The Future of Rotorcraft and other Aerial Vehicles for Mars Exploration

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ABSTRACT

The Ingenuity Mars Helicopter is a technology demonstrator. The hope is that Ingenuity will one day lead to future generations of ever-more capable rotorcraft and other aerial vehicles for Mars exploration and other planetary science missions. This paper builds upon nearly twenty-four years of Mars rotorcraft and planetary aerial vehicle work at NASA Ames Research Center. It is posited that a spectrum of different Mars aerial vehicle mission concepts and capabilities could be developed over the next couple of decades – all of which are now potentially enabled by Ingenuity. A series of technology challenges or problems are also detailed in this paper. These problems are presented as an aid in helping establish a nascent planetary rotorcraft or planetary aerial vehicle research community as well as, maybe, helping realize some of the vehicle/mission concepts discussed in the paper.

INTRODUCTION[1]

The Ingenuity Mars Helicopter was launched along with the Perseverance Mars rover on July 30, 2020. It landed at Jezero crater on February 18, 2021. The launch of Ingenuity was the culmination of a five year development effort led by the NASA Jet Propulsion Laboratory (JPL), NASA Ames Research Center, NASA Langley Research Center, and the

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industry partner AeroVironment. Ingenuity potentially leads the way to new generations of vertical lift planetary aerial vehicles. NASA Ames Research Center has long been a pioneer of Mars rotorcraft and planetary aerial vehicles, e.g. Refs. 3-7. This paper especially builds upon work in Ref. 10 to consider what an overall vision of aerial exploration of Mars might look like.

The main thrust of this paper is not to present 'solutions,' or advocate for preferred designs/missions, but rather to pose technology questions (or, rather, problems or challenges) for future researchers to consider for the development of future generations of Mars rotorcraft and other planetary aerial vehicles. The Ingenuity Mars Helicopter is not instrumented for science and so the future potential of such a vehicle that is specifically instrumented for science investigations – a brand new exploration element – calls for new thinking. Figure 1 presents a high-level roadmap of possible future missions that could be supported by Mars rotorcraft. The general discussion of the paper will be organized around this general roadmap.

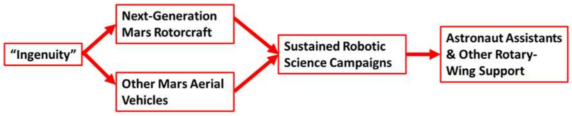


Figure 1. High-Level Missions Roadmap

KEY SCIENTIFIC QUESTIONS POTENTIALLY ADDRESSABLE WITH THE AID OF AERIAL VEHICLES

Most of NASA's Mars exploration and planetary science goals are defined from consensus input from the scientific community. This includes periodic input from the Mars Exploration Program Advisory Group (MEPAG), e.g. Ref. 22, and other science working groups, e.g. Ref. 23, and Decadal Surveys focused on planetary science (there are also other Decadal Surveys focused on other communities supported by programs of the NASA Science Mission Directorate (SMD)) that are sponsored by NASA and are organized by the National Science Foundation (NSF), e.g. Ref. 24. Finally, human exploration goals – including those for the eventual human exploration of Mars -- are defined and updated by Reference Missions initiated by the NASA Human Exploration and Operations Mission Directorate, e.g. Ref. 25. Ultimately, all future Mars rotorcraft missions will have to both respond to the evolving science and exploration goals defined in these planning documents as well as be competitively selected against competing non-rotorcraft and sometimes non-Mars missions.

Here on Earth, helicopters are not generally used for field research other than transporting scientists and equipment to and from sites that are otherwise difficult to access; terrestrial researchers can then gain access by foot to their intended sites to make observations, measurements and collect samples. On Mars, all sites are difficult to access and some are exceptionally challenging. For example, the walls of the Valles Marineris (up to 7 km deep) provide a multi-billion-year stratigraphic record that would be challenging to access. A rotorcraft with imaging and spectral instrumentation would provide a unique means of reading this record up close. A rotorcraft with specialized instrumentation might even be able to acquire samples from these immense cliffs. It is noteworthy, though, that there are less challenging sites where a standalone rover can access the vertical record of climate history – for example, the Curiosity rover is currently recording the stratigraphy of Gale Crater as it slowly climbs Mount Sharp.

More generally, as future Mars rovers like Perseverance carry out their missions, the support of an instrumented rotorcraft could safely extend their reach into sites that challenge a rover's mobility. At each site or station that the rover reaches, a supporting high resolution imaging and spectroscopic survey could be carried out to a radius of hundreds of meters by a rotorcraft – thereby magnifying and speeding up the science return. Potentially, samples could also be acquired from normally inaccessible sites.

POTENTIAL NEXT GENERATION MARS ROTORCRAFT

NASA JPL and NASA Ames have been jointly investigating potential second-generation Mars rotorcraft since 2019, before even the completion of the Ingenuity development. This includes the Advanced Mars Helicopter (AMH), Ref. 11, which is an improved performance Ingenuity-sized vehicle. Larger sized vehicles, on the order of 20-40 kilograms with 4-5 kilograms of science instrument payload, called the Mars Science Helicopter (MSH), Ref. 12, are also being examined; Fig. 2. Finally, yet another class of rotorcraft, one especially designed for mid-air-deployment from an entry and descent aeroshell back shell (Fig. 3) so as to explore the Martian highlands of the southern hemisphere of Mars, called the Mars Highland Helicopter (MHH), Ref. 13 and 21, is also being examined. These potential second-generation rotorcraft continue to be either coaxial helicopter configurations, like Ingenuity, or multirotor vehicles such as hexacopter configurations. Mid air deployment potentially allows a Mars rotorcraft to successfully reach the higher elevations of the highlands of the southern hemisphere.

The relatively low bending stiffnesses typical of larger diameter Mars rotorcraft blades means that they may be susceptable to large out-of-plane deflections due to flap bending moments. Aerodynamic damping resisting these out-of-plane deflections is nearly negligible for Mars rotorcraft blades because of the thin atmosphere. Until novel mechanical damping devices are developed for Mars rotor flap damping, multirotor configurations show more immediate promise from a flight dynamics perspective over simply “scaling up” Ingenuity’s coaxial design because of improved stability for missions that require larger payloads. Alternatively, the coaxial configuration shows promise for working in tandem with a larger vehicle, such as a rover, because of its small stowage footprint. Like any other spacecraft, packaging/stowing in aeroshells is a significant consideration for vehicle design. Assuming heritage entry, descent, and landing (EDL) systems, the aeroshell/lander constrains the rotor size and, ultimately, the vehicle performance for current designs.

In addition to carrying larger payloads, the range, hover time, and cruise speed can be significantly increased from the current state-of-the-art (i.e. Ingenuity) by optimizing rotor design and adding more robust and capable power systems. Increased speed and range means that many science sites can be considered for investigations that were not previously feasible. The potential for modular payloads, that could be swapped out at lander-based automated stations also means that multiple different types of science could be performed under one mission.

There are many remaining challenges to future Mars rotorcraft missions. To define such future missions requires discussions that include whether the rotorcraft should travel independently and carry all science instrumentation needed for the duration of the mission or to work collaboratively with a rover or lander to mitigate the burden of communications systems, collect and analyze samples, and carry secondary experiments. Additionally, one of the primary open questions for the science community is that of site selection and which areas are of adequate diverseness and uniqueness scientifically to benefit the most from the flexibility of a rotorcraft vehicle.

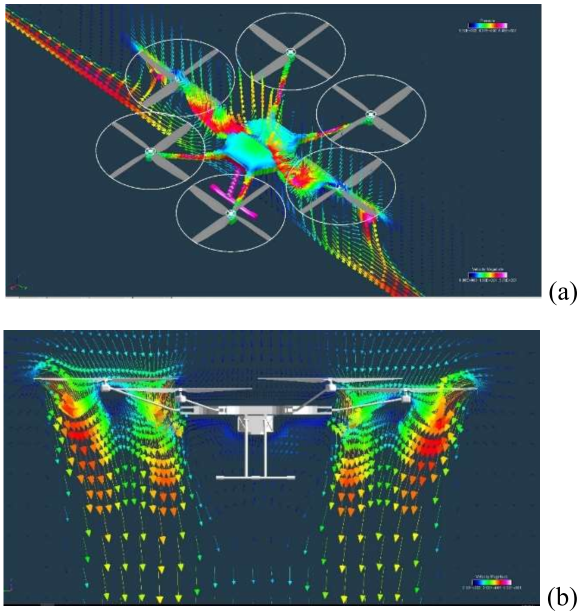


Figure 2. Mars Science Helicopter: (a) hover-in-ground-effect (HIGE) and hover-out-of-ground-effect (HOGE) CFD predictions

In addition to enabling vertical takeoff and landing, hover, and low-speed forward-flight, rotary-wings can also enable near-vertical descent and deceleration. This capability, as applied to planetary science missions, was recognized early in the work of Ref. 38. (Rotary-wing decelerators from reentry capsules and space planes have been studied even as far-back as the 1970’s by NASA – including work at NASA Ames – and other researchers from around the world.) Full or partial of rotary-wing deceleration post-release from entry aeroshells is, in fact, being employed by the Johns Hopkins University Applied Physics Laboratory (JHU APL), The Pennsylvania State University (PSU), et al team for the Titan Dragonfly mission, Ref. 37. Rotary-wing deceleration has also been recently studied by NASA for future Mars rotorcraft missions, Refs. 13-21. Undoubtedly more work will follow in this area in the future. Figure 3, based on the work in Ref.13, illustrates one mission/vehicle concept employing rotary-wing deceleration during entry (aka mid-air-deployment) called the Mars Highland Helicopter (MHH).

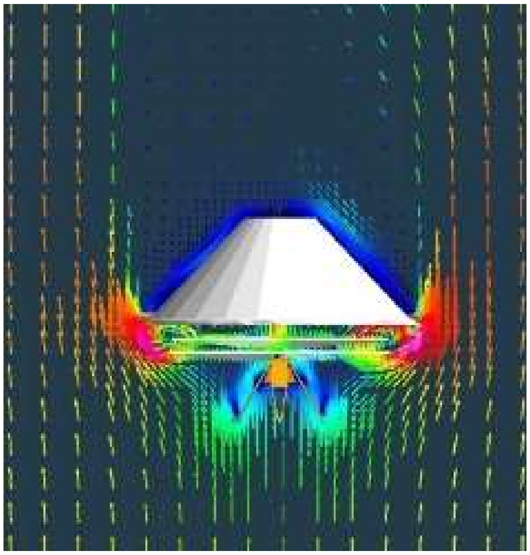


Figure 3. Mars Highland Helicopter about to be released from entry and descent aeroshell back shell in a mid-air-deployment (Ref. 13); CFD predictions at a descent velocity of 30 m/s

BEYOND-NEXT-GENERATION MARS ROTORCRAFT AND OTHER PLANETARY AERIAL VEHICLES

Two of the earliest Mars rotorcraft concepts explored (Ref. 3) were, first, a coaxial helicopter and, second, a Mars tiltrotor configuration. The coaxial helicopter was studied the most because of its overall compactness in both stowed and deployed states. As acknowledged in that initial work, tiltrotors, tailsitters, and other 'convertible' vertical lift aerial vehicles suffered from requiring large fixed-wing planform areas. At the time it was hard to rationalize the self-deployment of these types of vehicles on purely robotic missions. Over the years, tiltrotors, tailsitters, and tiltwing aerial concepts have persisted in the literature, including work at Ames; e.g. Refs. 17-19.

Bigger, Longer Range, Greater Endurance Vehicles

Though a Mars tiltrotor configuration would be more challenging to stow and deploy than a coaxial helicopter, its theoretical longer range and greater flight endurance is still appealing from a future Mars exploration perspective.

Figure 4 illustrates CFD results of the original Mars tiltrotor configuration introduced in Ref. 3. This figure presents the isosurface of velocity magnitude for the rotor wakes from the partially-tilted (thirty-degree nose-down) rotors at a forward-flight speed of 60 m/s.

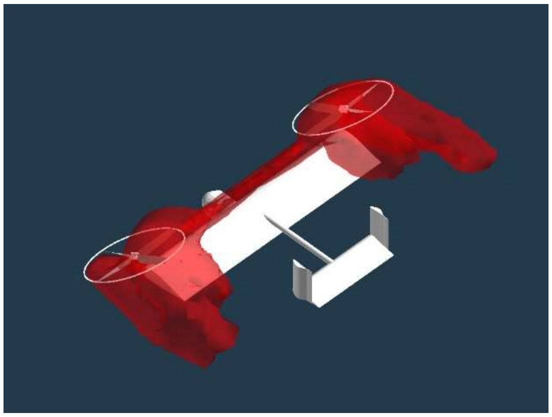


Figure 4. Mars Tiltrotor (Ref. 3)

Over the past several years, NASA Ames has examined other longer range and higher speed vehicles such as Mars tailsitters, of various forms, e.g. Ref. 17 and Figs. 5-7. In addition to issues regarding stowing and deploying such vehicles, there are also challenges in providing for acceptable conversion corridors whereby the vehicle transitions from having its lift predominately provided by rotors to that of lift being provided by its fixed-wings. This problem is compounded by the fact that compressible, low-Reynolds number effects tend to reduce the maximum lift achievable by rotary- and fixed-wing airfoils. Further, devices such as flaps, slats, and multi-element airfoils used for terrestrial fixed-wing aircraft – including tiltrotors and tailsitters – do not work as effectively under low-Reynolds number conditions. Finally, because of the necessity to employ ultra-lightweight structures for rotors, propellers, proprotors, and fixed-wings for Mars aerial vehicles, such structures will also tend to suffer from low bending-moment/torsional stiffness. This, in turn, might limit the maximum forward speed of highly-twisted rotors in helicopter-mode operation and, additionally, might present aeroelastic dynamic stability issues (such as whirl-flutter-stability) in high-speed airplane-mode cruise flight. All of these aerodynamic and structural dynamic issues can potentially manifest themselves in terrestrial aircraft but are anticipated to be even more troublesome for Mars tiltrotor, tiltwing, or tailsitter designs. Still, it must be emphasized that these challenges should not ideally deter future work on high-speed Mars rotorcraft; such vehicles could be, if realized, a powerful tool for Mars exploration. As the time of larger EDL systems – and the human exploration of Mars – approaches, the self-assembly/self-deployment challenges of such vehicles becomes less critical, as well. For example, it is not unreasonable to assume that astronauts or external industrial-type robotic systems could assist in the assembly of these large high-speed rotorcraft.

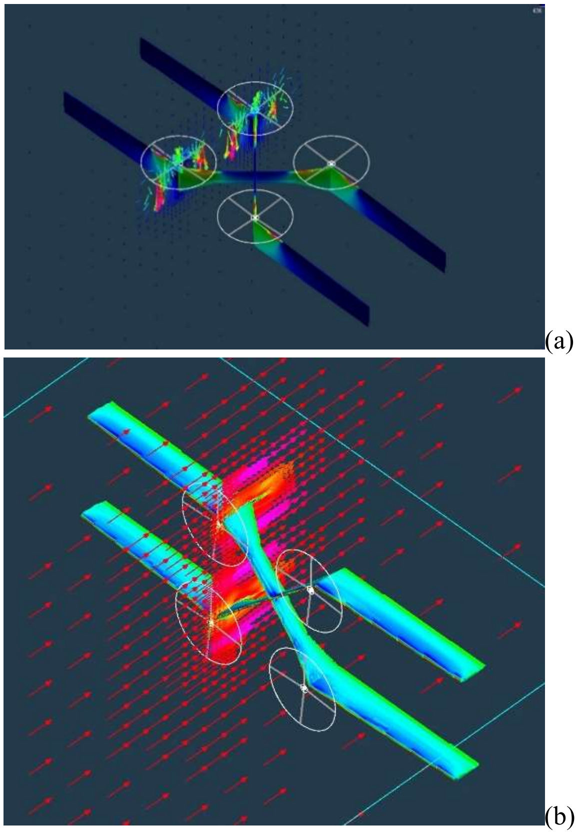


Figure 5. X-wing Mars Tailsitter: (a) hover and (b) forward-flight

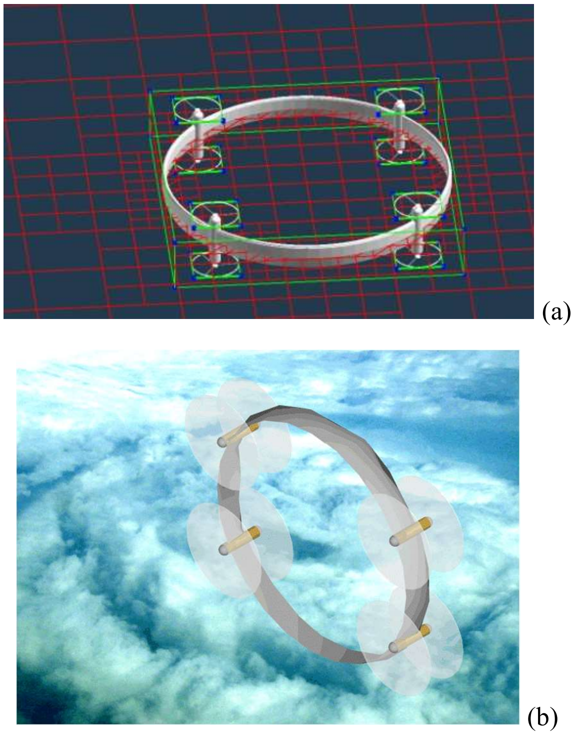


Figure 6. Ring-wing Tailsitter: (a) hover and (b) forward-flight

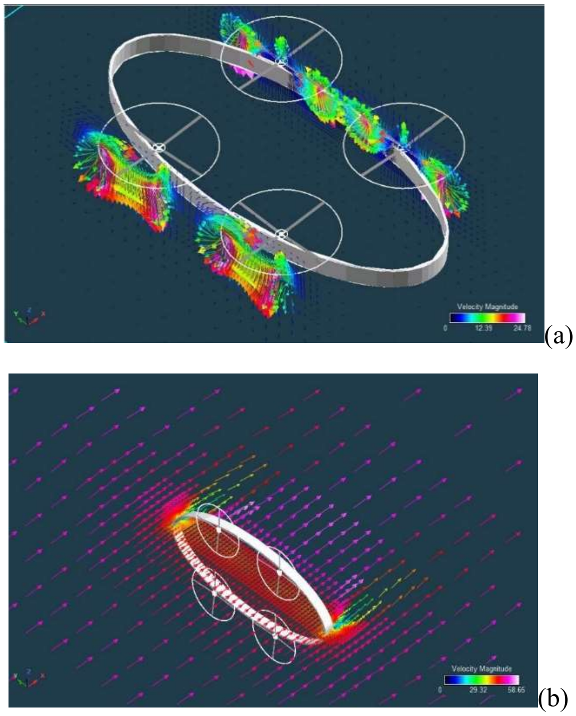


Figure 7. Elliptical-wing Tailsitter: (a) hover and (b) forward-flight

Alternate approaches to provide higher-speed rotorcraft from Mars exploration include the potential development of "lift+cruise" multirotor configurations (e.g. Ref. 32). The maximum speed for lift+cruise configurations (where two separate sets of rotors/propellers are provided with one set dedicated to providing lift throughout the flight and the second set dedicated to forward propulsion) is dominated by the maximum allowable advance ratio of the "lifting" rotors. Most terrestrial rotorcraft are approximately limited to advance ratios of ~0.4; it is currently unexplored as to the maximum advance ratio of a rotor designed for Mars operation in edgewise rotor forward-flight. Such rotors have to be ultra-lightweight and will likely suffer from low flap-bending stiffness and, consequently, may be limited to advance ratios below that of terrestrial vehicles.

Hybrid Mobility (Surface and Aerial) Vehicles

Future Mars vertical lift aerial vehicles might also incorporate hybrid mobility capabilities – i.e. where ground mobility is merged with flight capability. One example of that hybrid mobility is found in Ref. 19 and shown in Fig. 8; in this particular case, rotary-wing lift/propulsion is combined with "pogo" like motion. Hybrid mobility would seek to take advantage of the lower power and potential precision positioning of ground mobility while still retaining the speed, range, and ability to fly over uncertain terrain afforded by flight.

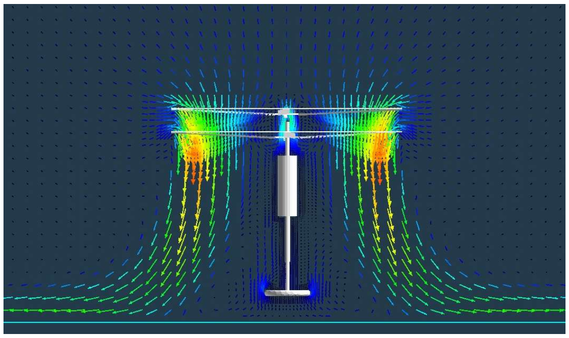


Figure 8. Pogo Rotary-wing Locomotion

Concepts where aerial vehicles also have some level of ground mobility must be trade-studied against: (a) aerial vehicles that carry small ground robots as payload/cargo and deploy them upon need or (b) working in co-equal concert/partnership with larger ground robots. Another Mars rotorcraft hybrid mobility concept is from Ref. 8 and shown in Fig. 9. This concept switches between level flight – in- and out-of-ground-effect – with short hops provided through a combination of impulsive periodic rotary-wing collective/thrust changes as well as, again, pogo-like spring/mass/damper legs.

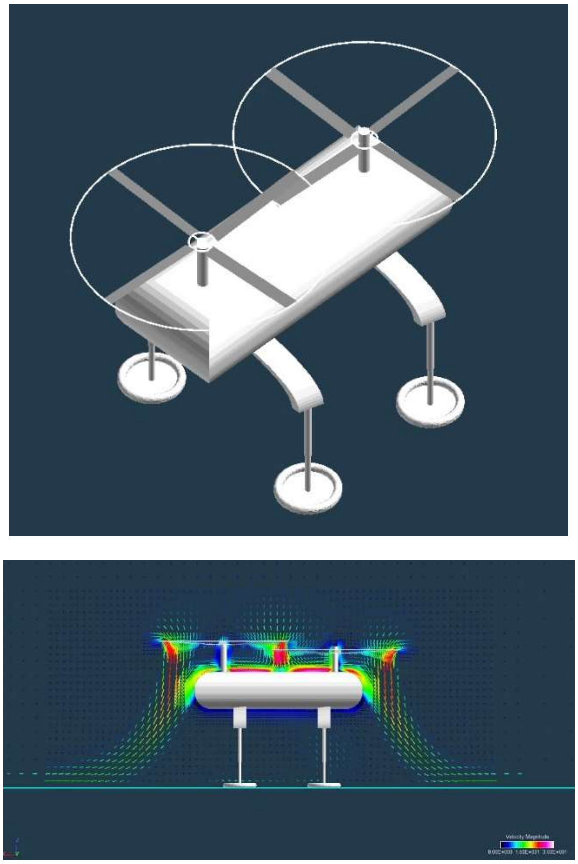


Figure 9. Skim, Skip, Jump, and Fly (Ref. 8)

Another hybrid-mobility enabled mission concept is the proposed LILI (Long-term Ice-field Levitating Investigator) mission. This vehicle and associated mission concept are being independently studied at NASA Ames. The vehicle is shown with skis/wedges to reflect exploration of the Martian polar regions but could, alternatively, work with free-wheeling wheels or a combination of wheels and skis. Through a combination of tilting tandem rotors providing for tandem helicopter flight as well as forward propulsion while on the ground, the vehicle could optimize overall mission energy expenditures by switching between flight and ground modes of operation.

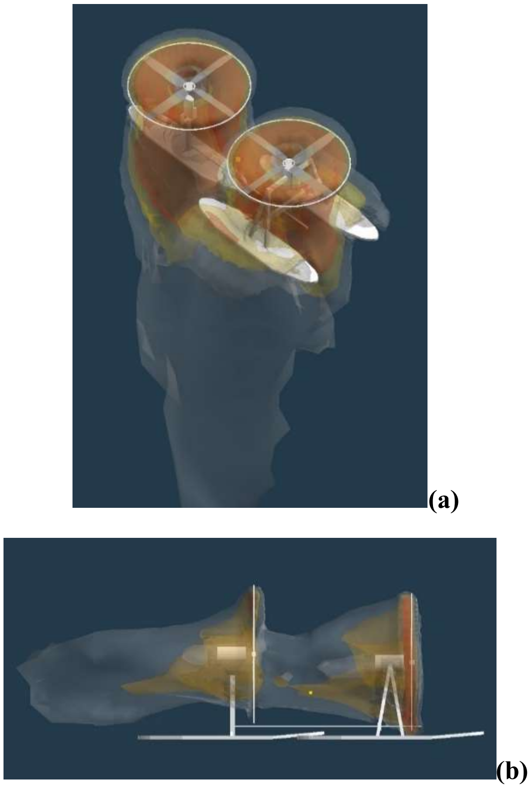
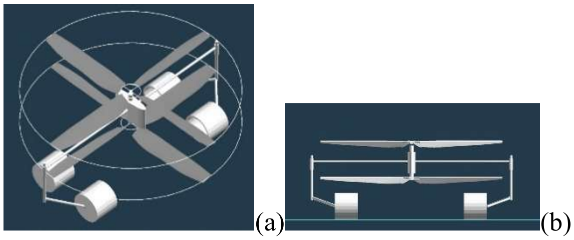


Figure 10. "LILI" Concept: hover/flight mode and (b) surface mode (with skis versus possible wheels)

Alternatively, it may be effective to simply add small electric-motor direct-drive wheels to Mars rotorcraft landing legs, e.g. Fig. 11. Weight is always a major concern when considering a hybrid-mobility vehicle. Accordingly, such a wheeled Mars rotorcraft would not be designed for long-range surface transit but only for precision ground movement for the final couple of meters after landing.



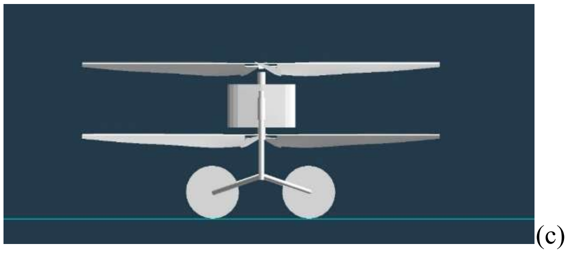


Figure 11. Rotors on Wheels: (a) isometric view, (b) front view, and (c) side view

There are four potential advantages of hybrid ground-air-mobility systems over purely aerial platforms: first, the overall mission energy efficiency can potentially be increased; second, precision movement/positioning on the surface can potentially be increased; third, exploration of inaccessible-by-air terrain features can potentially be realized and, fourth, ground-mobility is a mode of graceful degradation if aerial mobility becomes unsustainable at some point during the overall mission.

EXPANSIVE, SUSTAINED ROBOTIC SCIENCE CAMPAIGNS WITH NETWORKS OF MULTIPLE VEHICLES AND SURFACE ASSETS

Robotic Science Campaigns

There will be a natural evolution in mission design where the single, focused missions of today and in the past will be supplanted by a sustained, multi-objective robotic science campaigns along the way towards ultimately a true expeditionary human exploration of Mars. These next step robotic science campaigns present perhaps ideal opportunities to take full advantage of aerial vehicle exploration of Mars. Among other things, they will represent the greatest challenges in autonomous system technologies, robotics, and information/data networks.

A largely unexplored enabling capability is to examine new types of entry, descent, and landing aeroshells that could accommodate larger and/or multiple aerial vehicles.

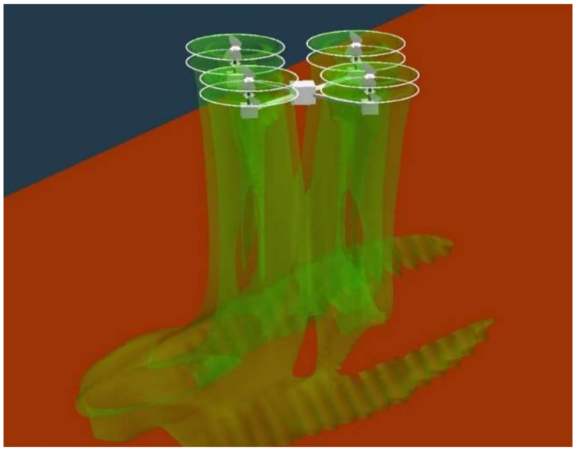


Figure 12. Entering Craters to Examine Recurring Slope Lineae; rotor wake visualization of an eight-rotor configuration over the sloped-surface of a crater interior (e.g. Ref. 28)

Additionally, sustained robotic science campaigns can contemplate concatenation of successive missions/systems to perform expanding/augmented missions. For example, a rover that was flown to Mars in one launch opportunity might be joined by a Mars rotorcraft flown during a subsequent launch opportunity to augment/expand and extend the mission life of the older rover robotic system. This would entail generalizing robotic explorers' ability to communicate with other robotic explorers, in addition to/through orbiters and direct-to-Earth telecom.

With time, increasing robotic system – and overall mission – sophistication will ultimately transform Mars planetary science missions from single-mission, single-robotic-platform endeavors to instead sustained, integrated networks of multiple platforms that can explore large expanses of terrain and/or exhaustively investigate regions of scientific interest. Such sustained robotic science campaigns will, in turn, ultimately lead to combined robotic/human exploration campaigns of Mars. It is reasonable to anticipate that such sustained robotic campaigns might evolve over time to various different (from simple to more complex) campaigns: first, perhaps starting with outposts (Fig. 13), then proceeding to long-rage solo or rove/rotorcraft treks (Fig. 14), followed then by loose networks of multi-robotic-systems traversing between one or more outpost stops (Fig. 15), to enabling integrated networks of vehicles performing back or forth transits between sites and outposts (Fig, 16), and finally culminating in full-fledged robotic ecologies or ecosystems (Fig. 17).

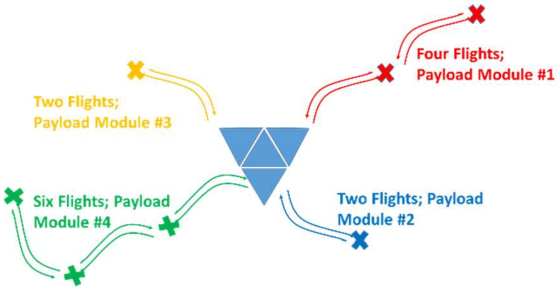


Figure 13. Generic Outpost Mission Profile

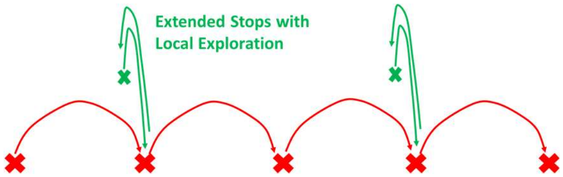


Figure 14. Generic Trek Mission Profiles

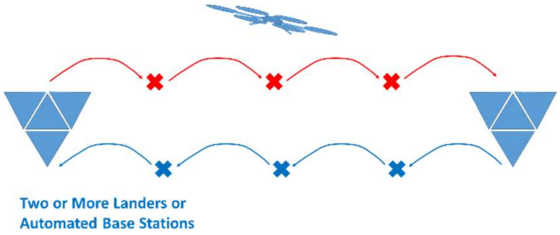


Figure 15. Generic Caravan, or Loose Network, Mission Profiles

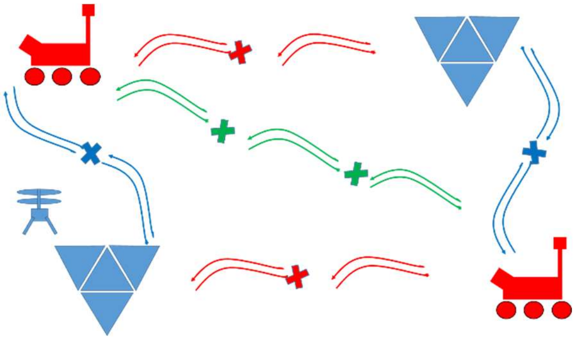


Figure 16. Generic Integrated Networks Mission Profiles

Robotic ecosystems are defined in terms of how tightly coupled and how sustained the interchange of functionality, data, and resources are across multiple robotic systems. In terms of both attributes – the degree of coupling and how much exchange of information/resources – robotic ecosystems represent a level just shy of the automated infrastructure required ultimately for human exploration of Mars. Robotic ecosystems could be established both prior to, during, and after the initial human exploration of Mars.

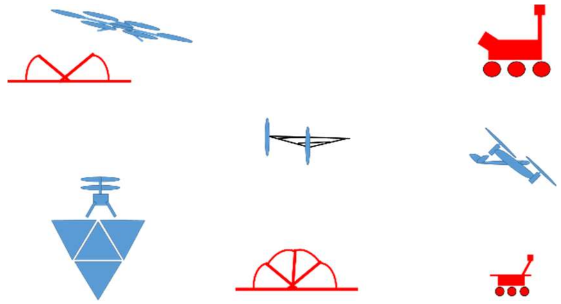


Figure 17. Generic Robotic Ecosystems Mission Profiles

Aerial Vehicles, Robotic Symbiotes, and Deployed/Distributed Sensor Networks

Though it is tempting for focus solely on new or more capable Mars aerial vehicle configurations (in the traditional aerospace sense to improve them – i.e. "higher, farther, faster") in this paper, it is equally important to consider them in another context. To fully maximize the utility of Mars rotorcraft, it is crucial to begin to think of these aerial vehicles as 'rotorcraft as robots' (RAR), e.g. Ref. 20. In this regard, this paper will discuss networks of Mars rotorcraft and other robotic systems that exchange some level of information and functions to accomplish the overall mission. It will be through such networks that expansive, sustained science campaigns (versus single missions with one, or few, rotorcraft) can be conducted. Such precursor science campaigns could then be followed by human exploration of Mars.

In addition to Mars aerial vehicles performing imaging or sensor surveys, they will also perform utility missions. Some of those missions would focus on the transport and distribution of drop probes and small robotic 'symbiotes.' This will be a role not only for Mars rotorcraft but fixed-wing aircraft as well (e.g. Fig. 4a). Reference 9 considered the deployment of fixed-wing aircraft, carrying robotic symbiotes of a variety of types (e.g. Fig. 4b), as an extension of the entry, descent, and landing process. This will be explored further at a high level.

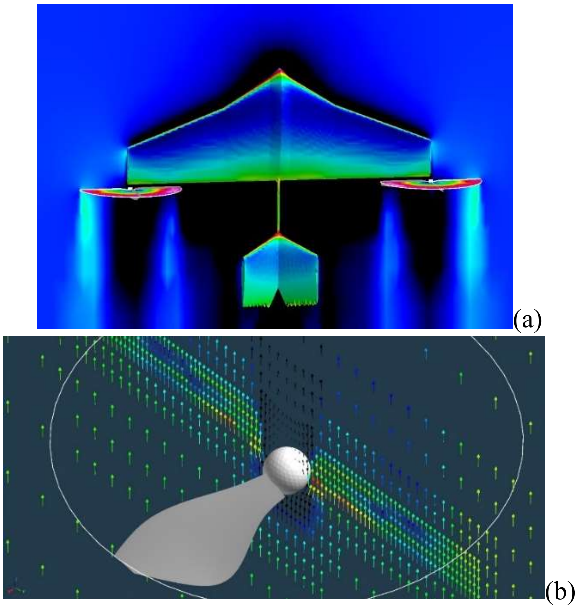
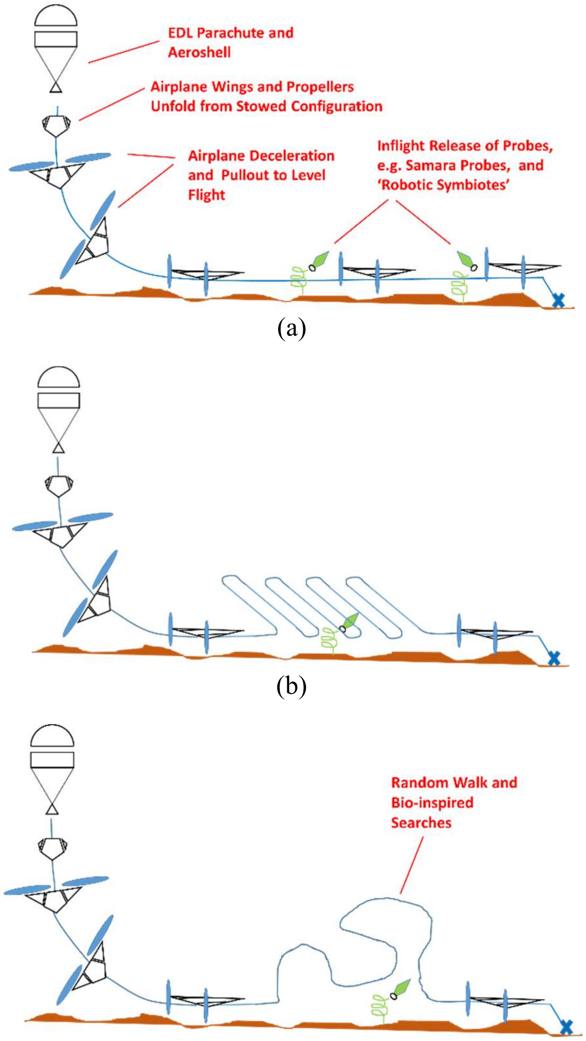


Figure 18. (a) Fixed-wing aerial explorers as one part of the entry, descent, and landing process as a means of distribution of probes and robotic systems and (b) samara rotary-wing decelerator; one possible micro-probe or robotic symbiote

References 9 and 33 discussed the reconceptualization of Mars airplane deployment and flight as being one additional/final stage of the overall entry, descent, and landing process. Additionally, because flight time and range are going to be limited resources, novel approaches to searching and distributing (deploying in flight) sensors and robotic symbiotes were also studied; among those approaches were bio-inspired search strategies, e.g. Refs. 6-7. This search, find, and distribute (SFD) type of mission would be enabled, in part, by the foundational advancements in Mars airplane technologies as established by the NASA ARES Mars airplane concept (e.g. Refs. 29 and 35). The ARES technology development effort proved that efficient aerodynamic airframes could be developed that were consistent or compatible with a number of volume/span-efficient wing and tail folds for stowage and deployment from an aeroshell. A key ARES milestone was the proof-of-concept demonstration of a high-altitude (~100,000 feet) release from a stratospheric balloon and the unfolding/deployment of the wings and tail surfaces and then the pullout to near-level flight as an unpowered glider. This high-altitude Mars airplane balloon drop built, in part, on independent, parallel 'Mars airplane' balloon drops, e.g. Ref. 34. The ARES concept used rocket-propulsion but could be adapted into incorporating more efficient propeller-driven propulsion – especially if those propellers could serve dual-purpose as rotary-wing decelerators for a portion of the vehicle release and descent from an aeroshell.



(a)

(b)

(c)

Figure 19. Generic SFD Mission Profiles: (a) straight and fast distribution, (b) grid search and distribution, and (c) bioinspired search and distribution

Automated Stations and Multi-Sortie Utility Missions

Even under the most benign Martian environmental conditions, robotic systems on the Martian surface are challenged to merely survive let alone maximize their productivity. For example, a large fraction of battery power has to be dedicated to providing for survival heat during the Martian evenings and winters. An additional example is that robotic systems that rely on solar-energy battery recharging are very susceptible to atmospheric-conveyed dust covering the solar array cells and, therefore, reducing the overall available power.

An automated base station – an aircraft hangar so to speak – to house, maintain, and otherwise support small Mars rotorcraft, both in aerial scout and utility roles, could greatly expand mission duration and capability; refer to Figs. 20-21. As noted earlier, the struggle to provide adequate battery margins for vehicle electronics survival heat can be ameliorated considerably by having the rotorcraft dock, and be housed, in an enclosed, heated hangar. The automated base station could accommodate larger solar cell arrays than could be carried by the rotorcraft and, so, the hangar could recharge the rotorcraft quicker. (Hangar retractable coverings could also protect those station solar cell arrays from long term exposure to dust.) Finite life batteries could be swapped out in the automated base station. Science instruments or other rotorcraft payloads could also be swapped out. Further, in addition to protecting and maintaining one or more Mars rotorcraft, such an automated base station could also protect rovers and other robotic systems (such as a robotic arm), station-based instruments, and science processing hardware. It can be readily imagined that such automated base stations might allow Mars rotorcraft to survive Martian winters or extensive dust storms. This, in turn, greatly increases mission return on investment. Even if a full-support hangar is not possible, there are still several advantages of combining an automated base station with one or more Mars rotorcraft. To develop such automated base stations will require significant technology development efforts by roboticists and information technologists.

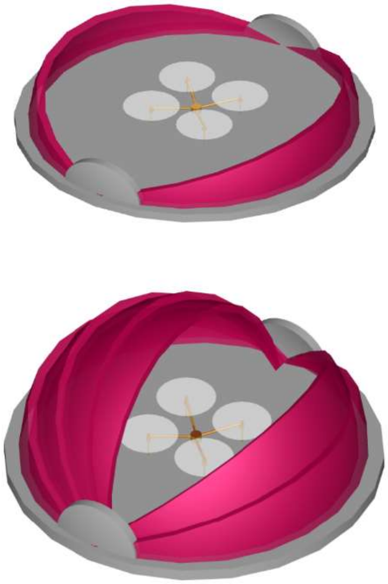


Figure 20. An Automated Base Station, aka 'Hangar' with 'Clam-shell' Siding/Roof, for Mars Rotorcraft

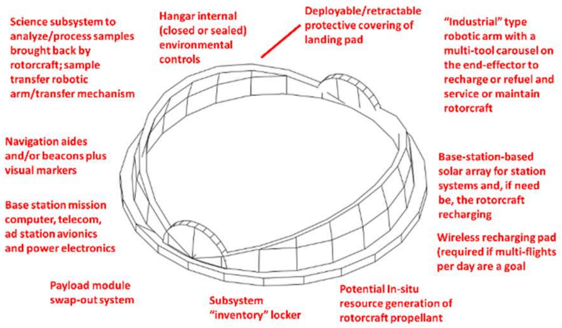


Figure 21. System flow chart of Automated Base Stations, aka Hangars, supporting Mars Vertical Lift Aerial Vehicles

One approach to increase payload capacity is to use external slung loads supported by two or more Mars rotorcraft to carry those payloads. This implies either human intervention to set up the slung load or a very sophisticated automated system to attach the slung load. An alternate approach is to consider the use of small modular Mars rotorcraft, physically connected together, to add to an aggregate payload capacity. Figure 22a is a single modular rotorcraft 'element' (showing isosurfaces of velocity magnitude while hovering in ground effect). Figure 22b show a swarm (not physically connected together but coordinated through a telecom network) of small vehicles (shown flying at different heights, and relative vehicle-to-vehicle spacing, while again showing isosurfaces of velocity magnitude in HIGE). Finally, Fig. 22c shows a number of small modular rotorcraft physically connected into a tiled array (approximately half the rotorcraft rely on tractor type propellers and half using pusher propellers) flying, again, in HIGE. External payload pods, with multiple attach points to the rotorcraft 'elements,' would be added and used to carry the larger loads.

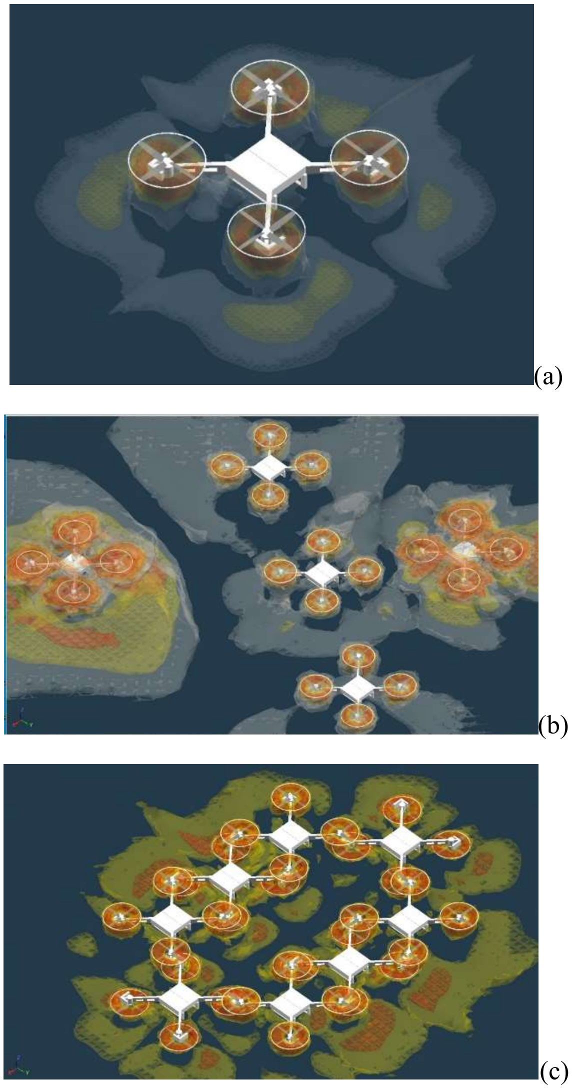


Figure 22. One Possible Modular Rotorcraft Configuration: (a) single vehicle 'element,' (b) swarm of small independent rotorcraft 'elements,' and (c) vehicle 'elements' integrated into a modular rotorcraft configuration

There are significant tradeoffs between missions that employ a single large, complex robotic system versus those proposed using multiple, small, simple robots. This is true, as well, for autonomous Mars rotorcraft. This tradeoff also depends on the general character of the mission – as to whether it is to principally perform aerial surveys or, alternatively, use the rotorcraft as utility platforms carrying varied science payloads that can perhaps be periodically exchanged. Underlying these tradeoff considerations will be assessments of: risk versus redundancy (both in terms of vehicle design and mission operations), the time criticality to survey/assess multiple sites, and the necessity for distributed, interconnected (through telecom) platforms and sensors to meet mission objectives. Such tradeoff assessments would greatly benefit from developing new system analysis tools and capabilities specifically tailored to all notional Mars rotorcraft types and missions.

The modular Mars rotorcraft concepts discussed earlier are also a compromise strategy between a large complex rotorcraft and many small simple rotorcraft. By performing on-demand assembly, or disassembly, of such modular rotorcraft, the complexity and number of aerial vehicles can be tailored to individual missions.

Novel Environments and High-Risk/High-Payoff Missions

Low altitude aerial surveys over relatively benign terrain (free of obstacles that might result in collision) is only the beginning of possible Mars rotorcraft mission flight profiles. Among the many more extreme terrains that such aerial platform could fly over, next to, or even inside the interior of, include: caves and lava tubes, polar out-gassing geysers, cliff faces, canyon walls, large geological formations, and crater interiors (with their sloped/unstable surfaces); e.g. Refs. 28 and 32. Flights could even intentionally attempt to fly during periods of extreme atmospheric and seasonal conditions such as during: dust storms, dust devil formation/propagation, dune Aeolian evolution, and dry- and water-ice formation and sublimation.

Attempting to fly next to (or into) extreme terrain, or geological obstacles, will dictate vehicle configurations that require unique design features such as protective guards for rotors, different landing gear geometries, configurations that are still flyable if the vehicle is accidently flipped upside down, hybrid air and ground mobility systems, and maybe deployment/retraction of tethers from the vehicles. The necessity and complexity of such novel design features would require specific and detailed design/mission tradeoff analyses.

ASTRONAUT ASSISTANTS AND HUMAN EXPLORATION OF MARS

References 8, 10, and 14-16 reflect early work on the concept of aerial vehicles – in particular, rotorcraft as robots – supporting astronauts in the human exploration of Mars. In particular, this paper is a continuation of Ref. 10 in that both papers comment on the near- and longer-term future of Mars rotorcraft. Not only can Mars rotorcraft support robotic science missions but they also potentially have a role supporting precursor missions for human exploration of Mars as well as play a key role as astronaut assistants during that exploration. In addition to Ref. 10, Refs. 14-16 recently also considered this question of Mars rotorcraft acting as astronaut assistants. Finally, one extreme engineering example of Mars rotorcraft supporting the human exploration of Mars is a crewed rotorcraft platform, e.g. Ref. 10.

Astronaut Assistants

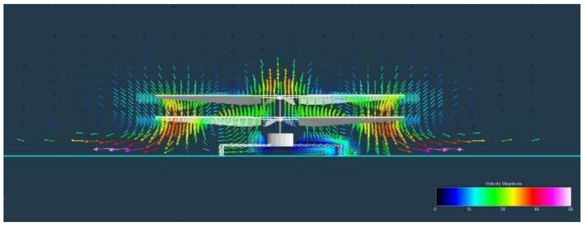
Trying to accomplish productive science and exploration campaigns while operating in a spacesuit will be a major challenge. The utility of small Mars rotorcraft as astronaut assistants is probable for future human missions to Mars. Such astronaut assistants could be operated/guided by astronauts from their habitats, their crewed transportation rovers, and, yes, from within their spacesuits.

One of the key paradigms of terrestrial UAVs is to use these vehicles to perform “dirty, dull, and dangerous” missions instead of relying on people on the ground or manned aerial platforms to perform such missions. This problem is compounded by the fact that not only will astronauts be encumbered by their suits and/or the limitations of their facilities but also limitations on their physical strength and endurance stemming from their outbound journey to Mars and further physical deconditioning when on the planet’s surface due to the lower gravity of Mars compared to Earth.

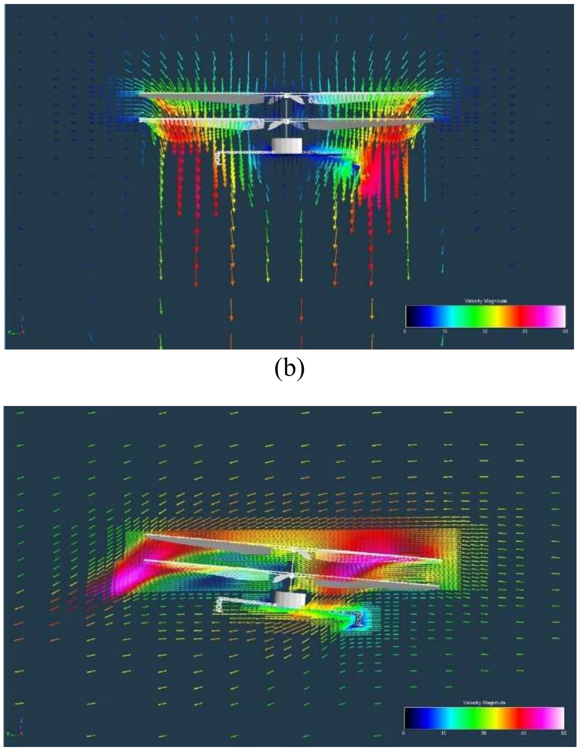
A considerable body of research into human/robot interactions exists for industrial-type robots. A similar large body of work has been performed for robots and UAVs supporting military applications. Only a limited amount of research into human/robot interactions have been performed for ‘astronaut assistant’ applications. Among this limited research is Refs. 14-16; more work is clearly in order. For Mars rotorcraft to effectively, productively support astronauts, it is essential that notional astronaut/robot interactions continue to be investigated in the future. Two fundamental types of interactions have to be recognized: those where the astronaut who was operating the rotorcraft and other robots is located in a habitat or pressurized vehicle and those where the astronaut is on the Martian surface in a space suit. It should be noted that Refs. 14-16 focused on rotorcraft – using commercial-off-the-shelf quadcopter and multirotor configurations – operations conducted by researchers in surrogate space-suits at Mars-analog sites.

Large Utility Platforms for Sustained Exploration Campaigns

One of the key challenges of early-generation Mars rotorcraft is their volumetric challenges in stowing and deploying from very confined entry, descent, and landing aeroshells. The constraints upon the size and payload capacities of Mars rotorcraft that are a part of standalone robotic missions can be expected to be relaxed somewhat when human exploration missions (including immediate precursor staging missions) of Mars get underway. If some assembly was provided by astronauts then larger, more capable utility-type Mars rotorcraft might be enabled.



(a)



(b)

(c)

Figure 23. Large Autonomous Utility Platforms: (a) HIGE, (b) HOGE, and (c) forward-flight at 30m/s

Crewed Rotorcraft

A very speculative type of Mars rotorcraft is that of a crewed rotorcraft for human exploration of Mars. Reference 10 briefly examined the possibility of the rotary-wing transport of a single-occupant, suited astronaut. The concept entailed examining a tandem coaxial-rotor helicopter configuration powered by a hydrazine, or potentially other monopropellants, Akkerman-type reciprocating engine (Ref. 40). This early work is partially supported by recent additional work briefly summarized below in Figs. 23-25. Further, advances into thinking as to in-situ-derived propellants (examples such as methane, hydrogen, and oxygen) might instead enable bi-propellant, or internal combustion-type, reciprocating engines and, therefore, improved propulsion efficiencies.

Alternate crewed aircraft have been proposed in the literature. One recent example is Ref. 39, which proposes a VTOL aircraft using rocket propulsion for takeoff and landing. As the era of human exploration of Mars approaches, such design studies – and tradeoffs between aerial and ground-mobile vehicle types – will gain considerable importance. There will be two key considerations for evaluating potential mobility options for astronauts on Mars: first, the health and safety of the astronauts, and, second, the productivity of the astronauts in terms of providing time-saving, effective tools to perform tasks.

Very large aerial vehicles will not only require some level of manual or semi-automated assembly but may also likely require on-site component fabrication using both materials sent from Earth as well as in-situ-derived materials. The clearest example of this is the extremely large rotor blades of such vehicles (and/or wings) that would likely have to be fabricated while on Mars rather than shipped from Earth.

Whether such vehicles might or might not be theoretically feasible, the practical logistics of realizing such vehicles would be extremely challenging. Alternate solutions, such as crewed ground-mobile rovers are far more likely. Still, it is important from a research and development community perspective to periodically reexamine the maximum practical size of Mars rotorcraft as new technologies and mission capabilities are introduced.

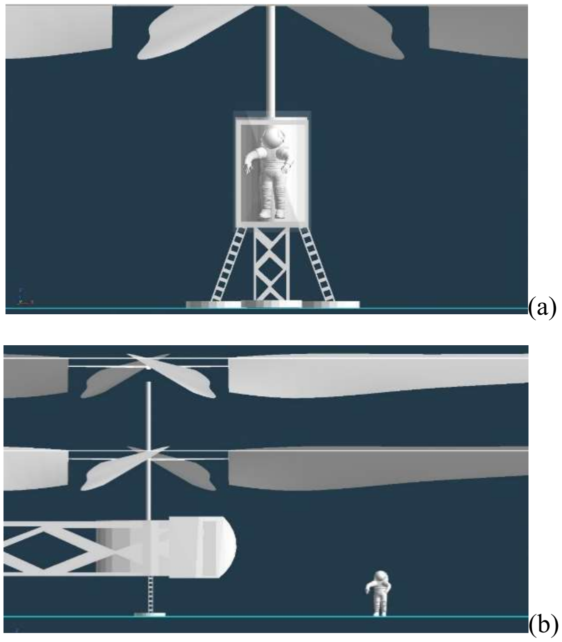


Figure 24. Building Leviathan (astronaut CAD model in foreground from Ref. 26)

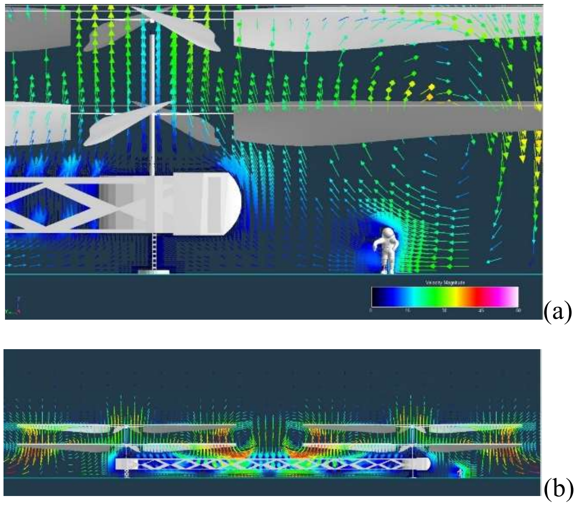


Figure 25. Mars Crewed Rotorcraft hover in ground effect

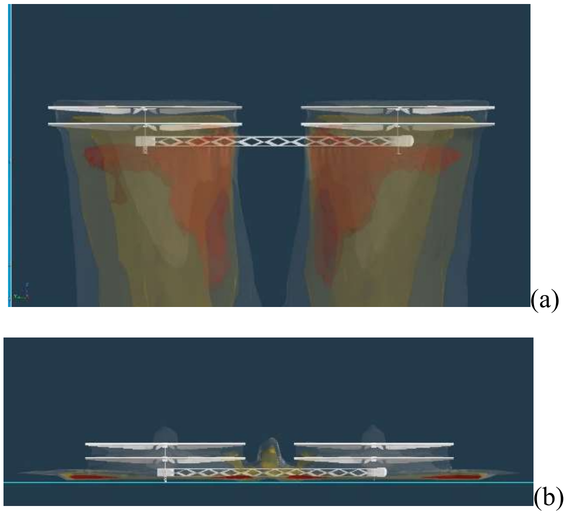


Figure 26. Notional Crewed Rotorcraft: (a) hover out of ground effect and (b) hover in ground effect

OTHER AERIAL PLATFORMS: MARS AIRPLANES, (SEMI-) BUOYANT AIRCRAFT AND (GAS-) HOPPERS

Hopefully, the Ingenuity Mars Helicopter and the Titan Dragonfly missions will act as catalyst for aerial explorers of all types for future planetary science missions. This potentially includes Mars airplanes, (semi-) buoyant aircraft including airships and balloons, and gas-hopper systems. Each of these aerial systems, in addition to future rotorcraft and vertical lift planetary aerial vehicles, can potentially address unique exploration opportunities. As briefly discussed earlier in the paper, Mars airplanes could potentially be thought of as a means of targeted distribution of sensor networks and robotic micro-systems. (Semi-) buoyant aircraft also have a long history of conceptual study – and actual NASA SMD mission proposals – within the planetary science and exploration community. Semi-buoyant vehicles may ultimately find their niche as regional aerial observers. Finally, gas-hopper (using hot- or cold-gas thrusters) platforms may become a potential technology bridge between 'aerial' exploration of planetary bodies such as Mars, Titan, and Venus to that of off- or near-surface exploration of airless planetary bodies such as Europa, Enceladus, and the asteroids.

The planetary aerial vehicle research community becomes stronger if various vehicle advocates can join together to try advancing the field as a whole. To nurture such a research community, it will be required to acknowledge and balance the interests of the mission-competition-driven NASA Science Mission Directorate (SMD) with the foundational research, or applied research and technology, approach of the NASA Aeronautics Research Mission Directorate (ARMD). Similarly, an efficient but collaborative means of drawing in academic institutions into the planetary aerial vehicle research community needs to be nurtured.

TECHNOLOGY TRANSFER OPPORTUNITIES TO/FROM TERRESTRIAL VERTICAL LIFT AERIAL VEHICLES

As exciting as the potentiality of planetary aerial vehicles is for supporting planetary science missions, such mission opportunities will inevitably be relatively rare. Accordingly, it is important to recognize that many of the technologies derived from the development of planetary aerial vehicles will also be cross-cutting for a number of other fields – such as terrestrial field science or public service missions/applications – that could or do employ vertical lift uninhabited aerial vehicles.

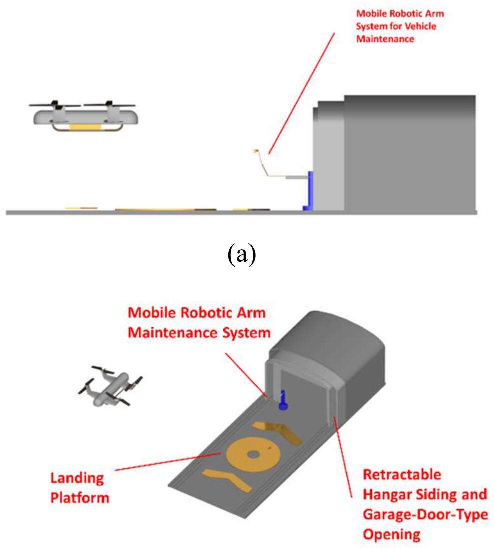
Smart Rotorcraft Field Assistants

Almost every terrestrial field science campaign could potentially benefit from small autonomous rotorcraft assisting those campaigns. References 8 and 30-31 were among the earliest discussions to consider the use of small autonomous rotorcraft to support not only planetary science missions but terrestrial field science. The aerial imagery from such platforms can provide context for the science being performed on the ground. Additionally, specialized science instruments can be integrated into these platforms in addition to imaging cameras to acquire unique data. Finally, such platforms can – just like planetary rotorcraft – could acquire samples from the ground at sites that are difficult to otherwise access.

Terrestrial Extreme Environment Explorers (TE^3) and Sentinel Networks

Field science campaigns oftentimes occur under extreme environmental conditions. In many cases, the science campaigns are adversely impacted by seasonal and other environmental conditions that practically prohibit year-round or sustained multi-year observations or investigations. To successfully employ autonomous aerial vehicles for field science campaigns that are year-round or multi-year will require the development of deployable automated base-stations that can support/protect those vehicles when they are not flying.

References 8 and 36 include, among other things, early conceptual descriptions of TE^3 and sentinel networks.



(a)

(b)

Figure 27. Sentinel Networks

Disaster Relief and Emergency Response, Environmental Monitoring, and Wildlife Conservation

Although the rotor and vehicle aerodynamics will be quite different between planetary aerial vehicles and terrestrial uninhabited aerial vehicles, many other vehicle technologies will be cross-cutting. This includes autonomous system technology, advances in avionics and flight computers, robotic systems that can interact and interconnect with aerial vehicles, novel deployable sensors and systems, electric-propulsion and power-electronics, novel health monitoring and thermal management techniques/systems. For example, one of the key capability demonstrations of the Ingenuity Mars Helicopter is the use of solar-electric propulsion with periodic between-flight vehicle battery recharging. This same general type of solar-electric propulsion for terrestrial vertical lift autonomous aerial vehicle will enable longer overall mission durations for a variety of terrestrial applications.

Three of the most compelling emerging applications for terrestrial vertical lift autonomous aerial vehicles are: disaster relief and emergency response (DRER); environmental monitoring; wildlife conservation. Reference 24, for example, discusses the potential for such aerial vehicles for DRER missions. Further, it has become commonplace to use multirotor configuration 'drones' for aerial surveys of disaster sites. UAV's are already being used for environmental monitoring. With, though, an improved understanding of the cause and effects of climate change, advanced autonomous aerial vehicles could also provide major advances in environmental monitoring. Finally, as well, UAV's are already being used for wildlife monitoring for conservation purposes. Being able to keep such conservation monitoring vehicles nearby the wildlife populations and onsite twenty-fours a day, 365-days a year through the use of advance sensors, solar-electric propulsion, and/or automated base stations would enable a tremendous expansion of conservation efforts.

Pushing the Boundaries of Autonomous Aerial (and non-aerial) Systems

Reference 9 outlined a level of autonomy (LOA) scale ranging from zero to ten. The penultimate rating of LOA=10 was reserved for robotic systems that will exhibit the autonomous system capability of being our legates (full surrogates for humankind) or even legacy (representatives of our civilization that might even outlast us). Such a level of autonomy would only be required for perhaps interstellar probes or otherwise remote multigenerational robotic scientific observers. This penultimate level of autonomy is not necessary for the vast majority of plausible Mars rotorcraft missions.

FUTURE MARS ROTORCRAFT: MISSION ARCHITECTURE AND TECHNICAL CHALLENGES

Mission Architectures Challenges

A key theme of this paper is promoting the vision of transitioning from a single mission perspective for Mars exploration to one of sustained robotic science campaigns, which in turn leads to a transition to human exploration missions. Aerial vehicles are a key component of realizing this vision. Further, it has to be emphasized that not one vehicle size or type is going to be sufficient to realize an expansive architecture for both near- and far-term missions. Accordingly, there is considerable room for the planetary aerial vehicle research and development community for design innovation and technology advancements.

Technical Challenges/Problems

Though the Ingenuity Mars Helicopter will result in key technology demonstrations for the flight in the atmosphere of Mars, to fully realize this vision of aerial vehicles as a critical component of the sustained scientific investigation, and human exploration, of Mars there are many advances in vehicle design, and technology development, required that go well beyond that demonstrated by Ingenuity.

Next generation Mars rotorcraft:

1. Assessing the engineering data, and lessons learned, information from the Ingenuity Mars Helicopter.
2. Development of advanced compressible, low-Reynolds number airfoils for the tip Mach range of <0.9 and Reynolds number ranges <30,000.
3. Improved understanding of vertical lift aerial vehicles in descent, especially studying the autorotative, vortex ring, and turbulent wake states.
4. Development of new structural/dynamic analysis tools to analyze rotors compatible

with novel high-performance compressible, low-Reynolds airfoils.

5. Development of new rotor control system technologies and structural damping mechanisms/approaches to provide for adequate rotor control despite the inherent aerodynamic damping of Mars rotors

Beyond next generation rotorcraft and other planetary aerial vehicles:

1. Development of, and/or study, of multi-element compressible multi-element airfoils for rotors and/or fixed-wing lifting-surfaces.
2. Development of and/or study, of flaps, flaperons, ailerons, and other fixed-wing control surfaces in the compressible, low-Reynolds number regimes.
3. Development of new types of vertical lift aerial vehicles – beyond that of coaxial helicopters and multi-rotor configurations – to increase range, speed, and payload capability. This would include developing hybrid multi-modal mobility solutions.
4. Develop new types of fixed-frame ultra-lightweight structures for wings, fuselages, landing gear, and rotor pylons/rotor-support-structures.
5. Expand vehicle/mission design concepts of novel planetary aerial vehicles.
6. In parallel, new design analysis tools need to be developed, including those that account for design constraints imposed: (a) by considering stowing and then deploying vehicles from Entry, Descent, and Landing systems; (b) integration and interaction with landers, rovers, and automated ground-stations; (c) integration and interaction with 'robotic symbiotes,' sensor networks, and modular payloads; and (d) incorporating hybrid multi-modality mobility capabilities.

Expansive, sustained robotic science campaigns:

1. Development of refinement of solar-electric propulsion Mars rotorcraft to extend their mission duration.
2. Development of novel power systems – and/or 'hanger' automated bases – to extend mission duration beyond a few weeks to years.
3. Development of novel propulsion systems for larger vehicles; (a) regenerative fuel cells; (b) advanced Akkerman (hydrazine or other monopropellant) engines; (c) 'vacuum rated' (pressurized) internal combustion engine motors/motor-generators for very large Mars vertical lift aerial vehicles.
4. Development of self-deploying or automated deployment rotors with mid-span hinges for folding, telescoping blades, and blades with (partial) flexible blade sections for folding or reeling into a compact stowed state.
5. Accelerated cross-cutting development of autonomous system technology for both aerial vehicles, mission science computers, and multi-agent robotic systems and distributed sensors.
6. Novel flight control of modular distributed arrays of rotorcraft to form larger payload capacity aerial platforms.
7. Development of new types of entry, descent, and landing aeroshells that could accommodate larger and/or multiple aerial vehicles.
8. Development of novel (ground and flight) control for hybrid mobility robotic systems; potentially requires novel fusion of sensors and path/trajectory planning algorithms.

Astronaut Assistants and human exploration missions:

1. Novel human/rotorcraft interfaces to maximize day-to-day mission flexibility.
2. Development of 'back-pack' (manually) deployable aerial asset for scouting for astronauts performing field science; proof of concept testing in analog-sites.
3. (Alternatively) development of rover-towed utility carts to transport/deployment Mars rotorcraft tailored to be astronaut assistants; proof of concept of analog-sites.
4. Development of very large aerial platforms that are assembled/deployed through manual/semi-automated approaches.
5. Development of very large ultra-lightweight rotor with blades that are rigidly joined together in multiple sections through novel structural joints, pinning mechanisms, or in-place bonding approaches.
6. Development of modular system to be able to scale aerial vehicles from the moderate to very large scale (from tens to hundreds of kilograms).

Other Planetary Bodies and (Maybe, One Day) Extra-Solar Planets

Vertical lift aerial vehicles will be limited to exploration of just three (four if you count Earth) planetary bodies in the Solar System: Mars. Titan, and Venus. This is because not only do these planetary bodies have sufficient atmospheres for powered flight but they also have well-defined and/or accessible planetary surfaces to explore (versus the gas giant planets who do not). There may well be opportunities for non-vertical-lift vehicles for the gas giant planets, e.g. Ref. 1. The increased flexibility of planetary aerial vehicles will enable expansive new planetary science missions. Additionally, some cross-cutting technologies from planetary aerial vehicle development could also find their way into small spacecraft (such as gas-hoppers with cold-gas thrusters) that could explore asteroids and other planetary bodies without atmospheres. Such cross-cutting technologies include avionics, visual navigation and other GNC technologies, ultra-lightweight but high-stiffness structures, and power electronics.

MARTIAN AVIATORS AND PLANETARY AERIAL VEHICLE DESIGNERS: HOW TO REALIZE THE FUTURE

In 2000, NASA Ames, Sikorsky Aircraft, and the American Helicopter Society International (AHS) (the precursor to the Vertical Flight Society) sponsored the first-ever student design competition on the topic of Mars rotorcraft. In 2002, NASA Ames and the NASA Office of Education's Minority University Research Program (MUREP) sponsored a student design competition on the topic of vertical lift aerial vehicles for exploring Titan, Saturn's largest moon. This was followed, in 2008, by the last (known to the authors) NASA student design competition on the topic of planetary aerial vehicles, sponsored by the NASA Aeronautics Research Mission Directorate. Hopefully, more such student design competitions as well as fellowships and grants will be enabled by the acceptance of the vertical lift aerial vehicles for planetary science missions.

Deriving the Most Benefit from Mars Analog-Site Field Testing

Mars analog site testing of prototype technologies provide important technology maturation opportunities. In particular, as more advanced planetary aerial vehicles and missions are contemplated beyond Ingenuity, higher levels of vehicle autonomy need to be developed and, importantly, demonstrated in relevant environments. The most relevant environments, short of on Mars itself, is testing in Mars-analog sites on Earth.

Enabling Terrestrial Field Science Campaigns and Other Public Service Missions

Technologies critical to enabling rotorcraft on Mars can be applied to Earth-based field science and various other missions as well. NASA technology "spin-offs" are ubiquitous in modern society, and there is no doubt that Mars rotorcraft will contribute "spin-offs" as well. Rotorcraft as rescue tools, whether as scouts or as active emergency de-escalation tools, are already gaining popularity. However, the aerodynamic conditions that such vehicles encounter are vastly different than typical rotorcraft flight conditions. In addition, the accuracy and decision-making of the autonomy for such vehicles is beyond current technological capabilities. However, as Mars rotorcraft gain popularity and the autonomous technology matures to enable such vehicles to meaningfully and efficiently explore Mars, such advances in autonomy will contribute to the ability of terrestrial autonomous rotorcraft as well.

Similarly, as rotorcraft on Mars enable the exploration of the Red Planet in a greatly expanded way, this will lead to the optimization of science tools for use on rotorcraft. A majority of Earth-bound rotorcraft science campaigns are limited to utilizing cameras on the rotorcraft. While cameras allow for remote sensing and mapping, they do not enable the characterization of surface or sub-surface materials. As science instruments are conceptually designed and subsequently tested and manufactured for Mars rotorcraft, this will open up the types of science that can be accomplished by rotorcraft on Earth as well, Ref 8.

The aerodynamics experienced with flight on Mars is vastly different than on Earth, and results in very low chord-based Reynolds numbers (Re $\sim 10^3$). The research and development into this aerodynamic flow regime will increase understanding of the flow regime experienced by Earth-based High Altitude Long Endurance (HALE) aircraft and micro-air vehicles. As Re decreases, conventional airfoils are less efficient, and the understanding of low-Re flow regimes has not been widely investigated prior to increased interest in rotorcraft for Mars. Thus, as understanding of this flow regime increases, research will be applicable to Earth-based flight experiencing reduced Re as well, resulting in more efficient aircraft.

CONCLUDING REMARKS

To fully realize the full potentiality of Mars rotorcraft and other planetary aerial vehicle it will be necessary to address numerous technology challenges or problems. A number of these key technology challenges are identified in this paper. These challenges are organized in the context of near- and far-term mission concepts and scenarios. These mission concepts and scenarios – as enable by various potential aerial vehicle implementations – are also summarized in this paper. These technology challenges reflect an opportunity for the nascent planetary aerial vehicle research community to broadly and noncompetitively contribute to future planetary science or exploration opportunities.

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