

Rotorcraft as Mars Scouts

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Abstract—A new approach for the robotic exploration of Mars is detailed in this paper: the use of small, ultra-lightweight, autonomous rotary-wing aerial platforms. Missions based on robotic rotorcraft could make excellent candidates for NASA Mars Scout program. The paper details the work to date and future planning required for the development of such 'Mars rotorcraft.'

INTRODUCTION

The need for mobility has been recognized by scientists for decades to be fundamental to the exploration of the highly varied and very rugged martian surface. Such mobility would allow in situ investigations of the many sites -- already identified using orbital data -- that hold the secrets of martian geologic, climatological and (potential) biologic history. At present, however, we are frustrated in our ambition to reach these sites by the size of landing error ellipses and the difficulty of maneuvering a surface rover among the many obstacles that litter the surface. Thus, presently we must land in "safe" sites (i.e. relatively smooth over large distances) and accept the fact that the range of our surface rovers is greatly insufficient to reach our priority targets.

In future, the size of landing error ellipses will decrease and terminal guidance will allow landings in the more rugged terrains that typify targets of real interest. In such cases the modest mobility of surface rovers will allow samples to be gathered and in situ measurements to be made in some exciting sites. Surface travel will, however, always remain limited in capability. Indeed, many of the most interesting geological features on Mars lie in terrains that are essentially unreachable by wheeled vehicles and current landing systems. Examples include the headwaters of the newly discovered small martian gullies and the layered cliff faces along the walls of Valles Marineris. Yet exploration of these features is critical to understanding their formation and the role of water in Mars' present and past climate.

Mobility provided by *aerial* vehicles promises to take our exploratory capability to a new level by obviating the need to maneuver around obstacles or to be enormously large to drive straight across boulder-strewn terrain. A planetary aerial vehicle would ideally have the flexibility to take off from its landing site, transit to, then hover over and examine high priority science targets. Such an ideal vehicle would also be capable of landing at any chosen site. Likewise the vehicle would be capable of returning to the more comprehensively instrumented lander from which it was deployed. Our ideal vehicle would also offer the opportunity to perform multiple flights by recharging at the lander.

This landing and take-off requirement for in situ science investigations makes a fixed wing aircraft unsuitable to replace a surface rover though well suited for long range, ultra-high- resolution remote sensing. Correspondingly, balloons trailing flexible tethers offer interesting possibilities for martian exploration including some in situ science but they lack the control necessary for reaching specific targets and for returning to a fixed lander.

Mobile vehicles able to carry out the kind of in situ investigations that scientists most ardently desire must be capable of both precise control and of vertical landings and take-off. This narrows the field to rocket-powered hoppers and rotorcraft. The former surely can be made to function (as demonstrated by the 3 meter hop made by Lunar Surveyor VI in 1967) but have been studied only a little. Rotorcraft for Mars exploration have been seriously studied in the last few years and have shown real promise.

In the near term a rotorcraft-equipped lander is viewed as a very attractive candidate for a Scout-class mission capable of high resolution remote sensing surveys, limited in situ science, and the return of samples to the parent lander for detailed analysis. Such a Scout-class mission would be targeted to a high priority science site that likely would be in rugged terrain. In the longer term rotorcraft could become essential elements on MSR missions and could support eventual human exploration missions in many ways. This paper considers the first steps in the development of Mars rotorcraft technology and its application to a first Scout-class mission (Fig. 1).

The Army/NASA Rotorcraft Division -- in collaboration with the Center for Mars Exploration -- at NASA Ames have been studying the design challenges and opportunities for martian autonomous rotorcraft for past several years. The feasibility of vertical flight in the martian atmosphere has been established by design studies by NASA Ames Research Center and independent analyses performed by several university teams [1-11]. Work on the Mars rotorcraft concept is moving on from preliminary system analysis to proof-of-concept test article design, fabrication, & assessment and fundamental experimental investigations of the unique aerodynamics of these vehicles. In particular, an isolated rotor configuration -- designed to constraints compatible with flight in the martian atmosphere -- has been designed and fabricated and is currently undergoing pre-test preparation for hover testing in a NASA Ames environmental chamber. Complementary work is also under way examining autonomous system technology and other critical enabling technologies for vertical lift planetary aerial vehicles.

Mars Scout missions, included in NASA's new Mars exploration strategy, are intended to be competitively selected small-scale projects that complement the baseline Mars program of remote sensing orbiters and complex sample return missions. An initial solicitation has been circulated for Mars Scout concept studies. A formal Announcement of Opportunity is expected by mid calendar year 2002. Both the baseline Mars Exploration Program and the Mars Scout missions are intended to meet the specific goals documented by the planetary science community's Mars Exploration Payload Analysis Group (MEPAG) [12]. A key feature of many of the MEPAG objectives is the requirement for multiple and diverse site investigations and sampling missions, one for which a Mars rotorcraft/scout would represent an excellent solution.

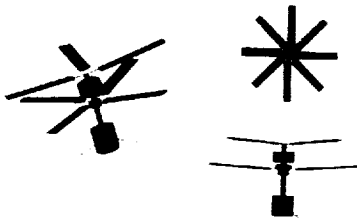


Fig.1 -- A Rotary-Wing Mars Scout

Specifically, a Mars Scout mission would entail landing on the martian surface a suite of science instruments to study the geology and organic chemistry of martian stratigraphic outcrops, rock fragments, soil and dust to determine its past water history and biological potential. The lander would likely be a variant of the 1998 Mars Pathfinder lander (also the basis for the 2003 lander missions) and would carry a rotorcraft (in the place of Pathfinder's Sojourner rover) to image and obtain spectral data of key geological sites, and to acquire samples from up to 10 km or so distance from the lander.

The ultra-lightweight rotorcraft will operate largely autonomously and will be targeted to sites of interest identified from available orbital imaging and spectral data after the actual landing site is accurately determined. The rotorcraft will acquire high-resolution imaging and spectral data and return small samples of soil and rock fragments from the designated sites. The instrumentation carried by the lander will include an optical microscope, an Infrared (IR) spectrometer and a Gas Chromatograph Mass Spectrometer (GCMS), capitalizing on instrumentation that has already been developed.

A NOTIONAL MARS ROTORCRAFT MISSION

Science Goals and Objectives:

Determining the mineralogy of the martian surface material is the first step in understanding martian geochemistry. *In situ* analyses of the martian surface material can determine the mineral and volatile content of martian surface material. Knowing the mineralogy of a sample of the martian surface material provides data on the environment under which it was formed and can be used to better define the early environment of Mars especially with respect to the history of water. For example, clays and evaporitic salts require the presence of water for their formation; as a consequence, if they form part of the martian surface material their presence would be evidence for water to have been on the martian surface for some length of time. Acquisition of samples from several locations in the region around the lander to provide a definitive characterization of the site is a key goal of a Mars rotorcraft mission. The three-dimensional mobility provided by a Mars rotorcraft would allow for exploration and science missions well beyond lander (accuracy as well as hazard avoidance) and rover capabilities (range/speed limitations and limited access to hazardous terrain). Because of the enhanced mobility represented by the vertical lift aerial vehicles, a lander can still land in relatively benign terrain but with a Mars rotorcraft providing mission support research could be conducted within surface areas that no other robotic explorer (or astronaut) could safely reach (Fig. 2).

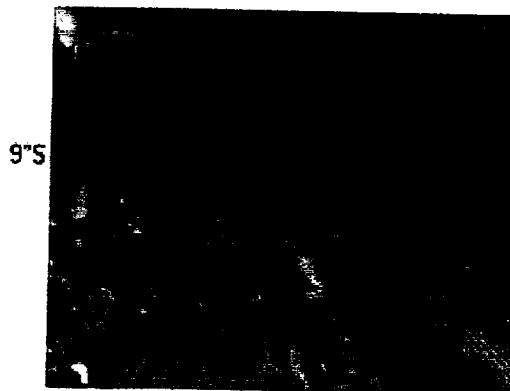


Fig. 2 -- Vertical Flight: Surpassing the Limitations of Landers and Rovers (Mars Rotorcraft Flight Path, Outlined in Red, Over Terrain Map of Mars Surface; EDLS Error Ellipse Also Shown)

After take-off a Scout rotorcraft would follow a specific flight plan over interesting terrain, for example the course of a small gully or along a specific cliff face selected from orbital images. Forward and aft mounted cameras would provide target-specific views (at a resolution of a few cm) unobtainable by fixed-wing aircraft or rovers. The rotorcraft will land at the chosen site, using imaging data to orient itself and touch down safely. Landing-leg mounted instruments would include a microscopic imager for measurement of grain characteristics and sizes. A sample-collecting scoop would be integrated into one landing leg to collect soil samples at the remote site that can be transported back to the lander for further analysis.

Sites well suited to rotorcraft exploration include (Fig. 3):

- The layered walls of, and mesas within, the Valles Marineris
- Young gullies on steep crater walls
- Headwaters of outflow channels and valley networks
- Basal scarp surrounding volcanoes, e.g. Apollinaris Patera, to search for hydrothermal spring deposits and explore sapping valleys.

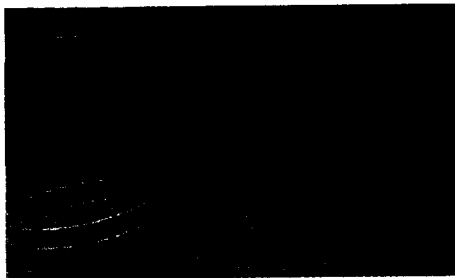


Fig. 3 – 'Search for Water'

Mission Description:

Prime Mission—10 to 15 Sols (a Sol is one martian 'day') devoted to acquisition, and in-situ analysis, of soil and small rock samples immediately adjacent to the lander (using a robotic arm); 5-10 Sols for the set-up (again using the lander's robotic arm) and checkout of the ultralightweight rotorcraft; 1 sol to demonstrate the ability to take-off from the lander and land back on its pad, all of the flight taking place within lander line of sight (e.g. to ~100 m radius); 1 sol to demonstrate a remote landing and take-off within line of site of the lander; then 20-30 Sols to carry out a series of flights to survey the landing site to a radius of several kilometers. All power would be provided by the lander solar array panels. The rotorcraft would be recharged between flights by the solar array panels (4-6 Sols between aerial survey flights and 6-10 Sols for time between sample return flights).

Extended Mission—20 to 40 Sols devoted to up to 4 remote-site soil/rock sampling mission flights to a distance of several kilometers from the lander. Each sortie would be accomplished (largely autonomously) within a ~ 6 hour period to avoid the need for the rotorcraft to survive the night sitting directly on the martian surface. The science analyses of the returned

samples would take place on the lander and results would be transmitted to Earth during the time that the rotorcraft was refueling. (Note that overall mission duration may be significantly affected by which of the two primary propulsion systems options are chosen for the rotorcraft.)

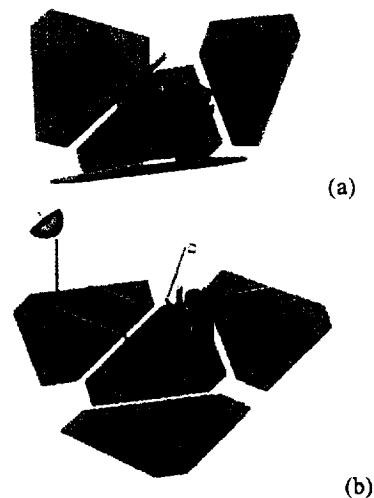
•Science Payload

Lander Instruments—Lander instruments would include as a minimum the following: microscopic imager; IR Spectrometer or Raman Spectrometer; Gas Chromatograph Mass Spectrometer (GCMS); wide-field optical camera for documenting/tracking Mars rotorcraft take-off and landing, and also used to guide lander robotic arm positioning for soil/rock sample transfer from the rotorcraft to the lander and to aid in the aerial vehicle set-up and recharging.

Vertical Lift Aerial Vehicle Instruments—The aerial vehicle instruments would include: forward- and aft-mounted optical cameras for Guidance/Navigation and aerial survey images; sun tracker; atmospheric temperature and pressure sensors for flight readiness and documenting remote-site climatology; landing-leg-mounted camera for soil/rock sample identification and leg-integrated sample probe/scoop positioning; several vehicle health and flight safety, navigation and control transducers; IMU and assorted accelerometers for flight control.

General Lander and Rotorcraft Description

A lander carrier with solar array petals similar in configuration of the 2003 MER and Mars Pathfinder landers [13-14]; an in-situ instrument science module for processing and analyzing soil and small rock samples; a robotic arm for sampling/transferring rock samples and further, assisting set-up, handling, and usage of the Mars rotorcraft; the vertical lift aerial vehicle itself, with a transport frame and auxiliary support equipment; lander mission computer and communication package. Fig. 4a-e summarizes the vehicle deployment from the lander.



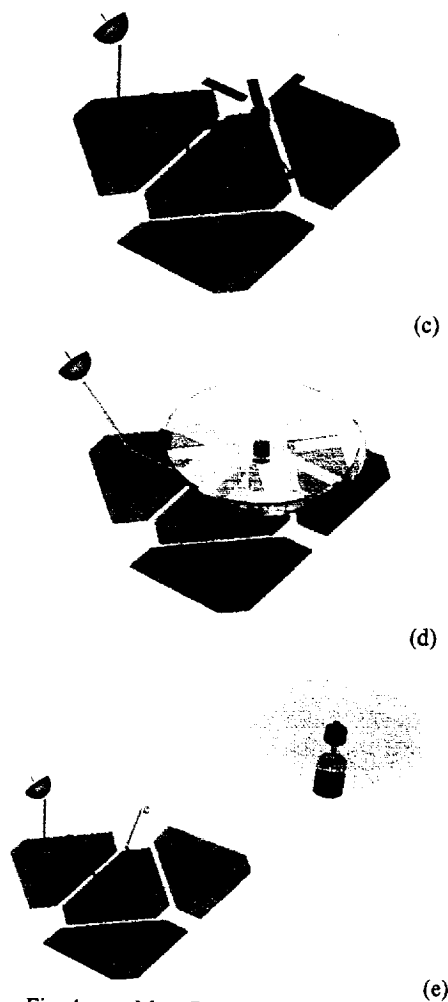


Fig. 4a-e – Mars Rotorcraft Deployment

Primary Mission Objectives

- Examine mineralogical and biochemical characteristics of soil and small rock samples..
- Perform low-altitude, high-resolution aerial surveys in hazardous or otherwise inaccessible terrain; identify remote-sites for follow-on sampling mission flights
- Perform a technology/flight demonstration of an autonomous vertical lift planetary aerial vehicle to support infrastructure development of a class of 'astronaut agents' that could enhance mission science return for human exploration of Mars.

Extended Mission Objectives

- Perform in situ science at, and return of soil samples from, up to four sites of special geological interest. These samples will be analyzed by instrumentation on the lander. The rotorcraft would fly, in a matter of minutes, to a site up to 10 km distant. Prior to landing it would hover to record high resolution, multi-spectral images to characterize the site and to orient the rotorcraft for landing. After landing a sampling probe – such as a scoop – would acquire soil and rock fragments for return.

The rotorcraft would then return by a direct path and set down on its pad. The samples would be transferred to the lander instruments by means of the lander's articulated arm and the Mars rotorcraft would be hooked up to lander auxiliary systems for recharging (Fig. 5).



Fig. 5 – Mission Objectives and Flight Requirements
(Background Photo Courtesy of USGS)

Implementation

Crucial to the success of any Mars Scout/Rotorcraft mission will be the formation of a strong project team that provides the critical multi-disciplined expertise and technology. Research and technical communities that heretofore have not interacted with each other will have to form close, efficient working partnerships. This process of opening communication and team building has begun between planetary scientists, spacecraft designers and mission developers, and the rotorcraft research community.

Mission and Flight System Architecture

To minimize overall real and perceived risk, a Mars Scout rotorcraft mission must use as much 'heritage' technology (i.e. previously demonstrated with flight hardware) as possible. Therefore, a Mars Scout rotorcraft mission will likely model itself on the Mars Pathfinder mission, substituting the rotorcraft for the Sojourner rover. The technology development will focus on the rotorcraft: its aerodynamic properties, its propulsion system and its autonomous operation.

The baseline Mars rotorcraft vehicle mass design target is 20 kg, but tradeoff studies should be made, varying the vehicle mass from 10 to 20 kg, to examine the impact on mission performance versus risk (Table 1). The vehicle needs to be capable of sustaining at least 30 minutes of flight in addition to 2 take-off and landings – at the lander and at the chosen distant site. The ability to recharge/refuel back at the lander will be an essential mission feature. The larger the vehicle the more payload (in the form of science instrumentation and soil/rock samples) can be carried by the Mars rotorcraft, but, for example, the greater the mission cost and overall power requirements.

Table 1. Mars Rotorcraft (Coaxial Helicopter) Sizing

Vehicle Mass (kg) =	10	20
# of Rotors	2	2
# of Blades per Rotor	4	4
Rotor Radius (m)	1.22	1.72
Disk Loading (N/m ²)	4.0	4.0
Mean Blade Lift Coefficient	0.4	0.4
Blade Solidity	0.19	0.19
Blade Tip Mach #	0.65	0.65
Forward Mean Cruise Speed (m/sec)	40	40
Maximum Power (Watts)	1550	3380
Total Range (km), 25% fuel fraction, electric propulsion w. fuel cell	~50	~50

Two different propulsion systems (which include the lander's power subsystem) will need to be examined in parallel in the conceptual and preliminary design stages of a Mars Scout/Rotorcraft effort: regenerative fuel-cell-based electric propulsion versus Akkerman hydrazine engine. Both propulsion technologies have their relative advantages and disadvantages. But, both types of propulsion are capable of meeting the primary and extended mission objectives outlined for the notional Mars Scout mission. Nonetheless, power will be a crucial constraint on Mars missions. Advanced solar cell array systems will likely need to be developed in order to meet the significant power demands inherent for future Mars surface missions (Fig. 6a-b).

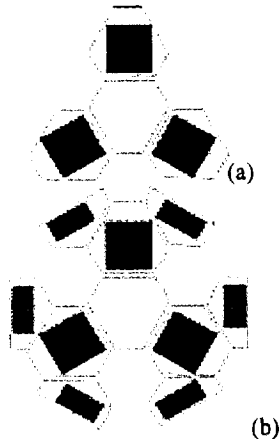


Fig 6a-b – (a) Mars Pathfinder Type Solar Array Arrangement; (b) Potential Advanced Array Layout

The ability to carry out multiple flights will be an essential for Mars rotorcraft scout missions. More analysis and developmental work needs to be performed before a final propulsion downselect can be made. Many other factors will need to be taken into account in making that decision – including reliability, toxicity of materials, and potential environmental contamination of the Mars survey sites.

Design studies and experimental investigations should also continue throughout the early stages of the Mars rotorcraft development effort to continuously benchmark coaxial helicopter configurations against quad-rotor

vehicle designs (Fig. 7) – the two leading vehicle configuration candidates for early Mars rotorcraft missions. Both vehicle configurations have considerable merit/potential for early robotic missions to Mars [9-11]. By pursuing parallel investigation of both aerial vehicle types in the early stages of a Mars Scout development effort, a strong final mission candidate design will likely emerge.

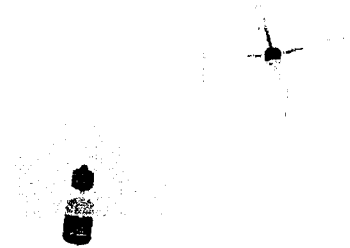


Fig. 7 – Coaxial versus Quad-Rotors

It is crucial to recognize that rotorcraft are not merely candidates for Mars Scout missions but are an essential enabling technology for Mars exploration effort – including, ultimately, human exploration of the planet (Fig. 8). Astronaut is going to a paramount issue with regards to the exploration of Mars. Competing with safety considerations would be the need to survey large areas of the planetary surface – and/or gain access to inhospitable terrain – so as to conduct mission critical research. A compromise solution would be to rely to on robotic explorers – particularly vertical lift aerial vehicles – to aid in the human exploration of the red planet.



Fig. 8 – Robotic Rotorcraft as 'Astronaut Agents'
(Background illustration courtesy of JPL)

Table 2 is a preliminary 'Science to Mission Traceability Matrix' for the notional Mars Scout rotorcraft mission outlined in this paper. Information contained in this table can be used by science team peers and reviewers, and mission planners, to aid in assessing whether or not a mission candidate concept can meet its identified goals and objectives. Rationale is provided within the matrix as the proposed science instrumentation for the notional Mars Scout mission, and mission features, that will meet a critical subset of the MEPAG Mars exploration science objectives.

Table 2. Science-To-Mission Traceability Matrix

Science Driver	Instrument Requirement	Mission Requirement	Flight Requirement	System Requirement	Comm. and Ground Data System Requirement	Mission Operations Requirement	Technology Requirement
1. MEPAG Goal I, Objective A, "Determine if Life Exists Today," Investigation 2, 3, 5, 6	GCMS (Gas Chromatograph Mass Spectrometer) Microscopic Imager	1. Perform low-altitude, low-speed aerial survey and select remote-sites where geologic formations would suggest water was once existent; 2. Acquire at multiple sites soil and small samples to assess existence of clays, hematites, and/or sedimentary rocks through spectrometry; 3. Through use of GCMS, assess potential of soil sample for containing organic compounds and/or levels of oxidants	EDL must be capable of delivering to the martian surface a 20kg aerial vehicle; 20 kg of science analysis package/station; and a tetrahedral solar array "petals" for power; a robotic arm and support frame for set-up and recharging		1. Aerial survey digital images will comprise the largest fraction (~75%) of data transmittal to Earth; aerial and remote-site (near- and far-field) images will need to be transmitted throughout mission duration in order to provide the scientific community the contextual background to accompany the soil and rock sample analyses; 2. Sophisticated software for science analysis, data prioritization and communication, and mission planning will be required for both the lander science station and the aerial vehicle.	1. Single shift operations required for Earth/Lander communication; 2. Two-three "off-days" between complete data set download and initiation of next aerial vehicle flight required for science team preliminary analysis and planning;	A. Heritage Instrumentation B. Development of a 'Mars Rotorcraft' C. Develop In-Situ Handling & Processing Tools for the Lander Science Package/Station. D. From an overall Mars program risk management perspective, it would probably be best to couple a 'low risk' and a 'high risk' (such as one employing a Mars rotorcraft) during the same Mars transit window opportunity.
2. Goal I, Obj. B, "Determine if Life Existed in the Past," Investig. 1 & 2	IR (Infra-Red) Spectrometer Microscopic Imager	Through use of microscopic imager and rock preparation/processing tools (grinding/slicing) assess rock samples for paleobiology potential.	Sample handling and processing techniques need to be developed to transfer samples from rotorcraft to lander science module.		---	---	A. Microscopic imager and IR Spectrometer will be heritage from 2003 MER missions. B. Robotic arm will have partial heritage from Mars Polar Lander hardware
3. Goal I, Obj. C, "Assess Pre-Biotic Organic Chemistry," Investig. 1	GCMS	---	Cross-contamination between samples must be minimized. Proper cataloging, archiving, and/or disposition of samples must be provided for.		Sophisticated data management tools will be required to optimize 'data fusion' between the in-situ analysis results for soil and rock samples and the sample 'context' information derived from the aerial survey and remote-site imagery.	--	GCMS will have heritage dating back to the Viking lander missions.
4. Goal III, Obj. A, "Determine Present State, Distribution, and Cycling of Water," Investig. 2	GCMS Microscopic Imager APXS (Alpha Proton X-Ray Spectrometer)	Through use of the APXS assess the morphology of small rock samples for origin (volcanic versus sedimentary)	---		---	--	APXS will have heritage technology dating from the Mars Pathfinder mission.

Requirements on Notional Mission

Orbiter	Not required; will utilize pre-existing communication assets and/or lander-based direct communication with Earth
Launch Vehicle	Delta II 7925-9.5
Launch Date	~ June 2007
Mission duration	90 Sols (upon landing)
Flight System Elements	Cruise stage; Entry, Descent, Landing System (EDLS): Pathfinder/MER-style tetrahedron with inflatable airbags

Requirements on Spacecraft Flight System

Control method	Spin stabilized; 2 rpm cruise stage.
Instrument Power	Minimum instrumentation (and power requirements) for trajectory corrections and spacecraft health monitoring; no spacecraft science instrumentation per se.
Special protection:	Mars rotorcraft will be composed of materials and sub-systems that will need to be assessed for their environmental compatibility with spacecraft cruise stage.
Radiation environment	No RTGs required; solar and battery power only.
EDL Maneuvering:	None required beyond matching MER or Pathfinder Error Ellipses.

Requirements on Communications & Data System

Data Volume (Mbytes per day):	~100 Megabytes (per flight)
Number of data downlinks per day:	1
Real time requirements:	None

CRITICALITY OF IN-SITU ANALYSIS CAPABILITY

It will be essential, in order to accomplish the ambitious notional Mars Scout outlined above, to not only emphasize the development of rotary-wing technologies but to also develop science instrumentation and tools to enable sophisticated in-situ analysis (on the lander) of soil and rock samples. A major area of investigation is the proper handling, processing, and archiving the soil and rock samples – both on the Mars rotorcraft and the lander-based in-situ analysis science system.

A variety of tools and robotic devices will be needed to effectively use a Mars rotorcraft as a sampling device for a lander-based system of in-situ analysis.

Mars Rotorcraft

Sponsons would be mounted to the rotorcraft to support robotic actuators/effectors. A robotic arm with several different types of end effectors (grippers, scoops, etc.) would be used to collect soil and rock samples in the immediate vicinity of the rotorcraft, while it is at rest on the ground. Short hops (of a few meters) with the rotorcraft might be necessary in order to acquire certain select specimens. A tethered spring-loaded 'harpoon' for collecting samples beyond the reach of a robotic arm might also be used. Such a 'harpoon' device could also have a camera attached to it so as to get panoramic photographs of the remote-site location, with possibly the Mars rotorcraft in the foreground. The Mars rotorcraft sponson would also support sample collection boxes for transport of soil/rock sample back to the lander.

Lander

The lander would need to have a large robotic arm to aid in the initial deployment of the Mars rotorcraft. Additionally, the lander robotic arm would be used to attach power cable to Mars rotorcraft for electric recharging, or a line for refueling vehicle propellant. Finally, the lander robotic arm would have to transfer soil/rock samples from the Mars rotorcraft collection boxes to the lander in-situ analysis science module.

Lander in-situ analysis science module would have to have a in-box hopper for transfer of the soil/rock samples to an internal array of handling and processing tools; such tools would include specimen fixtures/clamps, grinding and cutting wheels, and drills for studying the interior of rocks and generating fine particulate for chemical analysis. Internal mechanisms would also have to exist inside the lander in-situ analysis science module to transfer specimens to individual scientific apparatus/instrumentation. Lander would also require a set of sample storage bins for cataloging/archiving specimens, with the possible capability of withdrawing the sources from storage and retesting as needed/justified. Avoiding cross-contamination of soil/rock specimens during the handling and analysis process will be essential in ensuring data quality.

This whole process – sample collection and in-situ analysis -- would have to be fully automated, including the data acquisition, processing, and transmitting of information back to mission scientists on Earth. Scientists could adjust, as need be, mission planning between Mars rotorcraft flights, subject to preliminary results derived from the lander in-situ analysis.

DEVELOPMENT OF REQUIRED ROTARY-WING TECHNOLOGIES

Heritage systems and technology would be used as much as possible in this notional Mars Scout mission, and will include as a minimum: all lander-based science instrumentation, the lander and aeroshell/entry vehicle configurations, and the spacecraft system. New technology for this notional Mars Scout mission will primarily be in the form of the Mars rotorcraft.

Analytical assessments have been made of the Mars rotorcraft concept over the past two years both within NASA and other institutions [4-11].

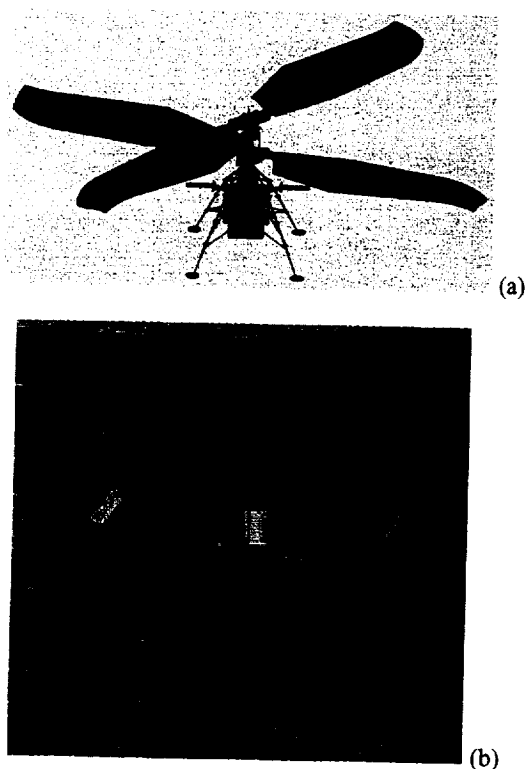


Fig. 9a-b – (a) University of Maryland MARV; (b) Georgia Institute of Technology GTMARS

Further, through the co-sponsorship of Sikorsky Aircraft and NASA Ames, the American Helicopter Society, International conducted its Year 2000 university student design competition on Mars rotorcraft (Fig. 9a-b). These highly detailed design studies of the Mars rotorcraft concept – based on a common set of design requirements very much consistent with the notional Mars Scout mission outlined in this paper – effectively constitutes a set of independent reviews/assessments of the feasibility of the concept by academic institutions [9-11]. In all cases, these academic AHS design competition

participants analytically verified the feasibility of the Mars rotorcraft concept. Additionally, funding from the NASA Institute of Advanced Concepts has been provided to university researchers [3] for complementary work on a very small rotary-wing platform which has Mars exploration potential, among other applications.

Isolated Rotor Hover Performance Experimental & CFD Investigations

A hover test stand, and a baseline proof-of-concept rotor (see Fig. 10 and Table 3), have been fabricated and are nearly ready for testing in a large environmental chamber – which can simulate Mars surface atmospheric conditions. This proof-of-concept rotor, though not as yet an optimized design, has been designed and fabricated to many of the exacting requirements dictated for a flight vehicle – including ultra-lightweight construction and blade dynamic tuning for low structural loads and vibration. The rotor airfoil used for this proof-of-concept rotor is the Eppler 387, a well-known low Reynolds airfoil. Recent unpublished two-dimensional airfoil test data in compressible, near transonic, test conditions at NASA Langley has been acquired for this airfoil, demonstrating moderately high lift coefficient values (R. Campbell - private communication). An advantage of rotorcraft, versus any other aerial vehicle proposed for Mars exploration, is the ability to conduct hover testing in existing ground-test facilities; additionally, it is also the unique advantage of the Mars rotorcraft concept that typically the most severe aerodynamic performance operating condition is in hover rather than forward-flight.

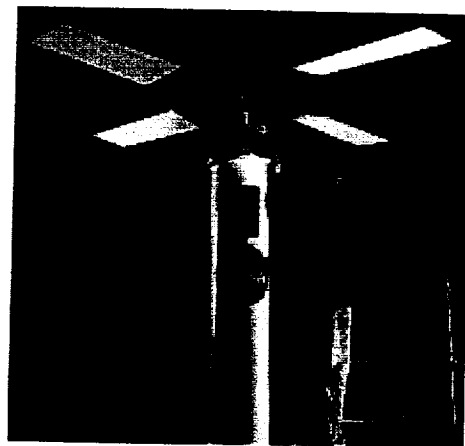


Fig. 10 – Mars Rotor Hover Test Stand

Table 3. Proof-of-Concept Mars Rotor Description

Number of Blades	4
Rotor Diameter	2.438m
Blade Root Cut-Out (To simulate blade telescoping required for storage/transport)	40% blade span
Disk Loading (Nominal '1G')	4 N/m ²
Tip Mach Number	0.65
Blade Tip Reynolds #	54,855
Thrust Coefficient, CT (Nominal '1G')	0.0108
Mean Blade Lift Coefficient	0.4
Blade Chord	0.3048m (constant) from 40% radial station outward
Rotor Solidity	0.191
Blade Linear Twist Rate	0 deg. out to 40% span; +2.4 to -2.4 deg. from 40 to 100% span.
Blade Weight	0.35 kg per blade
First Fundamental Elastic Modes	1.264 per rev -- first flap mode; 1.118 per rev -- first lag mode; 2.310 per rev -- first torsion
Outer Blade Span Airfoil Section	Eppler 387
Spar Section	Circular tube with chordwise flat plate stiffener (30% chord)
Blade Construction	Milled foam airfoil fairings with internal cavities & graphite LE cap; Circular graphite tube spar across complete span of blade; 45 deg. graphite chordwise flat plate stiffeners from 5% to 40% station.
Rotor Hub Configuration	Rigid/cantilevered hub, with tension/torsion straps, dry contact pitch bearings, & pitch arms at 5% station

The analytical tools used to date in assessing the aerial vehicle performance will be significantly upgraded in the near future by applying very sophisticated rotorcraft modeling tools to perform comprehensive analyses in forward-flight (Fig. 11a-c) and Navier-Stokes CFD predictions of the Mars rotorcraft in hover. Confidence in these CFD predictions will be gained through validation against the experimental data resulting from the proposed proof-of-concept hover testing. Subsequent to the initial isolated rotor hover testing and the CFD work, a tethered 'flight' of a stripped down proof-of-concept vehicle in the Ames environment chamber will be pursued. This vehicle, by necessity because of Earth's higher gravity, will have to be powered by ground-based power sources and flight controllers (among other things) but will represent a major step ahead in the development of a Mars rotorcraft.

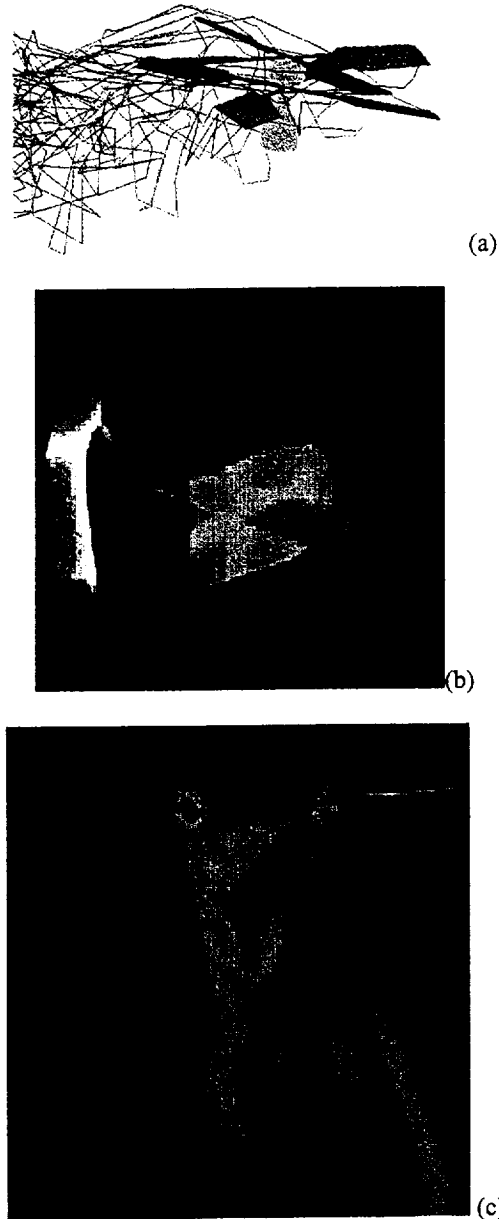


Fig. 11a-c– Advanced Computational Analyses; (a) comprehensive aeromechanics analysis; (b) Navier-Stokes CFD (OVERFLOW-D) grids; (c) OVERFLOW rotor wake vorticity prediction

Coaxial Rotor/Vehicle Hover Test

There is a considerable body of experimental data and analysis tools for coaxial helicopter hover performance (for terrestrial vehicles). There is no such data or validated tools for a coaxial helicopter designed to operate under martian environmental conditions. As a part of preliminary test preparation prior to tethered hover flight, a proof-of-concept coaxial configuration (the Martian Autonomous Rotorcraft Test Article, or MARTA) is

being developed to test coaxial rotor performance in- and out-of-ground effect. Performance measurements are to be made by means of load cells mounted to the coaxial helicopter's main sponsons/landing-gear (Fig. 12). The rotor blade sets for the coaxial helicopter ground test will be identical to the rotor blade set used in the isolated rotor hover test.

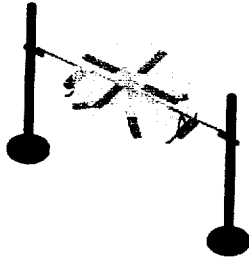


Fig. 12 - Mars Coaxial Rotor Hover/Ground Test

Coaxial Helicopter Tethered Flight (Hover) Demonstration

Upon completion of the MARTA hover/ground aerodynamic performance testing, the model will be modified and used as a tethered hover flight demonstrator (Fig. 13).

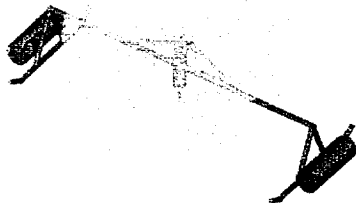


Fig. 13 - Coaxial Helicopter (MARTA) Demonstrator

This tethered 'flight' will be of a stripped-down version of the proof-of-concept vehicle. Demonstration testing will occur in the Building 242 vacuum/environmental chamber at Mars representative atmospheric densities. The demonstration vehicle, by necessity because of Earth's higher gravity, will have to be powered via its tether cables by ground-based power sources and flight controllers. Key to the demonstration will be whether or not hover out-of-ground effect is achieved.

Terrestrial-Analog Flight/Mission Demonstrations

It is essential that not only is the aeromechanics of rotors and vehicles in simulated martian environments (using vacuum/environment chambers) are studied during the early stages of the concept development, but it is also necessary to perform terrestrial-analog demonstrations of the flight and mission characteristics of such vehicles.

A low-cost approach is being taken in developing a coaxial helicopter flight demonstrator for terrestrial-analog studies (Fig. 14). Such vehicles are designated as Terrestrial-Analog Mars Scouts (TAMS). A series of such vehicles will be developed. The TAMS vehicles are constructed primarily out of radio-controlled hobbyist electric helicopter models. The TAMS vehicles have also acted as conceptual prototypes for the MARTA model tested under simulated Mars atmospheric conditions.

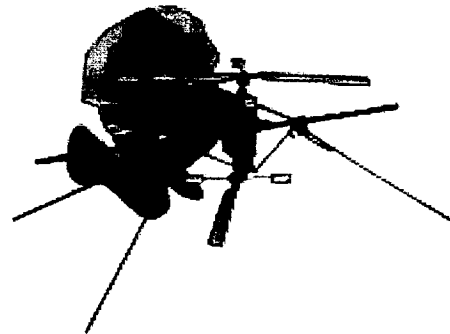


Fig. 14 - Terrestrial-Analog (TAMS) Flight Demonstrator

The aerial survey potential for rotorcraft for Mars exploration is self-evident -- terrestrial rotorcraft have been used for this purpose from their earliest inception. But using rotorcraft as mobile 'sampling' devices to find, acquire, and return to lander-based in-situ analysis equipment will also be required for rotorcraft acting as 'Mars Scouts.' How rotorcraft might be adapted and used for soil/rock sampling missions is still being defined/assessed. As a part of that assessment it is necessary to develop a second TAMS vehicle that features/employs various types of robotic actuators and effectors to validate the utility of such devices in representative mission scenarios (Fig. 15).

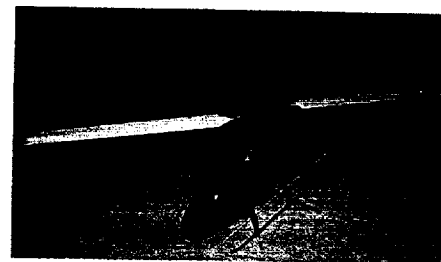


Fig. 15 - Integration of Robotic Actuators/Effectors for Soil/Rock Sampling

Vehicle Autonomy

Unprecedented levels of vehicle autonomy will need to be demonstrated to enable a Mars rotorcraft. Planetary exploration is, in fact, perhaps the ultimate challenge for autonomous systems. The distances and communication delays between Earth and other planetary bodies are too great to allow for any sort of direct flight/mission control of robotic aerial platforms. Further, many state-of-art terrestrial aerial robotic systems rely heavily on GPS positioning for navigation and control, an option not available for planetary aerial vehicles. Such vehicles will instead have to rely upon more subtle devices/techniques for GNC. Several of these advanced techniques rely on the emergent field of vision-based reasoning/processing. A study, resulting from a university grant issued by NASA Ames to Carnegie Mellon University, was conducted examining from a conceptual design perspective the challenges and potential of using vision-based navigation systems for a Mars rotorcraft; these preliminary results were very encouraging. Further, planetary environments will have poorly understood atmospheric characteristics and surface features. Adaptive control techniques coupled with contingency mission planning automated reasoning software will be essential for successful mission execution of these vehicles. Fortunately, many of the above vehicle autonomy issues are currently active research areas within rotorcraft and aerospace communities (Fig. 16).

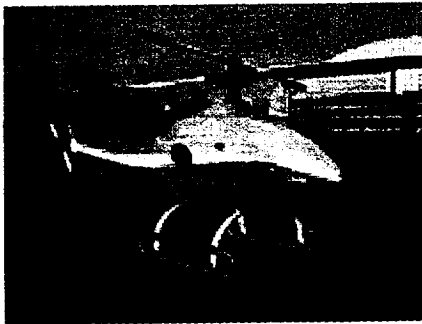


Fig. 16 – Army/NASA Rotorcraft Division Autonomous Rotorcraft Project

Ultimately, future generations of TAMS demonstrators will need to embody and test increasingly higher levels of autonomous system technology for overall risk reduction.

FUTURE INVESTIGATIONS & TRADE STUDIES

The work accomplished to date is only the beginning of what is required to satisfactorily develop a rotary-wing platform for the exploration of Mars. Many technical issues remain to be explored and satisfactory solutions

derived. Proposing the use of a rotary-wing aerial platform for a Mars Scout mission is not as mature a technical approach as many other concepts likely to be advocated for Mars Scout missions. And yet, the Mars rotorcraft concept offers such a tremendous potential increase in mobility for Mars exploration, with a corresponding near-order-of-magnitude increase in mission productivity, that a modest investment now, for the future, should be justifiable.

Martian aerial scouts offer the potential to dramatically expand the surface area of Mars that can be explored in future missions. By flying over difficult topography, aerial vehicles are capable of covering much more area than a rover in significantly less time. The 2003 mission Mars Exploration Rovers will cover approximately 100 meters per Sol; a Mars rotorcraft could cover over twenty times that distance per flight (assuming a seven day between-flight cycle for vehicle recharging and data analysis/transmittal to Earth). By operating above the ground surface, the potential line of sight of sensor systems also greatly expands. A martian aerial scout flying at 100m AGL would have a line of sight in excess of 25 km compared to the 5 km line of sight of a ground based vehicle assuming flat terrain.

Powered-flight aerial vehicles are superior to balloons/aerostats in all respects, except maybe, simplicity. However, even with respect to their conceptual simplicity, one has to acknowledge that balloons, as represented by their terrestrial counterparts, are not without their own unique failure mechanisms (for example, the early attempts to fly the erstwhile Ultra Long Duration Balloon experiments). The ability to select an area of interest on the martian surface, direct a powered aerial vehicle to that location, and to survey and conduct experiments as desired is essential for superior scientific investigations of Mars. Having a balloon passively, uncontrollably, skirt across the planet will be of modest benefit at best.

Vertical lift aerial vehicles – including rotorcraft -- combine the exploration area advantage described above with the ability to takeoff and land in unprepared sites of scientific interest. Unlike “single shot” fixed wing aircraft concepts, a vertical lift aerial scout offers the opportunity to perform multiple mission sorties by recharging at the lander site. A vertical lift aerial vehicle solution enables sample return missions. Samples could be gathered from a wide radius to a lander/primary-base. As demonstrated on Earth, rotorcraft uniquely have superior low-speed handling qualities. Rotorcraft Mars scouts would enable low-speed, precise movement in three dimensions allowing the craft to closely study cliff walls or capture a 360° surface view of large objects. Highly sloped terrain, possibly resultant from erosion, can be thoroughly studied. This terrain will remain unexplored by ground vehicles or fixed wing aircraft concepts while a rotorcraft can fly low to the ground,

allowing great image detail. Low speed handling qualities make takeoff and landing operations possible in unprepared terrain. Finally, fixed-wing aerial vehicles suffer from substantial technical challenges in their release from entry vehicles in descent, or launch/catapulting from ground-based assets. Even hypersonic rocket-propelled 'fixed-wing' aerial vehicles - that are both entry vehicle as well as aerial scout -- pose significant technical challenges; such hypersonic aerial vehicles have very limited developmental heritage for terrestrial applications, let alone their readiness for planetary exploration missions.

CONCLUDING REMARKS

The utility of rotary-wing aerial platforms for Mars Scout missions has been discussed in some detail in this paper. These 'Mars rotorcraft' provide unique mission capabilities that no other aerial vehicles can provide. Further, Mars rotorcraft would significantly enhance mobility above that provided by rovers while at the same time maximizing the science return of the mission.

Work is currently ongoing within NASA and its industrial and academic partners to address the critical technical issues for Mars rotorcraft.

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BIOGRAPHY

Mr. Young has worked at NASA Ames Research Center in the area of rotorcraft research for the past nineteen years. He has worked on several large-scale rotorcraft experimental programs in the National Full-scale Aerodynamics Complex at NASA Ames. Mr. Young has served as the Group Leader responsible for tiltrotor technology investigations within the Aeromechanics Branch as well as being the project manager responsible for the development of the Tilt Rotor Aeroacoustic Model (TRAM) -- a quarter-scale tiltrotor test stand. Mr. Young is currently leading several advanced rotorcraft technology efforts at NASA Ames, including the study of vertical lift planetary aerial vehicles and Mars rotorcraft.

