A Study of Past, Present, and Future Mars Rotorcraft

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ABSTRACT

Interest in utilizing rotorcraft to explore Mars is expected to increase following the anticipated successful technical demonstration of the Mars Helicopter, Ingenuity, during the Mars 2020 mission. Previously, science investigations have been limited by either the instrumentation resolution on orbiters or the roughness/accessibility of terrain a rover can traverse. Rotorcraft can enable low-altitude flight over and on-surface exploration at previously inaccessible locations. This paper describes potential mission concepts designed to utilize the unique capabilities of rotorcraft to advance the science performed in extraterrestrial environments. This includes missions tailored for investigating if Mars ever supported life, understanding climate processes and history, determining the evolution of Martian geology, and preparing for human exploration. The Mars rotorcraft mission concepts described in this paper can be divided into two categories: rover-assisted missions and independent (rotorcraft-only) missions. A number of concept vehicles, consistent with these proposed missions, are also discussed.

INTRODUCTION

The Ingenuity Mars Helicopter, if successful, will perform the first powered flight on another planet (Ref. 1-2). This capability will significantly expand the potential of extraterrestrial exploration. The Mars 2020 vertical lift aerial vehicle is intended to be a technology demonstration and has a camera for navigation but no dedicated science payload. A more capable rotorcraft that would enable full science missions will leverage the success from this demonstration, but there will remain a series of technology challenges to overcome. Mars' environment is vastly different from Earth's in terms of atmospheric composition and density, temperature extremes, and gravitational acceleration. The paper will provide a literature review summary of past and current efforts towards powered flight on Mars. The paper will follow by describing mission concepts enabled by rotorcraft on Mars, and discuss some of the challenges that must be addressed for these vehicles to be successfully utilized. The work for this paper was performed by a team of student research associates in the Aeromechanics Branch of NASA Ames Research Center during the summer of 2019.

BACKGROUND

Atmosphere

The Martian atmosphere is composed of mostly carbon dioxide with small amounts of other gases, as shown in Figure 1. Because of the relatively small percentage of oxygen, internal combustion and turbine engines are likely infeasible for the Martian atmosphere. With current technologies, any aircraft on Mars would need to run on either solar or nuclear energy to be considered viable. (There is some possibility in the future of using monopropellant reciprocating engines, aka Akkerman engines (Ref. 3), or in the far future, in-situ-derived pressurized bi-propellant combustion systems.) Nuclear power sources currently face considerable weight constraints but may be viable in the future. Battery-powered rotorcraft capable of solar-electric recharging are currently feasible and appear to be a logical design solution for near- and mid-term Mars planetary science missions.

Presented at the Vertical Flight Society's 9th Biennial Autonomous VTOL Technical Meeting, Virtual, January 26-28, 2021.

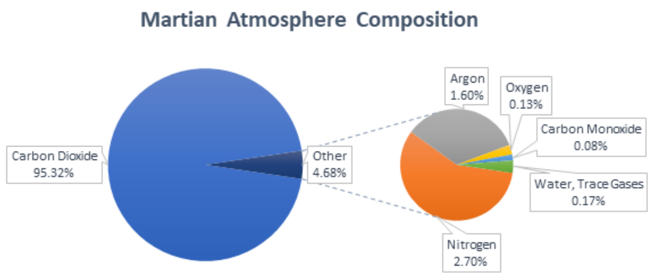


Figure 1. Martian atmospheric composition (Ref. 4)

Mars's surface temperature can range from -140 degrees C at the poles to up to 30 degrees C during the day on the equator (Ref. 5), creating a significant temperature range for the proposed vehicles to potentially endure. Mars also experiences extreme localized temperature variance. At night on the equator, the warmest region of Mars, the temperature can drop as low as -80 degrees C (Ref. 6). For battery powered rotorcraft, it is important to keep the battery insulated from these extreme temperatures. For example, low temperature lithium batteries operate between –50 and 40 degrees C (Ref. 7). For batteries to survive even equatorial nights they must have sufficient insulation and/or heating. Temperature must also be taken into consideration for electronic component and structural material selection.

Flying on Mars has numerous challenges that must be addressed, starting with the density of the atmosphere. The Martian atmosphere has a pressure averaging 6.36 millibars (0.6% the pressure of Earth's atmosphere) (Ref. 4). The low pressure results in a low average air density of 0.02 kg/m^2, just 1.6% of Earth's 1.225 kg/m^2. The low density is a significant challenge, as rotors experience reduced lift. In order to compensate for thin air with low density, rotor blades require a larger surface area and must operate at much higher speeds than they would require on Earth for the same mission. However, the rotor speed also has an upper bound because of rotor tip speed. Rotor tip speeds need to stay below about 0.8 Mach, and the speed of sound on Mars is a mere 240 m/s compared to Earth's 340 m/s (Ref. 8). Tip speeds above about 200 m/s will result in a loss of lift, increased drag, and create destructive vibrations in the rotor. In contrast, one of the primary beneficial differences of Martian flight is the reduced effects of gravity. Mars has a gravitational acceleration of 3.71 m/s^2 (Ref. 4), almost a third of Earth's 9.81 m/s^2. Lower gravity aids in flight and does not mitigate, but helps offset the challenges caused by the low density atmosphere.

The communication delay between Earth and Mars is between three and twenty-one minutes one way, depending on the relative orbital positions of the planets (Ref. 9). Thus, like any vehicle on Mars, the vehicle must operate autonomously. Additionally, it must either be able to carry the communication equipment required to communicate with Mars orbiters or have the ability to transmit data to another larger vehicle such as a lander with full communication abilities. On Earth, unmanned aerial vehicles utilize GPS for navigation. Since Mars does not have GPS architecture in place and will not for the foreseeable future, rotorcraft must have their own obstacle detection and avoidance capabilities.

AERIAL EXPLORER LITERATURE REVIEW

Past Mars Rotorcraft Studies

Discussions of rotorcraft use on Mars date back to the mid-1990s with G. Savu's (Ref. 10) proposal for a photovoltaic compressed-gas powered rotorcraft. In the early 2000s, L. Young studied the viability, capabilities and possible missions of a Mars rotorcraft, discussing tiltrotor, coaxial, and quad-rotor configurations (Ref. 11-13), and performed experimental rotor tests in Martian conditions (Ref. 14).

Around the same time, the University of Maryland and the Georgia Institute of Technology developed conceptual Mars rotorcraft designs for a 2002 American Helicopter Society student design competition. The University of Maryland designed Martian Autonomous Rotary-wing Vehicle (MARV), a 50 kg, 4.26 rotor diameter coaxial rotorcraft with 25 km range (Ref. 15), and the Georgia Institute of Technology developed the Georgia Tech Autonomous Rotorcraft System (GTMARS), a 10 kg, 1.84 rotor diameter quadrotor (Ref. 16). Figure 2 shows these designs.

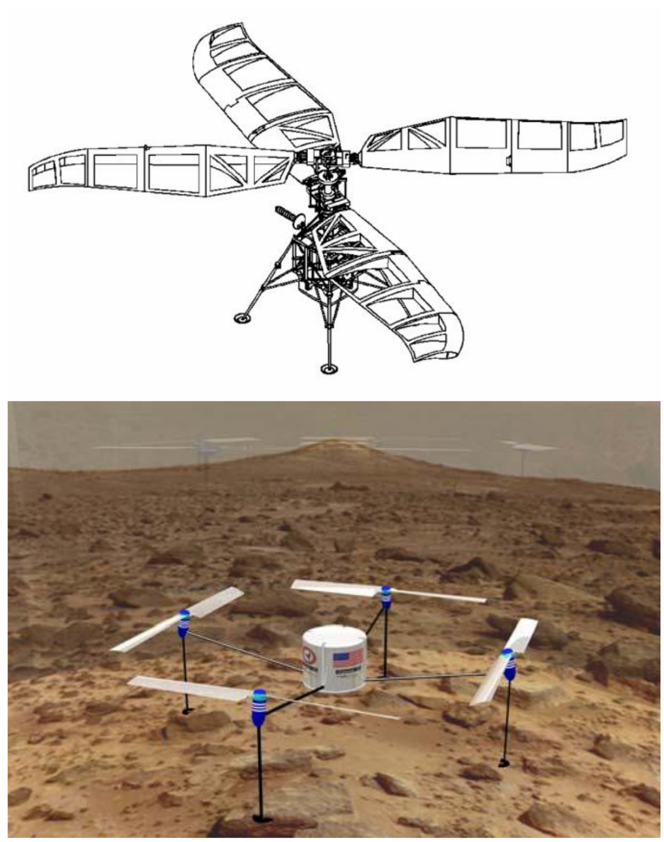
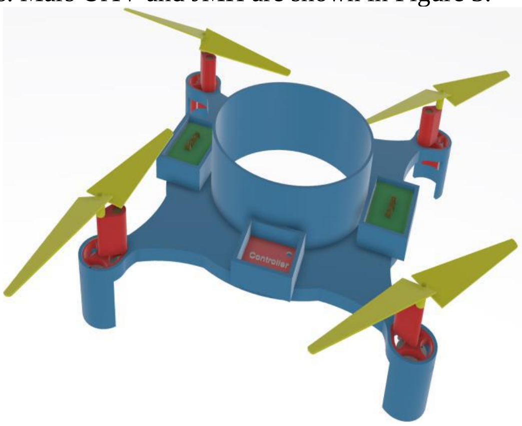


Figure 2. MARV (top) (Ref. 15) and GTMARS (bottom) (Ref. 16)

Recent years have produced more Mars rotorcraft concepts as well, with Georgia Institute of Technology's Mars UAV design in 2018 (Ref. 17) designed to be integrated with a rover, and Tohoku University's 10.7 kg Japanese Mars Helicopter (JMH) quadrotor (Ref. 18) designed for pit crater exploration with four, 1.05 meter diameter coaxial rotor blades. Mars UAV and JMH are shown in Figure 3.



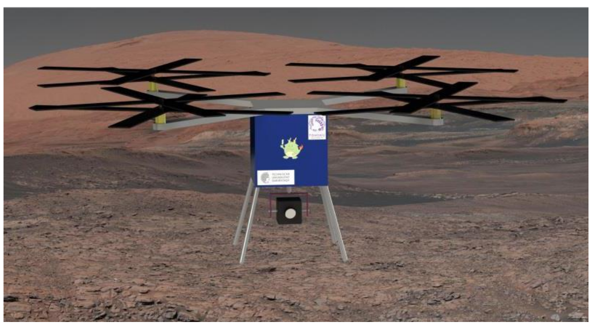
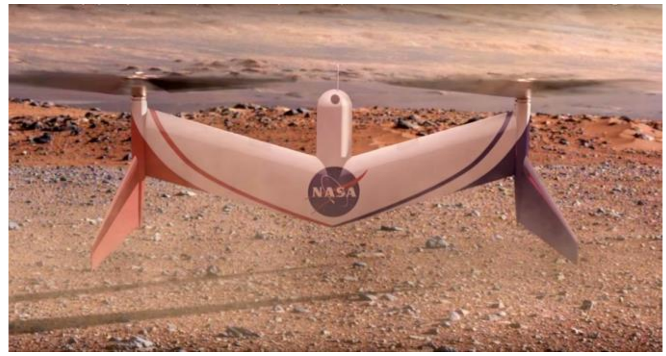


Figure 3. Mars UAV (top) (Ref. 17) and JMH (bottom) (Ref. 18)

In addition to coaxial helicopters and multirotors, VTOL aircraft, primarily tailsitter configurations, have been proposed for longer range missions. The University of Surrey (Ref. 19-20) describes a tailsitter aircraft designed for use on Mars. Both a reusable and single use power system were analyzed for a 15 kg aircraft with a 7 square meter wing area and two 1.4 meter rotors. The reusable variation had a range of 100 km and 38 minutes of flight per charge, while the single use variant had 450 km of range and 170 minutes of flight. NASA Langley Research Center has proposed a 3-foot wingspan VTOL tailsitter concept called the Mars Electric Reusable Flyer (Ref. 21). The Delft University of Technology designed a 14 kg X-wing style tailsitter called VITAS because of its Visual imaging, Ice deposit scanning, Trace gas detection, Atmospheric analysis, and Soil analysis capabilities (Ref. 22). It includes two rotors on each of its four arms, one optimized for hover, and one for cruise. The Mars Reusable Electric Flyer and VITAS are shown in Figure 4.



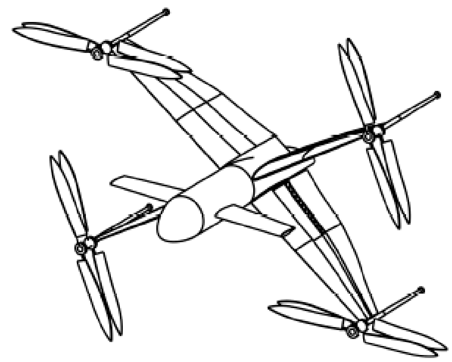


Figure 4. Mars Reusable Electric Flyer (top) (Ref. 21) VITAS (bottom) (Ref. 22)

There has been recent advancement in designing rotors for Martian flight. A 2017 study of developing a Martian coaxial rotorcraft blade can be found in Reference 23, and designs of a rotor for Martian micro air vehicles can be found in Reference 24-25. Rotor airfoil analysis and optimization for compressible, low-Reynolds number conditions can be found in Reference 26-28.

Current State of Mars Rotorcraft

Ingenuity

Ingenuity is a part of the Mars 2020 mission as a technology demonstrator for extraterrestrial flight. The coaxial design has a rotor diameter of 1.21 meters with collective and cyclic control on both rotors and a maximum speed of 2800 rpm. The helicopter has a total mass of 1.8 kilograms, with all systems directly contributing to the helicopter's flight (i.e. no science payload). The technology demonstration mission is designed to last for 30 sols with five 90 second flights scheduled throughout that period (Ref. 1). The short flight time is due to limited battery capacity, as more than half of the battery capacity is required to keep the helicopter systems warm during the frigid Martian nights. The capabilities and limitations of Ingenuity's design helped to guide the mission and vehicle concept development processes in this work.

Figure 5. Ingenuity (Ref. 2)

Controls and structures discussion related to the Ingenuity development can be found in Reference 29-31. Current solutions include utilizing an internal map to reference LIDAR or photogrammetry data to determine position or inertial navigation (accelerometers, speed, and distance sensors) combined with visual odometry. A photo of Ingenuity is shown in Figure 5. In the future, if the area of travel for a Mars rotorcraft is small enough, surface radio transmitters deployed upon atmospheric entry could triangulate the aircraft's position, allowing it to navigate.

Mars Science Helicopter (MSH)

MSH is a joint study between NASA's Jet Propulsion Laboratory (JPL) and NASA Ames Research Center (ARC) to develop critical technology for future generations of Mars rotorcraft. Performance results to-date from the study indicate that optimized rotor design enables a substantial increase in science payload capability, hover time, and range to be significantly increased from the first-generation Ingenuity design (Ref. 32-33). This study has produced three vehicle conceptual designs (shown in Figure 6) to be used as references for planning future Mars missions. The vehicle conceptual designs studied so far include a large coaxial and hexacopter, both of which are ~20-30 kg, and a small advanced coaxial design, which has the same rotor size as Ingenuity.

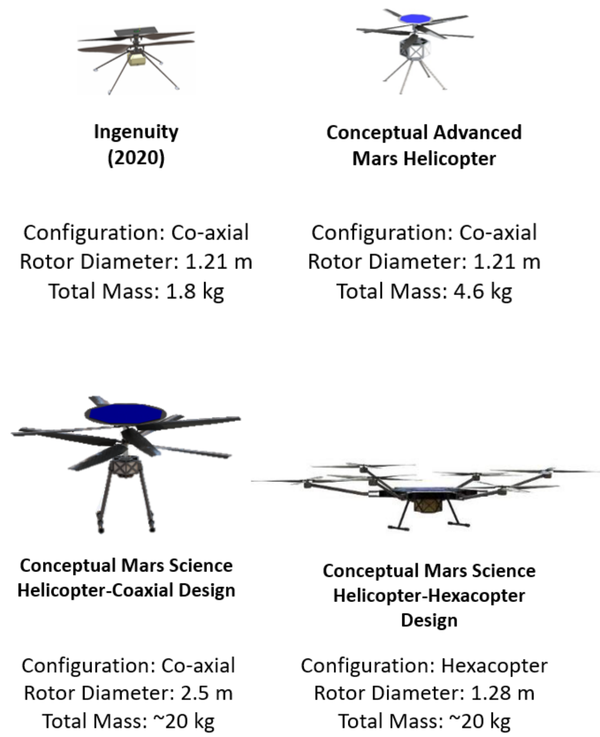


Figure 6. Size comparison of Ingenuity to MSH concept vehicles (Ref. 32-33)

The range/payload performance of a ~5 kg Advanced Mars Helicopter as compared to the Ingenuity technology demonstrator can be found in Figure 7.

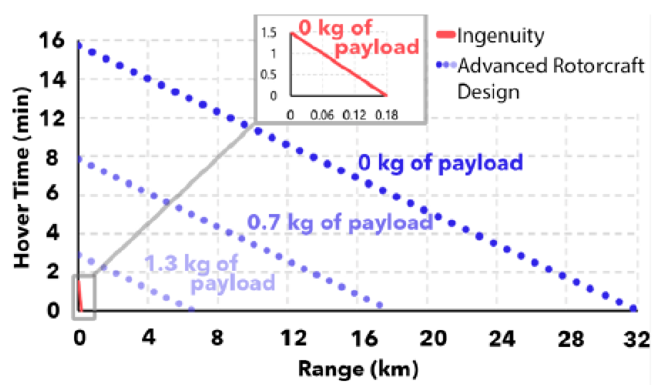


Figure 7. Mars Science Helicopter concept: 4.6 kg Advanced Mars Helicopter vs. Ingenuity performance (Ref. 32-33)

MARS SCIENCE GOALS AND POSSIBLE MISSION CONCEPTS

The 2013-2022 Planetary Science Decadal (Ref. 34) cites Mars as an important target for future research missions. Mars research can be categorized in terms of four broad scientific investigation goals for future missions: life, climate, geology, and human exploration (Ref. 35). Each mission described in this paper is applicable to at least one science goal. The following general missions are derived from input from both the Planetary Science Decadal survey and the 2018 Mars Exploration Program Analysis Group (MEPAG) goals Committee (Ref. 35). Below is a summary of the four goals as described in Ref. 34 and 35.

Search for Ancient or Existent Life

Discoveries of methane and dry water features suggest Mars may have once supported life in the distant past. The objective is to determine if life ever arose on Mars and, if so, to craft a narrative of its evolution with the surface climate. Discovery of biological life on Mars, past or present, could offer insight into parallel biological evolution and could help to predict future discoveries on other planets. If life is not discovered, then it will still provide valuable information about what is necessary to cultivate life beyond CHNOPS (carbon, hydrogen, nitrogen, oxygen, phosphorous, and sulfur) requirements.

Early and Recent Climate

Martian climate conveys an important narrative because the timeline of the planet's climate has important implications for the future of Earth. Martian climate has been divided into three time periods: ancient, recent past, and modern. Characterizing these three distinct periods is important in understanding how the planet's changing obliquity (the tilt of its polar axis) affects the pressure, temperatures, and survivability of water on the surface. This characterization also helps to understand the planet's dust, carbon dioxide, and water cycles. Understanding the characteristics of Martian atmosphere will also be critical to future mission design.

Geology

The evolution of the Martian landscape, such as its canyons and inactive volcanoes, is important because the global evolutionary process is still visible in its geological features. The surface of Mars is dotted with old lakebeds and preserved carbonates, suggesting the ancient version of Mars was less acidic and may have supported liquid water. Subsurface Mars, because of its separation from the harsh atmosphere above, could contain preserved or existing environmental biomes capable of supporting biological organisms. Creating a detailed image of the planet's internal structure, dynamics, and evolution is also important to creating an accurate profile of Martian geology.

Human Exploration

This goal aims to utilize the consolidated data from other narratives to achieve a human presence on Mars and within its orbit. To preserve the safety of human explorers on Mars, exploration is planned in four steps: prepare for exploration in Martian orbit, exploration on the surface of Mars, exploration on either Martian moon (Phobos or Deimos), and a sustained human presence on the surface of Mars.

The above goals will now be discussed in the context of rover-assisted and independent (rotorcraft-only) classes of Mars rotorcraft missions. The primary implications of these science goals on rotorcraft design is in defining payload mass, volume, power requirements, and overall installation details of the science instruments needed to meet the science goals. These science instrument payloads tend to drive the Mars rotorcraft conceptual designs to larger vehicle sizes compared to the technology demonstrator.

ROVER-ASSISTED CLASS OF MISSIONS

The primary goal of a rover-assisted mission would be to assist a rover in its operation and to increase the rover's productivity. A number of tasks (carried out by one of more rotorcraft) will be provided below as examples of rover support.

Pathfinding Assistance (Scout) Task

For the pathfinding assistance (scout) task, the rotorcraft would act as a scout, surveying the area ahead of the rover with a high level of detail to inform pathfinding decisions. Aerial images would help determine regolith composition, surface texture, and obstacles with greater confidence than satellite images and a superior perspective to that of the rover's on-board cameras. With this aerial imaging, scientists and engineers would be able to make better informed decisions about path guidance and navigation and rover safety, but also where to gather the most promising samples. Because the Pathfinding Assistance task is directly supporting a rover's mission, it will be furthering whichever science goals the rover is pursuing. The rotorcraft scouts would have the option of charging on its own using an onboard solar panel or landing on, or near, the rover and charging from the rover's power source through wireless induction or other means. An example concept of operations (CONOPS) is shown in Figure 8.

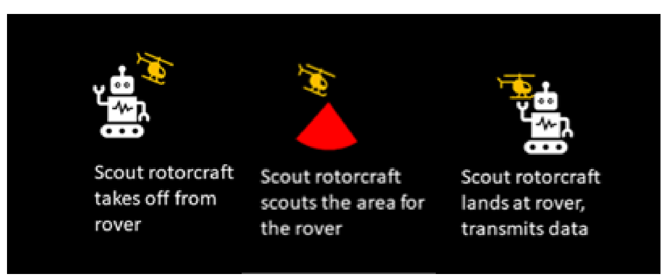


Figure 8. Pathfinding CONOPS

A major challenge of the Pathfinding Assistance task is the interaction between the rotorcraft and the rover. Since the rotorcraft will be operating within close proximity to the rover and potentially landing on, or next to, it, it is important that the rotorcraft has reliable, precision-controlled flight and sophisticated navigation and obstacle avoidance capabilities. Rotor protective guards, or other safety features, may be beneficial in reducing risk from collision, but may also affect the performance of the rotor.

Sample Transportation Assistance Task

In the sample transportation assistance task, a rotorcraft would aid in increasing the efficiency of a sample collecting rover by transporting its collected samples to a lander, cache, or other location. This would eliminate unnecessary distance and time spent traveling by the rover and would allow samples to be chosen more selectively and from a greater area. This task combines the transportation speed of rotorcraft with the benefits of robust sampling capabilities too heavy for flight.

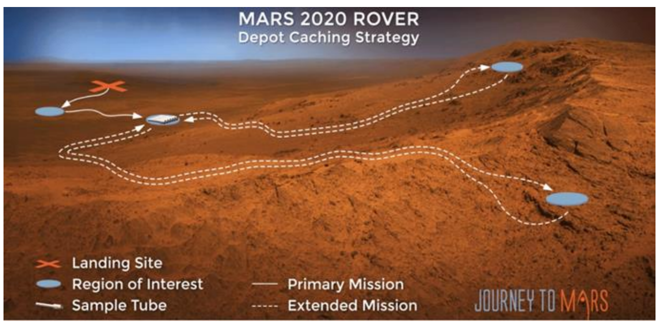


Figure 9. Perseverance rover path. (Ref. 36)

The Mars Perseverance rover's planned travel path is shown above in Figure 9. In order to cache the samples in one location for future retrieval, the rover must do a significant amount of backtracking. If the Perseverance mission included a rotorcraft capable of sample transportation, it would greatly reduce the rover's required travel distance for the current mission, allowing it to expand the mission to more regions of interest and collect more samples.

To illustrate the enhanced capability, performance data from the MSH hexacopter (Ref. 32-33) was plotted next to Curiosity's performance data in the form of distance traveled (Figure 10). Figure 10 shows the distance Curiosity covered in about 5 years could be covered by a rotorcraft in just three Martian days (sols). In the context of this task, it shows that rotorcraft are capable of transporting samples much faster than rovers, but it also holds implications for the amount of data that can be gathered by adding a rotorcraft "assistant" to a mission.

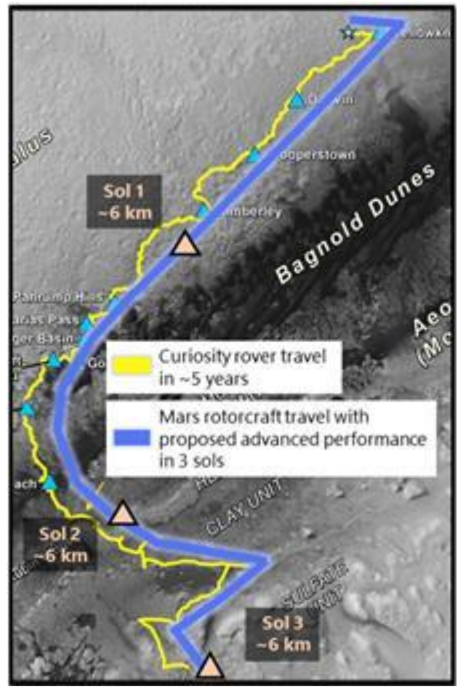


Figure 10. Comparison of travel times between Curiosity and a rotorcraft

The objectives of the mission are to enable sample collection over a large area and decrease the workload of the rover. The sample transportation rotorcraft would take off from the science base lander and autonomously fly to the rover, pick up the samples, and return to the lander or where the cache is stored. The rotorcraft charges after the samples are transferred to the lander. Depending on the range of the mission, the transport rotorcraft may be required to need multiple flights to deliver the samples, recharging between flights. Figure 11 shows an example CONOPS.

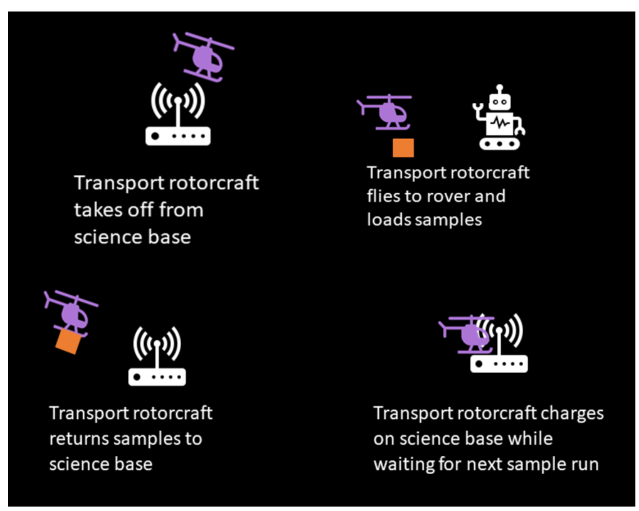


Figure 11. Sample transportation CONOPS

A challenge that arises with this task is determining the communication system between the rover, rotorcraft, and lander. If possible, it would be beneficial to keep only short-range communication equipment on the rotorcraft, leaving more payload room for samples. This means the rotorcraft must be in range of the rover or lander to receive new flight paths, potentially creating complications as the distance between the rover and lander increases and the rotorcraft may need to break the trip into segments to charge. It could be equipped with the ability to communicate with Earth, but that will reduce available payload allowance for samples.

Maintenance and Diagnostics Task

For the maintenance and diagnostics task, a rotorcraft may be able to perform tasks that help preserve the longevity of a rover or lander. For example, during dust storms, a solar powered rover's solar panels can get covered in dust, reducing charging capability. A rotorcraft could fly above the panels, using its wake to clear the fine dust. A rotorcraft could also be used as a diagnostic tool to inspect systems of a rover or lander. This would be particularly important if it is communications or imaging systems that were damaged on the ground-based equipment.

Challenges associated with this task are similar to the pathfinding task, as the rotorcraft would need to work in close proximity to the terrestrial systems.

INDEPENDENT (ROTORCRAFT-ONLY) MISSIONS

Independent (rotorcraft-only) missions may include lander and rotorcraft operations, or true rotorcraft-only missions. Entry, descent, and landing (EDL) of a rotorcraft without a lander will be discussed later in the paper. Solid sample collection, atmospheric sample collection, and data collection missions will be described in this section.

Solid Sample Collection

Since the cornerstone of the Mars 2020 mission is the ability to prepare and collect samples, solid sample collection is evidenced as a method of interest to investigate Mars. Unlike the Rover Assistance mission, where rotorcraft aid in the sample collection done by the rover, this mission focuses on eliminating constraints associated with the rover by using vertical flight to expand the regions available for consideration. Sample collection could be performed on several materials of interest, such as rock, ice, or regolith, with slight modifications.

The science goals achieved by the Solid Sample Collection mission are similar to the Mars 2020 missions of seeking past microbial life, looking for evidence of ancient habitable environments where microbial life could have existed, studying the rock record to reveal more about the geologic processes, and monitoring environmental conditions so mission planners understand better how to protect future human explorers (Ref. 37). The difference, however, is that the proposed mission can efficiently cover previously unreachable territory. This mission is tied to the life goal since it can focus on areas with a high probability of harboring life. The geology goal is also relevant if the vehicle is collecting rock samples. Canyons provide interesting subjects for rotorcraft sample collection since the walls expose multiple rock layers, potentially representing multiple geological areas in a single location. Rotorcraft, unlike rovers, would be capable of accessing these locations. Caves, valleys, and highlands are also regions of interest for sample collection difficult to reach with terrestrial vehicles, as discussed in the section: "Potential Sites for Outlined Mission Concepts".

The Solid Sample Collection mission shall utilize rotorcraft to aid in solid sample collection in previously inaccessible locations. The objectives of the mission are to enable sample collection in canyons, riverbeds, and poles, and to decrease sample return time compared to a land-based vehicle. The canyons, riverbeds, and poles have not been accessed by land-based vehicles yet due to risk factors such as large rocks, steep slopes, cold temperatures, and/or long traversal time.

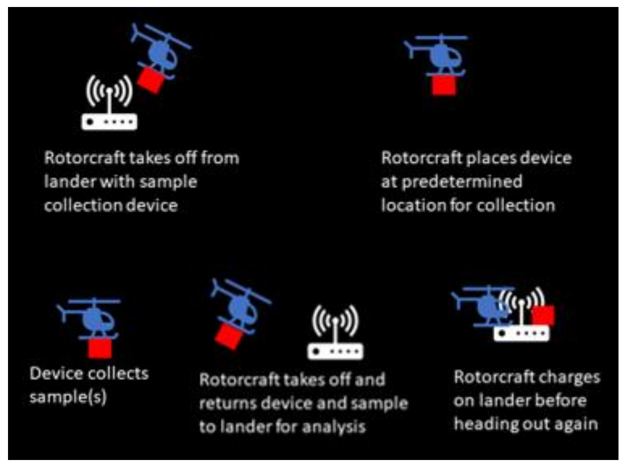


Figure 12. Sample collection CONOPS

A Solid Sample Collection mission would involve two vehicles: a lander and a rotorcraft. An example operation for this mission is shown in Figure 12. The mission would start with the rotorcraft taking off from the lander and autonomously flying to a predetermined location. It would land and begin to collect a sample. If the rotorcraft is in a sunny location, it will charge with solar panels while the sample is collected. If not, the rotorcraft will relocate to the nearest sunny location to charge. The charged rotorcraft with the sample would take off to return to the lander. The lander will have the science equipment necessary to analyze the samples and/or store them for later retrieval. The rotorcraft would land on or near the lander and the lander would collect the sample from the rotorcraft. The lander would then reload the rotorcraft sample collection device, so it can obtain another sample. The rotorcraft will charge and communicate with Earth via the lander to download its next flight path.

One of the challenges with the Solid Sample Collection mission on Mars is choosing the sample collection instrument. Currently, Mars rock samples are collected by an instrument such as the percussive drill mounted on the robotic arm of the Mars 2020 rover. The ROPEC drill, designed by Honeybee Robotics, was built to be mounted on a rover robotic arm similar in size to MER's robotic arm before the decision was made for the Mars 2020 rover, Perseverance, to be the size of Curiosity (Ref. 38). The resulting design produced a lightweight drill weighing only four kilograms. The percussive action of the drill is used to collect rock core samples from a wide variety of rock types. The drill is also capable of changing bits for situations requiring a different collection method. After collecting the sample, the drill stores the sample in a hermetically sealed container for future analysis. Previous rovers used drills to collect regolith for scientific observation but were not able to keep the samples. Honeybee Robotics has also designed a vacuum, the PlanetVac, for collecting regolith that is intended to be attached to the legs of a lander (Ref. 39).

Honeybee Robotics has explored a number of drill concepts for Mars besides the one used for the Mars 2020 mission. One drill, the Nano Drill (Ref. 40), was designed for use on the proposed Axel robot concept (Ref. 41), for steep slope exploration. The Axel robot concept has yet to be used for extraterrestrial exploration, but the proposed mission design requirements led to the development of a 1 kg percussive coring drill less than 6 inches long (Ref. 40). The existence of a more lightweight drill than the ROPEC makes the use of a percussive drill carried by a rotorcraft more plausible.

A drill designed specifically for Mars rotorcraft use will face its own unique design challenges. Weight is an even more important factor than on rovers, and power requirements, torque reaction, and vibratory loads need to be considered. The rotorcraft may be able to actively mitigate some of these issues. For example, if landed and drilling on flat ground, the rotorcraft could adjust the rotor pitch to provide reverse thrust, pushing the rotorcraft against the ground and increasing the force the drill is able to impart on the ground without tipping the rotorcraft. The ability to collect samples in hover, with a drill able to extend laterally out past the rotors would allow for samples to be collected from typically inaccessible areas such as steep canyon walls where landing is not possible.

Atmospheric Sample Collection

Our current knowledge of the Martian Atmosphere is primarily from orbital measurements and limited EDL measurements (Ref. 42) and while the scientific community has gained ample knowledge from these measurements, there are inherent limitations associated. An in situ study would provide a higher resolution profile of the atmosphere in specific locations and assist in quantifying the carbon dioxide, water, and dust cycles.

As mentioned in the decadal survey's discovery missions (Ref. 34), an atmospheric sample collection and return mission would be important in characterizing the Martian atmosphere. Understanding the present climate of Mars is a necessary first step in determining recent past and ancient Martian climates. Current satellite data is not sufficient to describe the processes controlling the present distributions of dust, water, and carbon dioxide in the lower atmosphere, a highly ranked objective for climate study. Direct, in situ measurements would make this possible and would provide calibration and validation for orbiter data and weather models (Ref. 35). Characterizing the atmosphere would assist in the preparation for human exploration, especially in the areas of in-situ resource utilization and human EDL conditions.

Because of the satellites' orbits, measurements are limited, specifically over the poles, so there is insufficient atmospheric data gathered for the polar atmosphere. A rotorcraft would not have the same limitations and could take polar atmospheric measurements. Since they are constantly moving in their orbits, orbiters are generally limited in local time coverage and are do not measure diurnal variations in an area (Ref. 35). A rotorcraft has fewer limitations to the time it can spend in an area measuring day-to-day variations, specifically in the polar region. Any area in the lower Martian atmosphere could have a vertical atmospheric profile created of higher resolution than satellites can provide, taken over ranges and altitudes not attainable by rovers.

The Atmospheric Sample Collection mission shall provide in situ atmospheric sample collection to be later studied on Earth. The mission will provide a high resolution vertical profile of Mars in multiple locations and provide diurnal observations that satellites cannot provide.

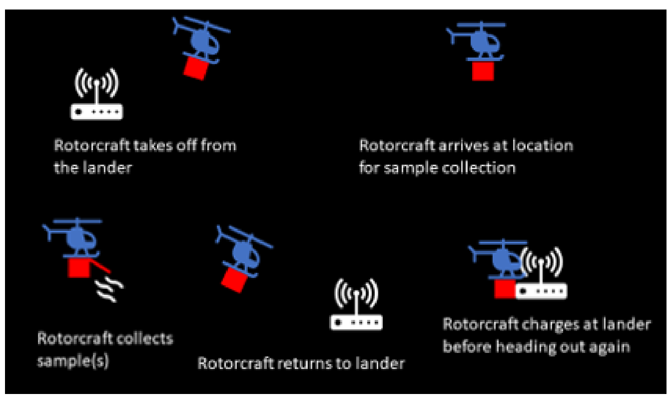


Figure 13. Atmospheric sample collection CONOPS

The Atmospheric Sample Collection system requires a lander and rotorcraft. An example CONOPS is shown in Figure 13. The rotorcraft takes off vertically from the surface of Mars and begins its flight to the area of interest. When in place, the atmospheric sample is collected. If multiple samples can be taken, the rotorcraft will move to the next sample collection location. Once the desired samples are collected, the rotorcraft returns to the lander. The lander receives the rotorcraft's collected sample(s) and restocks the rotorcraft with empty collection devices. The samples can now be either stored for an earth return mission or processed and analyzed by the lander. The rotorcraft charges and receives information for its next mission.

As with all systems on a Mars aircraft, the atmospheric sample collection device must be as light as possible. There are numerous methods to collect air samples, many involving fans or pumps to draw the atmospheric gases in, but these systems are typically heavy. In order to reduce weight in the design, a simple collection method should be used. A pre-evacuated canister with an actuated valve could be used as a whole air sampling component (WASC) (Ref. 43). However, due to the low pressure of Mars, pumps may still need to be used, pressurizing the canisters with Martian air to gather enough atmospheric matter to study. Each canister would be single use, so enough canisters to complete the goals of the mission would need to be sent to Mars with the rotorcraft. Because a rotorcraft will likely be significantly smaller than a rover, there should be no major volume constraint for carrying many sample canisters if a heritage aeroshell is used. The aircraft would also need to cache the samples for an Earth return mission, similar to the sample return mission for Mars 2020 (Ref. 44), unless on-site processing is possible. If weight allows, the rotorcraft could also carry instruments to measure temperature, pressure, winds, radiation, magnetic field strength, and other characteristics of the lower atmosphere. This allows the rotorcraft to provide information about the conditions when the sample was collected, as well as continue to make scientific measurements after the sample collection is completed.

Aerial Mapping

As stated previously, our knowledge of Mars has been informed by orbiting satellites and ground vehicles. The attainable resolution of satellites is limited and restricted to overhead angles. Ground vehicles are limited by the terrain they can travel on, the distance from a landing site, and ground based visual angles. Equipped with imaging equipment, radar, LIDAR, or other mapping sensor, rotorcraft have the ability to travel to places rovers cannot and gather in situ data and images at angles and resolutions rovers and satellites cannot achieve.

An aerial mapping mission would fulfill multiple science goals resulting in further understanding of the red planet. A rotorcraft is able to fly into canyons with walls too steep for rover traversal. Imaging of the layered deposits in the cliffs and walls of canyons will provide valuable insight into the history of Martian geology. This mission type could aid current or future sample collection missions, creating a detailed map of an area of interest and pinpointing the optimal sample collection locations.

For example, rotorcraft would provide a new vantage point for mapping the canyon walls of Valles Marineris. Valles Marineris and other sites for exploration by Mars rotorcraft will be discussed later in this paper.

The aerial mapping mission shall utilize air vehicles to provide high resolution in situ aerial surveys unobtainable by ground vehicles or satellites.

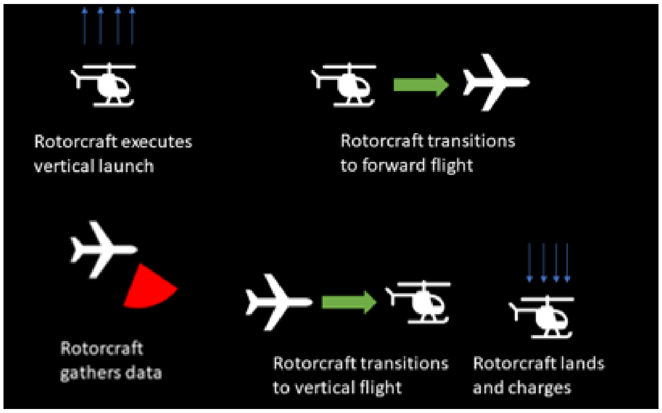


Figure 14. Aerial Mapping CONOPS

This mission will require one mapping rotorcraft that operates independently, not relying on a lander or rover. An example CONOPS is shown in Figure 14. Once transported to the surface in an aeroshell, the rotorcraft will be able to begin its operations. It must perform a vertical takeoff from the Martian surface. A preplanned flight pattern will be flown autonomously, and data will be collected for the duration of the flight and transmitted directly to an orbiting satellite. Once the battery level has reached its lower flight limit, the craft will use its navigation camera to find a landing zone and land autonomously. After landing, the rotorcraft charges via solar panels and receives data from Earth to determine its flight path. Since the rotorcraft will be self-sufficient, it will not be limited in range by any ground-based technology, and its mission will continue across the surface for as far and as long as the craft is capable of traveling.

A problem that arises with a completely independent data collection rotorcraft is the weight of the communication systems required. It will most likely communicate with the orbiters using ultra high frequency (UHF) radio and not have direct-to-earth communication capabilities. Curiosity's UHF radio weighs 3 kg (Ref. 45), and while a UHF system designed for rotorcraft will most likely be lighter, it will be a more significant payload than smaller communications devices needed to communicate with a lander or rover. A system with high data rates would be beneficial, as there will be significant amounts of data transmitted to the orbiters, with limited windows of time for transmission. At or above Curiosity's UHF transmission rate of 2 megabits per second would be a reasonable starting point.

POTENTIAL SITES FOR OUTLINED MISSION CONCEPTS

Site selection for Mars exploration is a multi-step process with two main considerations: scientific objectives and engineering constraints. Every time a new mission is proposed, there are typically three to four site selection workshops and may be over one hundred people who contribute. At the workshops, small groups of scientists propose sites, and the entire selection committee ranks the sites based on scientific merit and if the engineering constraints can be met. The committee also categorizes the sites into "Land On" and "Go To" to describe if the science location is viable for the initial landing. Between meetings, satellite data of high priority sites is obtained. The goal of these workshops is to narrow down the site list to three to five sites for NASA Headquarters, who will ultimately choose the site where the vehicle will land (Ref. 46). The selection committee sends a letter with a short discussion of the differences between the sites and emphasizes the preferred selection (Ref. 47).

One of many sites of potential interest, Valles Marineris (shown in Figure 15) was considered for the Curiosity landing site and the Mars 2020 site. While choosing the Curiosity landing site, Valles Marineris was considered as a possible landing site multiple times. Ultimately, the selection committee was concerned about the rocky landing and the long traversal required to reach the desired wide variety of rocks (Ref. 46). A rotorcraft would not face the difficulty of driving over the harsh rocky terrain, negating some of these concerns. The last aspect that led to the elimination of Valles Marineris as a landing site was the possible risk of slope winds near the canyon wall, something to evaluate during rotorcraft design and testing. During the Mars 2020 site selection, advancements in navigational systems (entry, descent, and landing) and higher quality satellite data enabled multiple locations inside Valles Marineris to be reconsidered (Ref. 48). Rotorcraft on Mars would eliminate some engineering constraints so more diverse sites can be safely chosen for future missions.

Figure 15. Valles Marineris (Ref. 49)

Another area of interest, Arsia Mons, has generated interest for its skylights and possible underground environment access. The Tharsis Volcanic Region of Mars is home to three main shield volcanoes: Arsia Mons, Pavonis Mons, and Ascraeus Mons shown in Figure 16. While all are now extinct, previous volcanic activity created geologically interesting features in the landscape around the volcanoes. The THEMIS instrument onboard the Mars Odyssey satellite has spotted seven skylights on the slopes of Arsia Mons, possibly evidence of caves formed from lava flows in Mars's past. THEMIS can see caves facing skyward with a diameter of more than a hundred meters and a depth that is greater than one hundred meters (Ref. 50). These caves could contain traces of past or current biological life. More detailed data is needed, as current satellites images are not sufficient to determine if these caves may also be ideal in providing shelter for future manned missions.

Figure 16. Tharsis volcanic region (Ref. 51)

Over the course of three years, opinion on the scientific merit of cavern exploration changed dramatically. In 2007, Cushing et al. (Ref. 50) proposed the caves were not ideal for exploration. Caves could provide protection from the hazards of the Martian atmosphere, but they also pose sufficient risk since not much is known about the atmosphere and geology of the interior areas. Since skylights are the only visible part of the cave to THEMIS, it is difficult to determine if the skylight is a cave or just a shaft. If it is only a shaft, it is possible the sun would have burned away any life and biosignatures found on the shaft floor and walls (Ref. 50). The Tharsis region is at high elevation, so any explorative vehicles would be required to spend time ascending the volcanoes (if using conventional EDL systems), and it is contested if past Martian life could have migrated up to those elevations. Reference 52 describes a new EDL concept of mid-air deployment, designed specifically for high-elevation areas. The rotorcraft would release from the aeroshell in the final subsonic stages of EDL and use powered flight for the remainder of the descent. This method eliminates the need for a lander, and therefore the limitations associated with traditional EDL.

Contrary to the position of Cushing, et al., interest into the similarities between caves on Earth and Mars sparked new interest in Martian caves in 2010. In Reference 53, Léveillé and Datta proposed that studying lava tubes will help in understanding the history and evolution of volcanism and global heat flux. Because caves on Earth harbor many types of life, it is reasonable to assume Martian caves could harbor current or extinct life forms. Inside the caves, past biosignatures could have been protected for future discovery.

Williams et al. (Ref. 54) modeled the lifetime of ice in caves on the Martian surface, specifically investigating water ice growth instead of carbon dioxide ice for water extraction purposes. Areas where water ice is sustained would be areas of astrobiological importance and potential future water sources for human exploration missions. The results of the simulation showed conditions in a Tharsis region cave could support water ice formation, in fact, the region is one of the best locations for water ice growth on Mars (Ref. 54). The high probability of water ice increases the scientific merit of the site for research of the Martian past and preparation for a future human presence.

The poles of Mars are largely unexplored and hold important information for furthering research into the planet's past climate. The poles consist of four layers: a seasonal layer of frozen carbon dioxide forms and sublimates with the seasons, a residual cap made of water ice that remains constant year round, layered deposits holding trapped dust mixed with water ice, and a bottom comprised of dust and sand held together by water ice (Ref. 55). Layered deposits hold the recent history of Mars's climate and are affected by the obliquity of Mars, climatic procession, and eccentric variation (Ref. 56). These layers are exposed in troughs or scarps in the ice (Ref. 57). A candidate location for study is the Chasma Boreale, a location deep in the North Pole where it is possible for layered deposits to be exposed (Ref. 58). While there has been great interest in studying the polar region (Ref. 35), engineering constraints are numerous for rovers in polar regions, both in EDL and surface operation. Rotorcraft, however, can bypass the hazardous terrain and EDL limitations (if the method of Reference 52 is successful).

Landing site selection is an important component of the Mars mission design process. Previously, rover engineering constraints eliminated many scientifically intriguing sites discovered through satellite research. With the introduction of Martian rotorcraft, some of the engineering constraints limiting site selection are no longer relevant, enabling new methods of research in previously inaccessible regions.

POTENTIAL FUTURE VERTICAL LIFT AERIAL VEHICLE CONFIGURATIONS RESPONSIVE TO MISSIONS CONCEPTS

High-level concept designs of possible Martian rotorcraft were created, considering the challenges and limitations imposed when flying on Mars. These designs are conceptual in nature and are meant to explore possible rotor and control configurations that may be beneficial or required on Mars. The models have not been sized or optimized at this stage, besides the constraint of heritage aeroshell size limitations. The propellers are all currently dimensioned at 1.0 meter in diameter, similar to the Ingenuity's 1.2 meter diameter. In the cold temperatures of Mars, the electronics need to be contained and insulated. For these conceptual models, the electronics are modeled as an insulated box, similar to Ingenuity.

Most traditional small multirotor aircraft use fixed rotors and variable RPM for control because of the simplicity and cost effectiveness of the system. In the thin Martian atmosphere, a large RPM change is required to increase the thrust, making RPM controlled motion less responsive. Collective pitch used to control the thrust from each rotor can be an effective and viable form of control. However, collective control adds complexity and small moving parts and linkages to each rotor. If using collective pitch for control, all of the rotors will be spinning at the same RPM, allowing the possibility of using fewer motors and a drive system to spin the blades. The aircraft must be capable of fully autonomous operation. Any control signal from Earth would take too long to get to Mars to allow the vehicle to react to flight conditions or obstacles.

Basic Aircraft Configurations

Multirotors

When long range or speed is not a high priority for the mission, increasing lift generation to carry larger payloads is an area of high interest for Martian flight. On Earth, more lift can be produced by building a larger aircraft with larger rotors, but this is primarily done for internal combustion or turbine power systems. As with Earth, the size of the electric aircraft is limited by battery weight in its electric propulsion system. Additionally, Mars aircraft are limited by the dimensions of the aeroshell transporting them. Multirotor systems offer large amounts of lift in battery powered systems. Multirotor configurations of at least six rotors adds redundancy, providing protection for the mission since the craft can be designed to complete its mission even if one of the motors goes out or a rotor is damaged, an important consideration for a vehicle that cannot be serviced. The MSH hexacopter (Figure 17) is an example of this configuration.

Figure 17. MSH hexacopter (Ref. 32-33)

Tiltrotors

In order to extend the range and endurance of a rotorcraft on Earth, wings are often added to produce lift so the rotors are not required to provide all of the lift and thrust forces, improving the longevity of the batteries and allowing the aircraft to operate at greater speeds. Due to the low air density of Mars, wings are not as effective as they are on Earth. A given wing traveling the same speed on both Earth and Mars would produce far more lift on Earth. The challenges are similar to those encountered by the tailsitter configurations mentioned in the Past Mars Rotorcraft Studies section (Ref. 19-22), and the viability of a wing remains in question. However, because an independent electric aircraft already needs a large solar panel, it may prove beneficial to utilize that solar panel as a wing, making a tiltrotor aircraft with a solar panel wing a candidate for long range flight on Mars. Furthermore, if a robust control system based on the thrust vectoring of the rotors can be developed, it could allow for the simplicity of a fixed pitch rotor instead of the collective mechanism used by the standard multirotor. On a rotorcraft that cannot be serviced, simplicity and reliability are valuable attributes. In addition to the lift from the wing adding range, the large solar panel wing can theoretically charge the battery during flight and further increase the flight time. Figure 18 shows an example of a possible tiltrotor design.

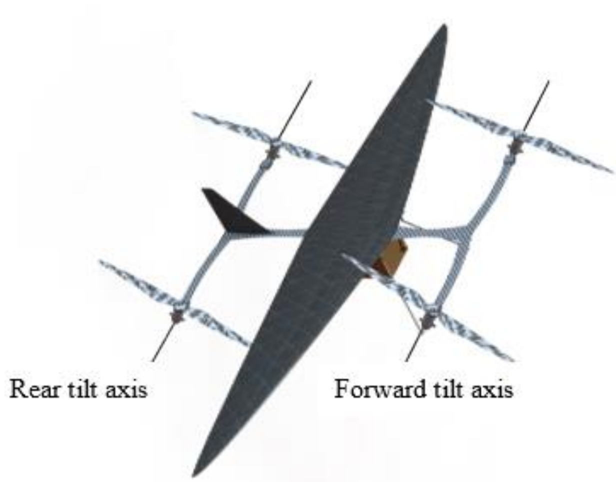


Figure 18. Tiltrotor concept

The vehicle would have to be sized for a specific mission to determine if the extra lift and power from the larger solar panel would justify the extra weight required to make the solar panel into a wing shape. Transition from hover to forward flight will be a significant challenge to address, as it is difficult even on Earth. It may be possible that a solution lies in a partially converted form, where the rotors are tilted at an angle between 0 and 90 degrees for the forward flight condition. The rotors would be responsible for thrust as well as some of the lift if the wing is not capable of providing the required lift. Such an unconventional system would require extensive analysis to determine the stability and control implications.

If use of a wing is proven not to be beneficial, a wingless tiltrotor may still be advantageous for long range, high speed flight. For example, a hexacopter could utilize all 6 rotors in hover, then tilt 2 of its rotors forward while maintaining enough lift with the remaining 4 rotors to enter forward flight. Instead of transitioning from a helicopter to an airplane, it would transition from a helicopter to a compound helicopter. An example of this configuration is shown in Figure 19.

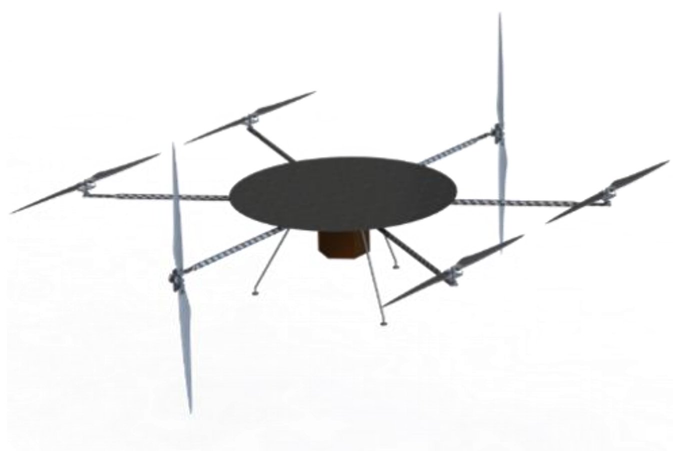


Figure 19. Compound tiltrotor

Influence of Stowage Considerations on Vehicle Conceptual Designs

Overlapping Blades

In the Martian atmosphere, ratio of rotor size to aircraft size is greater than on Earth because of the effect on lift from a thinner atmosphere. In order to conserve space, each rotor is placed at one of two alternating heights, allowing the rotors to overlap each other. Figure 20 shows an octocopter with overlapping blades at alternating heights. The rotors all spin at a constant RPM and have collective pitch to change their thrust output. The overlapping blades allow for more thrust in a more compact design, which is important for the transportation to Mars. It will be important to ensure the blades have sufficient stiffness and separation to avoid collisions when the blades deflect. The wake interactions for any overlapping designs must be thoroughly analyzed to determine if the flow interaction with the lower rotors is justified by the rotor radius increase, and how the control scheme is affected.

Figure 20. Octocopter with overlapping blades

Coaxial Rotors

The overlapping blade concept can be taken a step further, doubling the rotors by stacking them vertically on a similar frame. This is the approach taken by the coaxial configuration of Ingenuity, and it can be similarly applied to a multicopter or tiltrotor for additional redundancy and anti-torque benefits. This benefit must be balanced with the complexity of packaging for EDL and mass penalty. Figure 21 shows a quadcopter frame with coaxial rotors, resulting in an octocopter. This modification can be made to numerous configurations, even a tiltrotor, as seen in Figure 22.

Figure 21. Coaxial octocopter multirotor

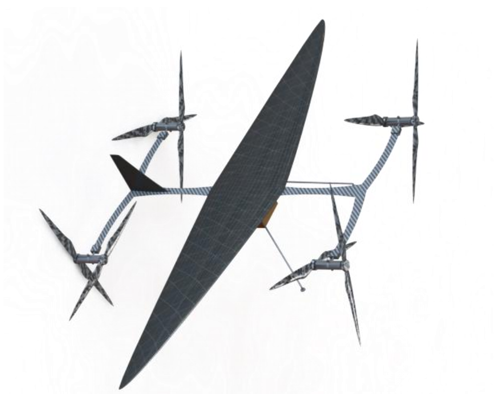


Figure 22. Coaxial tiltrotor

Folding/Extending Arms

In order to fit a large multirotor in to a smaller aeroshell, the arms and rotors can be folded into a dense, stored configuration, and expanded to flight configuration once on the surface. This could be linear (telescoping) extension, or hinged folding. An example of this is found in Figure 23, a proposed MSH hexacopter packing design.

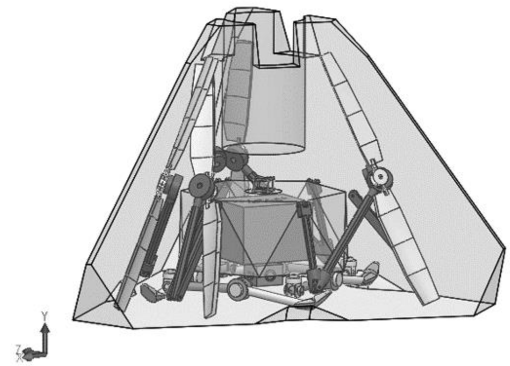


Figure 23. MSH hexacopter folding arms

Folding Solar Panels

In many designs, almost the entire area above the aircraft is under the rotor disk. In order to maintain a large enough solar panel area to charge without interfering with the thrust from the rotors or increasing the overall size of the rotorcraft, the solar panels can be designed to be foldable. When in flight, the panels are folded down and stored, then once landed the panels unfold for increased surface area to decrease charging time. Folded and unfolded states are shown in Figure 24. This would be a tradeoff of decreased charging time for extra weight in the folding mechanism, but may be beneficial in some applications.

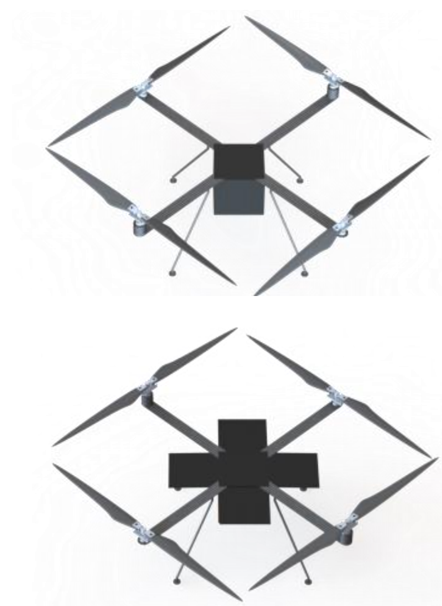


Figure 24. Folded and unfolded solar panels

FUTURE WORK

This paper is intended to be a snapshot of current interests in exploring Mars, describes potential future Mars missions for rotorcraft, and suggests possible rotorcraft concepts and configurations for use on Mars. For next generation Mars vehicles to transition from concept to mission-ready status, future teams should consider the following tasks. The scope will have to be narrowed around a specific mission. Parameters for missions will need to be input into NDARC (Ref. 59), or a similar rotorcraft design tool, to obtain sizing and design information for the rotorcraft. Conceptual configurations will need extensive further analysis to determine the effects of overlapped blades, tiltrotors in different flight configurations, solar panel interaction, etc. Control systems will need to be designed for uncommon control types such as collective control multirotors and especially for unorthodox control types like individually tilting rotors, a system that requires accounting for the changing torque of each rotor as it moves (Ref. 60). The conceptual configurations must be sized and turned into viable conceptual designs, analyzed, then developed into detailed designs. Individual systems will need to be engineered (tiltrotor mechanisms, solar panels, folding components, airframe, etc.), and sensors and instruments will need to be selected, and prototypes need to be built and tested. The culmination would be working with multiple NASA centers to design the total mission (from launch to flight mission completion on Mars), implementing it, and sending the rotorcraft to Mars.

CONCLUDING REMARKS

The Mars 2020 Ingenuity helicopter signals a shift in technology for extraterrestrial exploration. Some of the boundaries that faced previous Martian missions can be overcome by rotorcraft, opening up a new realm of discovery. Rotorcraft missions on Mars are an important component for expanding our knowledge of the past, present, and future of the planet's environment and may hold the key to unraveling mysteries involving Earth's transformations. Suggested missions focus on the categories of rover assistance, sample collection, and data recording to utilize this technology. These missions were designed with the MEPAG goals of life, climate, geology, and human exploration in mind. Each mission aims to further the research being done in at least one of these four areas.

Martian flight presents challenges far beyond those encountered on Earth. Vastly reduced lift, lower tip speed limits, extreme temperatures, and gravitational changes require new, innovative solutions. Even with the Ingenuity's success, achieving sustained flight in Mars's atmosphere continues to be a challenging endeavor. However, the scientific benefits make the technical challenges worth investigation and overcoming them can lead to a better understanding of our universe.

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ACKNOWLEDGMENTS

The authors would like to thank the Alaska, Missouri, and Wisconsin Space Grant Consortiums for their support of this project. Special thanks goes to Larry Young for his insight and encouragement of outside-the-box thinking, and Bill Warmbrodt for making everything possible. The authors would also like to thank Natalia Perez Perez and Witold Koning for generating Figure 10.

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