Experimental Investigation and Demonstration of Rotary-Wing Technologies for Flight in the Atmosphere of Mars

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Abstract

This paper details ongoing work at NASA Ames Research Center as to experimental investigations and demonstrations related to rotary-wing technologies that might be applied to flight in the atmosphere of Mars. Such Mars rotorcraft would provide a 'three-dimensional mobility' to the exploration of the Red Planet. Preliminary results from isolated rotor testing in Mars-representative atmospheric densities, as well as progress towards coaxial test stand development are discussed. Additionally, work towards the development and use of surrogate flight vehicles -- in the terrestrial environment -- to demonstrate key technologies is also summarized.

Introduction

Vertical lift planetary aerial vehicles hold considerable potential for supporting NASA planetary science and exploration missions. In particular, use of vertical lift aerial vehicles for the exploration of the planet Mars (Fig. 1) is receiving substantial attention within the rotorcraft and planetary science communities.

The Army/NASA Rotorcraft Division in collaboration with the Center for Mars Exploration (CMEX) at NASA Ames has been studying the design challenges and opportunities for Mars rotorcraft for the past several years. Several conceptual design studies of Mars rotorcraft – and other such aerial vehicles -- have been conducted and reported by Ames and other researchers (Refs. 1-14).

Recently work by the Army/NASA Rotorcraft Division and CMEX has begun focussing on experimental investigations and demonstrations of proof-of-concept rotor systems and vehicles to continue establishing the fundamental feasibility of autonomous rotary-wing platforms for the exploration of Mars.

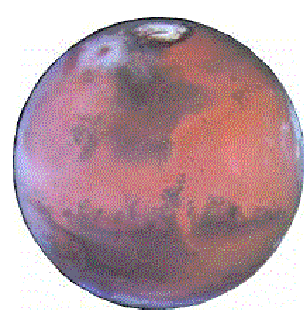

Fig. 1 – Mars as Imaged by the Hubble Space Telescope

The Martian atmosphere is 95% CO_2 with the remaining 5% comprised of N_2 and other trace gases (Table 1). Mars'

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gravity is slightly greater than a third of Earth's. The atmosphere of Mars is extremely cold and thin (approximately 1/100'th of Earth's sea-level atmospheric density). Further, a seasonal variation of approximately 20% of the planetary atmospheric mass occurs on Mars (a consequence of polar CO_2 condensation and sublimation). Given the thin, carbon-dioxide-based Martian atmosphere, developing a rotorcraft design that can fly in that planetary environment will be very challenging. Additional comparisons between Earth and Mars are shown in Table 1.

Table 1. Planetary Description (Ref. 15)

	Mean Radius (km)	Gravity (m/s^2)	Mean Surface Atmos. Temp. (^{o} K)	Mean Surface Atmos. Pressure (Pa)	Mean Surface Atmos. Density (kg/m^3)	Atmos. Gases
Earth	6371	9.82	288.2	101,300	1.23	N_2 78% O_2 21%
Mars	3390	3.71	214	636	1.55×10^{-2}	CO_2 95% N_2 2.7% Ar 1.6% O_2 0.1%

This paper will now discuss preliminary work on a series of rotor and vehicle ground tests in simulated Mars environmental conditions, as well as flight and mission demonstrations on terrestrial analog vehicles. Additionally, Appendices A and B discuss some of the mission architecture and programmatic issues underlying the development of Mars rotorcraft.

Design Tradeoffs

From an aeromechanics perspective, Mars rotorcraft will be very different from their terrestrial counterparts. Mars rotorcraft will have very large lifting-surfaces and will be required to have ultra-lightweight construction (Fig. 2). For example, referring to Fig. 2, in order to lift ten kilograms of vehicle mass on Mars, a single main rotor (at a disk loading of 4 N/m^2) would have to have a radius of approximately 1.7 meters. Rotors for flight in the atmosphere of Mars will also have to operate with a combination of low Reynolds number and compressible flow aerodynamics.

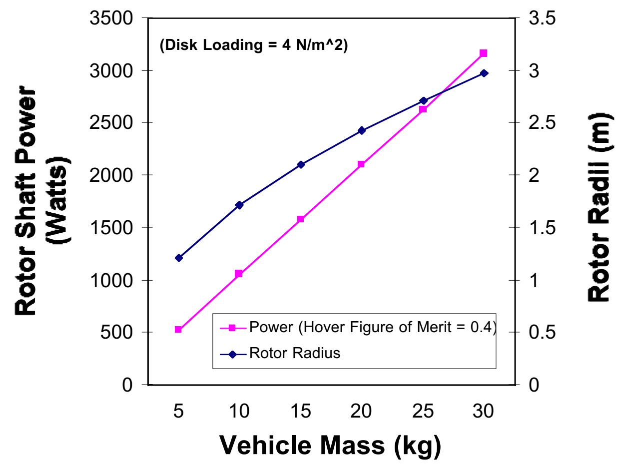


Fig. 2 – Sizing Trend for Mars Rotors

Conceptual design work to date has examined tiltrotor, quad-rotor, and coaxial helicopter configurations for Mars exploration. Both electric propulsion (batteries versus fuel cells) and Akkerman hydrazine (mono-propellant) reciprocating engines have been examined for propulsion for these notional vehicles. Tiltrotor configurations would seem to be a longer-term candidate for Mars exploration as compared to the other two vehicle configurations as a consequence of the increased difficulties of the deploying a tiltrotor on the Mars surface (or mid-air descent). Similarly, electric propulsion appears to be a more likely near-term candidate for Mars vertical lift vehicles because of comparative reliability, technology maturity, and environmental safety (hydrazine is a toxic substance that has to be carefully handled).

Currently, both coaxial and quad-rotor configurations – using electric propulsion and regenerative fuel-cell technology – continue to be seriously examined for NASA Mars Exploration and Mars Scout programs (Fig. 3).

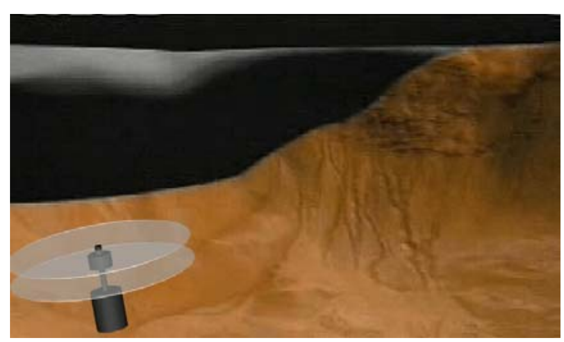


Fig. 3 – Mars Coaxial Helicopter

Isolated Rotor Hover Test

A hover test stand and a baseline proof-of-concept rotor were fabricated and tested in a large environmental chamber – which can simulate Mars surface atmospheric pressures and densities. An advantage of rotorcraft, versus any other aerial vehicle proposed for Mars exploration, is the ability to conduct testing in existing ground-test facilities. It is also the advantage of the Mars rotorcraft concept – as compared to other aerial explorer concepts -- that the most severe aerodynamic performance operating condition is typically in hover rather than forward-flight.

Rotor Description

Table 2 summarizes some of the characteristics of the baseline, proof-of-concept rotor studied in the isolated rotor hover testing.

Table 2. Isolated Mars Rotor Description

Number of Blades	4
Rotor Diameter	2.438m (8 ft)
Blade Root Cut-Out (To simulate blade telescoping required for storage/transport)	40% blade span
Disk Loading ('1G' Design Point)	4 N/m^2 (0.084 lb/ft^2)
Tip Mach Number (Design Point)	0.65
Blade Tip Reynolds # (Design Point)	54,855
Thrust Coefficient, CT ('1G' Design Point)	0.0108
Mean Blade Lift Coeff. (Design Point)	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	0.355 kg per blade
First Fundamental Elastic Modes (at 1200 RPM Design Point)	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 fairings with internal cavities; graphite leading edge 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

Figure 4 is a picture of the baseline proof-of-concept Mars rotor on its isolated rotor hover test stand. This four-bladed, 2.438 meter (eight-foot) diameter rotor is approximately sized for a 10 kilogram (total vehicle mass) coaxial Mars helicopter. This proof-of-concept rotor is a not an optimized design. The basic rotor construction approach, though, does emphasize the ultra-lightweight structures required for Mars rotorcraft. Future generation Mars rotors will yield further improvements in weight and robustness, as well as improved dynamic tuning for forward-flight testing.

Fig. 4 – Baseline Proof-of-Concept Mars Rotor and Hover Test Stand

As noted in Table 2, the baseline Mars proof-of-concept rotor uses an Eppler 387 airfoil for its constant chord outboard blade sections. The Eppler 387 is a well-documented low Reynolds number airfoil section – refer to Fig. 5 (Refs. 16-19). Derived effective mean rotor lift-curve slopes and profile drag coefficient data from the Mars rotor hover tests will be compared to an existing two-dimensional airfoil database. The Eppler 387 is by no means an optimized airfoil for Mars rotor applications. A number of researchers are currently developing advanced airfoils for operating in the low-Reynolds number, compressible flow regime. These advanced airfoils will not only have application for Mars rotorcraft, but could also be applied to high-altitude long-endurance (HALE) aircraft and micro air vehicles which require similar low Reynolds number airfoils.

The Eppler 387 low-speed lift/drag polar displays a sudden rise in airfoil drag for lift coefficients greater than 0.5. This ‘spike’ in airfoil drag for lift coefficients between 0.5 and 1.0 is due to the formation and evolution of a laminar separation bubble on the upper surface of the Eppler 387. The proof-of-concept rotor was designed to operate at nominal ‘1 G’ conditions at a mean lift coefficient of 0.4, just below the sudden increase in drag evidenced in the low-speed two-dimensional airfoil data.

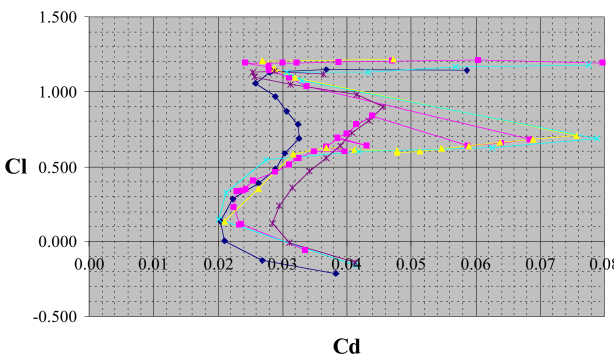


Fig. 5 – Eppler 387 Airfoil Lift/Drag Polar

The isolated rotor blade property spanwise distributions are shown in Fig. 6. The individual rotor blades weigh 355 ± 5 grams and have a spanwise center-of-gravity of 26 ± 0.2 inches. The predicted versus measured nonrotating (cantilevered) blade frequencies are shown in Table 3. The rotor dynamic frequency predictions are shown in Fig. 7. The nonrotating and dynamic frequency predictions were made with a Myklestad-type analysis. The rotor blade elastic and structural properties are not optimized for the Mars rotorcraft application. They represent a first generation attempt to incorporate ultra-lightweight structural concepts into blade fabrication. It is anticipated that subsequent, second-generation rotor designs will yield lighter blades while at the same time increasing lag and torsion blade frequencies to more desirable levels. In particular, the inboard blade spar design can be improved.

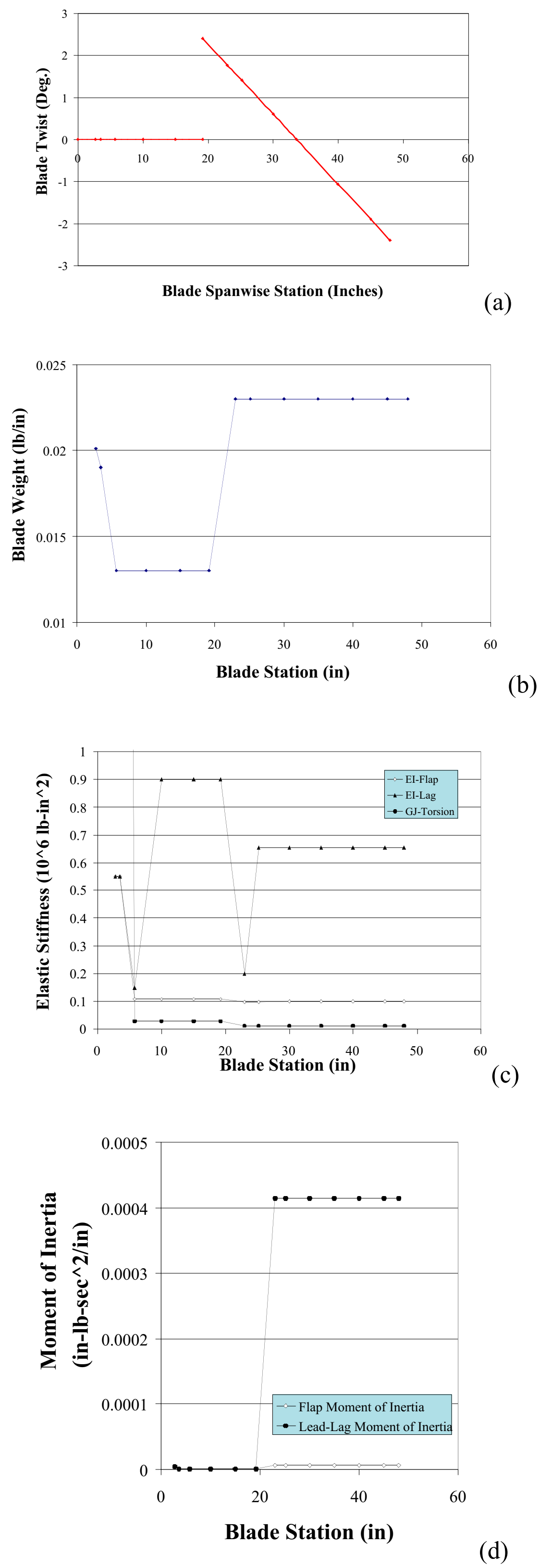


Fig. 6– Blade Properties; (a) twist; (b) weight; (c) stiffness; (d) moment of inertia

Table 3. Measured Versus Predicted Blade Nonrotating Frequencies (Hz)

	Flap		Lag		Torsion	
Prod. Blades	1st	2nd	1st	2nd	1st	2nd
1	11.0	69.0	19.5	123.5	34.5	103.5
2	11.5	70.5	19.5	125.0	34.0	107.0
3	11.5	71.0	19.5	124.0	34.5	106.5
4	11.0	69.5	20.0	124.5	34.0	103.5
Spare	10.5	69.5	18.5	121.0	34.0	107.0
	Flap		Lag		Torsion	
Final Predictions	1st	2nd	1st	2nd	1st	2nd
	11.55	71.75	19.97	121.7	37.29	112.69

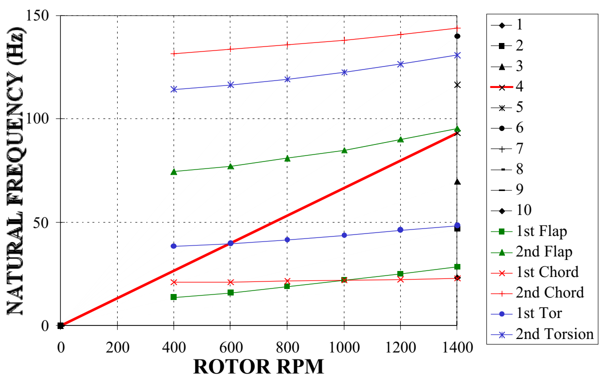


Fig. 7 – Rotor Predicted Dynamic Frequencies

Test Description

Rotor testing in simulated Martian atmospheric conditions was conducted in the NASA Ames Planetary Aeolian Laboratory's vacuum, or 'environmental,' chamber. This very large environmental chamber (Fig. 8) is capable of being pumped down to pressure levels consistent with Mars surface atmospheric pressures. As such, it represents a critical test facility for current and future testing of rotary-wing platforms for possible Mars application. This test facility is normally used for studies of Mars soil erosion processes using a small 'Mars wind tunnel.' The environmental chamber does have some limitations that should be noted. The test chamber working gas is air (versus CO_2 for the Mars atmosphere) for all rotor testing conducted. The working gas temperature could not be directly controlled/maintained. The test chamber, though large, was not empty and shared floor space with the "Mars wind tunnel,' among other test equipment. Rotor wake recirculation in the facility is likely to be higher than ideal, although the rotor was tested thrusting down, wake up, to minimize ground and recirculation effects. These issues, though important, are considered to be non-critical for the proof-of-concept testing conducted.

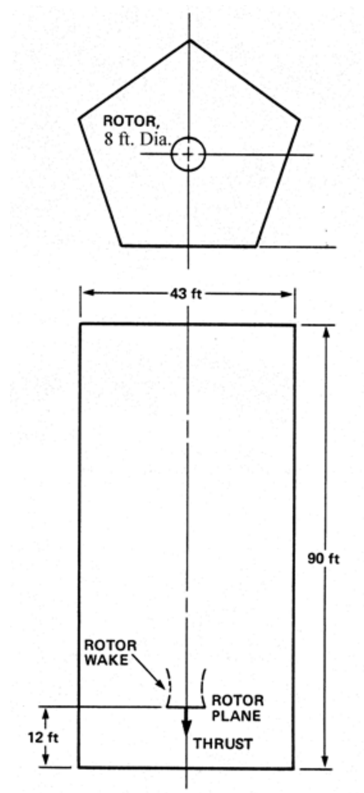


Fig. 8 – Hover Test Chamber

In order to keep test stand development costs to a minimum, the rotor thrust was measured by a set of three load cells. Rotor shaft power was derived by measuring the test stand electric motor input power -- and through a set of tares and motor efficiency measurements -- corrected to yield rotor shaft output power. Collective was set by a single fixed-system control actuator. The blade pitch angle was calibrated with respect to the actuator stroke tachometer output.

Experimental Results

The paper will now discuss preliminary results from the isolated rotor hover testing. Thrust, power, collective data was acquired for a variety of tip Mach and Reynolds numbers and atmospheric densities. This data represents a valuable resource for the development of Mars rotorcraft. The data from the isolated rotor hover test will also be correlated against Navier-Stokes CFD predictions (Ref. 20).

Figures 9 and 10 are rotor thrust measurements made at an environmental chamber atmospheric density of 1.24×10^{-2} kg/m^3 (or 2.41×10^{-5} lb-sec^2/ft^4). This is lower than the 'mean' Mars surface atmospheric density noted in Table 1. Data was acquired over a range of atmospheric densities in order to bracket the design point. The working gas in the environmental chamber is air. Because the environmental chamber cannot be independently controlled with respect to the chamber temperature, the tip Mach number can not be independently set with respect to tip Reynolds number. The data in Figs. 9 and 10 were acquired at a chamber temperature of ~13ºC (~55ºF) and a pressure of ~10 mBar (~0.14 psi). Because air is used as the working gas, and because the chamber temperature is higher than the Mars mean surface temperature, testing in the chamber is limited as to maximum tip Mach number (maximum test $M_{tip} \approx 0.50$ versus design $M_{tip}=0.65$) and Reynolds number (maximum test Reynolds number of ~37,000 versus a design Reynolds number of 54,000) at the 1.24×10^{-2} kg/m^3 atmospheric density. This issue can be partially addressed by relaxing the density set point constraint so as to define an aerodynamic sensitivity matrix for the rotor coefficients as a function of Reynolds number.

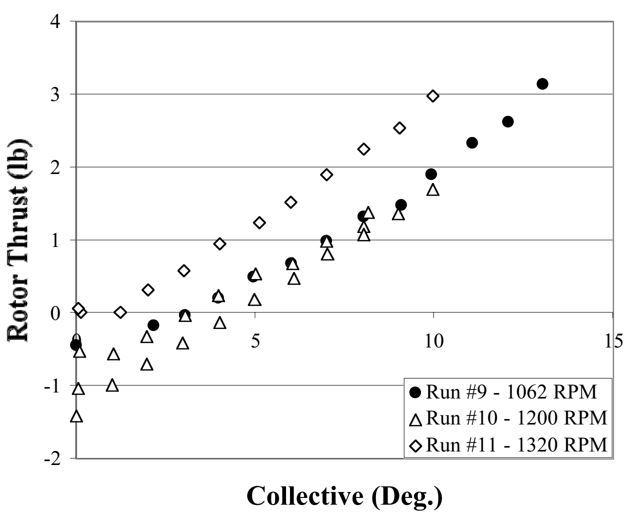


Fig. 9 – Rotor Thrust versus Collective for Various Rotor Speeds (No Hub Tares)

The (single) rotor thrust required for '1G' hover of a 10 kilogram Mars coaxial helicopter is ~18 N (or ~4 lb). Even at an environmental chamber atmospheric density approximately 20% lower (1.24×10^{-2} versus 1.55×10^{-2}) than the mean Mars surface atmospheric density, the isolated rotor results suggest that this thrust level is achievable at a collective of ~15 degrees for the 1200 RPM set point. The 20% knockdown in atmospheric density, in part, represents an extreme design condition that accounts for seasonal variations in the Mars atmosphere.

Referring to Fig. 9, Run 10 has a fair amount of hysteresis in the collective setting. This is currently being addressed. Also puzzling at this time is why the Run 9 (1062 RPM) and Run 10 (1200 RPM) data in Fig. 9 do not have a greater thrust offset between the two curves. More data, at a larger range of tip Mach and Reynolds number, will hopefully allow better insight into rotors operating a very low Reynolds numbers and compressible flow. The negative thrust generated at lower collective angles is a consequence of the twist of the rotor (-8 degrees linear twist rate) and the cambered Eppler 387 airfoil.

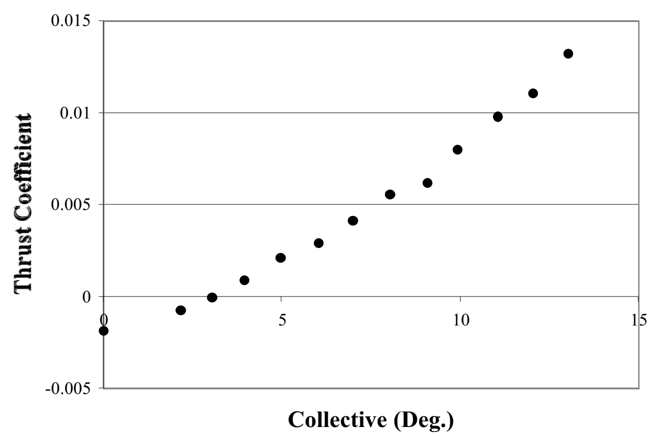


Fig. 10 – Rotor Thrust Coefficient versus Collective (Deg.); $M_{tip} = 0.40$ & $Re_{tip} = 29,900$

Using least-squares regression analysis, the mean rotor airfoil lift curve slope and zero-lift angle of attack can be derived from Figs. 9 and 10 data. Table 4 summarizes the regression analysis results. These derived mean rotor airfoil lift curve slopes and zero-lift angles of attack include three-dimensional rotor flow characteristics. No trip strips, or other turbulence inducing devices, are used on the blade airfoil. Given the very low Reynolds regime that the rotor blade airfoils are operating under – compounded by compressible flow effects -- it is not surprising to see nonlinear Reynolds effects influencing the derived mean lift curve slopes. Two-dimensional airfoil data for the Eppler 387 airfoil (Refs. 16-19) is limited to Reynolds numbers greater than or equal to 60,000 and at low Mach numbers (typically M_{tun}~0.2). Subsequent testing of the Mars proof-of-concept rotor will more closely examine the Reynolds number and Mach number effects on rotor performance and blade airfoil effective/mean aerodynamics.

Table 4. Mars Rotor Blade Airfoil Aerodynamics

	Run # 9 1062 RPM	Run # 10 1200 RPM	Run # 11 1320 RPM
Re_{tip}	29,900	33,600	36,900
M_{tip}	0.40	0.45	0.50
$C_{L\alpha}$ (1/rad)	5.03	4.09 (3.00[a])	2.92
α_0 (Deg.)	-1.72	-3.97 (-2.35[a])	-0.5

[a] Indicated parameters are derived without second collective sweep that might have hysteresis effects in the collective measurement.

The effective mean lift curve slope and zero-lift angle of attack estimates of Table 4 can be compared to a large body of two-dimensional airfoil data for the Eppler 387 (Fig. 11). This two-dimensional airfoil data is from several different sources and facilities (Refs. 16-19). The mean lift curve slopes (even for Run 9) are well below the two-dimensional airfoil results, though the zero-lift angles are in general agreement. It is anticipated that as isolated rotor data is acquired at Reynolds numbers closer to that for the airfoil data that there will be improved agreement between the two sets of results. Nonetheless, three dimensional flow results will still manifest themselves in the data. Finally, as noted before, the two-dimensional airfoil data (Figs. 5 and 11) reveals nonlinear, and not necessarily consistently repeatable, behavior of the Eppler 387 at low Reynolds numbers. It is still to be seen how this nonlinear flow behavior fully manifests itself in the rotor performance data. Development of improved airfoils for the Mars rotorcraft application will likely follow from this work.

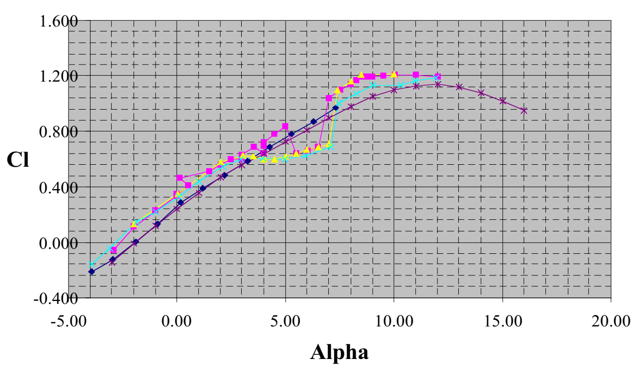


Fig. 11 – Airfoil lift coefficient versus angle of attack curves (low-speed data; Re ~ 60,000)

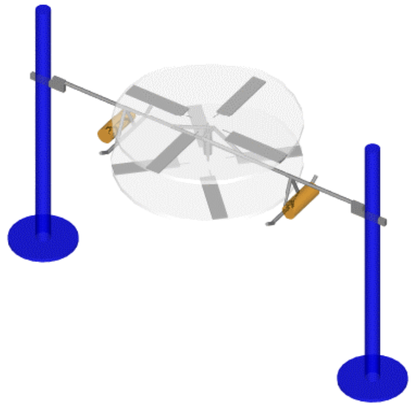
Power measurements have been made during the isolated rotor hover test, but will be reported at a later date in future publications. Rotor shaft power was measured only indirectly. Test stand motor input power and torque are directly measured. Estimation of the rotor shaft power requires an accurate estimate of the test-stand motor/drive-train efficiency, on condition, as to load and speed. Additionally, several bare shaft, hub, and blade spar (particularly important given the 40% blade root cut-out for the proof-of-concept rotor) tares will need to be applied to the rotor power estimates.

Preliminary test results suggest that the proof-of-concept rotor is capable of meeting the design targets for rotor aerodynamic performance. Follow-on second-generation rotors will yield improved aerodynamic, structural, and dynamic designs that will reduce blade mass while refining blade dynamic frequencies.

Coaxial Rotor/Vehicle Hover Testing

As noted previously, the Army/NASA Rotorcraft Division is currently focussing on coaxial helicopter configurations for Mars rotorcraft. There is a considerable body of experimental data and analysis tools (for example, Refs. 21 and 22) 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 for testing in- and out-of-ground effect in the Ames Research Center low-pressure environmental chamber. Hover performance measurements will be made by means of load cells mounted to the coaxial helicopter's main sponsons (cross-bars) at their attachment points with vertical support stanchions (Fig. 12). The rotor blade sets for the coaxial helicopter hover test are identical to the rotor blade set used in the isolated rotor hover test.



(a)

(b)

Fig. 12 – Mars Coaxial Rotor Hover Test; (a) conceptual sketch; (b) early stages of test hardware development

The four primary objectives of the planned coaxial hover testing will be: (1) continuation of hardware prototyping; (2) validation of the relative hover performance effects of coaxial versus isolated rotor configurations, out-of-ground effect; (3) acquisition of a data set for coaxial rotors operating in-ground-effect, for several heights above the ground; (4) determination of the effect of the rotor wake on dust ingestion in the rotor plane by placing a shallow bed of dust and sand on the ground, directly below the rotor.

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).

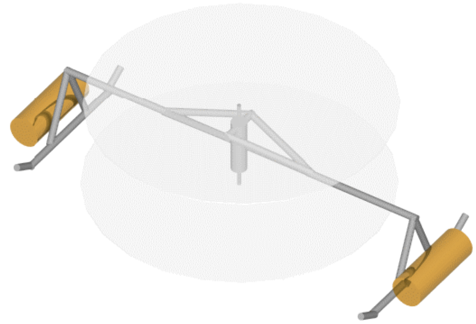


Fig. 13 – Coaxial Helicopter (MARTA) Demonstrator

Demonstration 'flight' testing will be performed in the Ames 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. The vehicle will be restrained by cables and will be limited to rotor speed control only. Hover out of ground will be the ideal goal, but considerable engineering insight will be gained from the vehicle in ground effect.

Terrestrial-Analog Flight/Mission Demonstrations

It is essential that not only are the aeromechanics of rotors and vehicles in simulated Martian environments (using vacuum/environment chambers) 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.

Coaxial Flight

A low-cost approach was taken in developing coaxial helicopter flight demonstrators for terrestrial-analog studies (Fig. 14). A series of such vehicles, referred to as Terrestrial-Analog Mars Scouts (TAMS), was developed. The TAMS vehicles are constructed primarily out of radio-controlled hobbyist electric helicopter models. The same general construction approach for the TAMS vehicles is also being taken for the MARTA demonstrator.

(a)

(b)

Fig. 14 – Terrestrial-Analog (TAMS) Flight Demonstrator; (a) pre-flight and (b) take-off on first flight

The TAMS coaxial helicopter demonstrator is based on an innovative design approach wherein the two two-bladed rotors are driven by independent (decoupled) electric motors and a single stage gear and pinion transmission. The rotor blades are untwisted (flat pitch) and the blade airfoils are symmetrical. Each rotor is two-bladed with a teetering hub and a Bell-Hiller flybar (with paddles) design. The rotor control systems are mechanically coupled together and can provide both differential collective and cyclic control. A 16-cell lithium-ion battery pack yields approximately 6 minutes of typical hover and low-speed loiter flight time. The rotor diameter is 0.982 meters and the gross weight is 3.5 kg.

Table 5 summarizes some of the objectives (near- and long-term) of the planned TAMS testing. As can be seen, TAMS testing can be broken into three categories: mission demonstrations, vehicle proof-of-principle assessments, and a platform for incorporating an incremental approach to implementing vehicle autonomy.

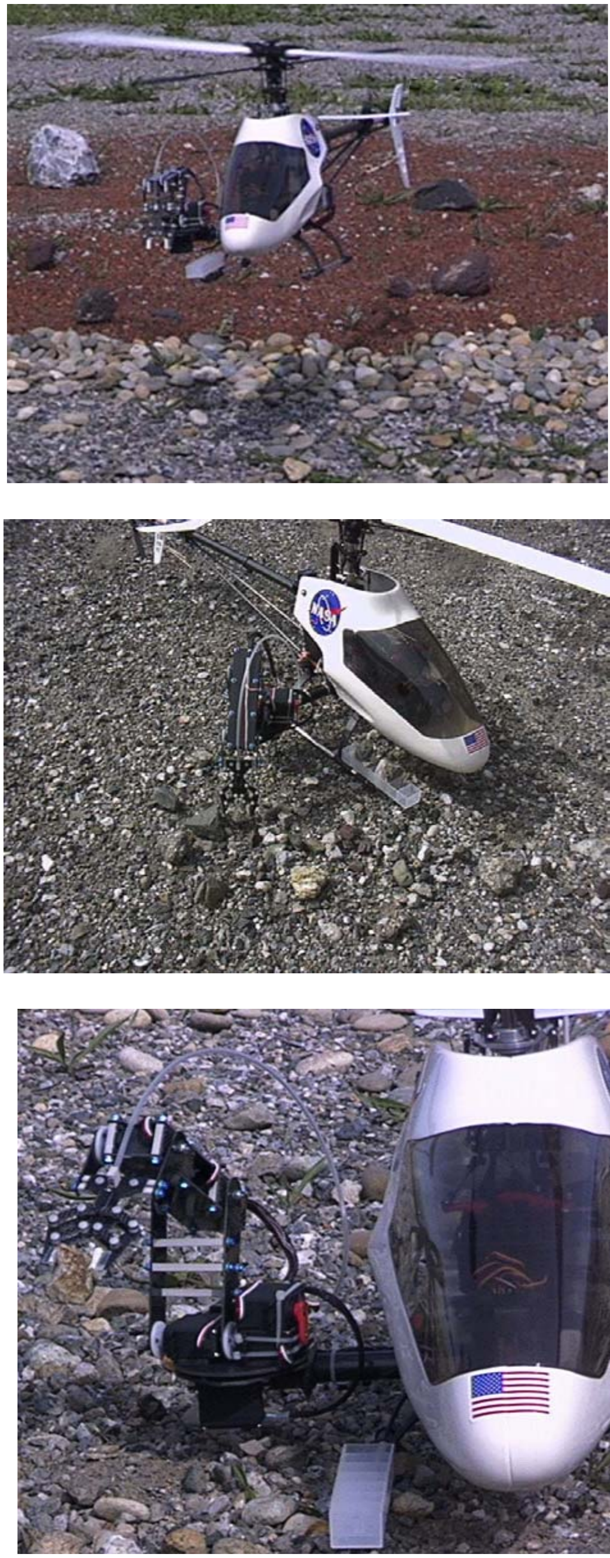
Table 5. TAMS Test Objectives

Mission Demos:
-Acceptable handling qualities for coaxial configuration
-Validate electric propulsion for vehicle using batteries
-Dev. & integration of robotic actuator/sampler for coaxial
-Establish limitations of landing on rough terrain
-Exhibit/demo model to inspire Mars science community
Vehicle Proof-of-Principle:
-Install/test miniature fuel-cells for propulsion (vs. batteries)
-Install onboard wireless video for data & remote piloting
-Mockup stowage/deployment simulation of Mars rotorcraft
Incremental Autonomy:
-Implement optical flow altitude & position hold system
-Install small micro-computer for flight & science data

Initial test objectives have been achieved: the TAMS vehicle exhibits satisfactory handling qualities, using radio control, and the overall electric propulsion strategy has proven acceptable for testing. A considerable amount of system integration and test and evaluation work still remains to be performed using the TAMS vehicle. However, most importantly, many hardware development lessons learned from the TAMS vehicle have already found themselves being applied on the MARTA hover test models.

Integration and Demonstration of Robotic Actuators/Effectors for Soil/Rock Sampling

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 has been 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).



(a)

(b)

(c)

Fig. 15 – TAMS 2; (a) in-flight to/from remote-site, (b) deploying robotic arm, and (c) acquiring rock sample

The TAMS 2 vehicle is a slightly modified commercially available large electric hobbyist radio-controlled helicopter. The single main rotor is 1.25 meters in diameter and the gross weight is 4.6 kg (including sponson and robotic arm). A robotic arm (at the end of a sponson) and a sample-carrying container (at the foot of the conventional skid landing gear) have been incorporated into the vehicle. Lightweight composite materials for the sponson and robotic arm structure were used to maintain flightworthiness of the TAMS 2. Currently, flight control of the TAMS 2, and control of its robotic arm, is effected by radio-control using two separate transmitters. The robotic arm will never be operated when the vehicle is in flight. Later refinement of the TAMS 2 demonstrator will focus on more technically sophisticated control approaches. Some of the questions that future work with the TAMS 2 vehicle will focus are summarized in Table 6.

Table 6. Questions that TAMS 2 Will Help Answer

Prototyping:
-Are there alternate robotic effectors for soil/rock sampling?
-How to catalog (including site & context) samples?
-How to avoid cross contamination of samples?
-Transferring samples from rotorcraft to lander?
-Transferring electric power from lander to rotorcraft?
Mission Strategy Feasibility:
-Sampler size & complexity vs. rotorcraft short hops?
-How many samples & images to characterize site?
Synergism:
-Cooperative interaction with lander (“Da Vinci”)?
-Interaction with rover (“Micro Scout”)?
-Interaction with other aerial explorers (“BEES for Mars”)?

Concluding Remarks

The development of rotary-wing flight vehicles for Mars exploration is an exciting and yet challenging goal. Conventional wisdom as regards rotary-wing design has to be re-examined when considering the flight of a vertical lift aerial vehicle in the atmosphere of Mars. The low Reynolds number, compressible flow regime that Mars rotorcraft will operate under is little understood and will need to be investigated in quite some detail. Further, new concepts and approaches as to structures, dynamics, propulsion, vehicle flight control, and automation will need to be developed in parallel.

This paper summarizes progress made towards experimental investigations and demonstrations of the performance and flight/mission characteristics of rotors and vehicles specifically designed for rotary-wing flight in the Martian atmosphere. Results from this initial proof-of-concept testing will guide the development of second generation rotor and vehicle designs and the conduct of follow-on testing. Engineering studies summarized in this paper contribute to the ultimate realization of vertical lift aerial vehicles for the exploration of planets beyond our own.

Acknowledgements

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Appendix A – Two Possible Strategies to Go to Mars

There are two potential strategies that could be taken to interject a Mars rotorcraft into the Mars exploration program: a dedicated mission as might be responsive to the proposed NASA Mars Scout program, or a 'piggyback' addition of a rotary-wing 'micro scout' to an ongoing planned Mars mission (such as a large surface rover mission).

Dedicated Mission: 'Da Vinci' Concept

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. 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 the capabilities of the lander (accuracy as well as hazard avoidance) and rover (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. 16).

Fig. 16 – "Da Vinci" Mission Approach

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 (Fig. 17). 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 would 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 soil and rock characteristics. 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.

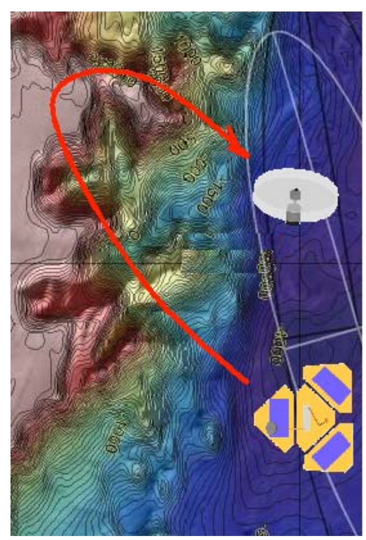

Fig. 17 – Three Dimensional Mobility

Sites well suited to rotorcraft exploration include: the layered walls of, and mesas within, 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.

'Da Vinci' 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 ultra-lightweight 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 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.)

'Da Vinci' General Lander and Rotorcraft Description

The Da Vinci mission would employ a lander carrier with solar array petals similar in configuration of the 2003 Mars Exploration Rover and Mars Pathfinder landers. The lander would have an in-situ instrument science module for processing and analyzing soil and small rock samples. Further, the Da Vinci lander would have a robotic arm for sampling/transferring rock samples and further, assisting set-up, handling, and use of the Mars rotorcraft. The Da Vinci lander would also, of course, transport and support the vertical lift aerial vehicle and a transport frame and auxiliary support equipment. The lander would have a sophisticated mission computer and telecommunication package. Figure 18 summarizes the vehicle deployment from the lander.

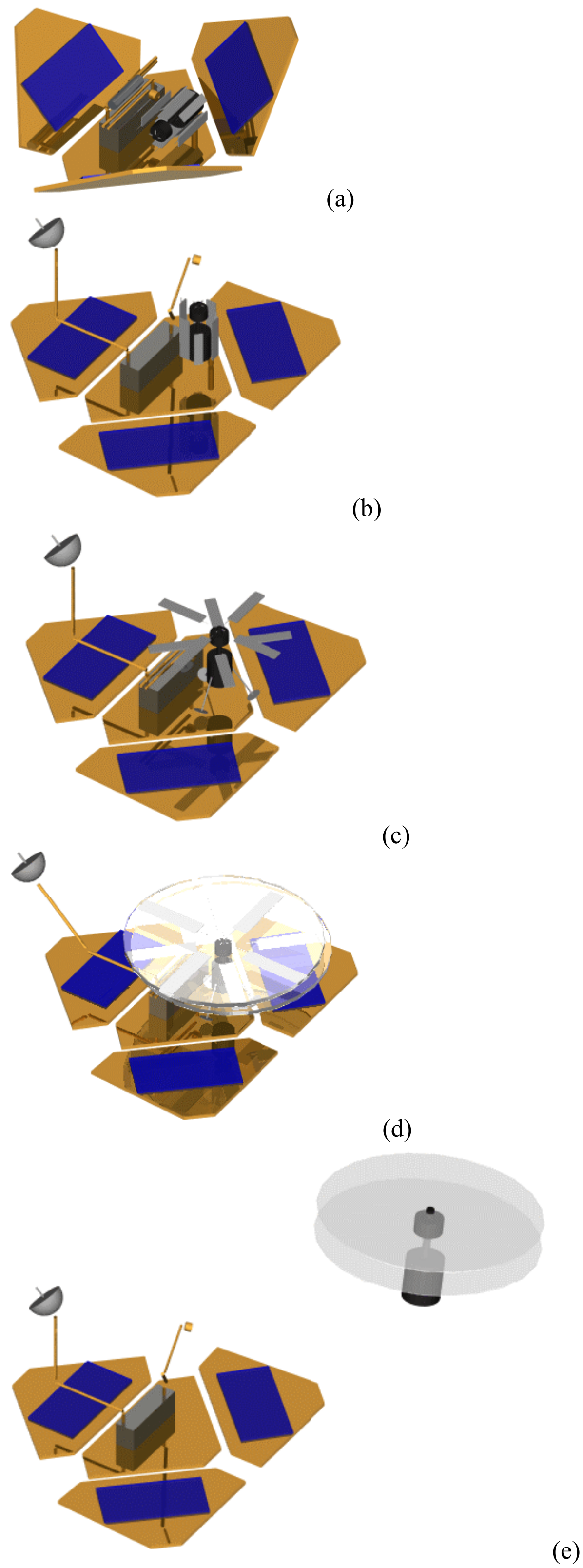

Fig. 18a-e – Mars Rotorcraft Deployment

'Da Vinci' Mission Objectives

1. Examine mineralogical and biochemical characteristics of soil and small rock samples.
2. Perform low-altitude, high-resolution aerial surveys in hazardous or otherwise inaccessible terrain; identify remote-sites for follow-on sampling mission flights.
3. 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.

23. Perform in-situ science, and return of soil samples from, up to four sites of special geological interest.

The rotorcraft would fly, in a matter of minutes, to a site up to 10 km distant. After landing, a sampling probe from the rotorcraft – such as a scoop – would acquire soil and rock fragments. The rotorcraft would then return to the lander. The samples would be transferred to the lander in-situ analysis instruments by means of the lander's articulated arm. The Mars rotorcraft would be hooked up to lander auxiliary systems for recharging (Fig. 19).

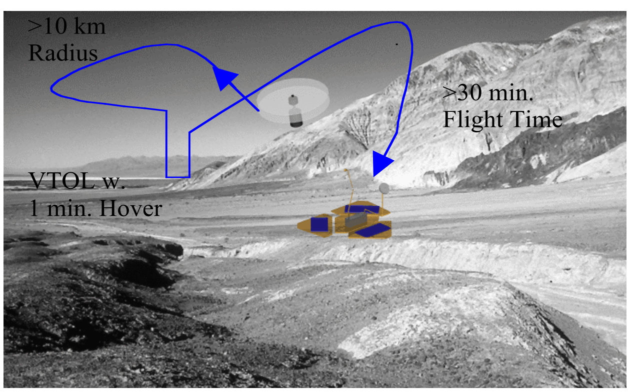

Fig. 19 – Mission Objectives and Flight Requirements
(Background Photo Courtesy of USGS)

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 7). 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 7. 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.

Piggyback to Existing Mission: 'Micro-Scout' Concept

An alternate approach to demonstrating rotary-wing flight on Mars is to piggyback a small (0.25 to 1.5 kilogram) Mars rotorcraft onto an existing Mars surface exploration mission.

'Micro-Scout' Mission Description

A large rover intended to traverse over more than a hundred kilometers across the Martian surface relies upon a small rotary-wing micro scout to assist it in navigation through hazardous terrain. The sole science instrument on the 'micro scout' rotary-wing vehicle would be a wide-field stereoscopic imager. The micro scout rotary-wing vehicle must be able to repeatedly and reliably dock with the rover (Fig. 20). The micro scout does not necessarily have to land on the Mars surface, though – but, instead, remain in flight except when docked to the rover.

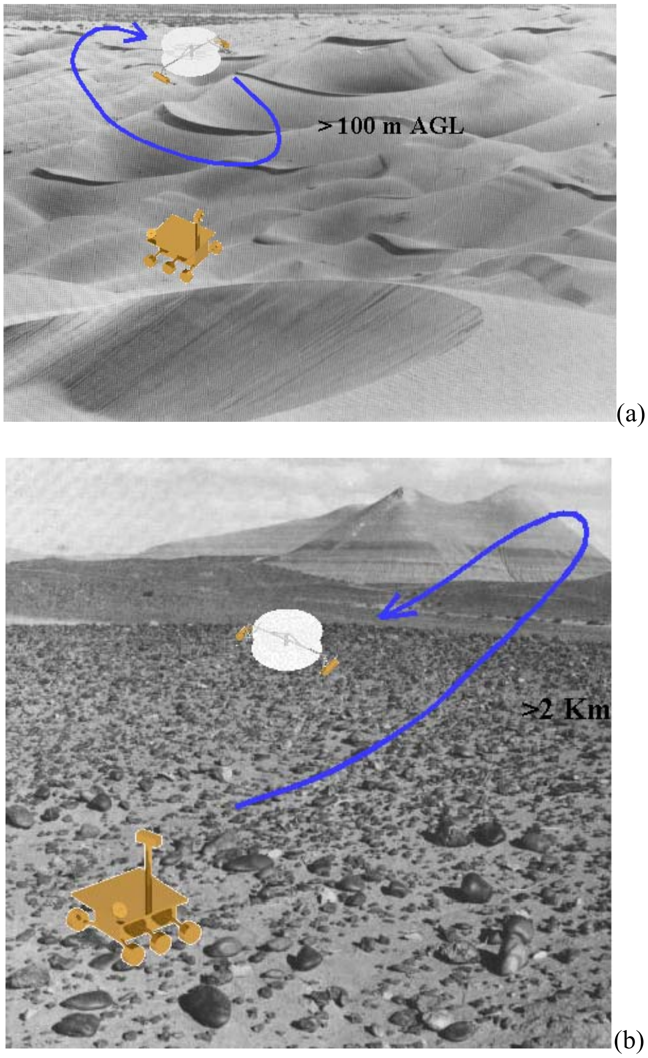

Fig. 20 – Micro-Scout Enabled Navigation of a Rover Across Rough Terrain; (a) circling overhead to scan to horizon and (b) 'trailblazing' (Background Photos Courtesy of University of Arizona)

'Micro Scout' Description & Trade-offs

A one kilogram coaxial micro scout rotary-wing vehicle would have rotor radii of approximately 0.75 meters diameter (Fig. 21). To minimize vehicle complexity and technical risk, a micro scout will likely rely on battery power. Additionally, a simple blade design using circular-arc 'flat plate' airfoils will likely be used in the vehicle design. Similar blade designs can be found for smaller, simpler radio-controlled hobbyist helicopters. Reference 23 summarizes incompressible flow two-dimensional airfoil data for circular arc 'flat plate'-type airfoils at low Reynolds numbers. Reference 24 acquired rotor hover performance data for rotors employing such circular arc flat plate airfoils.

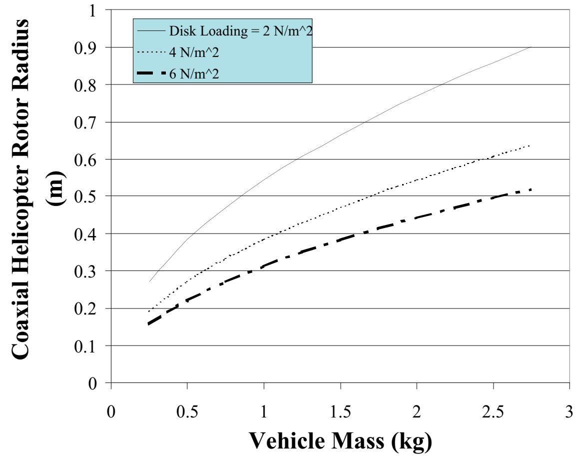

Fig. 21 – Micro Scout (Coaxial Helicopter Configuration) Rotor Radius as a Function of Disk Loading

Figure 22 shows estimated power requirements for a micro scout. The rotor shaft power requirements and range estimates assumes a 1 kilogram vehicle, a disk loading of 4 N/m^2, an induced power constant of 1.2, and a blade airfoil power drag coefficient, C_{do}, of 0.04. This profile drag coefficient, though consistent with Ref. 23 data may be somewhat optimistic in light of Ref. 24 micro-rotorcraft hover performance data. This issue will have to be examined more closely through refined analysis and experimental work. A fuselage/airframe parasite drag flat plate area ratio of f/A=0.04 is assumed. This is consistent with assuming a roughly cylindrical fuselage normal to the freestream forward velocity.

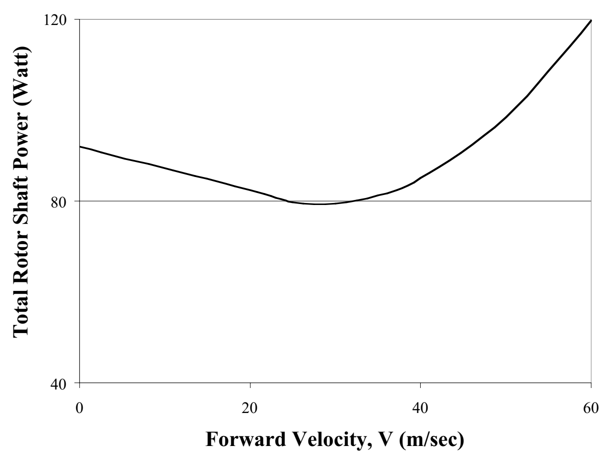

Fig. 22 – Micro Scout Power Requirements (Vehicle Mass = 1 kg & Disk Loading = 4 N/m^2)

If one assumes a minimum total range requirement of at least two kilometers for a micro scout, the first-order performance analysis results of Fig. 23 would suggest that this would be achievable for electric propulsion using battery power. A cruise speed of 20 m/sec is assumed in the analysis, with a one minute hover duration. If refined analysis proved this to be so, then this would result in a significant reduction in the overall technical risk level in micro scout development, as well as the overall simplicity of the vehicle design.

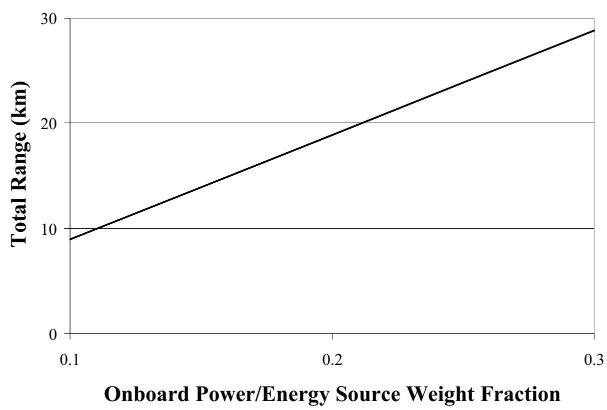

Fig. 23 – Micro Scout Range Estimates

Simplicity of design is an essential aspect for any micro scout vehicle. It will be extremely challenging to develop a vehicle design that builds in a robust mission/flight operation capability in very low mass hardware system. Though going to higher number of blades will result in more efficient aspect ratios for the rotor blade, going to high blade counts will increase rotor hub and control system complexity as well as increased design challenge for blade deployment and stowage. Deployment and stowage of the rotor blades (into a compact package for the overall aerial vehicle) between flights will have to occur a number of times throughout the mission, so as to enable efficient, trouble-free transport of the micro scout by the rover. It might be acceptable to contemplate less aerodynamically efficient designs -- such as low aspect ratio, two-bladed rotor designs -- in order to satisfactorily address these transport/deployment/stowage issues. In many ways, these issues are probably more crucial for a micro scout mission than the 'Da Vinci'-type vehicle/mission.

Because of the low mass design targets of a micro scout (0.5 to 1 kg), an extremely simple but robust method of flight control and navigation will need to be developed for micro scouts.

'Micro Scout' Mission Objectives

NASA currently has an active technology development program for long-range, large, highly capable planetary rovers. And yet, because of the limitations of two-dimensional mobility inherent in rovers, there will always be regions of the Red Planet that will remain inaccessible and/or impassible to rovers. The addition of a small rotary-wing 'micro scout' to an existing Mars rover mission would provide for exceptional navigational guidance – and hazard avoidance -- for a long range, large rover.

Such a micro scout would not have to fly very high, or very far, and would only have to carry as payload only a simple stereoscopic imaging device. Aerial images downloaded from the micro scout would be analyzed by the rover navigation computer to plot the rover's course across the Martian surface between micro scout flights. The micro scout would have to dock with, be transported by, and periodically re-energized and re-deployed from the rover. Such repeated deployment and docking would pose challenging flight control issues. Any such deployment, transport, or docking devices could not interfere with the proper functioning of the rover, including potentially blocking sunlight reaching a rover's solar cell arrays (if used). The docking issue might be somewhat reduced in difficulty, if the rover doesn't have to be moving during a micro-scout's flight. The micro scout could potentially rely upon navigation lights, beacons, and other such aids mounted on and supported by the rover to allow for precision navigation by the micro scout, while in flight. An extremely small/lightweight, but reliable, avionics system would be paramount for any Mars rotorcraft – but particularly so for a micro scout platform. It is highly unlikely that a micro scout would incorporate high levels of vehicle autonomy in its flight software. Flight control systems based on bio-inspired technologies – such as those being derived under the NASA Ames 'BEES (Bio-inspired Engineering for Exploration Systems) for Mars' project may be essential for a micro scout aerial vehicle.

Appendix B – Mars Rotorcraft as Robots

Although the demonstration of vertical lift flight in the atmosphere of Mars would be a tremendous technical accomplishment in itself, the planetary science community will likely be under-whelmed by the achievement. Planetary scientists would be more prone to consider only the implications of enhanced mobility of a new type of robotic device on their evolving plans for Mars exploration.

It is this concept of rotary-wing vehicles as aerial robots (that can also interact with the planetary surface in between flights) that will ultimately dominate the design paradigm for vertical lift planetary aerial vehicles. Further, Mars rotorcraft will not be independent agents. They will, by necessity, be part of a greater collective of other robotic/autonomous systems (rovers, landers, science stations, and isolated probes). Further in the future, human exploration of Mars can employ vertical lift planetary vehicles as 'astronaut agents.'

Very soon the critical enabling technology for Mars rotorcraft will transition from rotor aeromechanics to vehicle autonomy and flight control and navigation in a largely unknown environment. Unprecedented levels of vehicle autonomy will need to be demonstrated for Mars rotorcraft and other vertical lift planetary aerial vehicles. Further, this autonomy will need to be robustly demonstrated over large periods of time, several flights/sorties, and will require new modes of interconnectivity and cooperative interaction of multiple robotic systems. For some time now NASA has been considering the implications of such planetary robotic 'colonies,' but clearly inclusion of aerial robots in these colonies will raise autonomous system technology to new heights.

Currently, there is a plethora of field site Mars-analog science experiments, technology demonstrations, design competitions, and other assorted low technical readiness level precursor investigations that hopefully will lead to incorporation of the resultant technologies and strategies into the mainstream Mars exploration program. These exercises are in large part impromptu events that are focused mainly on the personal interests of the researchers involved in the investigation. Several impressive aerial robotics demonstrations have been conducted by academia under the sponsorship of the Association of Unmanned Vehicle Systems International (AUVSI), for example. Nonetheless, something more is needed.

The following field demonstration challenge is proposed for robotic colony investigations that include aerial explorers.

- A terrestrial test site would be established whereby a 'colony' of robotic systems/vehicles would be tested for extended periods of time – dating from weeks to months;

- The emphasis of the test site and associated field experiments would be the investigation, or examination, of exploration and science strategies to characterize the geology, and biological potential (past and present), of the field site;

- Robotic systems participating in the field site experiment/demonstration would perform their tasks with emphasis on cooperation with other systems;

- Human intervention in the ongoing experiment, though not disallowed, would be strongly discouraged and will count against the assigned measure of success of the overall experiment;

- Successive field site seasons should have a rotation of location so as to yield generalized techniques (versus those tailored to a specific field site) for scientific investigation and exploration by the robotic systems/elements and the overall 'colony.'

The fundamental criteria for the success of a field site experiment or demonstration is threefold. First, human intervention must be minimal for proper (as per instructions) operation of the robotic systems/elements of the field site colony. Second, cooperation between robotic systems is maximized during the experiment. Third, the field site is subjected to a level of scientific scrutiny by the robotic colony as to ideally match the knowledge gained of the field site as that derived by an independent team of human experts, using similar instruments.

Whether such a series of terrestrial robotic colony experiments can/will be conducted in the near future is yet to be determined. What is certain is that without such experimentation, it will be nearly impossible for aerial explorers -- and vertical lift planetary aerial vehicles -- to reach the technical readiness level sufficient to see to their implementation in a planetary science mission.

The introduction of rotary-wing technologies into the NASA Mars exploration infrastructure will enable three-dimensional mobility for robotic exploration of the Red Planet. This, in turn, will truly revolutionize the twenty-first century of exploration.