

An Advanced Mars Helicopter Design

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Ingenuity may be the first of many Mars aerial vehicles. Rotorcraft increase the range and speed that can be traveled to locations of interest. This enables mission concepts previously considered not viable on Mars, such as missions performing science investigations in regions of high elevation, steep terrain, caves/lava tubes, and surveys of the lower atmosphere. Recent work done at NASA Ames Research Center and NASA's Jet Propulsion Laboratory (JPL) show that significant science can be performed by rotorcraft either independently or as assistants to rovers and landers. Small rotorcraft of Ingenuity's general size can be potentially integrated into missions already scheduled for launch. Additionally, larger rotorcraft can support standalone novel mission concepts but are still be able to be sized and configured for deployment from heritage entry, descent, and landing (EDL) systems. One such mission concept of interest is to determine if organics are associated with clay-bearing or silica-rich soil. For such a mission, a small rotorcraft "robotic assistant" to a lander or rover could help determine if ancient sediment contains biosignatures in regions such as Mawrth Vallis. Ingenuity has demonstrated that rotorcraft can be developed relatively quickly and inexpensively and increase the types and amount of science that can be performed on any given mission. Recent research has suggested that rotorcraft of Ingenuity's general size can have their performance characteristics significantly enhanced – increasing their range, speed, and payload capacity – by using new generation rotor blade airfoils optimized for Mars operating conditions. Rotorcraft could potentially be a standard adjunct to all future lander and rover missions. This paper presents an advanced Mars helicopter design that leverages significantly the design heritage of the Ingenuity Mars Helicopter Technology Demonstrator (MHTD).

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I. Introduction

Ingenuity, the 2020 Mars Helicopter, will likely be the first of many “ride along” rotorcraft carried to the surface of Mars as well as other planetary bodies such as Titan and Venus. Ingenuity will demonstrate powered flight for the first time on another planet, which, in turn, will enable science in regions previously labeled “unreachable” by rovers or landers. Additionally, rotorcraft allow a larger region to be covered more quickly than a rover working alone, can gather samples beyond the immediate reach of landers, and can improve imaging or sensing resolution over that of orbiters. Recent collaborative effort by NASA’s Jet Propulsion Laboratory (JPL) and NASA Ames Research Center (ARC) have shown that the performance of Mars rotorcraft can be significantly improved with non-traditional, advanced airfoils enabling higher tip speeds and higher flight speeds. Increasing the blade area and having a larger motor and battery results in much higher lift capabilities for an aircraft with the same rotor radius and a size comparable to Ingenuity. The packaging of Ingenuity alongside Perseverance and the integration of the rotorcraft in a relatively short timeframe into the 2020 Mars mission, demonstrate that it is reasonable to add these vehicles alongside future rovers and landers in order to cover more surface area and conduct more science for the cost of a launch. The adaptations described above were applied to Ingenuity design heritage to create a more capable, conceptual design for an Advanced Mars Helicopter (AMH) which represents a modest technology evolution and represents a reasonable candidate for the next rotorcraft to fly to Mars.

II. Background

Ingenuity will be the first Mars rotorcraft, but, utilizing rotorcraft on Mars as science “platforms” is not a new concept. Young and others have been proposing rotary-wing-enabled exploration of the planet since 2000 (Refs. 1-5). Recent technological advances in aerodynamic performance, autonomy, and power systems have enabled this first non-terrestrial helicopter to be designed, fabricated, tested, and launched, with expected flights in the Martian environment in early 2021. The primary challenge to flying a rotorcraft on Mars is presented in Balaram et al. (Ref 6), “The challenge to helicopter use on Mars is the thin carbon dioxide atmosphere with approximately 1% of the density of Earth’s atmosphere.” However, the required autonomy, limited communications, ultra-lightweight rotors, flight controllability issues, and limited available power are nontrivial considerations. These requirements, as challenging as they were for Ingenuity, will be even more demanding for next generation Mars rotorcraft to perform science missions as an adjunct to, or independently, of a rover/lander. Early collaborative work at NASA Ames Research Center (ARC) and NASA’s Jet Propulsion Laboratory (JPL) had focused on a new generation of rotorcraft, called generically Mars Science Helicopter(s), that are larger, faster, carry more payload, and flyer longer than the first generation Mars rotorcraft, Ingenuity (Ref. 7 and 8). These vehicles are capable of operating in conjunction with, or independently of, rovers and landers. These initial second generation Mars rotorcraft conceptual designs were on the order of 20-30 kilograms in size but could also be packaged so as to fit within legacy, or near-legacy, entry, descent, and landing (EDL) systems. This early work was introduced in Ref. 7 and expanded on in Ref. 8. These studies proposed two primary classes of future Mars rotorcraft: in addition to large, scaled coaxial, or multirotor, configurations designed for independent/standalone science missions, smaller, Ingenuity-sized vehicles were also proposed that would interact with a larger rover or a lander based ground-station (Figure 1). The mission description and motivation for the Mars Science Helicopter (MSH) study are described in Ref. 9. Areas of research and technology for the second-generation vehicles include airfoil optimization, rotor performance, packaging, rotor and frame structural analysis, preliminary guidance, navigation, and controls, and accommodation of science instrument payloads. Each of these vehicle designs benefits from lessons learned during the development of Ingenuity. This paper will focus on the application of technology developed initially in support of the larger MSH concepts to a vehicle of the same diameter as Ingenuity, known as the “Advanced Mars Helicopter” (AMH).

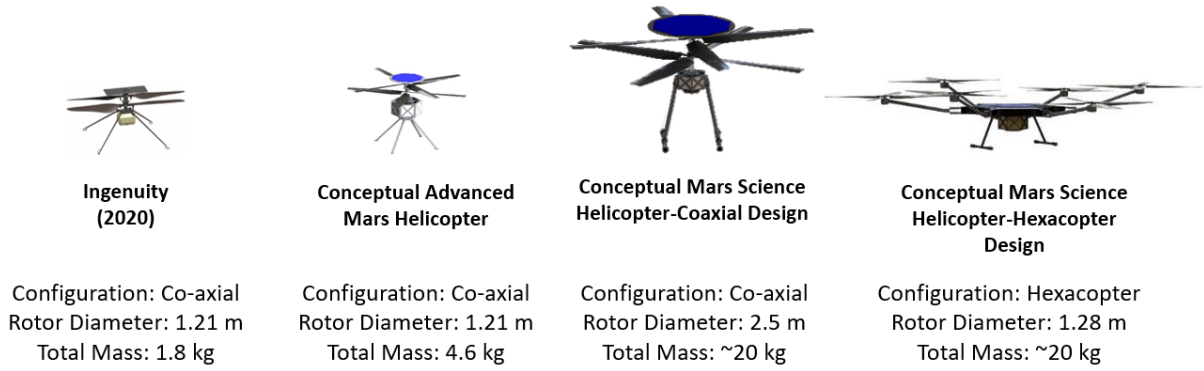


Fig. 1. Mars second generation rotorcraft concepts with Ingenuity for scale.

Ingenuity is a 1.21 m diameter, 1.8 kg rotorcraft in a coaxial configuration, and will be used as the reference design for the duration of the paper. Ingenuity has a camera for navigation, but does not have any science instrumentation apart from what is required for flight. Ingenuity’s mission includes a series of 90 second autonomous flights of increasing difficulty, serving as a technology demonstration of the first powered flight on another planet (Ref. 6). In the future, rotorcraft of this size could be used to assist the first human explorers of the red planet, in addition to conducting science alongside rovers and landers or independently.

III. Advanced Mars Helicopter Design and Performance

The AMH inherits the heritage size and configuration of Ingenuity. However, recent technology advancements suggest that a rotorcraft of similar size and form can go from having no payload to being able to carry a ~1.3 kg science payload. Accordingly, this class of small advanced rotorcraft is therefore ideal for future cooperative rotorcraft and rover, or rotorcraft and lander, missions. For these missions, the rotorcraft acts almost as any other science instrument, albeit deployable and mobile, to a rover or lander. For example, the AMH design could collect and return soil, rock, or ice samples to a lander where heavier equipment could be used to process the samples. AMH could also accompany a rover acting as a scout, to determine the most direct and safest route for the rover, as well as identifying nearby high-value science targets for in-situ exploration. These advantages come at a relatively low price as Ingenuity has already demonstrated that it is feasible to integrate rotorcraft as “assistants” to rover and lander-centric missions. For context, Ingenuity has a mass of 1.8 kg, while Perseverance has a mass of 1,056 kg; rotorcraft can be folded and stowed to ride beside, or even underneath, larger vehicles.

A. NDARC vehicle sizing

NASA Design and Analysis Code (NDARC) was used to size the AMH design with the same rotor radius as Ingenuity. NDARC has been validated against and used to size many terrestrial rotorcraft and has been used as a key analysis tool in the development of Ingenuity, as well as the early MSH studies. Relevant AMH vehicle parameters and assumptions can be found in Table 1. Table 2 shows the comparison of key performance parameters to Ingenuity. Advanced airfoils, more blade area, and large batteries and motor account for these differences and result in higher tip speed, flight speed, and the ability to carry a larger science payload.

Table 1. AMH vehicle parameters.

Constants	Units	Value
Gravity	$\frac{m}{s^2}$	3.711
Density	$\frac{kg}{m^3}$	0.015
Vehicle Parameters	-	-
Rotor radius	m	0.605
Gross Mass	kg	4.6
Payload Mass	kg	1.3
Number of Blades	-	4
Flap Freq	$\frac{1}{rev}$	2
Lock number	-	0.12
Disk Loading	$\frac{N}{m^2}$	39.310
Power req. for hover	kW	0.587

Table 2: Ingenuity and AMH comparison.

Parameter	Unit	MHTD	Advanced Design
 			
Design C_T/σ		0.1	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	2
		or	and
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/m^2	0.8	2
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 area	m^2	0.04	0.06
Battery	Ah	12	46

Figure 2 shows the potential increase in terms of range and hover time with advanced airfoils and design parameters as defined in Table 2.

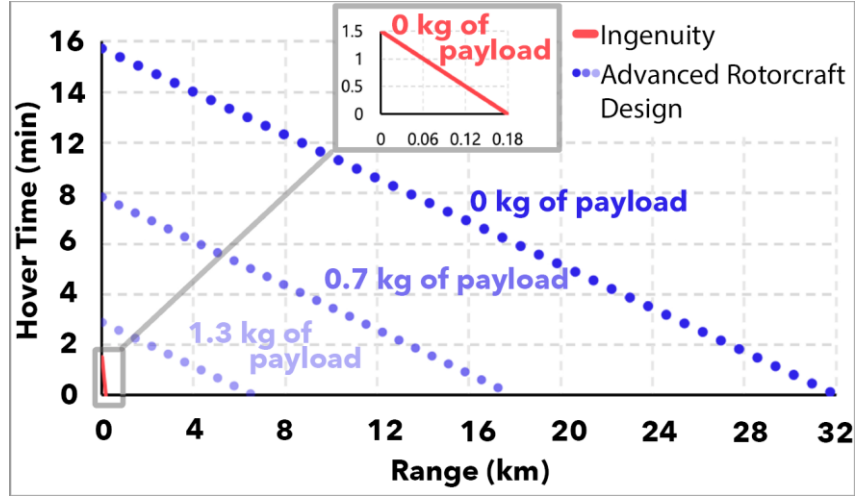


Fig. 2. Hover time versus range: Ingenuity and AMH.

B. Rotors and advanced airfoils

Thin airfoils with sharp leading edges have been shown to provide a significant increase in performance compared to Ingenuity's blades (Ref. 10-13). Such performance improvements as seen in Figure 2 are due primarily to the use of nonconventional airfoils. Flight on Mars occurs in the low Reynolds number (Re) ($\sim 10^4$), high subsonic Mach number (~ 0.8 at the tip) regime, which is not typically found in flight on Earth. Thus, ideal airfoils for Mars may look different than those conventionally used on terrestrial rotorcraft. At low Re , conventional airfoils experience laminar separation with no reattachment, which significantly increases drag. Animals in nature that fly in this low Re flight regime (such as the dragonfly) exhibit thin, unconventional airfoil shapes (Figure 3, Ref. 14). Koning discussed the increase in performance for thin airfoils with sharp leading edges compared to Ingenuity's blades (Ref. 10-13). These sharp leading edges immediately cause the flow to separate. Subsequently, unsteady vortex shedding is seen to actually cause an increase in performance compared to conventional airfoils at these very low Reynolds numbers. Compared to Ingenuity, an increase of up to 41% in peak lift-to-drag ratio can be achieved with an initial set of optimized airfoils.



Fig. 3. Low Re airfoils. (Ref. 10 and 14).

With this initial set of optimized airfoils, rotor blade twist and planform were also optimized using the well-known rotorcraft analysis software code CAMRAD II and the NDARC sizing tool used to predict and maximize performance. Blade taper and twist were varied to converge upon the optimum values. Using optimized airfoils, taper, and twist, an estimated Figure of Merit of 0.62 ($\sim 7\%$ higher than Ingenuity) is achievable for the AMH as well as a significantly

expanded maximum thrust capability prior to rotor stall in hover. Figure 4 illustrates the airfoils and the planform distribution of the AMH optimized rotor blade.

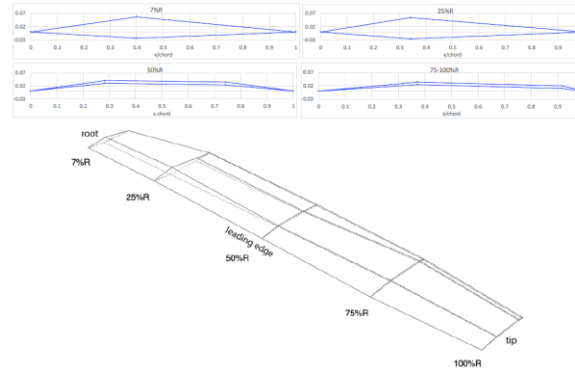


Fig. 4. Optimized rotor for second generation Mars vehicles (Ref. 8).

Research is still ongoing to determine the right balance for Mars rotor blade design between aerodynamic performance and blade weight, stiffness, strength, and frequency placement. Thin airfoils with sharp leading edges result in rotors with lower overall flap bending and torsion stiffness. The smaller aerodynamic loads that result from the low Mars atmospheric density mean that less stiffness is required from a purely aerodynamics perspective. However, flap mode frequency is critical for cyclic control of a coaxial helicopter, so the structural design of the rotor must take this into account. Initial studies show that sufficient controllability and stiffness is possible using carbon fiber skin, foam core, and aluminum root insert (Ref. 8).

The ROAMX (Rotor Optimization for the Advancement of Mars eXploration) project at Ames was recently funded through the NASA Space Technology Mission Directorate (STMD) Early Career Investigator program. ROAMX will perform further airfoil and rotor optimization and structural studies using computational models. The ROAMX team will verify these models through experimental testing in the Planetary Aeolian Laboratory low-pressure chamber at Ames where work for Mars rotorcraft research has previously been conducted (Ref. 3 and Ref. 15). This work will result in a validated design methodology that can be applied to all future Mars rotorcraft rotor designs.

IV. Mission Potential

A successful flight for Ingenuity will enable many science missions previously thought to be infeasible. Traditional EDL systems require relatively flat initial landing sites with minimal potential for collision with surface features. Larger, ground based vehicles then perform missions within a limited range of the landing site. Rotorcraft, however, possess the ability to land in “safe” region and travel to an area of interest (such as crater rims, cliffs, caves, etc.) to perform science at close range.

Balaram et al. discussed regions of potential interest for a Mars Science Helicopter (Ref. 9). Estimated payload capacities of these future generation helicopters on Mars could enable science such as geologic mapping, excursions to exposed ice deposits, astrobiology, and meteorology utilizing instrumentation such as thermal imagers, X-ray spectrometers, tunable laser spectrometers, imaging radars, visible-near infrared (VNIR) spectrometers, and light detection and ranging (LIDAR).

A. Geologic and/or Ice Surveys

Two examples of high-interest science investigations are geologic mapping and studying exposures of water ice, ranging from the mid-altitude regions to the poles of Mars, as identified by the Mars Exploration Program Assessment Group (MEPAG) (Refs. 15-18). Determining stratigraphic relationships in the geologic record provides insight into the climate and geologic history of Mars (Ref. 19). Rotorcraft can collect high-spatial-resolution imagery to produce detailed maps of Martian terrain, as compared to that of orbiter imagery, at a more efficient rate than landers/rovers. Additionally, while rovers are unable to transverse steep terrain or un-traversable surface material, small rotorcraft can fly and hover over these terrains, for example exposed water ice scarps, and could characterize surface properties

and processes at greater fidelity than assets in orbit (e.g., texture, geometry, sublimation rates, and atmospheric interaction). After collecting data and samples, the rotorcraft can return to the original landing site to take advantage of larger, heavier scientific and communication instrumentation built into the lander (Ref. 20).

B. Clays and astrobiology mission

Bapst, et al. described compelling science for the next decade enabled by Mars rotorcraft in a mission concept white paper submitted to the 2023-2032 Decadal Survey on Planetary Science and Astrobiology (Ref 21). In this paper, Bapst outlines a specific mission concept that would be ideal for the size of rotorcraft described above. Bapst states:

c)

Mawrth Vallis is a large outflow channel spanning ~640 km located in northwest Arabia Terra near 343°E, 22°N, at approximately –3000 m elevation. Along the channel are some of the clearest detections of phyllosilicate minerals (clays) on the planet, which were likely deposited more than 3.5 Gyr ago (Fig. 5). Detections mapped from orbit [ref 19–21 of Bapst, et al.] provide a window into early Mars and indicate periods of intense aqueous activity, both at the surface [ref 22 of Bapst, et al.] (e.g., wetlands/ponds) and in the subsurface (e.g., impact generated hydrothermal systems). In addition to revealing aqueous activity on early Mars, these minerals are known to preserve organic material on Earth...MSH would, if necessary, drill or disaggregate rock, followed by collection and delivery to a lander for subsequent physical and chemical analyses. The ability to travel a long range in a short period of time, and reach hard-to-access sites, *in situ*, allows for a more-selective approach in sampling—or if adequate samples are rare—the ability to visit many locations to find one suitable.

The goals of the mission described above would be to 1) determine if organics are associated with clay-bearing or silica-rich units, and 2) determine if ancient sediment contains biosignatures. The instrumentation would be divided among AMH for *in-situ* science (sampling arm and microdrill) and a lander (gas chromatograph mass spectrometer, micro-imaging suite, and life detection instrument).

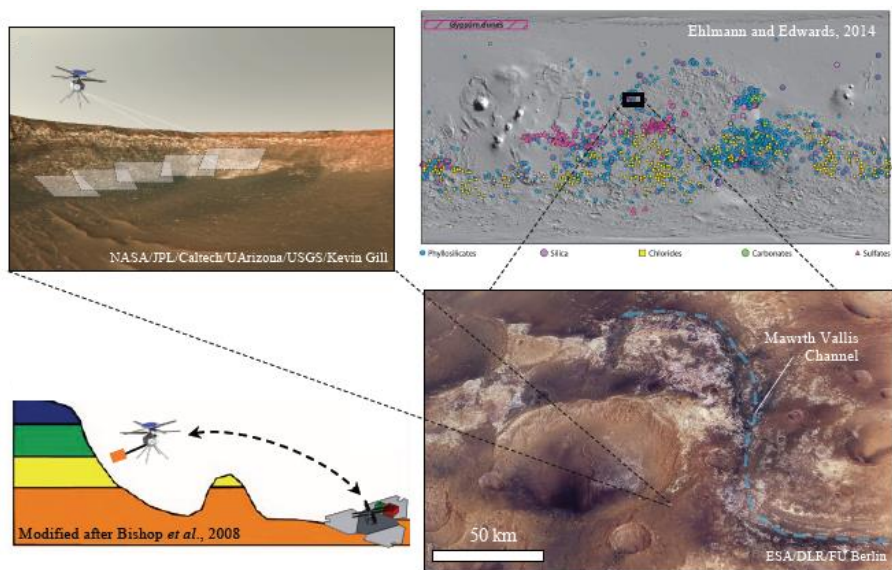


Fig. 5. (a) AMH identifying regions of interest. (b) Global detections of aqueous minerals. (c) Retrieval of samples and delivery to a lander that hosts instrumentation. (d) Perspective view of Marwth Vallis and crater exposing materials of interest (Ref 21).

V. Rotorcraft Packaging in EDL Systems and Deploying from Landers or Rovers

Before performing science on Mars, the rotorcraft must first survive the launch and journey to the surface of the planet. The thin, stiff rotor blades could be especially susceptible to damage if not packaged properly.

A. Volume Study and Estimation

A vehicle packaging study was performed, using the clay and astrobiology mission as a reference mission. It was assumed that adapting a heritage EDL system for a Mars rotorcraft of the size of the AMH class of vehicle would minimize cost to schedule and budget of a future Mars mission, rather than developing a new EDL system. Three systems were investigated including those used for the Pathfinder, Viking, and Mars Science Lab/Perseverance missions (Figure 6).



Photo Credit: New Atlas

Viking 1/2 Aeroshell
1976
Diameter: 3.505m



Photo Credit: NASA's Jet Propulsion Laboratory

Pathfinder Aeroshell
(size also used for MER A/B
and Phoenix missions)
1997
Diameter: 2.65 m



Photo Credit: New Atlas

Mars Science Lab Aeroshell
(size also used for 2020 mission)
2012
Diameter: 4.5 m

Fig. 6. Heritage aeroshells for Mars missions.

Of the three EDL systems, Pathfinder is the smallest and least expensive to launch. As such, the Pathfinder tetrahedral petal lander and aeroshell were used as the baseline EDL system for the vehicle packaging study. The AMH design was adapted to allow for rotor blade and landing gear folding to fit within the Pathfinder tetrahedral lander. Once a folding configuration was confirmed to successfully fit in the lander, various positions and folding methods were explored to maximize volume available for other mission instrumentation and payloads. Figure 7 illustrates several different arrangements of the AMH rotorcraft and other auxiliary science payloads. In Figure 7, the medium sized-green box included with the folded rotorcraft within the lander is approximately the volume of the x-ray lithochemistry system (based on Perseverance PIXL); the large, red volume approximates the gas chromatographer/mass spectrometer; and the small, orange box approximates the raman spectrometer. Figure 8 illustrates where batteries (blue) and micro-drill (yellow) are incorporated into the rotorcraft.

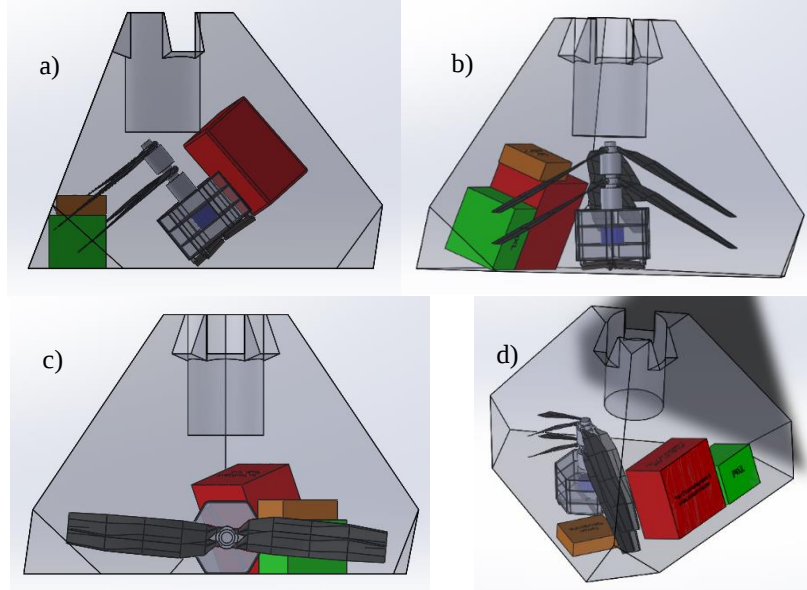


Fig. 7. AMH in Pathfinder tetrahedral petal lander at a) angled, b) flat, c) sideways, and d) offset positions along with boxes representing payload volume.

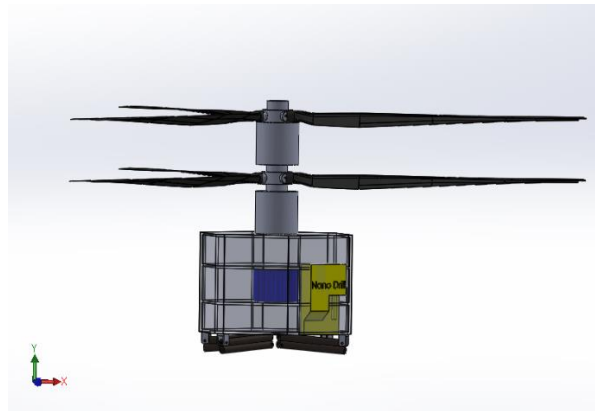


Fig. 8. Battery and micro-drill volumes relative to the internal rotorcraft volume.

Other MSH vehicle configurations, such as a 20-30 kilogram hexacopter and large coaxial helicopter (which also carry larger payloads), are constrained by the size of the Pathfinder lander and, consequently, challenging to adequately package. However, the smaller AMH, which was designed with a rotor radius of the same size as the Ingenuity rotors, has multiple viable folding configurations with a Pathfinder-type tetrahedral petal lander. (Note that the clay and astrobiology mission - and this volumetric study - implies a lander/rotorcraft mission CONOPS whereby the rotorcraft periodically flies from and back to the lander to perform aerial surveys and transfer data and samples to the lander.) While the ‘sideways’ configuration occupied the least volume of the configurations shown (Figure 7), it is also more mechanically complex to unfold. Furthermore, the volume saved was not critical for preserving space/volume for the other auxilliary science instrumentation for the reference astrobiology mission studied. Accordingly, mechanical robustness and simplicity were prioritized in the selection of the final folding configuration, (‘flat with blades drooped’) (Figure 9).

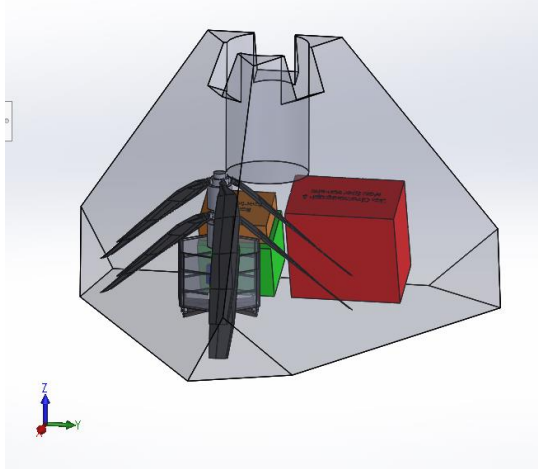


Fig. 9. Selected packaging configuration for AMH and payloads inside Pathfinder’s tetrahedral petal lander.

As mentioned previously, simple volumetric models of required instrumentation for the clay and astrobiology mission, as described in Baspt (Ref. 21), were placed in the lander with the rotorcraft. Additionally, accounting for the batteries and payload, usable interior volume for avionics and additional electrical and mechanical systems in the rotorcraft fuselage interior was approximated to be $\sim 40 \text{ cm}^3$. Usable lander volume was defined as volume that could reasonably be used for required subsystems and payload (i.e. excluding small spaces between rotors, legs, etc.) by creating a simplified model (Figure 10) of the rotorcraft that represented dedicated volume needed in the lander for the rotorcraft. Usable volume available in the lander was estimated to be $\sim 480 \text{ cm}^3$. This volume is available for communication hardware, rotorcraft solar panels, and additional payload.

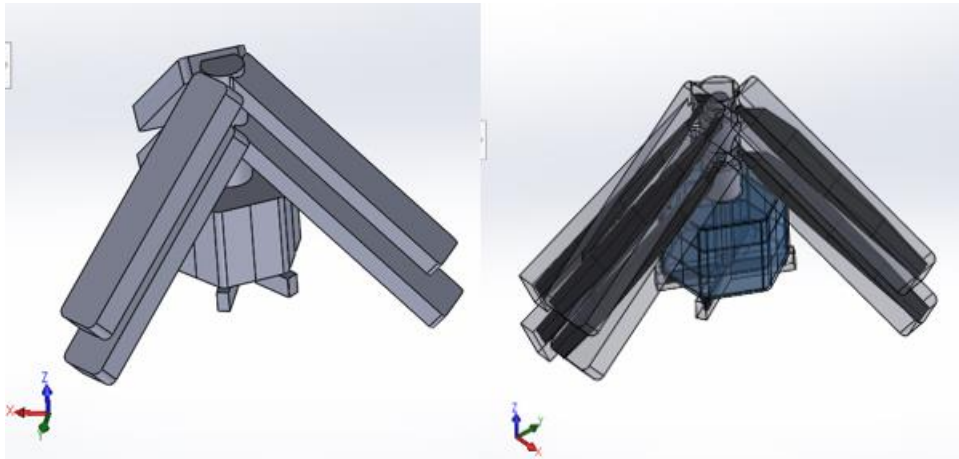


Fig. 10. AMH simplified volume ‘mock’ model (left); simplified volume model overlaid on the AMH vehicle (right).

B. Stowage, Activation (or Deployment), and Locking Mechanisms

After lander volume proof-of-concept requirements were satisfied, the next step towards assessing EDL feasibility was to explore the requirements for the rotorcraft to leave the lander once it is safely on the Martian surface. The transition from “stowed mode” to “flight mode” can be broken down into three phases: stowage, activation (or deployment), and flight mode. For this discussion, stowage refers to the state of the rotorcraft while in transit to Mars and while landing on the surface (Figure 11). Activation is the phase that encompasses the release of clamped and tethered components, using passive or active actuation to unfold the rotorcraft components, and transition into and readiness for entering flight state (Figure 12). Flight state refers to the rotorcraft being free of constraints and in

position to begin the mission sequence (Figure 13). The lander petals open and the rotorcraft and lander-based instrumentation systems are oriented into their proper deployed positions. (Note that it is assumed that the Pathfinder design heritage of airbags and the actuation mechanisms to unfold/orientate the tetrahedral petals is retained.) The rotorcraft blades are then unfolded from their canted stowed position and then the rotorcraft as a whole is raised through another actuation mechanism to a vertical position where the folded landing legs can unfold and snap into their flight-ready positions.

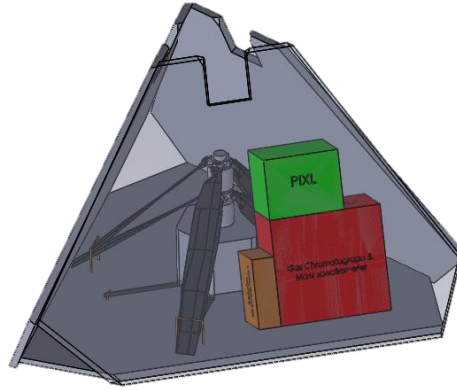


Fig. 11. AMH in the stowed position.

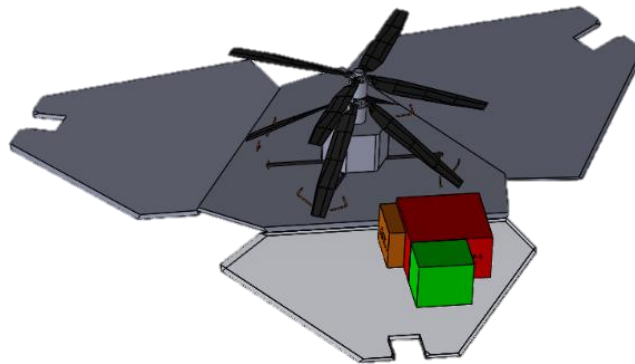


Fig. 12. AMH in the process of activation; transitioning from stowed to flight mode.

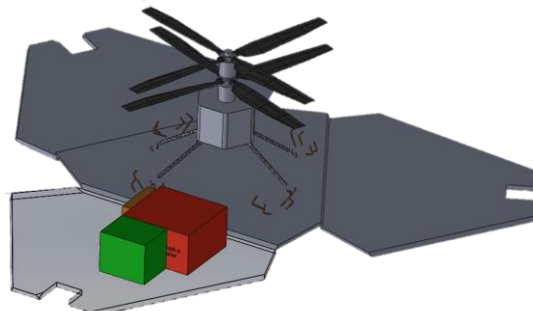


Fig. 13. AMH blades in flight mode.

It was necessary to fold the blades from their flight position in order to fit in the tetrahedral petal lander. The simplest method of folding that does not significantly compromise the stiffness of the blades was to place a hinge at the root of the blade; refer to Figure 14. Furthermore, since it is difficult to accommodate a hinge along a circular surface, the spar at the root of the blades was modified into an oblong shape (Figure 14). To avoid interfering with the aerodynamic performance, the inner 20% of this spar may be used to house hinges, springs, locks, and other components, but the outer 80% must maintain the airfoil shape. The primary consideration to any blade modification for this type of application is that the leading edge of the blade must maintain the same thickness and shape (curvature). Additionally, stiffness of the blade must be maintained to avoid excessive flapping to achieve acceptable controllability. This will require follow-on hinge mechanism design work to ensure the maximum stiffness of the blade in the unfolded position.

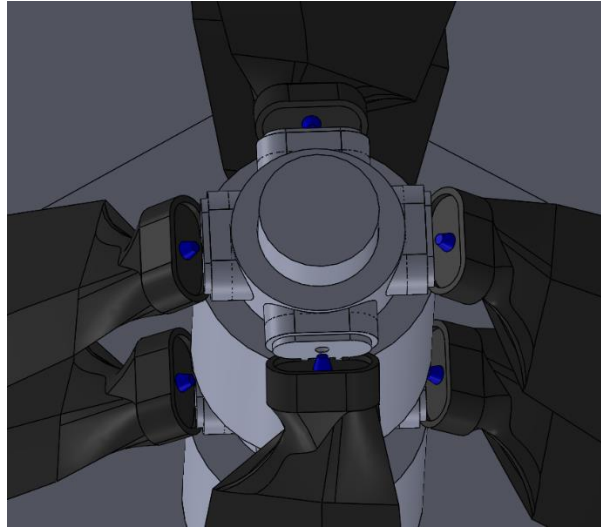


Fig. 14. Blade hinge placement.

One possible combination for blade unfolding actuation is pyrotechnic cutters (to cut two sets of wires securing the blades to the lander during flight) and loaded torsions springs to release the blades and allow them to move into place (Figure 15). Once the AMH is ready to transition into flight mode, the pyrotechnic cutters on the upper wires will activate, releasing the upper blades (Figure 16). Next, the lower blades will be released and will spring into place (Figures 17 and 18).

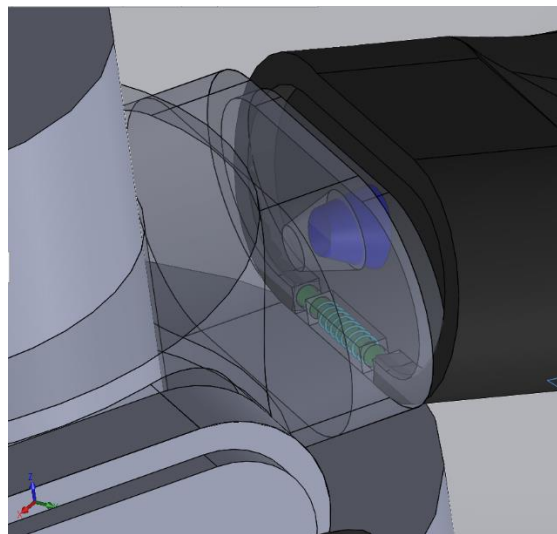


Fig. 15. Spring-loaded blade hinge.

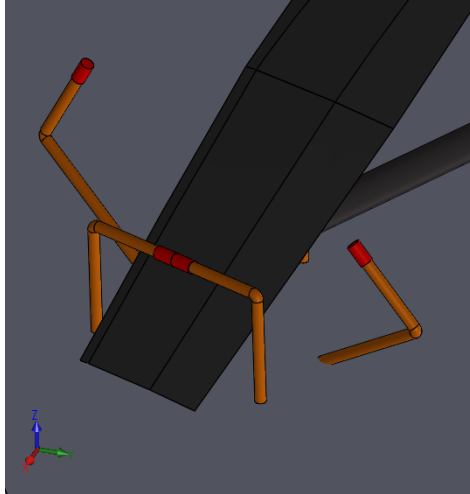


Fig. 16. Close up of already-activated upper blade wire and still-secured lower blade wire.

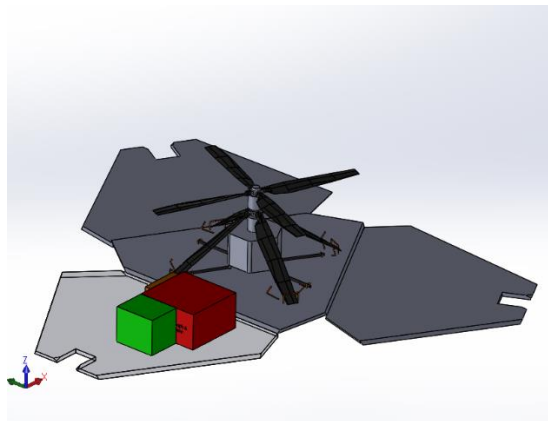


Fig. 17. Released upper blades and stowed lower blades.

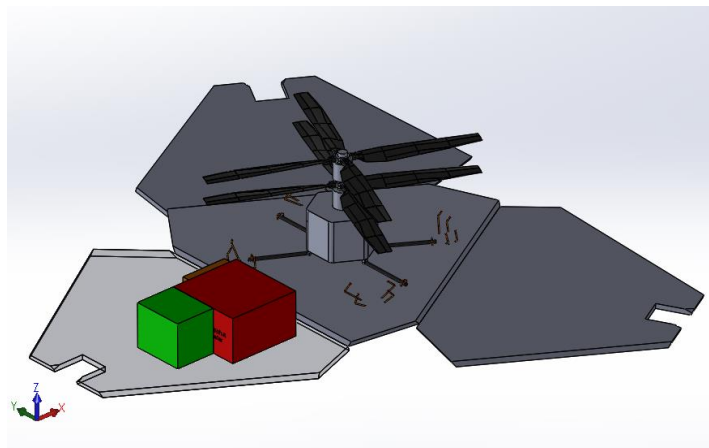


Fig. 18. Released upper and lower blades.

Other possible methods of activating the blades into flight mode include the use of motors, tethers, and rotation. Additionally, several locking designs to secure the blades into their final positions have been explored including: a fin

lock (similar to a toggle bolt), sealing fin lock (uses a compressible material), magnetic lock, and spring lock (similar to the leg locks on Ingenuity) all internal to the spar structure. It is currently assumed that the landing gear will maintain the heritage design of Ingenuity for springing and locking in place. Figure 19 shows the vehicle in flight mode. Follow-on work in this critical deployment/activation area will continue.

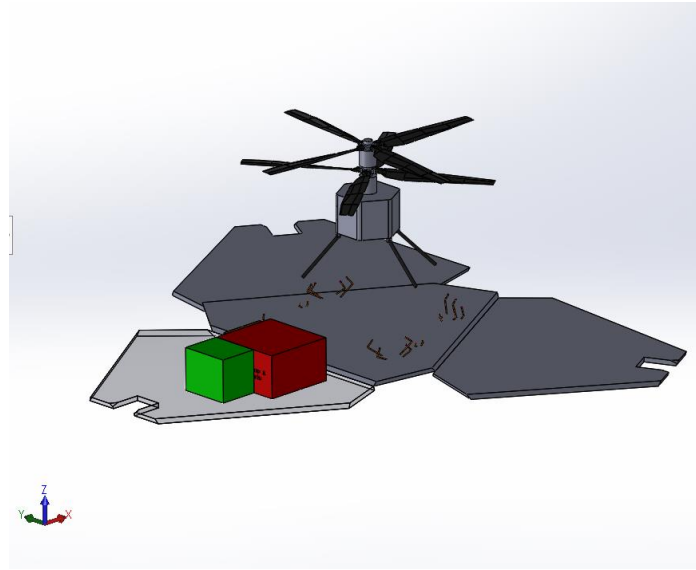


Fig. 19. AMH in flight mode.

Left for future work is the conceptual design of the lander subsystems to make it a fully functional base-station for the rotorcraft. This includes solar arrays on the lander petals, power electronics to supply all instrumentation and subsystems on the lander (and to perhaps be an alternative source of power for the rotorcraft), telecommunications equipment, robotic arms for sample transfer from the rotorcraft to science instruments on the lander, and perhaps a small tethered/untethered transfer rover to carry empty and full sample tubes to and from the lander and the rover for the final few meters between the rotorcraft landing site next to the lander and the lander itself. The whole process of the robotic symbiosis between the lander and rover needs to be defined in future work beyond the very high-level ideas detailed to date. An understated element of design heritage from Ingenuity is onboard solar electric recharging of the vehicle for multiple sortie flights. This capability is retained in the proposed AMH. This, in turn, implies a sustained robotic partnership between AMH and the lander base-station.

VI. Conclusion

The use of rotorcraft on Mars, and other planetary bodies with sufficient atmospheric mass, has the potential to complement both the speed and area covered by orbiters and the proximity of land vehicles to objects of interest, without as many terrain-based limitations. With low mass and volume compared to landers and rovers, rotorcraft can accompany these larger vehicles at relatively low cost and risk to the mission, while providing significant advantages. Because these rotorcraft can easily integrate into heritage EDL systems such as the Pathfinder lander or a lander/rover in a Mars Science Lab sized aeroshell, development teams can focus valuable time and energy on the science enabled by these aerial platforms. The fast development, testing, integration, and launch of Ingenuity demonstrates that it is feasible to launch this type of vehicle regularly, suggesting that, perhaps, rotorcraft should be a part of every future Mars mission. In the future, in addition to conducting science alongside rovers and landers or independently, rotorcraft of this size could be used to assist the first human explorers of the red planet.

Acknowledgments

The authors would like to acknowledge the interns of the NASA Ames Aeromechanics Branch who have contributed to this work including Winnie Kuang, Allysa Tuano, and Sara Mayne. The authors would also like to

thank Natalia Perez-Perez for generating Figure 2. Lastly, the authors would like to thank all members of the NASA Ames and JPL community who have contributed to and supported the study of Mars rotorcraft.

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