View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by NASA Technical Reports Server

Recent Efforts Enabling Future Mars Rotorcraft Missions

Shannah Withrow-Maser
shannah.n.withrow@nasa.gov
NASA Ames Research Center
Moffett Field, CA

Witold Koning
witold.koning@nasa.gov
Science and Technology Corp.
Moffett Field, CA

Winnie Kuang
winnie.kuang@nasa.gov
Science and Technology Corp.
Moffett Field, CA

Wayne Johnson
wayne.johnson@nasa.gov
NASA Ames Research Center
Moffett Field, CA

Abstract

The Mars Helicopter (MH), launching as a part of the Mars 2020 mission, will begin a new era of planetary exploration. Mars research has historically been conducted through landers, rovers, and satellites. As both government and private industries prepare for human exploration of the Martian surface within two decades, more in depth knowledge of what awaits on the surface is critical. Planetary aerial vehicles increase the range of terrain that can be examined, compared to traditional landers and rovers and have more near surface capability than orbiters. The Jet Propulsion Laboratory (JPL) and NASA Ames are currently exploring possibilities for a Mars Science Helicopter (MSH), a second-generation Mars rotorcraft with the capability of conducting science investigations independently of a lander or rover (although this type of vehicle could also be used assist rovers or landers in future missions). Preliminary designs of coaxial-helicopter and hexacopter configurations have targeted the minimum capability of lifting a payload in the range of two to three kilograms with an overall vehicle mass of approximately twenty kilograms. These MSH designs' sizes are constrained by the aeroshell dimensions (currently focused on employing legacy Pathfinder or MSL aeroshells), rather than vehicle structural or aeroperformance limitations. Feasibility of the MSH configurations has been investigated considering packaging/deployment, rotor aerodynamics, and structural analysis studies. Initial findings suggest not only the overall feasibility of MSH configurations but also indicate that improvements up to 11.1 times increase in range or 1.3 times increase in hover time might be achievable, even with an additional science payload, compared to the current design of the MH.

Introduction

Robotic planetary aerial vehicles, such as the Mars Helicopter (MH) that will fly with the 2020 rover, increase the range of terrain that can be examined, compared to traditional landers and rovers. Aerial mobility is a promising direction to consider for planetary exploration as it reduces the challenges that difficult obstacles pose to ground vehicles. Previous missions that could not be realistically considered from an operational risk perspective are now possible. For example, since unmanned aerial vehicles allow for access to more remote parts of Mars, they can be used to carry and retrieve small science samples from otherwise inaccessible locations. Furthermore, future rotorcraft could be used to explore regions of interest with exposed water ice or brines where microbial life could potentially exist. In these potential missions, rotorcraft could be used as a standalone vehicle on a mission or alongside and interacting with rovers/landers.

Presented at the VFS Aeromechanics for Advanced Vertical Flight Technical Meeting, San Jose, CA, January 21–23, 2020. *This is a work of the U.S. Government and is not subject to copyright protection in the U.S.*

The first use of a rotorcraft for a planetary science mission will be in 2021, where the MH technology demonstrator will be carried by and deployed from the Mars 2020 rover [2]. The goal of the MH is to demonstrate the viability and potential of heavier-than-air flying vehicles in the Martian atmosphere. MH is a coaxial helicopter with a mass of 1.8 kg and rotor diameter of 1.21 m. The helicopter relies on solar cells and a battery system for power, allowing up to 90 second flight endurance that is conducted fully autonomously due to the communication delay between Earth and Mars. The MH will perform five, ninety-second flight as a technology demonstration of the first powered flight on another planet[1,2].

The question, "What is next?" logically follows from an anticipated successful MH technology demonstration. The Mars Science Helicopter (MSH) project began in late 2018 with the goal of establishing the feasibility of flying a much larger, more capable rotorcraft on Mars [1]. The current MH does not have a dedicated science payload apart from the instruments required for flight. Design requirements for the MSH mission, though, includes a generic, two to three kilogram payload (such as could be used for onboard science instruments intended for mapping, stratigraphy, remote sensing, etc.), an extended range (2–4 km), and increased hover time (2–4 minutes) sufficient to enable significant science investigations both inflight as well as when on the surface. The aircraft design target mass to accomplish such science missions is around 20 kg. The MSH vehicle will require improved handling qualities for control, more efficient rotor blade performance, and optimized ultra-lightweight structural design in order to be successful.

The development of the Mars Helicopter was led by JPL with significant contributions from the NASA Aeronautics Research Mission Directorate (ARMD) Revolutionary Vertical Lift Technology (RVLT) project - supported by researchers at NASA Ames and Langley - with additional participation by AeroVironment. The ongoing conceptual design study of the Mars Science Helicopter is also a Jet Propulsion Laboratory (JPL) led project, which is currently supported by rotorcraft researchers in the Aeromechanics Office at NASA Ames Research Center. JPL leads the mission and science aspects of the MSH project, while Ames leads the vehicle design. This paper describes the activities at NASA Ames in the last year supporting the Mars Science Helicopter project.

Background

Early work regarding studies into aerial exploration of planetary bodies was performed by Young and Aiken [3] and [4], [5] and Young et al.[6]–[8]. Additional early work, subsequent to [1], includes University of Maryland and Georgia Institute of Technology documentation of Mars rotorcraft conceptual design studies in response to a 2002 American Helicopter Society, International student design competition sponsored by NASA and Sikorsky Aircraft. A more detailed summary of previous work specific to Mars rotorcraft is provided in Grip et al.[9] and Hirschberg[10]. The MH Technology Demonstrator (MHTD, aka MH) design is described in Balaram et al.[2]. Grip et al. describe the flight dynamics[9] and discuss the guidance and control[11] for the helicopter. Pipenberg et al.[12] describe the fabrication of the MH. Rotor performance analyses of the MH were performed by Koning, Johnson, and Grip[13]. Additionally, in recent years (including concurrently with the MH development), parallel conceptual/foundational research into Mars rotorcraft has been conducted by many researchers throughout the world, including continued foundational low-Reynolds number rotor performance research at NASA Ames for rotors capable of flight in the atmosphere of Mars. Recent work by Ament and Koning[14], Ament, Koning, and Perez Perez[15], and Perez Perez, Ament, and Koning[16] at NASA Ames has investigated experimental rotor testing at Mars atmospheric densities. This recent work has been important in the pursuit of the joint JPL and Ames study into the notional development of the next-generation Mars Science Helicopter, the principal focus of this paper.

Mars Science Helicopter Design

Design of an aircraft, helicopter or airplane, large or small, operating on Earth or Mars or Titan, involves the following process. First the mission is defined, in terms of payload, hover time, and range. The atmosphere characteristics (density and temperature) are specified based on the intended area of operation. For conceptual or preliminary design, all the vehicle components and subsystems must be identified. Weight models and performance models are developed that characterize the impact of vehicle size on component weight, calibrated to historical data or scaled from an existing aircraft. Then the aircraft is synthesized, sizing all components, and the complete vehicle to perform the required mission. The synthesis and analysis of the MSH rotorcraft were performed using NASA Design and Analysis of Rotorcraft ((NDARC; [17] and Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics II (CAMRAD II; [18]) software.

A modest science mission was defined for the preliminary MSH study consisting of a 2.0 kg payload, sufficient for carrying mapping, stratigraphy, and remote sensing instruments. The mission profile flight requirements were prescribed as being a 30 second takeoff, climb to 200 m altitude, flight range of 1 km to the science site, hover for 2 minutes at the science site, land, and then recharge the batteries on the ground using an onboard solar cell array.

The nominal atmospheric characteristics were specified at the Jezero Crater in the spring: 0.015 kg/m^3 and –50ºC. (This is the same location and conditions faced by the MH technology demonstrator in 2021). These conditions, particularly the low atmospheric density and the resulting low speed of sound, are what makes flight on Mars challenging.

Flight on Mars for the MH and MSH vehicles is enabled by electric propulsion: batteries supplying power to motors and recharged by solar cells. Hence the design of a helicopter on Mars shares many of the issues encountered designing electric-powered VTOL aircraft for air taxi operations on Earth. The initial models for the weight and performance estimates for MSH were calibrated to the MH. Additionally, JPL provided projections of advanced battery technology for the expected time period of a MSH development. Further, the MSH size is constrained by legacy aeroshell dimensions, rather than anticipated vehicle hardware limitations. For initial conceptual design purposes, the legacy Pathfinder aeroshell was considered, notably imposing a maximum diameter of 2.5 meters for the aircraft when folded/packaged in the aeroshell prior to deployment on the Martian surface. Initially, the blade loading (mean rotor blade lift coefficient) and hover Mach number were fixed at the values of the MH. Taking advantage of optimization of the rotor aerodynamics (described below), the blade loading and tip Mach number were increased, resulting in more range and hover time (2 km and 4 minutes) for the same weight and power.

Two basic configurations emerged from the initial sizing exercise: a scaled-up coaxial helicopter and a hexacopter (Table 1). Both rotorcraft configurations were sized to have a gross takeoff weight of about 20 kilograms. The coaxial configuration has a blade radius of 1.25 meters; the hexacopter rotors were initially sized at a radii of 0.64m. Advantages of the coaxial helicopter include some design heritage with MH, while the primary disadvantages identified are flight dynamics concerns and, secondarily, packaging issues. A hexacopter was initially chosen over a quadcopter as a nominal baseline design because the extra rotors would reduce the flight risk due to motor failure. Other advantages of the hexacopter configuration include improved controllability, robustness, flexibility of packaging, and increased physical area available for solar cell arrays. Disadvantages include lack of flight heritage and the airframe weight. Figure 1 compares these two MSH designs with the MH.

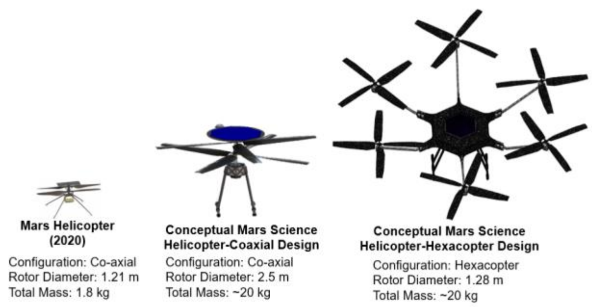


Figure 1. Size comparison of the MH and MSH concept aircraft.

Table 1. Coaxial helicopter and hexacopter designs for the Mars Science Helicopter mission.

Parameter	Unit	Coaxial	Hexacopter
Design M_tip		0.8	0.8
Rotor Radius	m	1.25	0.64
Gross Weight	kg	19.31	17.69
Disk Area	m^2	9.82	7.72
Required Solar Cell Area	m^2	0.62	0.62
Total Power Required	kW	3.58	2.80

Several aspects of the MSH conceptual designs required additional study such as packaging, on-surface deployment, improved rotor aerodynamic design, and more detailed structural/weight analysis of the vehicle fixed-frame structure (cross-arms and centerbody). These additional areas of study differ significantly from the work performed for MH due to the larger vehicle size and potential configuration change of MSH. Packaging with aeroshells was explored for both the coaxial and hexacopter configurations. Rotor aerodynamic optimization and fixed-frame structural design focused primarily on the hexacopter.

Aeroshell Packaging

An aeroshell packaging study was performed to determine if the initial conceptual designs could fit within and be landed using modified versions of legacy Martian entry, descent, and landing systems (EDLS), or if the proposed vehicles would require additional time and resources in creating a new EDLS. Aeroshells considered include Pathfinder, Viking, and Mars Science Laboratory. As Pathfinder is the smallest and least expensive of the three aeroshells, it was selected as the initial volume constraint. The initial packaging approach assumed that the problems of landing and extraction are solvable and most of the volume within the aeroshell is potentially usable. (Later, more detailed studies, would consider the volumetric implications of not only fitting MSH vehicles inside the aeroshell but also fitting within the original Pathfinder airbag tetrahedral petal lander.)

Numerous folding methods for both the coaxial and hexacopter designs were examined to determine which yielded the most efficient use of the aeroshell volume. Some initial folding methods that were considered included drooped folding and in-plane folding for the coaxial helicopter, and rotating and hinging arms for the hexacopter with three- and four-bladed rotors.

(a) (b)

Figure 2. Hexacopter configurations: (a) four-bladed rotating, (b) four-bladed hinged.

(a) (b)

Figure 3. Coaxial configurations: (a) four-bladed, drooped, (b) three-bladed, in-plane folding.

The drooped configuration allowed for the largest rotor radius (1.25 meters) for the coaxial configuration in the Pathfinder aeroshell, while the largest rotor radius for the hexacopter was 0.64 meters with the rotating configuration. The hexacopter was chosen as the primary design moving forward due to its performance advantage, controllability advantage, and ability to remain in flight with one or two rotors inoperative (Table 1).

If the aeroshell size were increased, the vehicles could become larger and more capable with increased rotor size. The preliminary conclusion from this portion of the packaging study was that a feasible rotorcraft design exists and a reasonable EDL system based on heritage technology could deliver it to Mars.

Lander and Deployment Options

With current technology, it is unlikely that a whole aeroshell would/could be devoted to stowing a Mars rotorcraft, and so the next challenge was to explore lander options and the ability to stow rotorcraft in such landers instead of only examining stowage in aeroshell volumes. Low air density at the Martian surface leads to very low aerodynamic damping, therefore blades must be comparatively stiffer than on Earth. Blade folds (with discrete mid-span hinges or pivots) could significantly decrease the stiffness of the blades, and, thus, were considered an undesirable option for this study. All folding configurations presented have stiff blades with the fold hinges at the blade-roots and with supplemental structural support for folded blades in the vehicle's stowed configuration. Lander designs using a "sky crane" or other propulsion-based lander – similar to Mars Science Lab and Viking, respectively – were considered. However, because of the significant emphasis placed on determining the feasibility stowing the MSH in a legacy EDL system, the Pathfinder petal lander was selected as the baseline lander design for the follow-on packaging/stowing/deployment studies. This airbag tetrahedral petal lander was inherently consistent with the Pathfinder aeroshell used in the initial packaging studies. This design study decision reinforced further investigation of the hexacopter over the scaled coaxial configuration, which could maintain a larger blade area when placed in the lander than the scaled coaxial design.

The rotating (arm) configuration of the hexacopter was designated as the baseline model because it provided the best performance, compared to other hexacopter folding designs considered, within the aeroshell volume constraints. However, it was quickly found that this configuration had to be adapted to avoid interference with the sides of the petal lander, refer to Figure 4.

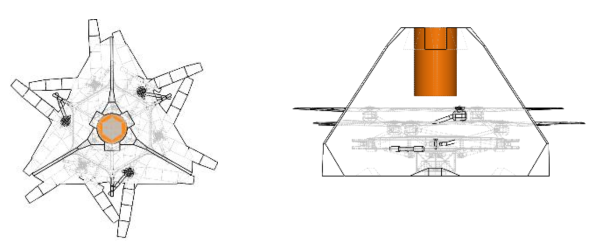


Figure 4. Top and side view of the base model hexacopter in Pathfinder petal in closed configuration, showing blade interference with walls of lander.

Multiple subsequent design iterations resulted in a hexacopter design that took advantage of the long diagonal sides of the petal lander while maintaining the placement of the payload at the bottom of the craft for camera visibility. Maximum rotor diameter was determined to be 0.50 meters, with no blade scissoring, to be able to fit in the petal lander. If the blades are scissored (folded so that they rest on top of one another), though, the blade radius can be increased to 0.58 meters, thereby increasing performance. The most significant disadvantage of this approach is the mechanical complexity of the scissoring blades, which will require further future study.

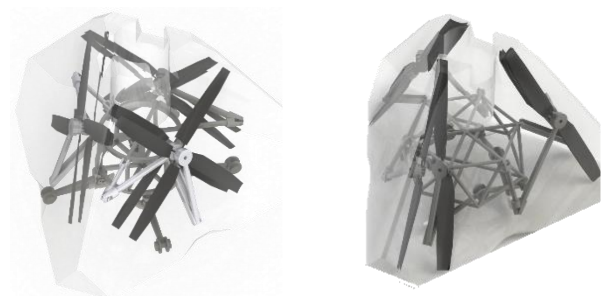
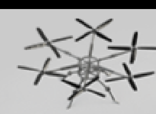


Figure 5. Layered hexacopter in stored position without scissored blades, R = 0.5 m.

Vehicle geometry and performance are compared in Table 2 for the scissored and non-scissored designs.

Table 2. Layered hexacopter performance: non-scissored (v4) versus scissored blades (v5).

Configuration	Layered v4	Layered v5
Open Configuration		
Closed Configuration		
Radius (m)	0.50	0.58
Solidity	0.250	0.176
Mean chord (m)	0.1029	0.0837
Aspect Ratio	4.9	6.9
Weight (kg)	19.06	17.99
Power (kW)	3.51	2.87
Energy (MJ)	2.37	1.98
Remaining volume in lander (m^3)	0.168	0.215

The stowed configurations shown fit in a heritage EDL and meet the minimum defined mission criteria. A tradeoff exists between using a small, heritage EDL system and vehicle performance. If a larger and capable vehicle were desired, these stowed hexacopter designs could be adapted to a larger aeroshell and lander.

Lastly, extra volume was identified for additional payload "black boxes" that could be used to provide for lander "ground station" functionality. This approximate available volume in the lander, nestled around and, in some cases, in between the folded MSH structure, could be for additional lander scientific instrumentation, telecom and data processing, lander solar array power electronics, or even secondary, swappable payloads for the MSH vehicle (if the appropriate mechanisms could be devised to robotically exchange payloads between the lander and MSH between flights). The notional black boxes were placed symmetrically around the edges of the lander in a manner that would not interfere with the rotorcraft as the lander petals unfolded. Payload black boxes can be included around all sides of the rotorcraft, as the MSH will take off vertically from the lander during its initial flight (subsequent flights would either land back on the lander or land nearby, off the lander; the better approach is still open for discussion), rather than driving off the lander like a rover. Current estimates of additional payload volume are between 0.168 to 0.215 cubic meters, respectively, for the hexacopter configuration with scissored and non-scissored blades. Unlike most other lander missions to Mars, the EDLS problem for MSH will likely not face mass restrictions but, rather, volumetric restrictions for the landed spacecraft systems.

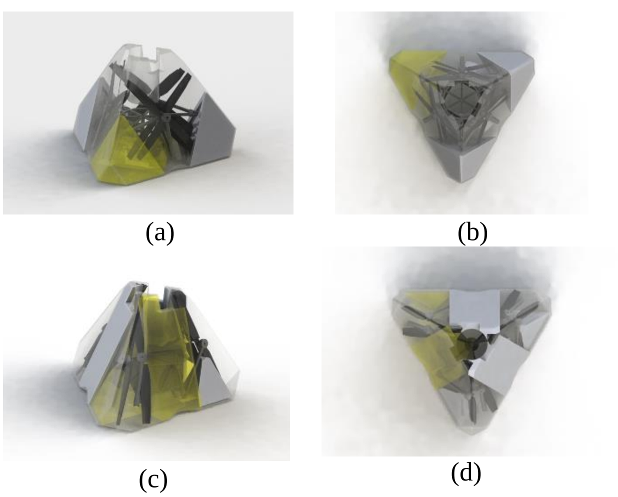


Figure 6. Available volume (one side is highlighted) for: a) side view, non-scissored blades, b) top view, non-scissored blades, c) side view, scissored blades, and d) top view, scissored blades.

Rotor Aerodynamic Design

Efficient airfoils at very low Reynolds numbers are relatively unexplored: their applicability for Earth-based vehicles is mainly limited to small Unmanned Aerial Vehicles (UAV), Micro Aerial Vehicles (MAV), and Nano Aerial Vehicles (NAV). Performance of conventional airfoils at low Reynolds numbers have been discussed in the works by Carmichael[19] Lissaman,[20] and Mueller and DeLaurier[21], although most Reynolds number ranges considered are higher than that required for Mars rotor application. A comprehensive overview of the challenges for Micro Air vehicle development was presented in Pines and Bohorquez[22]. The MH uses conventional airfoil geometries for a chord-based Reynolds number of around Re = 10^4 over the blade[23]. The difficulty of finding or designing efficient airfoils for Mars rotorcraft, including MSH, is compounded by not only the low Reynolds numbers at which they are expected to operate but, also, the compressible flow conditions that they are subjected to (tip Mach numbers on the order of 0.7 to 0.9 for hover and forward-flight respectively).

Recent work indicates that unconventional airfoils (cambered flat-plate-type airfoils, very thin airfoils, or airfoils with sharp edges) can provide good aerodynamic efficiency at the low Reynolds numbers (and compressible) flow regime. Thus, these configurations are being considered for the MSH in addition to the more conventional, though very thin, airfoil used for the MH (Figure 7).

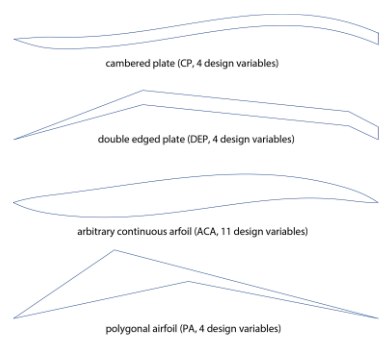


Figure 7. Examples of Unconventional Airfoil Shapes Considered.

Work including low Reynolds number airfoils for rotary wing applications is scarce. Young et al. [5, 16] indicate the potential of cambered flat plates for airfoils for increased rotor performance. Young, et al, [15, 18] also compared rotor hover performance measurement, with the blades using the Eppler 387 airfoil, under Mars-like conditions (in the first ever published experiment) to CFD results from Corfeld, et al, [17] (showing, in part, the necessity of thin airfoils for acceptable Mars rotor operation). Ames researchers, Koning, Romander, and Johnson[24] have analytically shown the performance increase when using flat and cambered plate airfoils as direct substitutes for the MH rotor. Additionally, Shrestha et al.[25] shows experimentally that cambered plate airfoils are feasible for a Mars rotor applications, and recently, Escobar, Chopra, and Datta[26] described the complexities in developing rotor systems for a coaxial Mars rotorcraft.

Koning, Romander, and Johnson[27] have performed single objective optimization for unconventional airfoil shapes with sharp leading edges and a range of airfoil geometries in the low Reynolds number compressible regime. Figure 8 shows an example of the double-edged plate (DEP) airfoil at a chord-based Reynolds number of Re_c = 16,682.

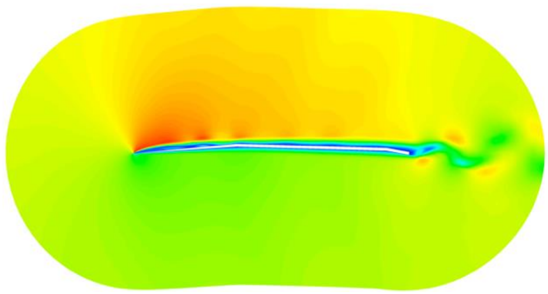


Figure 8. Velocity magnitude over a double-edged plate optimized airfoil for *Re* = 16,682, *M* = 0.50, c_l = 0.70, and c_l/c_d = 23.43.[27].

Koning, Romander, and Johnson[28] extended the study to multi-objective optimization for aerodynamic performance at representative Reynolds-Mach combinations for a concept rotor. Both studies show significant increases of attainable efficiency over the conventional Mars Helicopter airfoil and a cambered plate airfoil. Sharp (or thin) leading edges initiate flow separation, and the occurrence of large-scale vortex shedding is found to contribute to the relative performance increase of the optimized airfoils, compared to conventional airfoil shapes. The oscillations are shown to occur independent from laminar-turbulent transition and therefore result in sustainable performance at lower Reynolds numbers[28]. Comparisons to conventional airfoil shapes show peak lift-to-drag ratio increases between 17% and 41% for similar section lift.

Generation of a rotor model (in similar fashion to Ref. [29]) was used to estimate the rotor performance for an advanced concept 4-bladed concept rotor. The planform is shown in Koning et al.[28] with the rotor radius of R = 0.64 meters and a solidity of σ = 0.193. The performance predictions from the CAMRAD II comprehensive analysis tool for figure of merit versus thrust and power versus forward flight speed are shown in Figure 9 and Figure 10, respectively. The predictions use the same inboard rotor airfoils, and the outboard airfoils are varied to reflect the performance for the clf5605 airfoil (CLF) from the MH rotor[23], a circular arc cambered plate, and the double-edged plate airfoil [27].

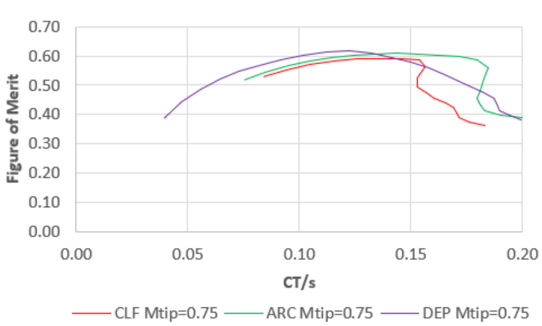


Figure 9. Figure of Merit versus thrust for the concept rotor for three airfoils.

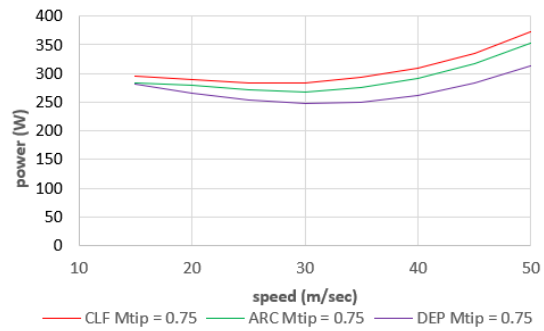
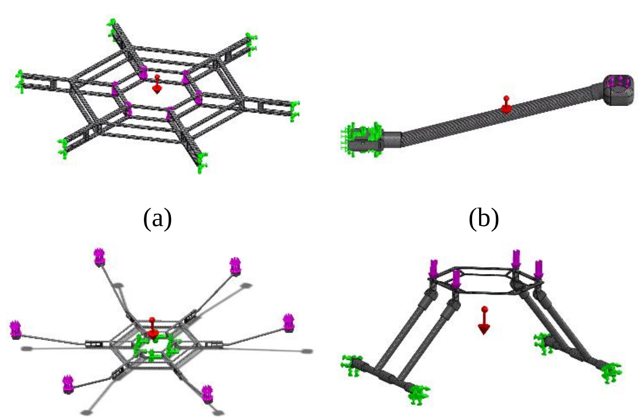


Figure 10. Power versus forward flight speed for the concept rotor for three airfoils.

Improvements in 2D airfoils show peak figure of merit improvements of around 4% to 7%. For equal power, the airfoils allow for 12 - 23% increase in forward flight speed (or, conversely, power in forward flight is reduced around 6 – 10% for equal forward flight speed). The improved efficiency of this rotor design enables the MSH to potentially perform more efficiently than the rotor design for the MH, thereby increasing the rotorcraft's capabilities. Detailed rotor design has only recently initiated and several open questions regarding manufacturability, meeting stiffness/frequency /mass targets, and achieving structural robustness still need to be addressed for rotors accommodating these new airfoils. Future work also includes expanding current simulation cases to 3-D analysis using OVERFLOW computational fluid dynamic (CFD) software.

Airframe Structure Design

Preliminary finite element analysis (FEA) was conducted on the hexacopter configuration was completed in SolidWorks Simulations^{TM}. Two preliminary linear static analyses were performed on the assemblies shown in Figure 11: preliminary analysis I (PA-I) and preliminary analysis II (PA-II).



(a) (b)

(c) (d)

Figure 11. Overview of assemblies in the studies, shown are: (a) Fuselage, (b) Arm, (c) Fuselage and Arm, and (d) Landing Gear and Payload Attachment. Legend: gravity (red), applied constraints (green) and applied loads (pink).

Preliminary analysis I (PA-I) was performed on the first iteration of the hexacopter model. The first iteration of the hexacopter model was designed to be lightweight and meet the packaging constraints of the aeroshell but not the Pathfinder-like tetrahedral petal lander. The objective of PA-I was to determine any immediate concerns with the configuration and implement any necessary modifications to minimize stress and displacements. Preliminary analysis II (PA-II) was performed on a modified version of the hexacopter based on results from PA-I. Consequently, the modified hexacopter has more mass than the original hexacopter. PA-II included the same test conditions as the original cases in addition to more extensive flight maneuvers. These flight maneuvers include hover, forward flight, roll, pitch, and yaw. Values for the forces involved in these flight maneuvers were based on NDARC values. To evaluate the design, a displacement threshold/limit of 12.7 mm (0.5 inch) was selected as an initial design target for displacement.

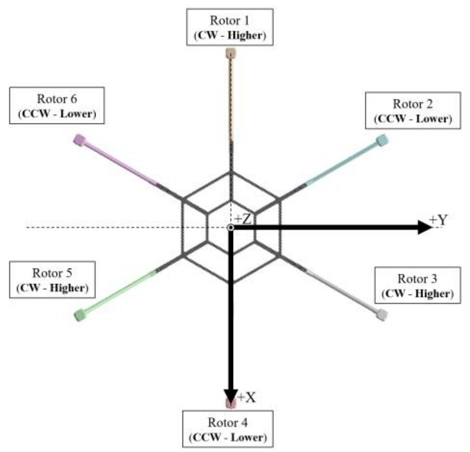


Figure 12. Hexacopter model used for structural analysis.

The two assemblies studied were primarily composted of the composite material, MTM45-1 resin and M46J fiber. Material properties of this composite were implemented in SolidWorks. FEA of two assemblies (original and modified models) was performed. In the first case, the structural components are composed of solid homogeneous composite throughout. In second case, the structural components are composed of composite oriented plies.

Results from PA-I indicated that there were large displacements in the arms that exceeded the threshold, as shown in Figure 13. Additionally, high stress concentrations can be seen where rotor hubs would be located. These results helped inform the modeling for the PA-II analysis. For PA-II, the thickness of the walls of the modified hexacopter were increased. The frame of the fuselage was also modified to match the change in the outer diameter of the arms to strengthen the connection between the arms and fuselage. However, due to the changes in the fuselage and the arm assemblies, the modified hexacopter has greater mass than the baseline design.

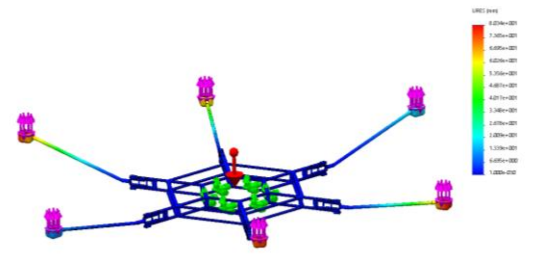


Figure 13. PA-I Fuselage and Arms (solid) for hover conditions – displacement.

As anticipated, the overall displacement of the arm assembly is decreased in the PA-II model and does not generally exceed the design threshold except during more extreme flight maneuvers. However, the consequence of this arm assembly displacement reduction is an increase the overall weight of the vehicle by ~10 kg. (Target weight for the vehicle is ~20kg.) It is noteworthy that, in both FEA analyses, the assemblies defined as a shell often did not perform as well as assemblies defined as a solid. This is logical as shell definitions in SolidWorks assume that the components defined in the assembly are hollow, thus lacking internal support. The solid and shell methods were used to provide “bounds” for the analysis. Experimental studies are planned to validate current results produced by the shell definitions. Additionally, the rationale underlying the arm assembly displacement threshold will be more closely examined and adjustments made, if need be.

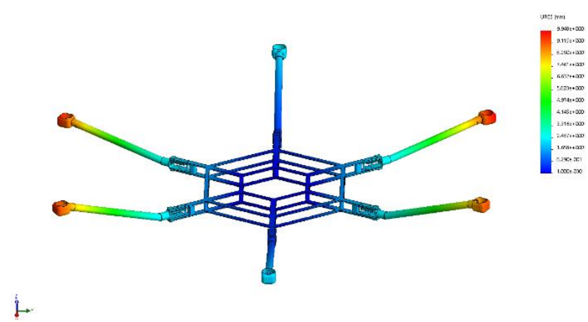


Figure 14. PA-II Fuselage and Arms (solid) for hover conditions – displacement.

Based on the results from the preliminary analyses, efforts are currently focused on bolstering the structural performance of the arms assembly and identifying where mass can be reduced. Preliminary investigations into modifying the fuselage are also underway, including adding trusses/pegs between the two frames to increase support. However, these new modifications on the fuselage attachment points have had so far insignificant mass improvements and resulted in higher stress values.

Additionally, some refinements to the arm assembly structural design that have the potential to lower the mass of the hexacopter without compromising the structural integrity were also studied. These arm structural design modifications include decreasing the arm tube wall thickness, localized modification of areas of high stress, and implementing new support designs for the fuselage. Examples of the arm assembly tube modification are shown in Figure 15. Future structural design studies will also include manufacturability trades.

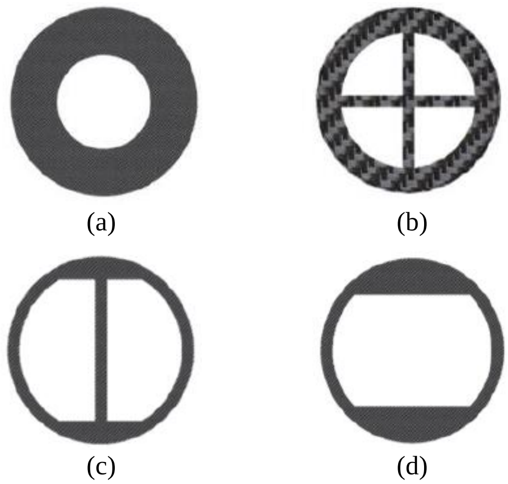


Figure 15. Arm designs considered: (a) original, (b) cross supports, (c) I-beam support and (d) wall reinforcement.

Additionally, the design requirements for PA-II have been adjusted to now focus on strain, rather than displacement, as the limiting constraint for the vehicle arm assemblies. Although low displacement is important on a multirotor configuration Mars rotorcraft, this issue is being reevaluated and has resulted in the new conclusion that until displacement produces mechanical interference, the more constraining parameter was strain. The strain limit was chosen to 0.001, based on applying a factor of safety on the maximum strain of the MTM45-1/M46J carbon fiber composite (0.004).

Results from these recent design efforts have shown that including internal structures allowed for maintained structural strength with the advantage of lowering the overall mass. Furthermore, they have also shown that using strain was a better method for determining the structural performance of the design because it was based on material specifications, better suited given the size of the hexacopter, and allowed opportunity to better access design modifications to the arms.

Flight Dynamics

A flight dynamics study is also in progress. It is hypothesized that the hexacopter will have significant controllability advantages over the scaled coaxial design. However, this study will help quantify how much controllability differential exists between the two vehicles. The study will also investigate the effect of scaling on the controllability and handling qualities of the different vehicle configurations.

Potential of Design Improvements

If applied, the advancements described above have the potential for substantial impact in enabling extraterrestrial science through powered flight. To illustrate this, the advanced airfoils along with a larger payload (1.3 kg) and batteries were added to the frame of the MH. Table 3 shows the impact of these advancements, if applied to the MH frame as it will fly it 2020. Note: the mission designer must choose increased range, increased hover time, or an adjusted combination of the two.

Table 3: Advanced Design Applied to MH.

Parameter	Unit	MH	Advanced Design
design C_T/s		0.10	0.115
design M_{tip}		0.7	0.8
cruise speed	m/sec	2	30
advancing tip M		0.71	0.93
payload	kg	0	1.3
range	km	0.18 or	2
hover time	min	1.5	2
rotor radius	m	0.605	0.605
gross weight	kg	1.8	4.6
number rotors		2	2
disk loading	$kg/m2$	0.8	2.0
solidity		0.148	0.248
tip speed	m/sec	163	186
rotor speed	rpm	2575	2943
total power	kW	0.36	0.88
solar cell	$m2$	0.04	0.06
battery	Ah	12	46

Improvements potentially result in up to 2.44 times power increase, addition of a science payload, and up to 11.1 times increase in range or 1.3 times increase in hover time.

Conclusion

A successful flight of the MH in 2021, will begin a new and exciting era. There will no doubt be many potential vehicle configurations based on the unique science that can be accomplished with powered extraterrestrial flight. The study described above describes two reasonable rotorcraft designs with the hexacopter configuration being the more capable vehicle (if volume is constrained to a Pathfinder-sized EDL system). Performance is significantly improved with non-conventional airfoils due to the high velocity and low Reynold's number regime in which the vehicles will be expected to operate. Noteworthy challenges include fabricating and characterizing these unique airfoils, decreasing structure mass while maintaining sufficient strength/stiffness, and developing refined control systems for this unique application. Finally, the authors conclude that an EDLS based on heritage designs is feasible for the provided mission. Larger aeroshells/landers, such as the aeroshell used for Mars Science Laboratory, increase potential vehicle performance even further.

Acknowledgements

The authors would like to acknowledge their JPL teammates, especially Teddy Tzanetos, Bob Balaram, and MiMi Aung for their inspiration and the opportunity to collaborate. The authors would like to thank Larry Young for his foresight, advice, and passion for extraterrestrial flight. Lastly, the authors appreciate the time and creativity of the Aeromechanics interns who contributed to the packaging and structural portions of this paper: Mireille Fehler, Siobhan Whittle, Malorie Travis, Athena Chan, and Allysa Tuano.

References

[1] J. Balaram, I. J. Daubar, J. Bapst, and T. Tzanetos, "HELICOPTERS ON MARS: COMPELLING SCIENCE OF EXTREME TERRAINS ENABLED BY AN AERIAL PLATFORM" in *Ninth International Conference on Mars*, 2019.

[2] J. (Bob) Balaram *et al.*, "Mars Helicopter Technology Demonstrator," in *AIAA Science and Technology Forum and Exposition (AIAA SciTech)*, 2018.

[3] "Larry_Design Opurrunities and Challenges.pdf." .

[4] L. A. Young and E. W. Aiken, "Vertical Lift Planetary Aerial Vehicles: Three Planetary Bodies and Four Conceptual Design Cases," in *27th European Rotorcraft Forum*, 2001.

[5] L. A. Young and E. W. Aiken, "Engineering Studies into Vertical Lift Planetary Aerial Vehicles," in *AHS International Meeting on Advanced Rotorcraft Technology and Life Saving Activities*, 2002.

[6] L. A. Young, E. W. Aiken, V. Gulick, R. Mancinelli, and G. A. Briggs, "Rotorcraft as mars scouts," in *IEEE Aerospace Conference*, 2002.

[7] L. A. Young, E. W. Aiken, M. Derby, R. Demblewski, and J. Navarrete, "Experimental Investigation and Demonstration of Rotary-Wing Technologies for Flight in the Atmosphere of Mars," in *58th Annual Forum of the AHS International*, 2002.

[8] L. Young, E. Aiken, J. Johnson, R. Demblewski, J. Andrews, and J. Klem, "New Concepts and Perspectives on Micro-Rotorcraft and Small Autonomous Rotary-Wing Vehicles," in *20th AIAA Applied Aerodynamics Conference*, American Institute of Aeronautics and Astronautics, 2002.

[9] H. F. Grip *et al.*, "Flight Dynamics of a Mars Helicopter," in *43rd European Rotorcraft Forum*, 2017.

[10] M. Hirschberg, "Vertical Flight Society Applauds NASA's Mars Helicopter Selection," Fairfax, Virginia, May-2018.

[11] H. F. Grip *et al.*, "Guidance and control for a Mars helicopter," in *2018 AIAA Guidance, Navigation, and Control Conference*, 2018, p. 1849.

[12] B. T. Pipenberg *et al.*, "Design and Fabrication of the Mars Helicopter Rotor, Airframe, and Landing Gear Systems," in *AIAA Scitech 2019 Forum*, 2019, p. 620.

[13] W. J. F. Koning, W. Johnson, and H. F. Grip, "Improved Mars helicopter aerodynamic rotor model for comprehensive analyses," *AIAA J.*, pp. 1–10, 2019.

[14] G. A. Ament and W. J. F. Koning, "Isolated Rotor Forward Flight Testing From One Atmosphere Down to Martian Atmospheric Densities," in *AHS Conference on Aeromechanics Design for Transformative Vertical Flight*, 2018.

[15] G. A. Ament, W. J. F. Koning, and B. N. Perez Perez, "Isolated Rotor Forward Flight Testing at Martian Atmospheric Density Data Report," Moffett Field, California, NASA/TM–2018–219736, 2018.

[16] B. N. Perez Perez, G. A. Ament, and W. J. F. Koning, "Experimental Forward Flight Rotor Performance Testing From Terrestrial to Martian Atmospheric Densities," Moffett Field, California, NASA/CR–2019–220229, 2019.

[17] W. Johnson, "NDARC. NASA Design and Analysis of Rotorcraft." NASA TP 2015-218751."

[18] W. Johnson, "HeliJapan 1998: AHS International Meeting on Rotorcraft Technology and Disaster Relief," in *Rotorcraft Aeromechanics Applications of a Comprehensive Analysis*.

[19] B. H. Carmichael, "Low Reynolds Number Airfoil Survey, Volume 1," Capistrano Beach, California, 1981.

[20] P. B. S. Lissaman, "Low-Reynolds-number airfoils," *Annu. Rev. Fluid Mech.*, vol. 15, no. 1, pp. 223–239, 1983.

[21] T. J. Mueller and J. D. DeLaurier, "Aerodynamics of Small Vehicles," *Annu. Rev. Fluid Mech.*, vol. 35, no. 1, pp. 89–111, Jan. 2003.

[22] D. J. Pines and F. Bohorquez, "Challenges facing future micro-air-vehicle development," *J. Aircr.*, vol. 43, no. 2, pp. 290–305, 2006.

[23] W. J. F. Koning, W. Johnson, and B. G. Allan, "Generation of Mars Helicopter Rotor Model for Comprehensive Analyses," in *AHS Aeromechanics Design for Transformative Vertical Flight*, 2018.

[24] W. J. F. Koning, E. A. Romander, and W. Johnson, "Low Reynolds Number Airfoil Evaluation for the Mars Helicopter Rotor," in *AHS International 74th Annual Forum & Technology Display*, 2018.

[25] R. Shrestha, M. Benedict, V. Hrishikeshavan, and I. Chopra, "Hover performance of a small-scale helicopter rotor for flying on mars," *J. Aircr.*, vol. 53, no. 4, pp. 1160–1167, 2016.

[26] D. Escobar, I. Chopra, and A. Datta, "Aeromechanical Loads on a Mars Coaxial Rotor," in *Proceedings of the 74th Annual Forum*, 2018.

[27] W. J. F. Koning, E. A. Romander, and W. Johnson, "Performance Optimization of Plate Airfoils for Martian Rotor Applications Using a Genetic Algorithm," in *45th European Rotorcraft Forum*, 2019, pp. 1–15.

[28] W. J. F. Koning, E. A. Romander, and W. Johnson, "Optimization of Low Reynolds Number Airfoils for Martian Rotor Applications Using an Evolutionary Algorithm," in *AIAA Science and Technology Forum and Exposition (AIAA SciTech)*, 2020.

[29] W. J. F. Koning, W. Johnson, and H. F. Grip, "Improved Mars helicopter aerodynamic rotor model for comprehensive analyses," *AIAA J.*, vol. 57, no. 9, pp. 3969–3979, 2019.