Capabilities of Mars Helicopters Using Optimized Rotors

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The Rotor Optimization for the Advancement of Mars eXploration (ROAMX) project has demonstrated that rotor designs optimized for the Mars aerodynamic regime can provide substantial improvements in aerodynamic efficiency relative to heritage designs. This paper evaluates the vehicle-level performance implications of these improvements using the NASA Design and Analysis of Rotorcraft (NDARC) tool. Performance predictions for Ingenuity-class and Mars Science Helicopter (MSH)-class rotorcraft are generated using ROAMX rotor aerodynamic inputs and are compared against a configurations using the Ingenuity rotor. Parametric studies are conducted to investigate the trade between increasing payload mass and resulting changes in vehicle range and hover time, including the effects of rotor solidity and rotor type. The results show that ROAMX rotor designs enable significant increases in payload capability and operational range across both vehicle classes. These findings demonstrate how ROAMX rotor performance gains translate directly into enhanced mission capability at the vehicle level and provide a quantitative foundation for future Mars rotorcraft designs.

Nomenclature

α	=	Angle of Attack
σ	=	Rotor Solidity
c_d	=	Section Coefficient of Drag
c_l	=	Section Coefficient of Lift
C_T	=	Coefficient of Thrust
M_{tip}	=	Tip Mach Number
CFD	=	Computational Fluid Dynamics
ELISA	=	Evolutionary aLgorithm for Iterative Studies of Aeromechanics
FM	=	Figure of Merit
JPL	=	NASA's Jet Propulsion Laboratory
MSH	=	Mars Science Helicopter
NDARC	=	NASA Design and Analysis of RotorCraft
ROAMX	=	Rotor Optimization for the Advancement of Mars eXploration
RPM	=	Revolutions Per Minute

I. Introduction

HELICOPTERS on Mars are a reality and have the potential to be able to explore the Red Planet over significantly more terrain than has thus far been possible. The Ingenuity Mars Helicopter Technology Demonstrator showed in 2021 that flight is possible on Mars. In 72 historic flights, Ingenuity was able to traverse a total of 17 km and fly for over 128 minutes [1]. Ingenuity far surpassed its expected number of flights and was able to contribute to the science mission of the Perseverance Rover, signaling a new type of exploration option for Mars. Exploration of Mars has been limited to satellites, which can travel large distances but have low resolution; to rovers, which have much greater resolution than satellites but traverse the surface of Mars very slowly; and to landers, which have high resolution but are unable to move once they have landed. Helicopters can bridge the gap between satellites and rovers, providing higher resolution data than satellites across a much greater range than rovers.

Flying on Mars is difficult for many reasons, but technology advancements can make flying on Mars easier. Mars provides a harsh environment, with cold temperatures and carbon dioxide-based atmospheric composition. Because of the distance from Earth to Mars, there is a significant communication delay, which means that all flights must be autonomous. The low density atmosphere makes it difficult to generate lift and makes it difficult to have control authority over vehicles in flight. In addition, the low temperatures on the surface of Mars reduce the speed of sound, pushing tip Mach numbers into the high subsonic and even transonic region, and significantly degrade battery efficiency and usable energy. Improvements in autonomous navigation capabilities, flight dynamics and control, weight reduction of components, and battery efficiency all contribute to having

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a vehicle that can exhibit improved vehicle performance. The focus of this paper is to show the significant advances in vehicle performance that are possible by improving the aerodynamic characteristics of the vehicle. This is done specifically by optimizing the airfoils and rotors of the vehicle.

The Rotor Optimization for the Advancement of Mars eXploration (ROAMX) project is a project at NASA Ames Research Center that seeks to computationally optimize rotors for flight on Mars under the harsh conditions mentioned above and experimentally validate the rotor performance [2, 3]. This aerodynamic optimization is done specifically for the aerodynamic conditions that are experienced on Mars. In particular, the Reynolds number and tip Mach number are the focus for the rotor optimization that was conducted through ROAMX. On Mars, the atmospheric density is 1% that of Earth. This significantly reduced atmospheric density results in a Reynolds number that is two orders of magnitude less than experienced under typical flight conditions on Earth. In addition, the temperature on Mars is significantly lower than Earth. It varies depending on season, but during Ingenuity's flight campaign, the temperature was near -50 degrees Celsius. The lower temperature, combined with the carbon dioxide-based atmosphere, results in a speed of sound that is much lower on Mars than on Earth (233 m/s, compared to 340 m/s). This reduced speed of sound results in tip Mach numbers that are significantly higher for rotors spinning on Mars compared to Earth, which limits how fast the rotors can spin before reaching transonic and supersonic speeds. Limiting tip speed can result in higher torques required to generate equivalent power, which leads to heavier aircraft. Additionally, control responsiveness may be worse at lower rotor speeds. This low-Reynolds number, high subsonic Mach number aerodynamic regime has been specifically analyzed and optimized for via the ROAMX project in previous work [4–7]. Results from that work show significantly improved rotor blade performance is possible. Validation efforts also show that the performance of the ROAMX airfoil does indeed perform better than the baseline Ingenuity airfoil [8–10]. This paper shows the impact of these improvements in rotor performance on overall vehicle performance. By equipping Mars rotorcraft with optimized rotors, these vehicles can cover greater distances and operate longer, enabling the collection of meaningful scientific data while carrying substantial science payloads.

II. Current State of the Art

The Ingenuity Mars Helicopter Technology Demonstrator successfully demonstrated powered, controlled flight on Mars, achieving forward flight speeds of up to 10 m/s and traversing more than 700 m in a single flight. Ingenuity accompanied the Perseverance rover to Mars and was stowed in the rover's belly during cruise and entry. As a technology demonstrator, Ingenuity's primary objective was to establish the feasibility of flight in the Martian atmosphere. Consequently, its development schedule and budget were significantly constrained compared to flagship assets such as the rover itself. These constraints limited opportunities for vehicle-specific design.

The rotor blade airfoil was adapted from a low Reynolds number airfoil originally developed for Earth applications. Terrestrial application usually imply low Reynolds number of 100,000 and above, whereas for helicopter flight on Mars the Reynolds number ranges from roughly 5,000-30,000. Thus, while this airfoil performs well at low Reynolds numbers relative to terrestrial flight, those conditions are still substantially higher than Ingenuity's operational Reynolds numbers on Mars. Ingenuity's rotor design used the clf5605 airfoil, which is designed to maintain laminar flow at low Reynolds numbers, in contrast to conventional terrestrial airfoils that rely on transition to turbulent flow. The clf5605 airfoil and resulting rotor design enabled Ingenuity's successful flight operations on Mars; however, subsequent advances in understanding low Reynolds number aerodynamics have shown that airfoils can be optimized to achieve significantly higher performance under Martian conditions.

Ingenuity is a coaxial helicopter with counter-rotating rotors of 0.605 m radius. Electrical power is supplied by onboard batteries that are recharged via a solar panel, supporting both propulsion and avionics systems.

Building on the Ingenuity heritage, the Mars Science Helicopter (MSH) is a conceptual vehicle configuration developed for future rotorcraft science missions to Mars [11]. Unlike Ingenuity, the MSH design incorporates airfoil geometries generated by the authors as part of an initial optimization effort. As shown in later sections, the performance of the MSH configuration benefits from the use of optimized airfoils. The MSH is a hexacopter configuration with a rotor radius of 0.64 m, resulting in an overall vehicle diameter of approximately 2.5 m.

The Sample Recovery Helicopters (SRH) were proposed as part of NASA's Mars Sample Return (MSR) architecture to provide a backup capability for transporting cached samples from the Perseverance rover to the return vehicle [12].

Although the future of the SRH concept remains uncertain, a conceptual vehicle design was developed. Due to the increased mission requirements relative to Ingenuity, several design modifications were necessary; however, the overall configuration retained strong heritage from Ingenuity. The SRH employs a coaxial rotor system with an increased rotor radius enabled by the larger entry vehicle volume available for transport to Mars. In addition, SRH includes a robotic arm for sample acquisition and wheels to enable limited ground mobility for sample retrieval and deposition.

III. Approach

To increase the science and exploration possible on Mars via helicopter, vehicle performance improvements are necessary. Improved battery performance, for example, will extend the endurance and range of helicopters on Mars. The ROAMX project focused on aerodynamic improvements that increase rotor performance for the low Reynolds number, high subsonic Mach number aerodynamic regime found on Mars.

Through the ROAMX project, rotor blades and airfoils were designed and optimized for flight on Mars using the Evolutionary aLgorithm for Iterative Studies of Aeromechanics (ELISA) optimization framework [4, 6, 7]. ELISA uses a genetic algorithm and OVERFLOW high-fidelity Computational Fluid Dynamics (CFD) to provide a Pareto-optimal set of airfoils at a specified Reynolds number, Mach number, and airfoil thickness-to-chord ratio, maximizing section lift for a minimized section drag. The OVERFLOW CFD methodology approaches Implicit Large Eddy Simulation (ILES), as Reynolds Averaged Navier-Stokes without the use of a turbulence model applied in the OVERFLOW CFD solver was found to match well when compared to extensive wind tunnel tests conducted on the Eppler 387 airfoil at up to $Re \approx 200,000$ [4, 13]. Using the optimized airfoil set, ELISA then uses the comprehensive analysis code CAMRAD II to produce a Pareto-optimal rotor blade shape by varying blade chord and twist, maximizing thrust produced while minimizing power used. CAMRAD II [14, 15] is a comprehensive rotorcraft analysis software including multibody dynamics, nonlinear finite elements, and rotorcraft aerodynamics. CAMRAD II uses lifting-line theory, 2-dimensional airfoil tables, and a vortex wake model for the rotor aerodynamics.

The ELISA optimization framework was developed and utilized in the ROAMX project and resulted in novel airfoil shapes and development of a full-scale Mars helicopter rotor; the airfoils and rotor were computationally evaluated and experimentally tested, and performance of the airfoils and rotors was validated [5, 8–10]. The ROAMX airfoil classes use the notation roamx-n_c, p_c, n_t, p_t, where n denotes the number of nodes present on the Bezier curve and p denotes the Bezier segment order (i.e. p = 1 indicates first-order Bezier curve), with the subscripts c and t referring to the camber and thickness distributions, respectively. This parameterization is used in ELISA; see [5] for a more detailed description. The airfoil used in this study for the outboard sections of the blade is the roamx-0201 airfoil, indicating a second degree polynomial is possible for camber and indicating that the thickness is fixed (in this case at 1% thickness-to-chord ratio). The resulting airfoil is similar to a cambered plate shape, with a sharp leading edge, as seen in Figure 2. The inboard airfoils are roamx-0202 airfoils, indicating a second degree polynomial for camber and thickness.

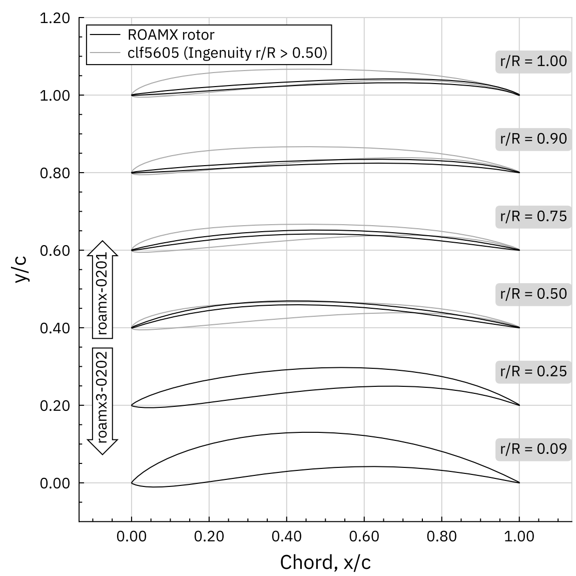
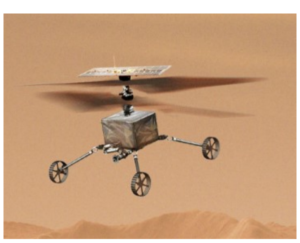


Fig. 2 ELISA framework used to design the ROAMX rotor and airfoils, compared to the Ingenuity airfoils at different radial stations (r/R) [5].

CAMRAD II and NASA Design and Analysis of RotorCraft (NDARC) [16, 17] were implemented in this study to quantify the vehicle-level impacts of the ROAMX rotor design on sizing and performance. NDARC is a conceptual design tool capable of sizing and evaluating performance of aircraft. Its modular, component-based architecture allows for new or novel aircraft designs and configurations to be analyzed. Each component uses surrogate models for weight and performance estimation, and these surrogate models can be calibrated using higher fidelity tools or information.

CAMRAD II models of the optimized ROAMX rotor and the Ingenuity rotor were used to create the rotor performance calibration data for the surrogate rotor performance model in NDARC [18]. Because of the low advance ratio



(a) Sample Recovery Helicopter. Credit: NASA Mars Sample Return Mission.

(b) Mars Science Helicopter [11].

Fig. 1 Sample Recovery Helicopter and Mars Science Helicopter.

in forward flight (~ 0.16), the calibration was performed only in hover conditions.

Increases in airfoil performance result in a 20% increase in Figure of Merit (FM), a measure of rotor efficiency. Likewise, increases in FM have a significant impact on increasing vehicle performance. Table 1 shows the increase in ROAMX airfoil performance compared to Ingenuity's airfoil performance in terms of c_l and c_d.

IV. Vehicle Configurations

To investigate the impact of increasing aerodynamic performance of the airfoils and rotor blades on overall vehicle performance, two vehicle configurations were chosen. These configurations were chosen as the same vehicle configurations presented in Reference 11, to demonstrate the increased performance that is possible. Reference 11 utilizes preliminarily optimized airfoils, which the ROAMX project built upon to design the airfoils and rotors used in this paper.

Ingenuity-class vehicles are shown and compared to the Ingenuity vehicle as it flew on Mars. Reference 11 dubbed these "Advanced Mars Helicopters" to signify that they are a conceptual advancement over the Ingenuity vehicle that flew on Mars [11]. The Mars Science Helicopter configuration was also presented in Reference 11 and has been widely used as a conceptual vehicle that could perform science missions on Mars.

An NDARC model for the Ingenuity vehicle was used in Reference 11, and for this work was calibrated to as-built component weights and on-planet performance. For the NDARC model of Ingenuity with ROAMX rotors, the same base NDARC model is used, with only the rotor performance model and design parameters outlined in Table 2 modified. Of note, the design C_t/σ is higher for the ROAMX rotor, as is the design hover M_{tip}. Though Ingenuity's forward flight speed was kept to less than 10 m/s on planet, for comparison in this study, Ingenuity's forward flight speed was allowed to be 30 m/s, which is the same as the Ingenuity-class vehicle with ROAMX rotor. Also to note in Table 2, the vehicle gross weight, disk loading, and total power increase with increasing solidity. The MSH NDARC model from Reference 11 was used as the basis for all MSH-class models in this work. Again, for the MSH variants with Ingenuity and ROAMX rotors, only the rotor performance model and design parameters listed in Table 2 were changed. As for the Ingenuity-class vehicle, the design C_t/σ and hover M_{tip} are increased for the ROAMX rotor, compared to Ingenuity. Gross weight and disk loading also increase for the ROAMX rotor configuration, though solidity was kept at 0.25 for the ROAMX and Ingenuity configurations.

Generally, when sizing with NDARC, the mission requirements are prescribed, and the vehicle components are sized to perform the mission. For the purposes of this exercise, the parameters in Table 2 were fixed, and then the design gross weight was fixed and varied to achieve the desired rotor solidity. Then the mission hover time or cruise distance (and therefore battery weight) was varied to achieve the desired payload capacity as fallout. This allows for all components of the vehicle to undergo the proper sizing procedure, but still end up with the rotor geometries desired for comparison.

Payload sweeps are conducted on the Ingenuity-class and MSH-class vehicles, with payload ranges tailored to the capabilities of each variant. For every payload sweep, the design gross weight is kept constant, and battery weight is traded for payload, consistent with the approach in [11]. The Ingenuity-class vehicle with ROAMX rotors also includes three different solidities to show the effects of higher solidity on Martian rotorcraft capability. The performance metrics are curves of maximum hover time and maximum vehicle range.

Each case in this work resizes the vehicle for every change, ensuring secondary cascading weight effects are captured using NDARC's parametric weight equations. For example, with an increase in solidity and vehicle mass, the resultant fuselage weight increase needed to support the heavier structure is also calculated.

A. Ingenuity-Class Vehicle

The Ingenuity-class vehicle is a vehicle that has the same rotor diameter as Ingenuity and has two, two-bladed counter-rotating rotors in a co-axial configuration, as seen in the picture of Ingenuity in Figure 3. The rotor radius is maintained at 0.605 m to demonstrate the significance of rotor aerodynamic improvements. The advanced vehicles in this class could fit in the same packaging as Ingenuity, though Ingenuity traveled to Mars stowed on the belly of the Perseverance rover and future helicopters are unlikely to utilize the same mode of transportation.

There are several example use cases of vehicles that fit in this class, or nearly fit in this class. Withrow, et al. expanded upon the design presented in Johnson, et al. to describe the packaging of the Advanced Mars Helicopter [19]. The Sample Recovery Helicopters were conceptually designed to maintain much of Ingenuity's heritage design, though their rotor radius was slightly increased to increase performance [12]. The Sample Recovery Helicopter design maintained Ingenuity's clf5605 airfoils outboard because of the rapid development time required to meet the Mars Sample Return schedule, though the choice was not optimal from a technical perspective. An Ingenuity-class vehicle is also presented in Delaune, et al. to demonstrate the use case of using Mid-Air Helicopter Deployment to allow a helicopter to land at higher elevations than possible with traditional Entry, Descent, and Landing techniques [20],

Table 1 Comparison of airfoil performance for Re = 20,000, M = 0.60 [6].

Airfoil	c_l/c_d, peak	Relative change, %	Section lift, c_l	Angle of attack, α
clf5605	19.90	–	0.91	2.50
roamx-0201	25.89	28%	1.13	4.48

Fig. 3 Ingenuity's co-axial helicopter configuration, as flown on Mars (image from NASA/JPL-Caltech).

and is used as part of the six vehicle swarm concept called Skyfall [21].

As a scout for a rover, or as a dedicated science mission that fits inside a small aeroshell, the Ingenuity-class vehicle can serve a vital mission purpose. Even with a small payload, a vehicle this size can carry scientific or exploration instruments such as magnetometers and cameras for imaging. Ingenuity-class helicopters could also be sent to Mars in swarm groups, working in tandem with each other to accomplish science or exploration goals. Ingenuity-class rotorcraft are mentioned in the Decadal Survey on Planetary Science and Astrobiology as being able to perform sample collection to bring to a lander, which would analyze the samples for biomarkers [22]. In addition, while Ingenuity-class vehicles are attractive to mission designers due to their demonstrated flight heritage, this vehicle class can also be scaled to slightly larger configurations that remain compatible with existing aeroshells.

The solidity of the ROAMX rotor was increased beyond conventional solidities (for example, Ingenuity's rotor has a solidity of 0.148 [11]). Research is limited in the area of high solidity rotors since Earth-based helicopters favor increasing radius to increase thrust, and the aerodynamic effects of increasing solidity to very high values (above solidity of 0.3) are not well understood. Increased power is also required to support higher solidity rotor designs, though because Mars helicopters must fit inside heritage Entry, Descent, and Landing vehicles, higher power is a penalty worth paying to achieve higher lift capabilities. The ROAMX rotor was optimized to have a 6-bladed rotor with a solidity of 0.25, to modestly increase the solidity beyond conventional solidities (which are well understood) while staying in a conservative range of high solidity. Future helicopters for Mars will need to employ even higher solidity rotors to be able to further increase lift and range capabilities. Research has started at NASA Ames to investigate these higher solidity rotors, and additional research is needed [23].

For the NDARC study presented here, the ROAMX rotor blade shape was retained, but applied in a coaxial configuration using two, two-bladed rotors to enable an aerodynamic performance comparison against Ingenuity. In addition, ROAMX rotor performance with three different solidities is shown: first, the ROAMX rotor was modified to match Ingenuity's solidity to isolate the performance improvement from increasing the airfoil and rotor performance; second, the ROAMX rotor is shown using its design solidity of 0.1667, representing the four-blade configuration rather than the original six-blade design; and third, the ROAMX rotor is shown with the original design solidity of 0.25. All of the design parameters can be seen in Table 2.

B. Mars Science Helicopter-Class Vehicle

The Mars Science Helicopter-class vehicle (MSH) is a hexacopter with six, six-bladed rotors, as seen in Figure 4. The radius of each rotor is 0.64 m with a maximum overall vehicle diameter constrained to 2.5 m to fit inside the Pathfinder aeroshell [11].

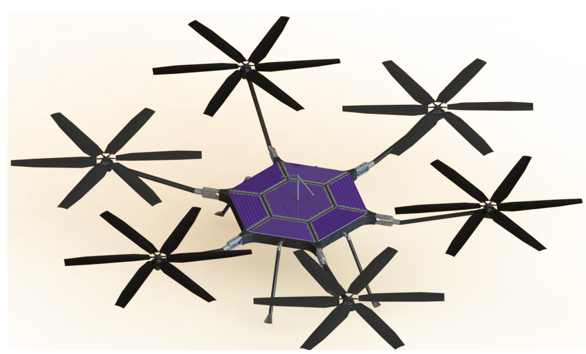


Fig. 4 MSH vehicle with 6-bladed rotor design [24].

Table 2 Design Summary for Ingenuity-Class and MSH-Class Vehicle Configurations.

Ingenuity-Class Vehicle				
Design Parameter	**Ingenuity Rotor**	**ROAMX Rotor, σ = 0.148**	**ROAMX Rotor, σ = 0.167**	**ROAMX Rotor, σ = 0.25**
design C_t/σ	0.10	0.12	0.12	0.12
hover M_{tip}	0.7	0.8	0.8	0.8
cruise speed (m/s)	30	30	30	30
advancing M_{tip}	0.74	0.93	0.93	0.93
rotor radius (m)	0.605	0.605	0.605	0.605
gross weight (kg)	1.8	2.85	3.2	4.8
number of rotors	2	2	2	2
disk loading (kg/m^2)	5.8	9.2	10.3	15.5
solidity	0.148	0.148	0.167	0.25
rotor speed (rpm)	2575	2943	2943	2943
total power (kW)	0.36	0.56	0.66	1.15

MSH-Class Vehicle		
Design Parameter	**Ingenuity Rotor**	**ROAMX Rotor**
design C_t/σ	0.10	0.12
hover M_{tip}	0.7	0.8
cruise speed (m/s)	10	30
advancing M_{tip}	0.83	0.93
rotor radius (m)	0.64	0.64
gross weight (kg)	20.8	32.5
number of rotors	6	6
disk loading (kg/m^2)	10.0	15.6
solidity	0.25	0.25
rotor speed (rpm)	2435	2782

This hexacopter configuration has become the most commonly referenced independent, science-capable conceptual vehicle for future Mars missions. Mission capabilities of the hexacopter design include the ability to function independently without relying on a rover or lander-based communication system, survey horizontal and vertical terrain for geologic and meteorologic mapping of icy scarps [25], and answer questions about the evolution of terrestrial planets at Valles Marineris [26]. MSH has also been utilized as a starting point for other concepts, such as the Long-Range Mars Rotorcraft [27] and the Chopper program at NASA's Jet Propulsion Laboratory (JPL), which both incorporate ROAMX-designed airfoils [24, 28].

The MSH concept demonstrated analytically that Mars rotorcraft could meaningfully extend exploration reach, based on initial airfoil optimization results [11]. The ROAMX airfoil and rotor designs are the progression of this foundation that was established, and thus the roamx-0201 airfoil and subsequent rotor were selected for further development because of their higher performance. Both the airfoil and rotor were manufactured and were validated experimentally under Mars aerodynamic conditions [10]. To further contextualize advancements in Mars rotor performance, the plots also include predictions for the MSH platform operating with Ingenuity rotors (meaning planform and airfoil), enabling direct comparison among two rotor types: Ingenuity and the experimentally validated ROAMX rotor. The solidity was maintained at 0.25 for both rotor types to isolate the aerodynamic advancements; the ROAMX rotor was specifically designed at 0.25 solidity, whereas the Ingenuity rotor was designed at a lower solidity. The increase in solidity provides an increase in performance. Design parameters for both rotors applied to the MSH configuration are shown in Table 2.

V. NDARC Results

A. Ingenuity-Class Vehicle NDARC Results

For an Ingenuity-class vehicle with two, two-bladed rotors in a coaxial configuration, the performance for different rotor designs is shown in the following figures. Figure 5 compares Ingenuity's actual Mars performance to that of an Ingenuity-class vehicle equipped with a ROAMX rotor of matching solidity, σ = 0.148. Ingenuity carried no science payload, but the Ingenuity-class vehicle using ROAMX technology is able to carry a science payload. Figure 6 compares Ingenuity's performance to that of an Ingenuity-class vehicle using a ROAMX rotor at the ROAMX design solidity of σ = 0.167, and Figure 7 shows the vehicle using a ROAMX rotor of σ = 0.25. Table 3 summarizes the zero payload performance for the Ingenuity and ROAMX rotors at σ = 0.148.

Figure 5 isolates the aerodynamic improvements of the ROAMX rotor by holding solidity constant, while Figure 8 illustrates the effect of increasing solidity on range for a fixed payload. Table 4 further quantifies the impact of varying solidity on the payload and range capability of the ROAMX rotor.

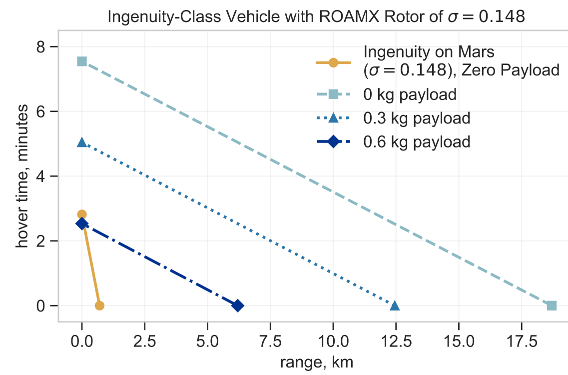


Fig. 5 Ingenuity-class vehicle with ROAMX rotor of σ = 0.148.

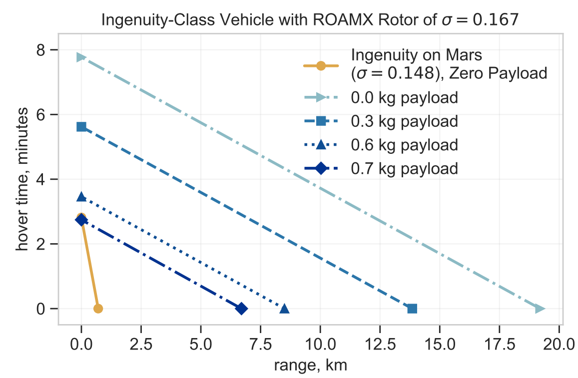


Fig. 6 Ingenuity-class vehicle with ROAMX rotor of σ = 0.167.

From an aerodynamic efficiency perspective, the ROAMX rotor clearly outperforms the Ingenuity rotor and enables an Ingenuity-class vehicle to carry a meaningful science payload. While carrying no payload, the ROAMX rotor allows the Ingenuity-class vehicle to travel 18.7 km, compared to Ingenuity's longest flight of 0.704 km. This represents a 2,500% increase in range capability.

The impact of increasing solidity on lift performance is demonstrated by the σ = 0.25 case shown in Figure 8. A solidity increase of 13% from σ = 0.148 to σ = 0.167 results in a range increase of 37%, while a solidity increase of 50% from σ = 0.167 to σ = 0.25 yields a range increase of 56%. Increasing solidity improves both payload capacity and range, enhancing the science and exploration capabilities of Mars helicopters.

Table 3 Ingenuity-Class Vehicle Carrying 0 kg Payload.

Performance Parameter	Ingenuity on Mars	ROAMX Rotor σ = 0.148
Payload (kg)	0	0
Hover Time (minutes)	2.82	7.55
Range (km)	0.704	18.7
Gross Vehicle Mass (kg)	1.8	2.85

Table 4 Ingenuity-Class Vehicle With ROAMX Rotors of Varying Solidity Carrying 0.6 kg Payload.

Performance Parameter	ROAMX σ = 0.148	ROAMX σ = 0.167	ROAMX σ = 0.25
Payload (kg)	0.6	0.6	0.6
Hover Time (minutes)	2.5	3.5	5.5
Range (km)	6.2	8.5	13.25

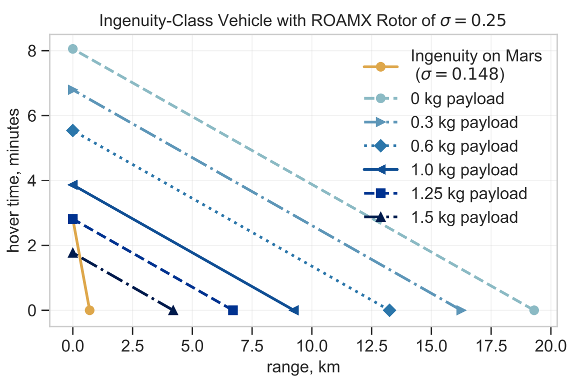


Fig. 7 Ingenuity-class vehicle with ROAMX rotor of σ = 0.25.

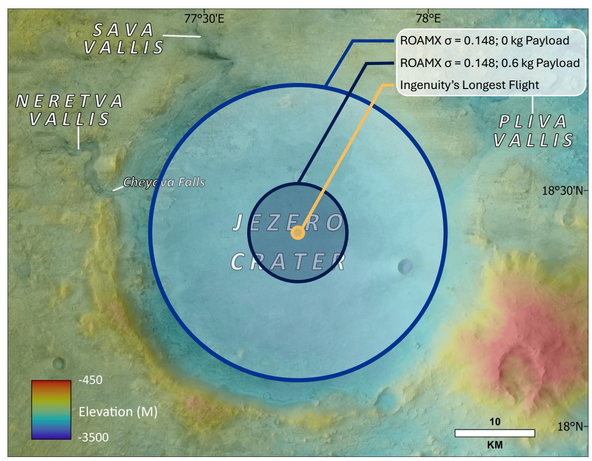


Fig. 9 Range of an Ingenuity-class vehicle with a ROAMX rotor of σ = 0.148 shown at Jezero crater. Image credit: ESA/DLR/FU Berlin/HRSC.

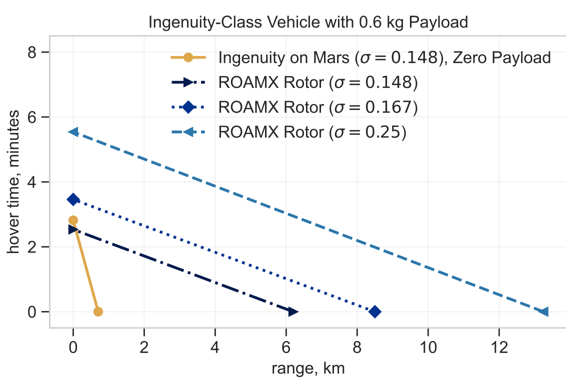


Fig. 8 Ingenuity-class vehicle with various ROAMX rotor solidities, all carrying 0.6 kg of payload.

To illustrate the impact at the planetary scale, Figure 9 compares Ingenuity's longest flight to the predicted range of an Ingenuity-class vehicle with a ROAMX rotor of σ = 0.148. The figure is overlaid on a map of Jezero Crater, where Ingenuity conducted its flights [29]. This comparison is limited by assumptions, such as maintaining communications hardware identical to Ingenuity's, which constrains range due to reliance on rover-based relays. Extending operational range would require additional communications payload or autonomous return to relay range.

B. Mars Science Helicopter-Class Vehicle NDARC Results

Performance of an MSH-class vehicle equipped with six, six-bladed rotors of 0.64 m radius is illustrated in the following figures for two rotor configurations: the Ingenuity rotor and the ROAMX rotor. For each configuration, a payload sweep is presented, with the ROAMX rotor demonstrating the highest payload capability over operationally meaningful ranges. Figures 10 and 11 show the payload sweeps for each rotor individually, while Figure 12 compares vehicle range and hover time for specified payloads. Table 6 summarizes the payload sweep for the vehicle equipped with the ROAMX rotor, and Table 5 provides the corresponding range and hover time comparisons for the fixed payload case.

It is evident that although the Ingenuity rotor can generate sufficient lift for an MSH-class vehicle, achieving meaningful science payload capability at this scale requires a more efficient rotor system. The ROAMX rotor delivers higher overall performance, as expected. As shown in Table 2, the ROAMX rotor can carry up to 10 kg of science payload with a vehicle gross weight of 32.5 kg, corresponding to 31% of the total vehicle mass. For the 2 kg payload case, the ROAMX rotor provides 338% more range than the Ingenuity rotor.

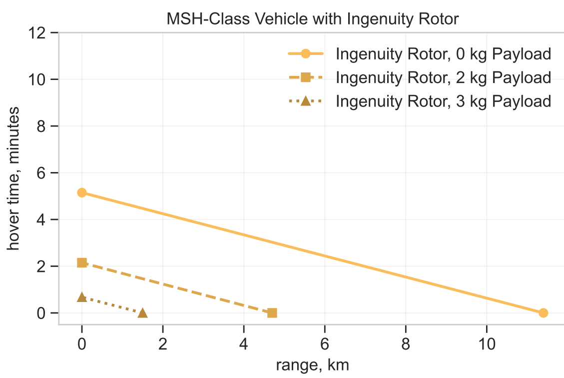


Fig. 10 MSH-class vehicle with Ingenuity rotor.

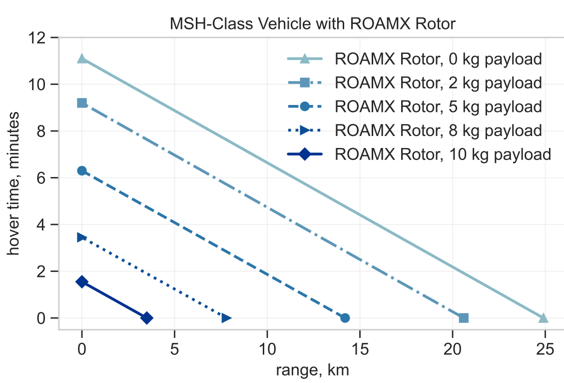


Fig. 11 MSH-class vehicle with ROAMX rotor.

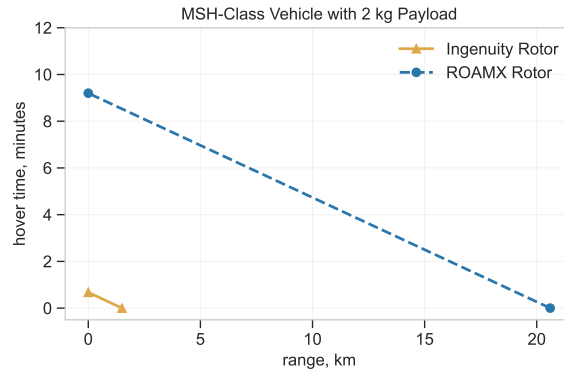


Fig. 12 MSH-class vehicle carrying 2 kg of payload.

VI. Conclusion and Future Work

The aerodynamic efficiency and payload capacity enabled by ROAMX optimized rotors directly expands what future Mars rotorcraft can accomplish. Higher thrust margins allow accommodation of more capable science payloads, ranging from cameras and spectrometers to environmental sensors, transitioning rotorcraft from technology demonstrators to primary science platforms. Likewise, increases in range and endurance enable regional-scale flight capability, supporting reconnaissance and detailed investigation of steep slopes, canyon walls, layered deposits, and other scientifically compelling terrains that remain inaccessible to landers and rovers. These advancements introduce new operational modes for Mars missions, including multi-target sorties, rapid terrain mapping, and autonomous selection of science sites, ultimately improving science and exploration capabilities on Mars.

In addition, ROAMX technologies open new possibilities for mission design. Rotorcraft with increased lift and efficiency can support distributed measurements on planet, deployable sensor networks, and coordination with rovers or landers to refine path planning and target selection. Recent conceptual vehicle studies demonstrate how these aerodynamic advancements translate into mission-scale capability: both the Chopper platform and the Long-Range Mars Rotorcraft (LRMR) incorporate ROAMX airfoil and rotor technologies directly, enabling tens of kilometers in range and substantially increased payload capacity [24, 27, 28]. Higher-level mission concepts for Ingenuity-class vehicles such as the joint JPL/AeroVironment Skyfall concept also build on the expanded operational envelope made possible by ROAMX rotor technology, envisioning roles in regional surveys, hazard mapping, and human landing site identification [21]. At larger scales, ROAMX technologies enable Mars Science Helicopter–class vehicles capable of carrying science payloads in the tens of kilograms, allowing more comprehensive investigations of planetary geology, climatology, and astrobiology. These rotorcraft could also

Table 5 MSH-Class Vehicle Carrying 2 kg Payload.

Performance Parameter	Ingenuity Rotor	ROAMX Rotor
Payload (kg)	2	2
Hover Time (minutes)	2.1	9.2
Range (km)	4.7	20.6

Table 6 MSH-Class Vehicle With ROAMX Rotor.

Payload (kg)	Hover Time (minutes)	Range (km)
0	11.1	24.9
2	9.2	20.6
5	6.3	14.2
8	3.4	7.8
10	1.5	3.5

support sample scouting and retrieval activities, enabling faster recovery of widely dispersed samples compared to rovers.

As Mars exploration shifts toward human exploration, more ambitious science goals, and broader geographic reach, aerial mobility will play an increasingly central role. The experimentally validated performance of the ROAMX rotors demonstrates that significant gains in flight range, hover time, and payload capacity are achievable, providing a clear pathway for integrating capable rotorcraft into future missions. In this context, ROAMX represents not only an advancement in rotor design, but a key enabling technology for a new era of Mars exploration: one in which aerial vehicles expand scientific access, accelerate discovery, and reshape how the Martian surface is investigated.

Future work should extend the ROAMX results by maturing rotor and vehicle performance across the full Martian flight envelope, including for forward flight and unsteady loads. Higher solidity rotor designs will be required to increase lift capability within the constraints of a lander shell, and integrated structural–aerodynamic blade design will be necessary to ensure the blades maintain their intended aerodynamic shape under load and therefore generate the required lift. System-level integration studies, including controls and autonomy, will further enable the transition of ROAMX technologies and ROAMX-derived technologies into future conceptual platforms such as Chopper and Skyfall. Increasing technology readiness will ultimately require flight testing under Mars atmospheric conditions, providing end-to-end validation of rotor, vehicle, and autonomy performance. Together, these efforts will advance ROAMX from experimentally validated rotor technology to a fully integrated capability for next-generation Mars exploration.

The vehicle level performance improvements quantified in this study demonstrate how ROAMX rotor designs translate into meaningful gains in range, hover time, and payload capacity within NDARC analyses for both Ingenuity-class and MSH-class concepts. These results provide a clear technical basis for integrating ROAMX technologies and unconventional airfoils into future Mars rotorcraft designs, enabling increasingly capable aerial platforms for scientific and exploration missions on Mars.

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