of the PYTHIA vehicle development. The mission profile could also be repeated multiple times in different lava tubes, allowing the PYTHIA project to gain information from more than one area of scientific interest. The mission phases dictate the necessary performance characteristics and power requirements.

The overall goal of the proposed baseline mission is to utilize high Technology Readiness Level (TRL) scientific instruments to map and explore Martian lava tubes. Martian surface data will be used to identify the open-air skylights of desirable lava tube locations. The density of the atmosphere was assumed to be a constant 0.0065 kg/m^3, which is the approximate atmospheric density of Arsia Mons (although a sensitivity study of the PYTHIA vehicle to changes in density is conducted in the next section to account for possible variations in density). The characterization of the lava tubes will be conducted via a combination of LiDAR and sensors that are represented in the design as part of payload weight. Utilizing a rotorcraft will allow the vehicle to access the lava tube entrance and approach a specific scientific point of interest. For this effort, the onboard battery provides the power for each flight, including a full charge in between (with the assumption of no charging within the lava tube).

Before conducting the SM and LTE phases of the mission, the PYTHIA rotorcraft must navigate to the near-edge of the lava tube of interest. Whether starting from the landing site or another lava tube, the PYTHIA vehicle must be able to navigate across the Martian surface at a flight speed of 10 m/s for the maximum cruise distance. The distance of each flight will be determined in the conceptual design section of this paper. The total distance could be covered over multiple days, with the vehicle charging fully via solar electric power in between each flight. This phase of flight will be considered complete when the PYTHIA vehicle is within 60 m of the site of descent into the cave (either the center of the entry skylight, or a desired distance away from the skylight wall). This location will be called the 'recharge location' and will be the start and end location for both the SM and LTE phases of the mission.

Once at the entrance of the lava tube, the PYTHIA vehicle can begin the SM/LTE portion of its mission, shown in Figure 4. The SM phase will exist as a build-up to the LTE phase, gathering information on the lava tube by mapping the interior of via LiDAR and using that information to influence the LTE phase. During the SM phase, the PYTHIA vehicle will begin at the recharge location, climb and fly over the descent site of the lava tube, and then conduct descents of increasing depth, each time descending to a safe location identified by the previous SM iteration and scanning the cave to identify the next safe location (up to 100 m in depth can been analyzed, which may be required as shown in Table 2). This descent will be conducted multiple times with increasing depth until the location of the LTE phase is identified, which will be either the bottom of the lava tube or some other location identified from the scans of the SM descents. At this point, the SM phase would be considered complete, and the LTE phase would begin.

The LTE phase is the portion of the mission where the science objectives will be conducted, shown also in Figure 4. The vehicle will fly from the recharge site to the descent site over the lava tube, descend up to 100 m to arrive at the science location of interest, and then perform science objectives for up to 5 minutes, before returning to the recharge location. The science payload and objectives will be developed in concert with Mars planetary scientists. The LTE phase can be conducted in multiple iterations, with a full recharge in between. Each 5-minute cave exploration could also complete a different science goal, until every science objective is achieved.

Once the SM and LTE phases are completed for a particular lava tube, the PYTHIA rotorcraft then has the capability of moving to another lava tube and conducting both mission phases in a new location. This capability highlights the benefit of using a rotorcraft instead of proposed single-mission lava tube explorers discussed in the background section, as the PYTHIA vehicle would be capable of exploring multiple lava tubes and adapting the mission profile at each site of interest.

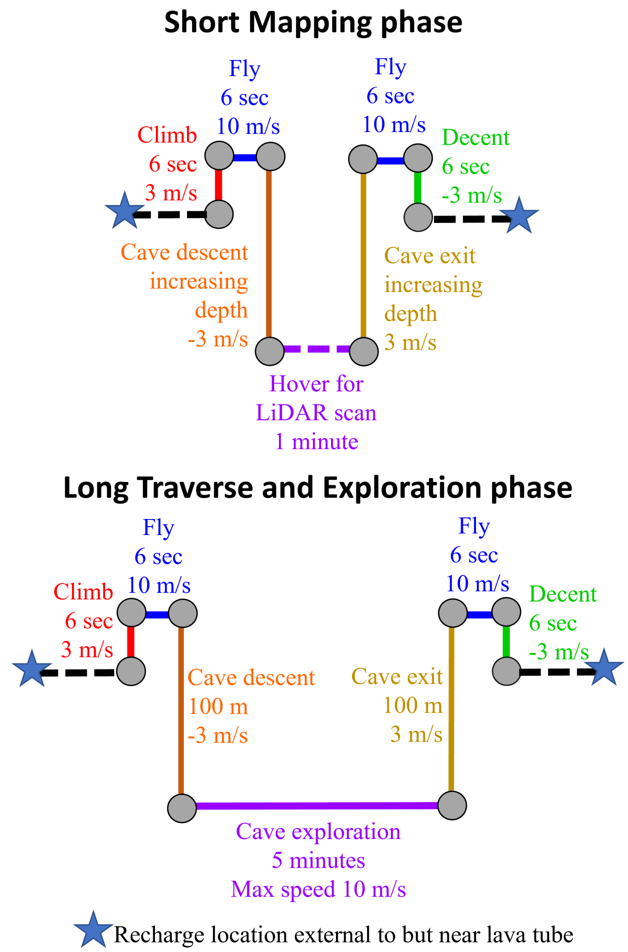

Figure 4. Representative baseline mission for the PYTHIA project. Density is assumed to be constant at 0.0065 kg/m^3. Dashed lines represent segments with no horizontal movement. The LTE phase is used for the NDARC sizing mission explored later in this paper.

VEHICLE DESIGN

At present, Mars rotorcraft missions are designed for the atmospheric conditions in the Jezero Crater. MSH has proven the benefit of a multirotor vehicle for flight on Mars, and the PYTHIA project wished to leverage this knowledge. However, with the selection of Arsia Mons as the mission location, there is a non-trivial difference in atmospheric density and pressure, which drives the flight capability of the vehicle. Additionally, to reduce vehicle complexity, a quadrotor was selected over a hexacopter. As there are two fewer rotors, there are fewer parts that have a potential to fail. For these reason, a 'clean sheet' design was considered a starting point for the preliminary NDARC design studies. The intention of the NDARC study is to explore a Martian rotorcraft in low atmospheric densities with a quadrotor vehicle design.

For this work, a collective-controlled quadrotor design was selected for adequate control while reducing the complexity that a cyclically controlled vehicle introduces. As discussed by Johnson et al., selecting a multirotor configuration instead of a single rotor configuration may help to reduce blade flapping by reducing radius as there is reduced aerodynamic damping on Mars [15]. The geometry of the multicopter configuration also contains performance benefits. The solar panel is placed outside of the inflow region of the rotors to avoid performance reductions from a blocked inflow region, and distancing the science payload from the downwash of the rotors reduces flow interference with sensitive devices. With these benefits in mind, the quadrotor was selected as a feasible vehicle for Mars exploration, especially in the low density region of Arsia Mons. The conceptual design section further details the feasibility of the quadrotor design for the PYTHIA mission, including vehicle size, initial performance, and payload capability. Vehicle configuration capability (i.e. coaxial, quadrotor, hexacopter, traditional designs), blade structure, dynamics and controllability, and detailed solar-electric power plant selection are topics that may be studied in future work.

Conceptual design

The conceptual design for the PYTHIA vehicle was conducted using NDARC. NDARC is a rotorcraft system analysis tool that can be used for conceptual design. The main tasks are to design (also referred to as 'size') an aircraft and to analyze the performance of that aircraft at different flight conditions. The aircraft is modeled by its components, including fuselage, rotors, engines, wings, and tails. A combination of low-fidelity models, NDARC is capable of rapidly analyzing both conventional and unconventional rotorcraft configurations [45]. NDARC also features a 'surrogate model' for rotor performance. This model uses higher fidelity codes to calibrate the equations in NDARC, that determine rotor performance. This highlights the importance of selecting a surrogate model that is as close as possible to the rotor being explored. For this work, an internally-developed MSH surrogate rotor performance model was used.

Atmospheric conditions in the Arsia Mons region were used in NDARC to ensure the aerodynamic environment was similar to the densities, pressures, and Reynolds number regimes a rotorcraft in that region would experience. For the NDARC sizing mission, the LTE phase profile was selected, shown in Figure 4. The LTE phase was selected for the NDARC sizing mission as the SM phase is essentially the LTE phase without the 5 minute cruise section. If the vehicle conducts a full battery charge in between each iteration, then the SM phase will be able to be completed as it will require the same power and thrust but less energy than the LTE phase.

Several design constraints were selected to provide bounds on the NDARC effort. First, the rotor radius must be as small as possible while still being able to support the NDARC sizing mission. While not conducted in this work, the vehicle will eventually need to fit within an aeroshell, so blade radius will need to be carefully considered. Additionally, a smaller rotor will be able to fit in smaller lava tubes, and so a small radius was desired. Second, the rotor tip Mach number needed to be below Mach 0.95 to avoid compressibility effects reducing performance. The hover tip Mach number needed to be as close as possible to the onset of compressibility effects, with a small margin for forward flight speed additions. Third, atmospheric density was a large constraint on the sizing of the vehicle. The quadrotor must be able to fly in the low density environment of Arsia Mons and be able to handle small changes in density that may occur. Fourth, the vehicle must be able to support a payload to conduct the science goals of the PYTHIA mission, although the payload size was not a hard constraint at the beginning of the design process. Finally, several general rotorcraft constraints were applied. The first was that the maximum allowable solidity is 0.35 to ensure the blade does not cover too much of the rotor disk. The second was that the blade aspect ratio must be between 10 and 15 for aerodynamic performance and structural design considerations.

Similar to the MSH, a six-bladed rotor was selected initially to produce high enough lift while maintaining a reasonable aspect ratio for structural stability, vibratory, and solidity considerations. This was later adjusted to an eight-bladed rotor to improve the aspect ratio of the blades at the required solidity. The NDARC sizing analysis was conducted iteratively, with each study being completed several times as different design conditions were considered. Therefore, only the results for an eight-bladed rotor are shown, although the same analyses were done for the initial six-bladed rotor design.

A density sweep was the first analysis conducted in NDARC. While the density of Arsia Mons was nominally set at 0.0065 kg/m^3, it is important that the vehicle can operate in a range of atmospheric densities, as this varies based on different locations, seasons, and altitudes. The results of the density study are shown in Figure 5. Atmospheric density greatly influences design gross weight, as lower densities require higher power and a higher solidity from the rotor to generate the same lift, which requires larger batteries on the vehicle. For an eight-bladed rotor, the NDARC sizing mission can successfully be flown in Arsia Mons for a variety of densities. In order to conduct the NDARC sizing mission successfully, the vehicle must stay between a density of 0.006 kg/m^3 and 0.015 kg/m^3 and have a radius no smaller than 0.8 m, as all other cases were unable to successfully conduct the mission.

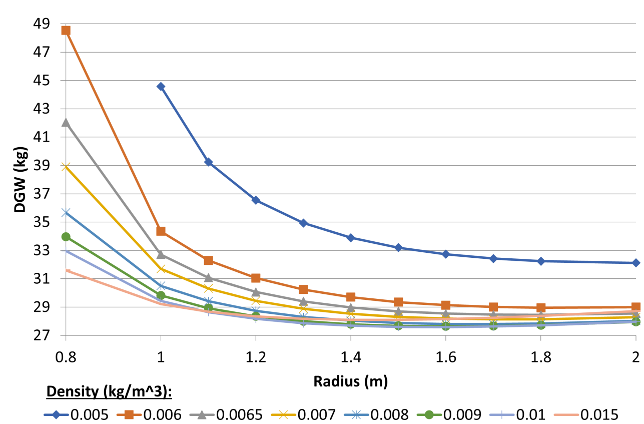

Figure 5. Atmospheric density sweep in NDARC for the PYTHIA quadrotor for various design gross weights and radii (Tip Mach: 0.85, Payload: 2.5 kg, Number of blades: 8).

Once it was proven that the vehicle could fly in a given density, a tip speed sweep was conducted, shown in Figure 6. In general, a higher tip speed leads to a more efficient rotor, which drives down the required battery weight. The main constraint on tip speed, however, is when shock formation and compressibility effects are experienced as the tip speed approaches the speed of sound. When a rotor experiences these compressibility effects, the efficiency decreases and the weight of the vehicle grows. For this study, it was found that the vehicle converged to the lowest design gross weights at tip speeds of Mach 0.8 to 0.9, with the lowest vehicle weight occurring at a tip speed of Mach 0.85. As the tip speed shown is hover tip Mach number, the tip speed will increase with forward flight. Therefore, a tip speed margin should be reserved for the increase due to forward flight. For this effort, a rough margin of 0.05 Mach (11.6 m/s) was reserved. With this reserve considered, a tip speed of 0.85 Mach was selected for the final PYTHIA vehicle, as it also produced a minimum of weight.

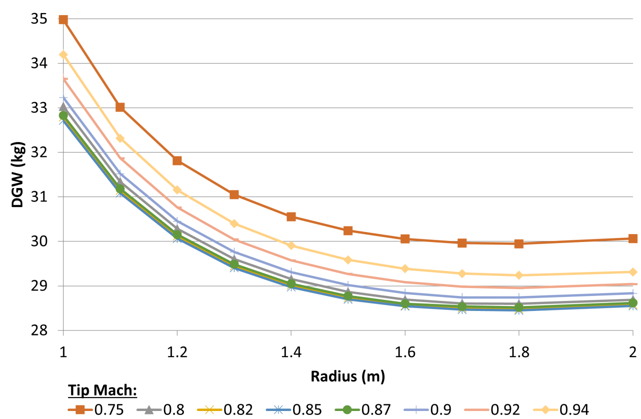

Figure 6. Tip speed sweep at Arsia Mons in NDARC for the PYTHIA quadrotor for various design gross weights and radii (Payload: 2.5 kg, Number of blades: 8, Density: 0.0065 kg/m^3).

A number of blades study was conducted next. In NDARC, changing the number of blades has a major effect on the blade chord and aspect ratio (to achieve a desired solidity), but very little effect on the design gross weight. This is due to the number of blades primarily changing the chord size to achieve the same lift and weight, which can end up being close to the same design weight. Consequently, the number of blades parameter can be used to give the blades a more ideal aspect ratio. Since NDARC uses a rotor performance surrogate model to conduct its calculations, things like blade geometry in the NDARC model need to remain close to the values used in the surrogate model. Therefore, the PYTHIA blades needed to be kept close to the aspect ratio of the MSH model, which was around 10 to 15. Figure 7 shows that in order to keep the blades within the desired aspect ratio, the number of blades may need to be tweaked depending on the desired blade radius. Generally, a smaller blade radius leads to a higher chord length. To obtain an appropriate blade thickness, another blade can be added to reduce blade thickness while maintaining constant solidity.

Finally, a study on the achievable science payload was completed. As payload dictates the type of science experiments that can be accomplished, maximizing the achievable payload

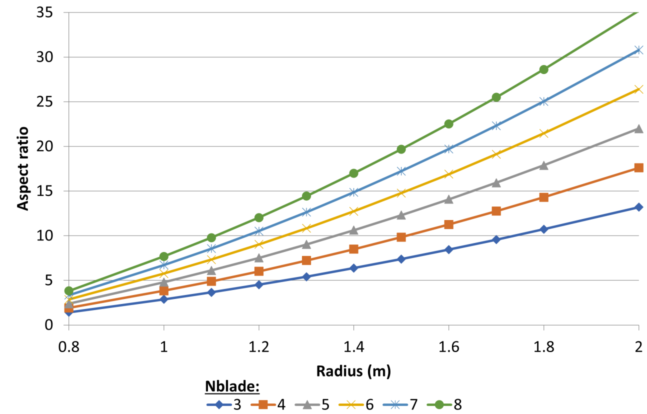

Figure 7. Blade number sweep at Arsia Mons in NDARC for the PYTHIA quadrotor for various design gross weights and radii (Tip Mach: 0.85, Payload: 2.5 kg, Density: 0.0065 kg/m^3).

is desired. Therefore, a payload sweep from 0 kg to 5 kg was conducted. Besides payload, weight and blade radius are the main variables to consider. A balance between blade radius, vehicle size/weight, and payload capacity is necessary to meet mission criteria. The radius dictates both stowage for delivery to Mars and which lava tubes are available to be explored (although from Table 2, lava tube size is not expected to have much of a constraint). The weight dictates the disk loading needed to support the vehicle during the NDARC sizing mission, which informs much of the rotor design and size. Finally, the payload requires both the weight and radius to grow, as it is a weight 'unusable' to the vehicle that still needs to be supported by the rotors, which need the main vehicle weight to provide power. Figure 8 shows the design gross weight as a function of weight for various payload masses.

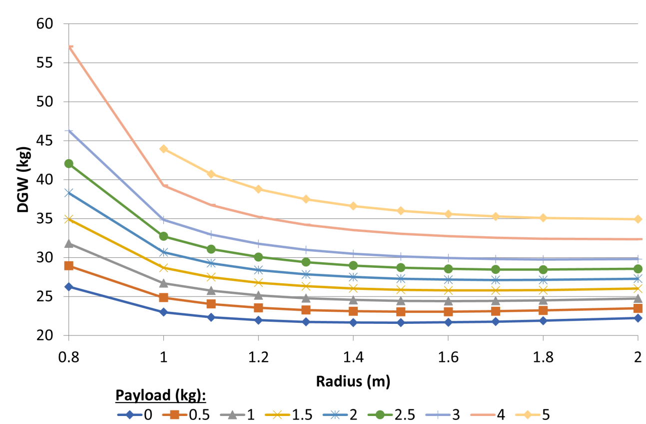

Figure 8. Payload size sweep at Arsia Mons in NDARC for the PYTHIA quadrotor for various design gross weights and radii (Tip Mach: 0.85, Number of blades: 8, Density: 0.0065 kg/m^3).

A final vehicle design was selected based on the results from the previous three sweeps. For the design density of 0.0065 kg/m^3, a radius between 1 m (0.80 for most cases) and 2 m was able to converge for all conditions tested. The next constraint, though, was aspect ratio. As shown in Figure 7, to stay within the desired aspect ratio of 10 to 15, a radius of 1.1 to 1.8 was required. As stated previously, minimizing rotor size was desired, so only the lower range of the allowable radii were considered, and a radius of 1.2 m was selected. A 1.2 m radius would allow for an eight-bladed PYTHIA quadrotor to have the desired blade dimensions (exactly in the middle of the desired aspect ratio range) and is where design gross weight begins to level out in all sweeps except for tip speed.

The payload was the final design consideration that needed to be made. The exact payload of the PYTHIA project has yet to be defined, so an initial payload of 2.5 kg is selected. This number was selected based on the proposed payloads of other Mars rotorcraft, namely MSH [15]. This payload should allow for the visualization and LiDAR systems, as well as some scientific payload. Additionally, the selection of a payload on the lower end allows for some payload growth while still being in the range of feasible designs. With all previous design decisions in mind, the final description of the PYTHIA quadrotor is summarized in Table 4.

Table 4. PYTHIA quadrotor final configuration.

Number of rotors	4
Number of blades	8
Blade radius (m)	1.20
Chord length (m)	0.095
Taper ratio	0.77
Linear blade twist (deg)	-18
RPM	1575.71
Hover tip Mach number	0.85
Cruise speed (m/s)	10
Maximum cruise distance (km)	5.25
Solidity	0.20
Design gross weight (kg)	30.06
Payload (kg)	2.50

Vehicle render

An initial render of the PYTHIA quadrotor was generated in the commerical 3D CAD and graphics software Rhino, shown in Figure 9 [46]. Rotor parameters were based on the results of the conceptual design section, shown in Table 4. Rotor mast arm size and shape, fuselage, solar panel, and landing gear were added to create an estimate of what the PYTHIA vehicle may look like, but are subject to change. PYTHIA's fuselage measures about 2.33 m in length, 1.70 m in width, and 1.32 m in height. It is likely that the current aerodynamic fuselage design will need to be altered for weight considerations, but to provide an initial image of the PYTHIA vehicle, it was considered sufficient.

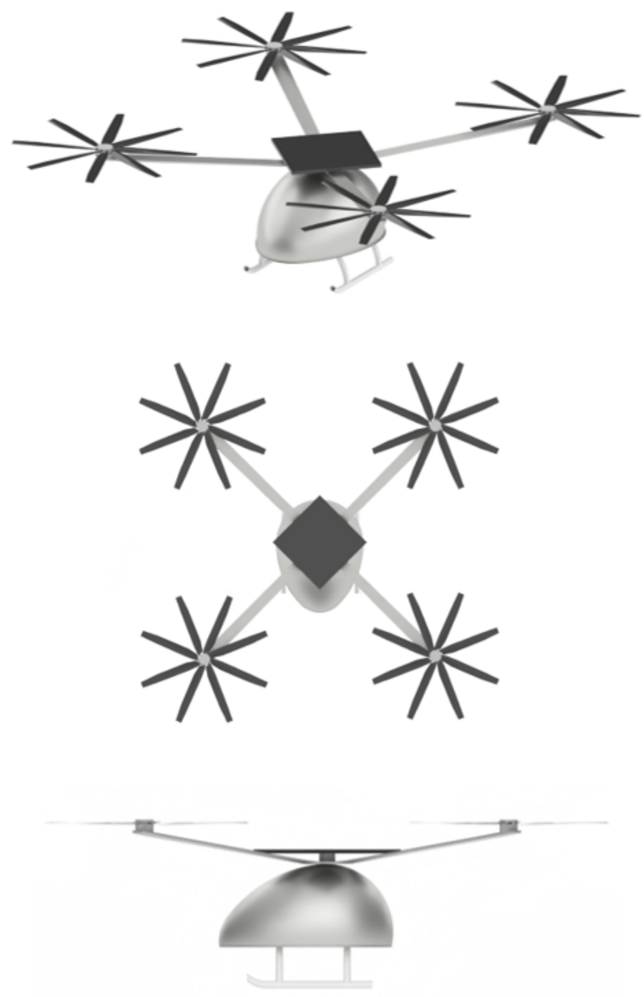

Figure 9. Isometric, top view, and side view render of the PYTHIA quadrotor concept vehicle.

To provide a sense of scale, the PYTHIA quadrotor is compared with Ingenuity, SRH, and MSH shown in Figure 10. To ensure the sizes shown are correct, the images were scaled by the proportionality of their rotor radii to the PYTHIA quadrotor's 1.2 m radius (see Table 1).

COMPUTATIONAL FLOW VISUALIZATION

Lava tube and cave environments present interesting challenges for rotorcraft flight and operation. A quantitative performance and qualitative wake study is performed for the NDARC sized PYTHIA vehicle for two cases, one without the presence of lava tube walls and one with. This study was performed using the RotCFD software [47].

Simulation setup

RotCFD calculations were completed using the mid-fidelity Rotor Unstructured Navier-Stokes (RotUNS) flow solver,

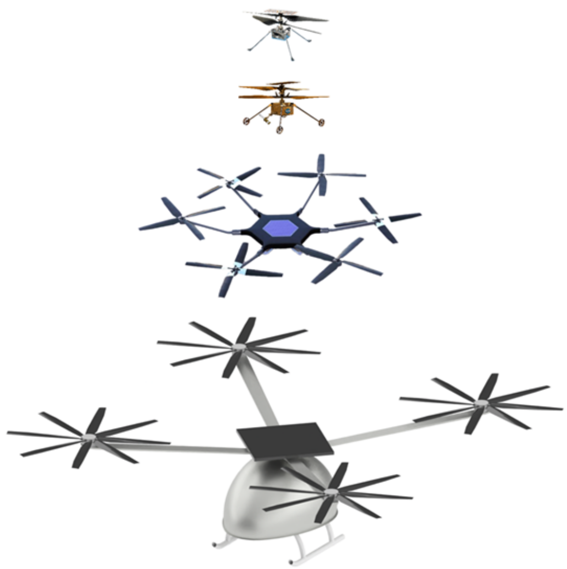

Figure 10. Approximately scaled visual comparison between Mars vehicle concepts and the PYTHIA concept vehicle. From top to bottom: Ingenuity, SRH, MSH, and PYTHIA.

which was chosen because it bridges the gap between comprehensive rotorcraft analysis and high-fidelity CFD analysis [48]. RotUNS uses 3D incompressible Unsteady Reynolds Averaged Navier-Stokes (URANS) equations and an unstructured grid. For all simulations presented, the rotor is modeled as an actuator disk to reduce computational time. Input requirements for the model require a table of 2D airfoil coefficients for a range of angle of attack and Mach number values. This table is required, as the local angle of attack and Mach number at each blade element section are computed, and the aerodynamic coefficients are retrieved from this airfoil table.

Airfoil tables

The MSH airfoil tables were selected for PYTHIA RotCFD simulations. The first iteration of next generation rotor blade design was completed by Koning et al. in 2020 in support of the MSH project [49]. In their study, unconventional airfoil geometries were optimized using an evolutionary algorithm and then analyzed for their performance characteristics using the Reynolds-Averaged Navier-Stokes (RANS) flow solver OVERFLOW [49]. The MSH rotor blades that were developed using this evolutionary algorithm showed a 17 to 41 percent increase in the peak lift-to-drag ratio for optimized airfoils when compared with the Ingenuity airfoils. This work was continued and evolved as part of the Rotorcraft Optimization for the Advancement of Mars eXploration (ROAMX) project [50, 51]. A total of 7 airfoil stations were used at 0.10, 0.20, 0.30, 0.40, 0.52, 0.76, and 0.92. The Arsia Mons atmospheric conditions were chosen to coincide with NDARC input at the desired location of interest; see Table 3.

RotUNS setup

The RotUNS time step consisted of three layers to ensure convergence was achieved by decreasing degree per time step, with time steps shown in Table 5. The first run had 360 steps coarsely set at 100 degrees azimuth. The second set was set for 360 steps every 5 degrees azimuth, and finally 1,800 steps for 1 degree azimuth. Two grid refinement boxes were placed around the cave body and rotors at respective refinement values of 9 and 10, as shown in Figure 11. Grid refinement values correspond to the density of the grid in an area. A coarse grid density was used for preliminary performance and qualitative wake simulations. A complete list of total nodes, faces, and cells for each case are provided in Table 6.

Table 5. RotUNS time steps used.

Layer	1	2	3
Time length	4.04	0.20	0.20
Time steps	360	360	1800
Iterations	10	10	10
dt (s)	0.011	0.00056	0.00011
dts (deg/time step)	100	5	1

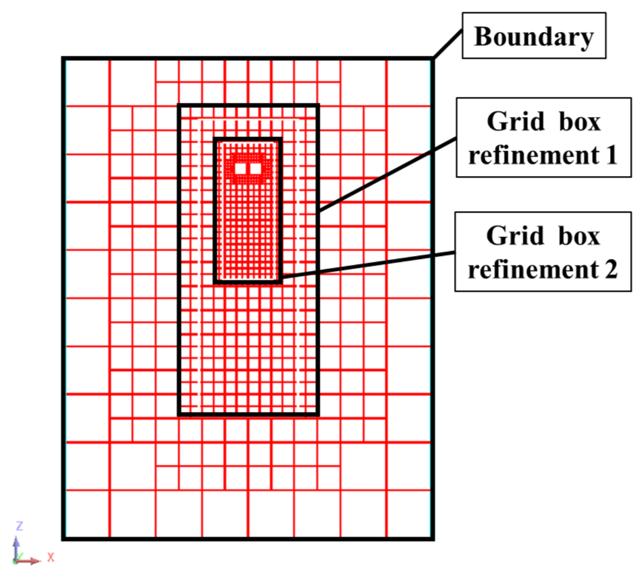

Figure 11. RotUNS boundary and grid refinement boxes for the PYTHIA quadrotor free field simulation.

Simulation flow field and performance results

As described earlier in this paper, the Arsia Mons region of Mars contains a number of skylights indicative of lava tube formations. While the skylight diameters and depths described in Reference 40 and shown in Table 3 provide some information on how large these lava tube structures may be, these estimated dimensions may be too large to effectively simulate potential flow re-circulation and rotor outwash qualitatively. For this reason, smaller dimensions were decided, with the cave walls approximately 15 m from the tip of the rotors. The simulations excluded the fuselage due to the preliminary phase of the vehicle design and to simplify wake analyses for this study. Additionally, reducing the potential cave dimensions results in a less computationally intensive CFD simulation, due to reduction in grid cells required for the analysis. Two different simulations of the PYTHIA rotor configuration were performed: one in the free field and one with a lava tube that is approximately 35 meters in diameter. Figure 12 shows the location of the simulated rotors with respect to the cave skylight and lava tube walls. Table 6 provides detailed information for each case including lava tube diameter, length, width, and height, and the total number of grid nodes, faces, and cells, as well as performance results.

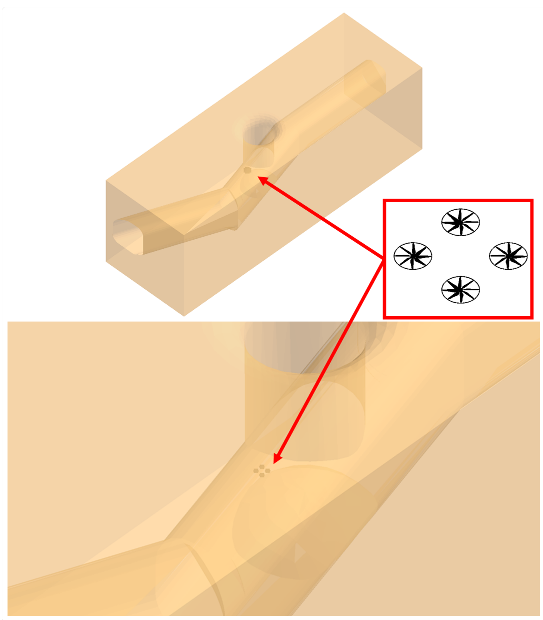

Figure 12. Isometric view of the PYTHIA vehicle isolated rotors in a lava tube.

Table 6. PYTHIA quadrotor configuration RotUNS grid refinement and performance result without and with lava tube walls present.

Case	Free field	With lava tube
Lava tube diameter (m)	N/A	35.4
Lava tube length (m)	N/A	278.7
Lava tube width (m)	N/A	95.6
Lava tube height (m)	N/A	91.6
Grid nodes	32,838	3,103,251
Grid faces	83,276	7,727,949
Grid cells	25,392	2,313,201
C_T	0.0264	0.0261
C_P	0.0052	0.0050
FM	0.59	0.60

The RotUNS simulation of the cave results in a higher number of grid nodes, faces, and cells needed for the simulation. Performance values reveal a higher figure of merit when the lava cave walls are present due to wall effects, which leads to less overall power required with a coefficient of power difference of 0.0002 and figure of merit difference of approximately 0.01.

A qualitative study of wake flow field is shown in Figure 13 for rotors in a) the free field and b) inside a lave tube. Wake flow field results reveal a more turbulent wake is present in a cave when compared to the hover case. The presence of the cave introduces wall effects and therefore the inflow between with and without walls will result in differences in performance parameters such as coefficient of thrust and power. This means that the PYTHIA quadrotor may experience different rotor performance environments at different locations in the lava tube, which requires careful consideration for flight planning.

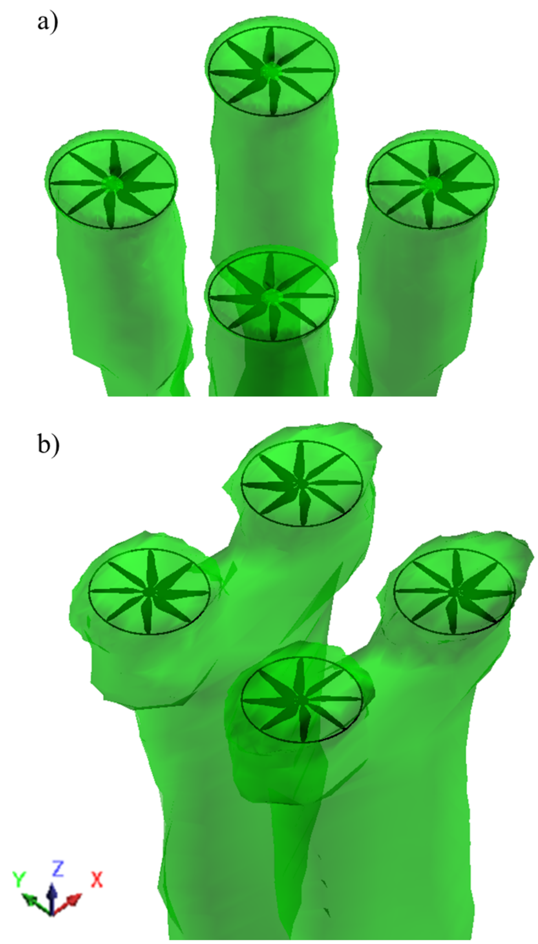

Figure 13. PYTHIA quadrotor RotUNS visualization of rotor wake in the a) free field and b) in a lava tube.

A velocity magnitude plane is compared for PYTHIA without and with the presence of the cave, see Figure 14. The plane highlights the back two rotors in the Y-plane, as the quadrotor is symmetric without a fuselage and is expected to be mirrored between the front and rear rotors. Results reveal wake interaction with the presence of the lava tube wall, likely due to flow reflection off the wall pushing the flow towards the center of the two rotors, producing wake on wake interactional effects. In conclusion, the turbulent wake and velocity magnitude wake visualizations reveal that wall effects are present and resulted in an increase in performance. This result both ensures the PYTHIA quadrotor's ability to fly even in a 35 m lava tube (35 m was chosen to be significantly smaller than the expected lava tubes that could be encountered, see Table 2) without having to worry about wall effects negatively impacting performance. Wall effects and the effect of the vehicle performance will be further explored in future work.

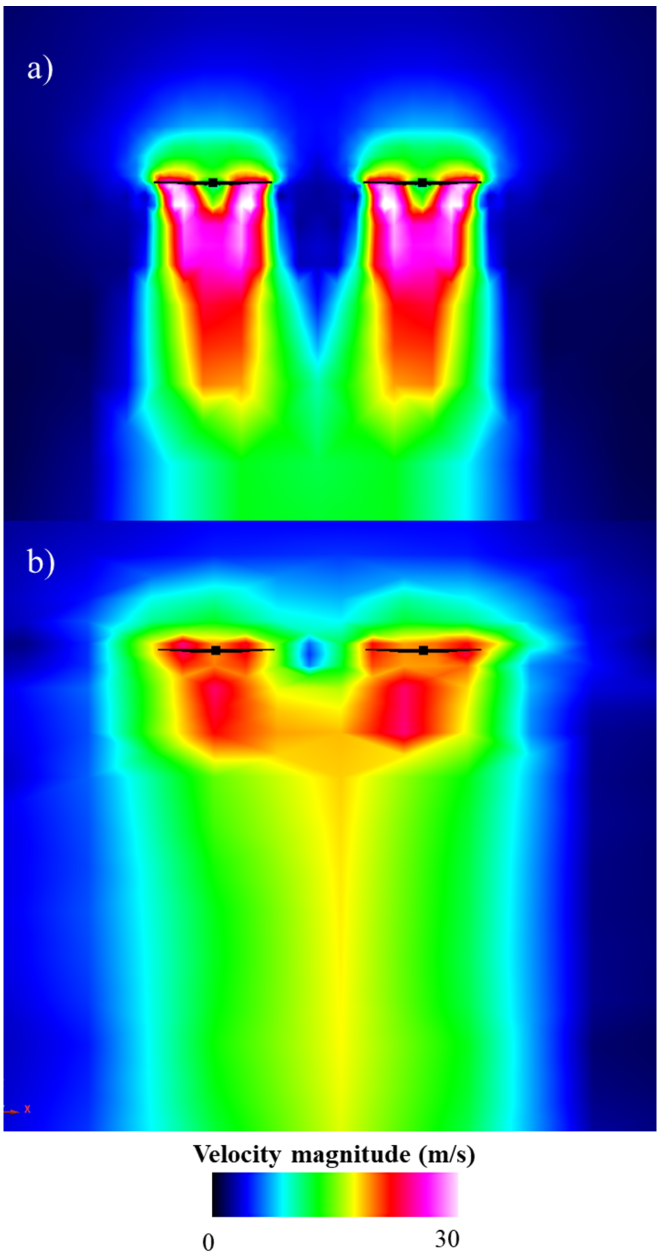

Figure 14. PYTHIA RotUNS simulation velocity magnitude contour plane a) free field and b) in a lava tube.

CONCLUDING REMARKS

A representative mission and vehicle to conduct the exploration of Martian lava tubes via rotorcraft was proposed. The PYTHIA project aims to study the history and makeup of Mars using rotorcraft to enter previously inaccessible regions of Mars, namely lava tubes. A literature review of other Martian exploration ideas and projects was conducted to identify areas in which a rotorcraft could complete science-forward missions. The location of the PYTHIA mission, Arsia Mons, was selected from 3 contending exploration sites due to the region's frequency of lava tubes, interesting weather patterns, and difficulty to access without a rotorcraft. This region of Mars was used to create a preliminary mission profile that contains a two-phased mission approach. Sizing and design work for a solar powered quadrotor was done in NDARC, leading to the selection of an eight-bladed, 1.2 m radius quadrotor. To further analyze the aerodynamic environment in a cave in a low density flight regime, the selected PYTHIA quadrotor configuration was analyzed in RotCFD in the freefield and within a lava tube with a 35 m skylight diameter. The RotCFD results showed an increase in FM of 0.01 and a decrease in C_T and C_P of 0.0003 and 0.0002, respectively, suggesting the cave walls had an influence on the overall rotor performance, but may work in the vehicles favor.

FUTURE WORK

The work conducted for the PYTHIA project thus far was focused on mission selection and conceptual design. Several tasks still need to be completed to produce a comprehensive, fully-scoped mission. The PYTHIA project plans to address the following areas of research in future work:

- Compare various rotor configurations, including a coaxial design, hexacopter, and octocopter, to further understand the sizing and performance of a vehicle in the Arsia Mons region.
- Conduct design excursions for possible additions to the PYTHIA vehicle, namely with wheels for landing gear to provide extended ground traversal and rotor shrouds for possible wall impact protection. This study would analyze these design additions for their weight and performance trade-offs.
- Explore implementation of a ROAMX blade geometry optimized for the Martian atmosphere [50, 51]. Optimized airfoils may improve flight performance in low density regions like Arsia Mons.
- Consider how the quadrotor will fit in an aeroshell for launch and entry. Ideas such as folding rotors will be considered before selecting an appropriately sized aeroshell.
- Before settling on a final design, the current quadrotor should go through several iterations with NDARC, RotCFD, and a mid-fidelity comprehensive analysis tools

like CAMRAD II and CHARM. Codes like CAMRAD II and CHARM will also allow studies on vehicle flight dynamics (to ensure the PYTHIA quadrotor is not experiencing flapping issues seen with MSH [15]).

- Flight control is critical to consider in the design space, as there are known issues with vehicle controllability in the low Reynolds number regime of Mars [12]).
- Conduct a weight and structure analysis on the fuselage and rotor mast arms.
- Refine the power plant of the vehicle, such as solar panel size and shape, battery size, and wiring. While the PYTHIA quadrotor battery has been sized in NDARC to conduct the proposed mission successfully, further refinement could be conducted on battery size and capacity for the LTE phase flights.
- Operating underground presents potential challenges for communication and sensing. A study of potential signal interference, effects of a degraded visual environment, and communication robustness needs to be completed to determine imaging and sensing capabilities as well as communication ranges for a vehicle exploring lava tubes.
- Vehicle heating to handle the cold Martian climate is also required and needs to be considered.

This list is not comprehensive of all potential research areas that could be considered by the PYTHIA project. However, it acknowledges the next steps necessary to evolve the design beyond the preliminary stage and establish a comprehensive mission to explore lava tubes on Mars.

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