Vertical Lift – Not Just For Terrestrial Flight

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Abstract

Autonomous vertical lift vehicles hold considerable potential for supporting planetary science and exploration missions. This paper discusses several technical aspects of vertical lift planetary aerial vehicles in general, and specifically addresses technical challenges and work to date examining notional vertical lift vehicles for Mars, Titan, and Venus exploration.

Introduction

The next few years promise a unique convergence of NASA aeronautics and space programs. NASA planetary science missions are becoming increasingly more sophisticated. Manned and robotic exploration of the solar system planets would be greatly enhanced through the development and use of robotic aerial vehicles. Since the 1970's a number of Mars (fixed-wing) Airplane concepts have been proposed for Mars exploration.

The Army/NASA Rotorcraft Division -- in collaboration with the Center for Mars Exploration -- at NASA Ames has been performing initial conceptual design studies of Martian autonomous rotorcraft for planetary exploration and science missions (fig. 1). Initial results have been quite promising. As a result of this early work, the utility of rotorcraft, VTOL vehicles, and hybrid airships for Mars exploration and planetary science missions as a whole can be technically justified as follows.

Why vertical lift vehicles for planetary exploration? For the same reasons why these vehicles are such flexible aerial platforms for terrestrial exploration and transportation: the ability to hover and fly at low-speeds and to take-off and land at unprepared remote sites. Further, autonomous vertical lift planetary aerial vehicles (PAVs) would have the following specific advantages and capabilities for planetary exploration:

- Hover and low-speed flight capability would enable detailed

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and panoramic survey of remote sites;

- Vertical lift configurations would enable remote-site sample return to lander platforms, and/or precision placement of scientific probes;

- Soft landing capability for vehicle reuse (i.e. lander refueling and multiple flights) and remote-site monitoring;

- Hover/soft landing are good fail-safe ‘hold’ modes for autonomous operation of PAVs;

- Vertical lift PAVs would provide greater range and speed than a surface rover while performing detailed surveys;

- Vertical lift PAVs would provide greater resolution of surface details, or observation of atmospheric phenomena, than an orbiter;

- Vertical lift vehicles would provide greater access to hazardous terrain than a lander or rover.

In addition to the potential science and technology benefits resulting from the development and use of vertical lift planetary aerial vehicles, there are substantial opportunities for technology transfer from a vertical lift PAV development effort. These technology transfer opportunities include: advanced high-efficiency propeller or proprotor designs; precision guidance, navigation and control at low altitudes and near-terrain obstacles; adaptive (inner-loop) flight control; autonomous systems work based on vertical lift vehicle applications; high-frequency open- and closed-loop smart structures/actuators.

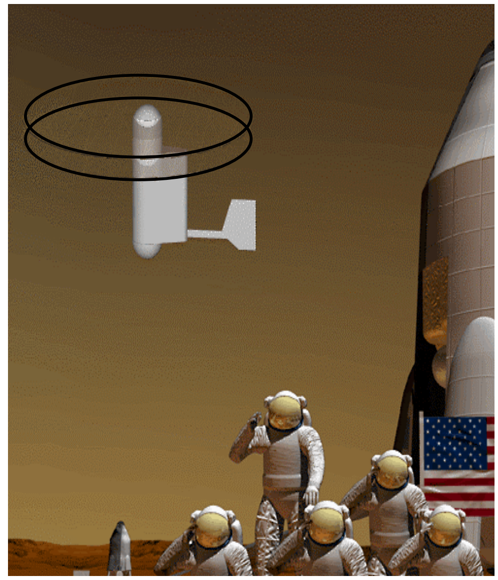


Figure 1 – Vertical Lift Planetary Aerial Vehicles as ‘Astronaut Agents’

Ultimately, the objective of this paper is to inspire the vertical flight research community to consider and to embrace the concept of vertical lift planetary aerial vehicles and to participate in their ultimate development and use. Specific opportunities for vertical life PAVs in planetary science and some of the PAV design challenges are presented in this paper. Ongoing work, including that in academia, is also described.

Opportunities

As noted earlier, work is being pursued at the Ames Research Center’s Army/NASA Rotorcraft Division on a Martian autonomous rotorcraft for scientific exploration of Mars. Why not, though, a Venusian hybrid-airship? Or, a Titan VTOL? Or, alternatively, why not any number of vertical concepts that could provide unique mission capability for planetary science?

This paper examines the question of the feasibility of vertical lift planetary aerial vehicles. In particular, discussion in the paper will be directed at the three planetary bodies in our solar system where vertical lift vehicles might prove feasible. Table 1 is a summary of the key surface atmospheric properties for Mars, Titan, Venus, and Earth. This information will be used to examine the general aerodynamic attributes of vertical lift PAVs.

Table 1 – Summary of Planetary Descriptions (Ref. 1)

	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
Venus	6052	8.87	735.3	$9.21x10^6$	64.79	CO_2 96% N_2 3.5%
Earth	6371	9.82	288.2	101,300	1.23	N_2 78% O_2 21%
Mars	3390	3.71	214	636	$1.55x10^{-2}$	CO_2 95% N_2 2.7% Ar 1.6% O_2 0.1%
Titan (Saturn moon)	2575	1.354	94	149,526	5.55	N_2 65-98% Ar<25% CH_4 2-10%

[!] Mean values noted for planet radii and gravity to account for the oblateness of the planet.

Mars surface temperature, pressure, and density varies significantly spatially and temporally; surface temperature range of 140-300^{o}K; surface pressure 636±240 Pa. Seasonal CO_2 sublimation and condensation at the polar caps (particularly at the southern polar cap) is the chief reason for the atmospheric pressure and density variations.

Figures 3 and 4 are approximate estimates of the speed of sound and kinematic viscosity for various different planetary bodies in the solar system. These estimates were derived in reference 2.

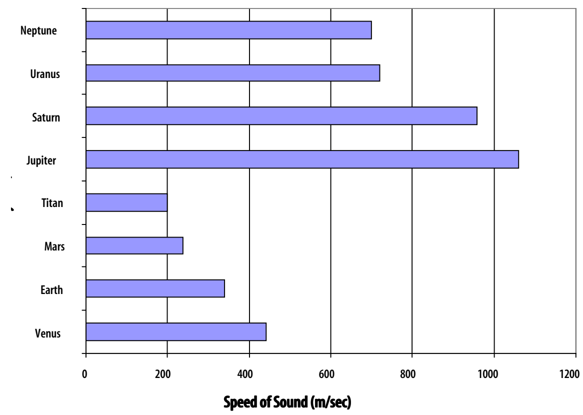


Fig. 2 – Estimates for the Speed of Sound

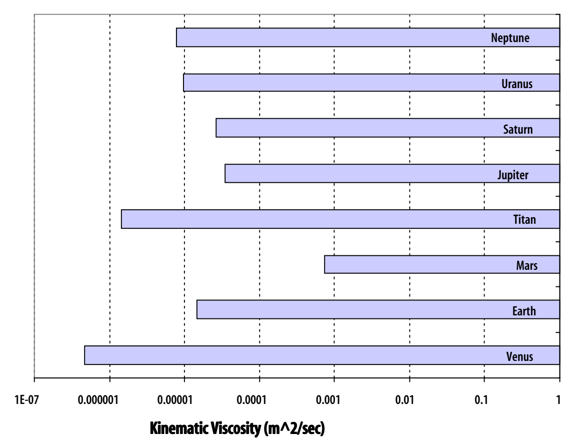


Fig. 3 – Estimates of Kinematic Viscosity

Additional data related to planetary atmospheric properties can be found, for example, in Ref. 3-6.

Despite the considerable amount of data related to planetary atmospheres, much more data can, and must, be discovered during the course of the development and general application of PAVs.

In establishing the feasibility of vertical lift (and other) PAVs, it is not sufficient to merely question whether or not flight in extraterrestrial atmospheres is theoretically possible. Clearly defined planetary science goals and opportunities are also required so that vertical lift PAV designs can be optimized. Table 2 summarizes a partial list of planetary science goals/opportunities in which vertical lift, or rotary-wing, platforms could contribute.

Table 2 – Planetary Science Opportunities (A Partial List Only)

	Science/Exploration Opportunities
Mars	• Search for water or past signs of water (characterize global distribution) • Search for life or evidence of past life • Understand the atmospheric and geological evolution of Mars; perform comparative analyses of the Mars planetary evolutionary process with the other terrestrial-type planets in our solar system • Survey for resources that would expand exploration capability and support for an extended human presence on Mars
Titan	• Search for the precursor biochemical components of life • Perform atmospheric science studies to understand the unique nature of the Titan atmosphere (i.e. its high density/pressure) • Survey for chemical resources/volatiles that could enable in-situ propellant and fuel production; resulting propellant could be used for sample return missions to Earth and expanded surveys of the other Saturnian moons
Venus	• Correlate space-based cartographic and inferred geological data with detailed surveys in targeted areas using vertical lift PAVs. • Acquire adequate data to understand the fundamental atmospheric and geological evolutionary processes that led our 'sister' planet to be radically different from Earth • Determine if planetary-scale 'green-house' effects can be halted and/or reversed

Finally, in addition to the scientific benefits resulting from the employment of vertical lift vehicles, considerable enthusiasm and support from the American public could be generated for both the demonstration of extraterrestrial atmospheric flight.

Mars, Titan, and Venus

Mars, Titan, and Venus are as different from each as they are with respect to Earth. Each planetary body -- each major science/exploration mission, in fact -- will entail radically different aerial vehicle design challenges. This will be highlighted in the discussion to follow which outlines some thoughts regarding notional vehicle configurations and design considerations for each of the three planetary bodies in our solar system where a vertical lift capability might theoretically make sense for exploration/scientific investigation.

<u>Mars</u>

Most of the work to date investigating the feasibility of vertical lift planetary aerial vehicles has focused of rotary-wing configurations for Mars exploration. Mars, of all the planetary bodies in the solar system, holds the greatest interest for NASA researchers. Both the Offices of Space Science and

Space Flight actively promote/direct research and engineering effort for the robotic and, ultimately, human exploration of Mars (fig. 4). Reference 7 details NASA' strategic plan for the Human Exploration and Development of Space (HEDS) -- which clearly emphasizes the importance of Mars mission planning.

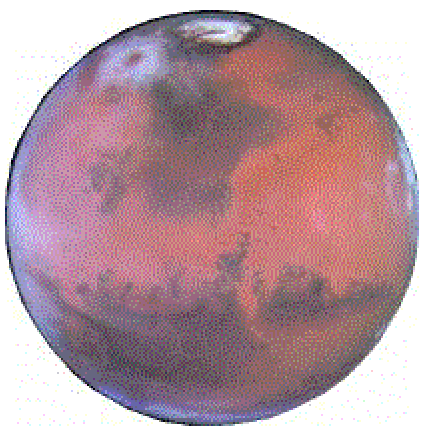


Fig.4 – Mars (Image from Hubble Space Telescope (HST))

Martian autonomous rotorcraft will have large lifting-surfaces and will be required to have ultra-lightweight construction (refer to figure 5 for isolated rotor sizing for hover in Martian atmosphere). This in turn will pose a challenge in making them sufficiently robust to operate in the Martian environment. Some early work and discussion on Martian vertical lift vehicles can be found in Ref. 8 -- 13.

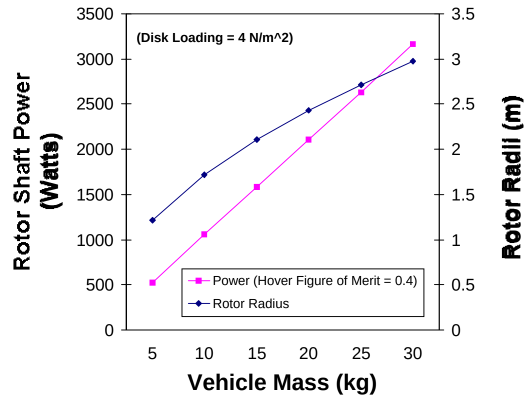
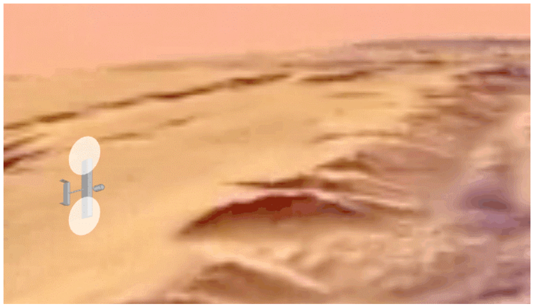


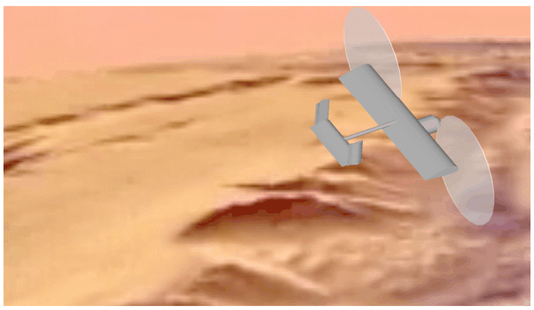
Fig. 5 – Martian Autonomous Rotorcraft: Large, Ultra-lightweight, Fragile-Looking…

Early conceptual design study work at NASA Ames focused on a Mars tiltrotor configuration (Fig 6a-b and Ref. 2). This configuration reflected an aerial platform that potentially maximized overall mission flexibility. Assuming the use of an Akkerman hydrazine reciprocating engine (Ref. 14), a small (10 kg) Mars tiltrotor was shown to potentially have a range capability on the order of 150-250 kilometers (assuming a limited amount of hovering and vertical take-off and landing operation). Alternate propulsion systems were not examined in this initial work.

This early Mars tiltrotor work at NASA Ames illustrated the promise of vertical lift planetary aerial vehicles. However, it was also clear from this work that deployment of even a small Mars tiltrotor requires human assistance in vehicle assembly. Alternative vehicle configurations needed to be examined for early robotic missions that did not require human presence on Mars.



(a)



(b)

Fig. 6 -- A Mars Tiltrotor: (a) helicopter-mode in vertical climb over Valles Marineris; (b) airplane-mode

Recent work at Ames has focused on a coaxial helicopter configuration for early Mars exploration missions (fig. 7).

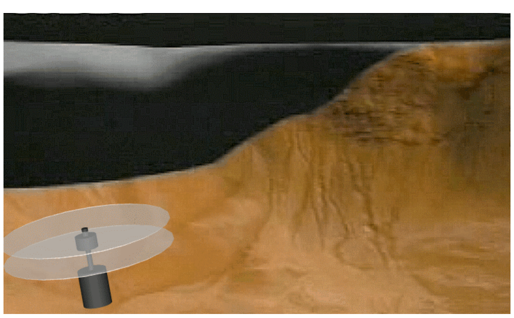


Fig. 7 -- A Coaxial Helicopter Configuration for Mars Exploration ('Search for Water')

Figure 8 shows first-order estimates of the forward-flight performance of a 10kg coaxial helicopter configuration. The performance estimates for this small coaxial helicopter assumes that the rotor tip Mach number is 0.65, the disk loading is 4 N/m^2 and the rotor diameters are 2.44 meters. A very conservative set of induced power constant and mean blade profile drag coefficient were used for the rotor performance estimates. These conservative performance coefficients were selected to account for the high profile drag seen for low Reynolds number airfoils, as well as the effect of a very large blade root cutout to allow for rotor fold and telescoping for transport/deployment, and the high tip losses for large aspect ratio rotor blades. References 15-16 provide general design analysis guidance for this first-order performance assessment.

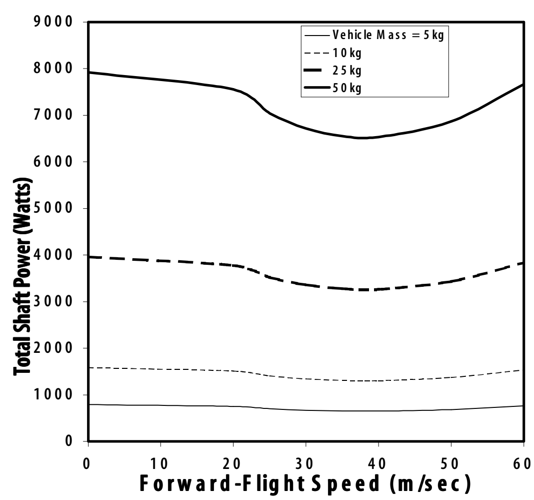


Fig. 8 – Mars Coaxial Helicopter Performance Estimates

Figure 8 shows first-order estimates for vehicle range as a function of fuel/energy-source weight fraction for the 10kg vehicle. Three families of curves are shown in the figure: range estimates using battery technology, estimates for fuel cells, and propulsion from a hydrazine-based Akkerman engine. These range estimates are for forward-flight power levels only (for a vehicle velocity of 40 m/s or an advance ratio of 0.26) and do not account for the energy/fuel increment for vertical take-off, hovering, and landing. Drive train and transmission efficiencies are taken into account in the range estimates. Note that additional battery or fuel cell capacity is required for scientific instrumentation and mission/flight-control power.

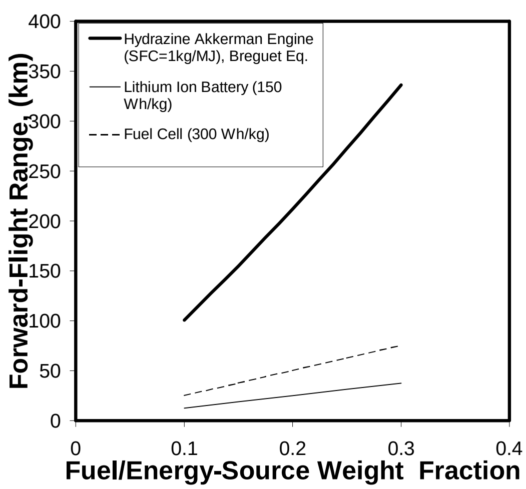


Fig. 9 – Mars Coaxial Helicopter Range Estimates

A clear trade-off can be seen from the coaxial helicopter range estimates. The Martian rotorcraft could either use hydrazine reciprocating engine technology that uses a non-replenishable supply of fuel, or battery or fuel cell technology which could be recharged using almost inexhaustible (lander-based) energy sources such as solar cell arrays and/or nuclear radioisotope thermoelectric generators (RTG's).

Exciting advances are being made in battery and fuel cell technology. The energy density numbers used in the range estimates of figure 9 are conservative with respect to today's technology. Future advances may have a considerable impact on mission capability of planetary aerial vehicles. On the other hand, reciprocating engines driven by hot gases from mono-propellants (such as hydrazine) or bi-propellants have undergone considerable analysis in the past and should not be discounted for their use in planetary aerial vehicle propulsion.

The flight dynamics of a Martian rotorcraft will likely be quite unique as compared to its terrestrial counterparts. The rotor(s) for a Martian rotorcraft will have very low Locke numbers and will have correspondingly have very low aerodynamic damping. The blades will also likely have relatively low values of torsion and bending stiffness because of their large blade planform area and ultra-lightweight structure.

The key to the successful development of Martian autonomous rotorcraft will be the development of ultra-lightweight structures and equipment for such vehicles. Though a considerable body of statistical and semi-empirical weight prediction tools exist for rotorcraft (see, for example, Ref. 17-21), none are directly applicable to the unique design challenges of Martian rotorcraft. These tools need to be modified/refined to accommodate the innovations in materials and structural components to arrive at acceptable preliminary design methodologies for planetary aerial vehicles that have acceptable engineering accuracies.

Titan

Titan, Saturn's largest moon (fig. 10), is unique in the solar system in that it is the only moon that has a substantial atmosphere. Titan's atmosphere is comprised primarily of nitrogen, argon, methane – and may have similar properties to Earth's early atmosphere, before life began. The Voyager 1 and 2 'Grand Tour' missions provided a substantial amount of information about Titan. Nevertheless, Titan's surface is shrouded by a thick atmospheric haze and little is known about it. Recent Hubble Space Telescope and ground-based telescope astronomical observations relying on new infra-red techniques are starting to provide some insight into the surface features of Titan, but only a faint hint of what may lie on Titan's surface can be discerned from the existing available data. By 2004, the joint NASA, ESA, and Italian space agency Cassini space mission will reach Saturn's orbit and release the Huygens probe (descending via parachute) into Titan's atmosphere. The Huygens atmospheric probe and the complementary Cassini observations will provide invaluable insights into the atmospheric chemistry/properties of Titan. It is unclear whether the Huygens probe will be able to soft-land on Titan's surface and successfully communicate data back to Earth (this might be possible, but is outside the official mission scope). This accomplishment will likely come from future missions post-Cassini/Huygens.

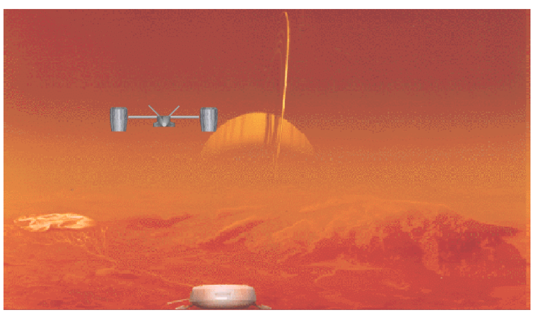
The use of vertical lift planetary aerial vehicles to explore Titan would be a tremendous enabler of scientific investigations of one of the solar system's more mysterious planetary bodies. References 22–23 provide some important insights into the potential for vertical lift aerial exploration of Titan.

Fig. 10 – Titan (Image from HST)

With the arrival of the Cassini/Huygens spacecraft to Saturn and Titan in 2004 -- and the anticipated science and outreach bonanza from this mission -- there may be an opportunity to take advantage of the excitement underlying this adventure to advocate possible follow-on missions. Among these possible follow-on missions is an exploration of Titan employing small robotic vertical lift aerial vehicles.

A key consideration in the development of a Titan vertical lift aerial vehicle is the robustness of the platform, the ability to execute multiple flights, while minimizing overall vehicle mass. Transport of such a vehicle from Earth to Titan will be an expensive undertaking. Maximizing science return and overall mission duration will be crucial given the expense of the enterprise.

Because of the thin atmosphere of Mars – and, therefore, the large rotor diameter and blade planform area required for vertical flight -- ducted fan vertical lift vehicles are impractical for Mars exploration. The opposite is true for aerial vehicles for Titan. Ducted fan configurations such as tilt-nacelle aircraft are perhaps ideally suited for Titan (fig. 11). Ducted fan aerial vehicles would inherently be more robust operating at low-altitudes in an unknown, potentially hazardous environment, than conventional rotors. A variety of ducted fan VTOL concepts have been tested on Earth, both in model- and full-scale, wind tunnel and flight test. Among these ducted fan vehicles are the Doak VZ-4, the Grumman 698 (tilt-nacelle) and the Bell X-22A (quad fan) aircraft (see Ref. 24-27). For low-speed, short ranges, configurations analogous to the Sikorsky Aircraft Cypher ducted coaxial-rotor UAV could also potentially be applicable to Titan exploration.



(a)

(b)

Fig. 11 -- A Titan Tilt-Nacelle VTOL: (a) take-off; (b) cruise.

Figure 12 shows a first-order estimate of hover total shaft power for a notional Titan tilt-nacelle VTOL vehicle having two ducted fans that can pivot at the wing tips (similar in configuration to the VZ-4). A conservative shroud thrust fraction of 0.3 (i.e., 30% of the total thrust is provided by the duct/nacelle aerodynamics in hover, see Ref. 28-29) is used in the hover performance estimate. The hover performance and fan sizing estimates are for a disk loading of 600 N/m^2, a fan blade tip Mach number of 0.7, and a fan solidity of 0.25. This corresponds to a mean fan blade lift coefficient of 0.75, which should be reasonable for the airfoil Reynolds numbers estimated for the Titan ducted fan vehicle. A nacelle centerbody fairing radius of 20% of the fan blade span is assumed in the analysis. Fan airfoil Reynolds numbers are greater than 10^6 at the fan blade tip. (Compare that to the rotor blade tip Reynolds numbers for Martian rotorcraft which are estimated to be less than 10^5.) A Titan VTOL's ducted fans will be very small and consume very little power as a result of the very low gravity field for Titan. As the atmospheric density near Titan's surface is quite high compared to Earth, forward-flight profile and parasite power will be correspondingly quite high and will restrict the maximum velocity of the vehicle to relatively low speeds.

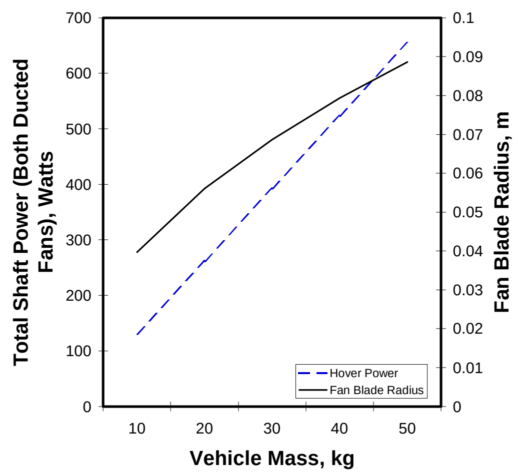


Fig. 12 – Ducted Fan Hover Performance for Titan Vehicle

Figure 13 shows range estimates for a 50kg Titan twin tilt-nacelle/ducted-fan VTOL vehicle, assuming power matching between the hover and cruise design points. The range estimates are based on the estimated power from figure 12 with reasonable drive train and electric motor efficiencies applied. The cruise speed is assumed to be 50 m/sec. These range estimates do not include the impact of take-off, landing, and hover on power availability.

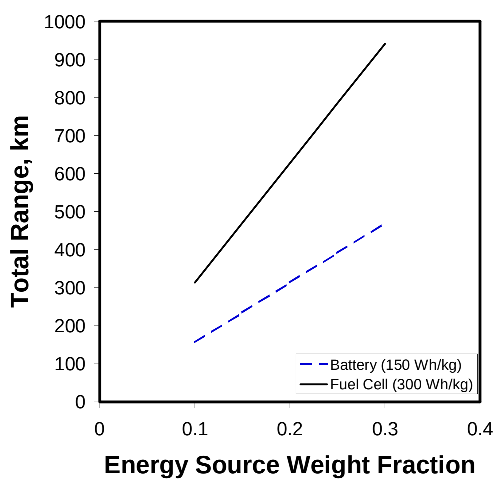


Fig. 13 – Range Estimates for a Twin Ducted Fan Titan VTOL

Venus

Of the three planetary bodies besides Earth where it theoretically might be feasible to design and fly vertical lift aerial vehicles, Venus (fig. 14) will likely pose the greatest challenge. This is particularly ironic as, to date, only Venus can lay claim to having had aerial vehicles fly within its atmosphere (discounting, of course, entry/descent parachutes for probes and landers). The former Soviet Union with its Vega 1 and 2 missions traversed across the upper atmosphere of Venus with two balloons. These balloons drifted with high-altitude (~50-55 km) winds almost across 30% of the circumference of the planet. Though many other planetary missions have been proposed using balloons/aerobots and fixed-wing aircraft, this accomplishment was the first and so far only demonstration of aerial flight in an extraterrestrial environment.

Fig.14 -- Venus (Image Based on Radar Map from Magellan Spacecraft)

The extremely high atmospheric densities near Venus' surface (plus the near-Earth-magnitude of its gravitational field) would suggest that a buoyant, or semi-buoyant, vehicle might represent the most practical design for exploration of Venus (fig. 15). In fact, Venus' surface atmospheric density is so great that such a semi-buoyant vehicle would in some ways likely have attributes more in kind with an underwater submersible than a terrestrial airship. The airframe of a Venusian hybrid-airship would be a rigid hull, which would have to be able to sustain substantial pressure differentials across the external/internal surfaces of that hull.

Venus' high surface temperatures also pose tremendous challenges for aerial vehicle design. Power usage must be kept to a minimum for propelling the vehicle so as to minimize waste heat generation and build-up from the vehicle propulsion system and electronics. Though active and passive technologies exist for thermal management of planetary science hardware, extended operation of such hardware near Venus' surface is currently problematic with today's technology. This will therefore mean that the lift required for take-off and landing will need to be kept to an absolute minimum (thus necessitating buoyancy fractions greater than 75%). It is also likely that electric propulsion will be required to maximized overall propulsion efficiency. The use of high-temperature batteries (such as NaS batteries) or fuel cell systems will also be required.

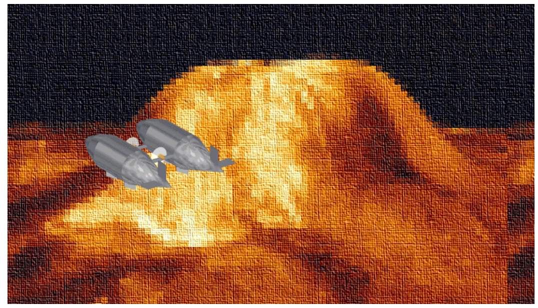


Fig.15 -- A Notional Venusian Hybrid Airship with Twin Hulls and Tandem Tilting Propellers and Wings

A Venus vertical lift vehicle mission's duration and science return could perhaps be maximized by designing it to have two phases/stages. The first phase would entail low-altitude powered flight with the vehicle acting as a semi-buoyant hybrid-airship capable of take-off and landing on the Venusian surface. This phase would be comprised of a few hours of powered flight at most, given likely limitations in power availability. Then, when vehicle power and temperature reach critical levels, ballast in the form of drained batteries (and potentially unnecessary surface science instruments) could be released and a longer duration high-altitude (unpowered) flight phase could be executed with the vehicle acting purely as a balloon. This two stage mission approach could potentially maximize the science return and overall investment of a Venus vertical lift vehicle by optimizing overall flight endurance and vehicle and scientific instrumentation operation.

Figure 16 shows a first-order estimate of a notional Venus hybrid-airship's hull size. This hull volumetric sizing estimate is consistent with the above described two stage (combination of powered and unpowered flight) mission approach. This hull size estimate parallels in general the analysis given in reference 30 for a low-altitude (~10km) Venus balloon. The results shown in this figure assumes a hybrid-airship buoyancy fraction of 0.9, a propulsion energy-source (batteries, fuel cells, etc.) weight fraction of 0.25, and an unpowered balloon altitude (after completing low-altitude powered vertical lift flight and then dropping the propulsion energy-source as ballast) of 3.1km. Helium is assumed as the hybrid-airship lifting gas in the figure 16 hull volumetric size trend. A thin skin of titanium alloy is assumed for the hull. Hull skin thickness using titanium alloys ranges from 0.5 to 1mm thick for vehicle mass from 10 to 50 kg. This skin thickness is derived such that skin stresses are less than the material yield strength, with a small margin of safety (Ref. 31). The hull was modeled as an ellipsoid with a fineness ration of 3. More rigorous follow-on analyses will need to consider thin wall pressure vessel elastic buckling effects in more accurately defining the hull crush pressures and the hull geometry and skin thickness. The proposed thin titanium alloy hull skins will be very hard to form/bond and will be subject to easy damage. Advanced types of high-temperature and high-strength materials should also be considered for the hull skins.

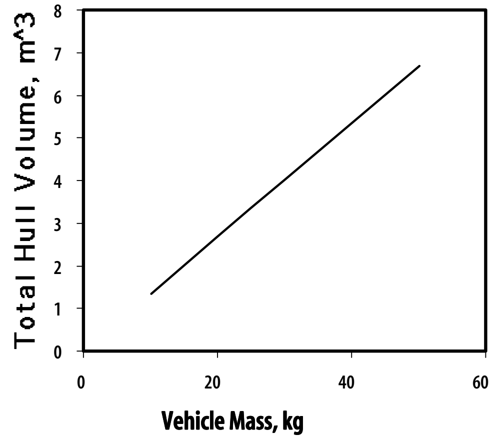


Fig. 16 – Hull(s) Size Estimate

Figure 17 shows how drift altitude (altitude for unpowered neutral flotation) varies with respect to ballast (propulsion energy-source) weight fraction. This analysis assumes that there is thermal and pressure equilibrium at the drift altitude across the external and internal surfaces of the hybrid-airship hull(s).

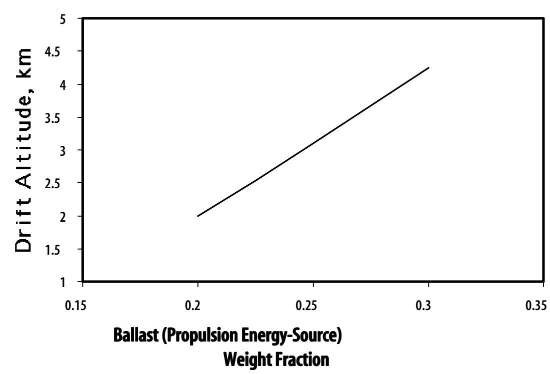


Fig. 17 -- ‘Drift’ Altitude of Unpowered Vehicle After Ballast Drop

Figure 18 shows a first-order estimate of the hover performance and sizing of a tandem propeller/tiltwing combination (sandwiched between twin airship hulls) that could be used to take-off and land from Venus’s surface. The performance and sizing estimates shown in the figure assume the airship buoyancy fraction of 0.9 (therefore, the propellers have to lift only 10% of vehicle weight in hover), a tip Mach number of 0.1, a 200 N/m^2 disk loading, and a solidity of 0.4 for the propellers. These propeller characteristics are more in common with submersible propulsors (see, for example, Ref. 32) than the conventional terrestrial rotary-wing platform. Adopting a twin hull (side-by-side) configuration for a Venusian hybrid-airship is perhaps reasonable so as to protect the propellers of such a vehicle from hazardous terrain/obstacles during take-off and landing. The obvious tradeoff for such a configuration is the handling characteristics of the vehicle in sideslip in forward flight, potential substantial nonuniform flow field effects on the propeller performance due to the presence of the twin hulls, and increased overall complexity of the vehicle. These issues will need to be examined in closer detail in future design studies of this concept. References 33-34 provides additional insight into airship design considerations.

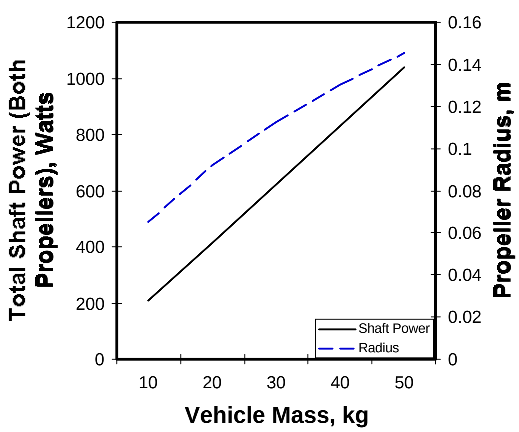


Fig 18 – Hybrid-Airship Tandem Propellers Hover Performance and Sizing Estimates

Only limited information exists for the operation of mechanical and electronic components at the extreme temperatures expected at Venus's surface. References 30 and 35 go into limited discussion of this topic, but it is clear that a substantial amount of research remains to be performed in this area before extended duration exploration of Venus' surfaces or low altitude atmosphere can be effected.

Technical Challenges and Opportunities

Autonomous vertical lift PAVs will be high-risk and high-payoff development ventures. Though an impressive – and ever-expanding -- amount of data exists for the planetary bodies in our solar system, nonetheless, these data are barely adequate for the purposes of designing and building PAVs. Such vehicles will need to be highly adaptive (from a controls and structures perspective), have conservative performance margins, and will require high degrees of mission/flight autonomy to adequately deal with corresponding levels of uncertainty in the mission and flight environment.

Rotary-Wing Aeromechanics

Several rotary-wing aeromechanics challenges exist for the development of vertical lift planetary aerial vehicles. First of all, in many cases, inadequate planetary atmospheric data and/or modeling may exist to design vehicles with required performance margins. Further, very limited empirical data exists for vehicle and control/lifting surface aerodynamics for such extreme environments – including the low-Reynolds number, compressible flow required for flight in the Martian atmosphere. This will inevitably result in the reliance on analytical tools with limited validation to predict vehicle aerodynamics for flight in other planetary atmospheres. Correspondingly, limited data exist for the high disk-loading, high solidity, large aspect ratio blades, rotor designs required for exploration of Venus and Titan. It is especially critical to acquire airfoil and rotor performance databases consistent with these planetary environment extremes to validate design and analysis tools. Achieving aeroelastic stability for rotors and/or wings will be challenging, given ultra-light weight structures required for most PAV configurations. As can be seen from the discussion so far, a mixed fleet of vehicle types is likely needed to comprehensive planetary science missions.

Vertical lift PAVs are not likely to be all-weather vehicles. Season, location, existence of atmospheric disturbances of a certain magnitude, and even time of day may dictate whether a PAV mission can be initiated or not. For example, Mars undergoes seasonal extremes of atmospheric mass due to sublimation and condensation of CO_2 at the polar caps. Further, seasonal 300-500 km/hr planetary-wide storm fronts (or 'sandstorms') also exist. It is unlikely that PAV missions can be sustained during these seasonal storms. Accordingly, preservation of flight vehicle (and other) assets in the face of these weather extremes will be a key consideration for human exploration of Mars. Rotor blade 'icing' will take on a whole new meaning for flight on Titan. And, finally, consider the environmental effects of corrosive atmospheric chemical compounds on vehicle performance and reliability for flight in Venus' atmosphere.

<u>Autonomous System Capability</u>

It is currently beyond the demonstrated autonomous system technology state-of-the-art to enable vertical lift flight in an extraterrestrial environment. NASA currently has several initiatives underway investigating autonomous flight control of spacecraft and planetary science platforms, as well as terrestrial aircraft. Though extraterrestrial rotary-wing platforms will pose unique challenges for autonomous system technology, it should be hoped that there will be a general applicability of the these automated reasoning and autonomous flight control efforts to the vertical lift PAV problem. The problem is not just software-related, but light-weight, low-power, computationally intensive, reliable (radiation tolerant, for example) flight control and mission computer systems capable of meeting vertical lift PAV requirements will also need to be demonstrated. It is crucial to initiate proof-of-concept demonstrations for key hardware/software components for autonomous flight of terrestrial platforms from which vertical lift PAV mission performance can be extrapolated. A key assumption underlying any autonomous system technology development effort for vertical lift PAV should be that limited use of lander or orbiter assets should be assumed for guidance, navigation, and control (GNC) and mission/flight support. A complete onboard package of sensors and autonomous system flight control capability should be assumed for vertical lift PAV -- although, such complete vehicle system autonomy has not been demonstrated.

Guidance, Navigation, and Control

Unlike terrestrial UAVs, PAVs can not rely on GPS systems for guidance and navigation (Ref. 36). Further, high-precision digital maps will not likely exist either for GNC (development of such maps is instead a goal/mission of PAVs). Onboard navigation sensors, appropriate for an extraterrestrial environmental for a highly mobile robotic vehicle, have yet to be demonstrated. In particular, planetary atmospheres such as Venus and Titan could be nearly opaque to light in the visual range; therefore, non-optical sensors might be required for GNC. Exotic (as compared to terrestrial UAVs) types of control actuators or control strategies may need to be developed to minimize vehicle weight, to operate under severe environmental conditions, and to minimize flight control processor workload.

Structures and Materials

Ultra-light weight structures will be essential for vertical lift PAVs – particularly for vehicles for Mars exploration. Structures and materials will be subjected to incredible extremes of temperature and pressure as well as being subjected to poorly understood levels of atmospheric turbulence, varying weather conditions, and multi-component and multiphase (and potentially corrosive) chemical constituents.

Propulsion

Outside of Earth, there is very little free oxygen in other planetary atmospheres. Therefore, new propulsion systems will have to be devised that do not rely on oxygen (or provide for the onboard storage of oxygen that has either a terrestrial origin or was generated by chemical in-situ production from a lander/main base). Reliability issues must be taken into account (including auxiliary systems for start/restart) for current implementations of mono-propellant engines such as the Akkerman hydrazine engine (Ref. 14). Solar flux availability is greatly diminished for other planets (in the case of Venus because of cloud/haze cover, and in the case of Mars, Titan and the outer planets because of distance from the Sun) for solar energy based propulsion systems. Average Mars solar flux is only ~43 % of Earth's (Ref. 1). Nuclear-energy-based (for example, using RTGs (Ref. 37-38)) electric motor propulsion is possible, but a significant weight penalty would be associated with this approach. Advanced battery and fuel-cell technology are propulsion system possibilities (Ref. 39), but still need to be matured for space systems.

For flight in Titan's atmosphere, in-situ methane may be extracted from the moon's atmosphere and combusted with oxygen/oxidizer from a terrestrial source. Electric power generation on a lander platform could recharge an onboard battery or fuel cell on a PAV between missions.

Deployment

Planetary aerial vehicles will be subjected to considerable constraints regarding mass and volume. This will pose challenges for all vehicle development disciplines, but will particularly affect the means and systems involved in the vehicle deployment. Vehicle assembly, configuring for flight, and deployment of PAVs pose unique challenges compared to terrestrial aerospace vehicles. New design approaches, mechanical systems, and structures will need to be developed for PAVs. The advantage of vertical lift PAVs (over other types of PAVs) is that they can be assembled (if need be), configured for flight, and launched from a lander, with adequate time for deployment; they will not have to rely on deployment during entry into a planet's atmosphere. Reelable (Ref. 40-41), foldable, or telescoping variable-diameter rotor blades are all possible candidates for achieving minimum vehicle volume (in stowed/package form) for integration into launch and entry vehicles.

Telecommunication

Telecommunication poses a considerable challenge for robotic planetary science vehicles. Communication delays are substantial to and from Earth to other planetary bodies, particularly when taking into account relative orbital rotation of those bodies with respect to Earth, the location of the aerial vehicle on the planetary surface, and delays in satellite overflight with respect to the aerial vehicle (or delays until vehicle return to the lander). Further, high-bandwidth signals for data-intensive science missions dictate even tighter constraints in communication options and data transfer opportunities to Earth.

Ongoing Work

Work to date within the NASA Ames Rotorcraft Division has focused on vehicle conceptual design studies. As a result, reference 2 provided an initial discussion of the technical challenges and opportunities of vertical lift PAVs. This conceptual design work continues and focuses on not only alternate vehicle configurations for Mars exploration but has begun to consider vehicle concepts for other planetary bodies.

In addition to vehicle configuration studies, a university grant with Carnegie Mellon University developed a baseline conceptual design of a mission/flight control computer architecture for a notional Martian autonomous rotorcraft. This initial mission/flight control work has focused on the use of visual cueing systems to provide for vehicle guidance and navigation. Onboard visual systems for GNC for vertical lift aerial vehicles are potentially an ideal solution for autonomous extraterrestrial flight. Impressive gains have been made in this field but a considerable amount of work remains to be accomplished in this area.

Ongoing work on vertical lift planetary aerial vehicles within NASA Ames continues to focus on the design and analysis of Martian autonomous rotorcraft for science (MARS) configurations (fig. 19). This effort includes initiating development of low-cost proof-of-concept test articles for demonstrating critical MARS technologies – including the development of a hover test stand for testing full-scale rotors at Mars atmospheric densities and a tethered hover flight demonstrator (Fig. 20a-b). An initial baseline Mars rotor is in the final stages of fabrication. This rotor is a nonoptimized configuration but reflects many of the design constraints required for an actual flight article. The blades are composed of lightweight Rohacell foam hollowed out internally with a leading edge fiberglass layup for protection and chordwise mass balance. The blades are dynamically tailored to minimize hover ground resonance, but have not yet been optimized for forward-flight blade/hub loading. The blade root cut-out for the rotor simulates the unfaired blade span required for the blade fold/telescoping needed for vehicle transport and deployment.

The focus of this initial proof-of-concept hover testing is the assessment of overall rotor hover performance. The proof-of-concept rotor blades will have constant chord and will use the Eppler 387 (Ref. 42-43) airfoil. Recent unpublished results from NASA Langley would suggest that the Eppler 387 has fairly high lift coefficients (and low pitching moment cofficients) for the Reynolds and Mach number ranges of interest. Future Mars rotor test articles will likely see the use of optimized airfoils, a significant evolution in blade/rotor geometry, and improved dynamic characteristics.

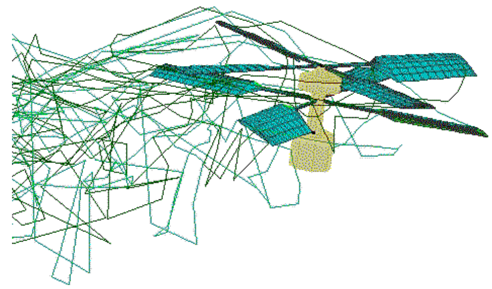
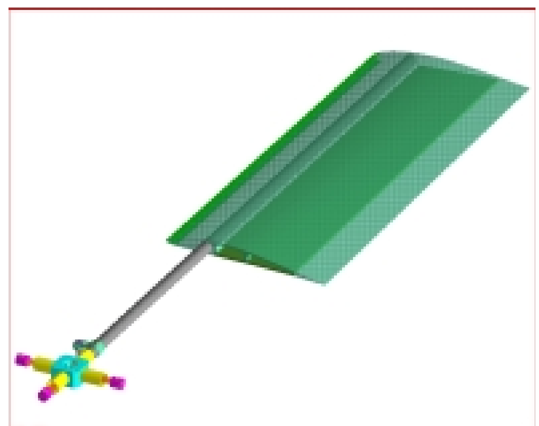


Fig. 19 – Inhouse Analysis



(a)

(b)

Fig. 20– Proof-of-Concept Test Article Development: (a) Baseline rotor design; (b) Proof-Blade Fabrication

In addition to the inhouse research and development efforts, a considerable amount of emphasis has been placed on public and educational outreach for the project.

Public and Educational Outreach

Educational outreach in the early stages of this endeavor is vitally important for a number of reasons. First, the successful development of planetary aerial vehicles will be by necessity a highly collaborative, multidiscipline effort including universities as well as NASA and the rotorcraft industry. Second, an early introduction of this new concept to today's students will hopefully prove to be an important inspirational catalyst to a founding/pioneering generation of extraterrestrial aviators and planetary aerial vehicle designers.

In this regards the Year 2000 American Helicopter Society Student Design Competition was successfully initiated on the design topic of a Martian autonomous rotorcraft (Ref. 44). A follow-on NASA-sponsored student design competition for the conceptual design of a Titan vertical lift aerial vehicle is currently being planned.

Proposals for the AHS competition (undergraduate and graduate level) were solicited for three design areas: vehicle configuration, propulsion system, and mission/flight-control computer architecture. Briefly summarized, the general mission/design requirements for the AHS student design competition for a Martian rotorcraft were:

> Assume a Mars Mission landing date 2005. A Martian autonomous rotorcraft will be deployed from a lander on the surface. The mission of this Martian autonomous rotorcraft would be threefold: a proof-of-concept demonstration of rotary-wing flight in the Martian atmosphere, a limited aerial survey (with photographic telemetry) while in flight, and successful soft-landing on the Martian surface.
>
> Required Mission Elements include:
> - Deployment from Mars lander
> - System Checkout
> - Start / Warm-up
> - Hover
> - Cruise /Maneuver / Send Telemetry
> - Return to specified location
> - Hover
> - Land
> - Shutdown
> - Optional Enhancement:
>   - Restart
>   - Hover
>   - Reposition small distance
>   - Hover
>   - Land
>   - Shutdown

Or, more specifically, for the vehicle study, the design requirements were:

- Vehicle 'Gross Weight' mass not to exceed 50 Kg

- Minimum sustained 'controlled-flight' duration of no less than one half-hour is required. Range is of secondary concern; ideally, range should be greater than 25 km.

- Maximum cruise altitude (AGL) to 100 meters (low-level flight).

- Vehicle is capable of hovering / soft-landing on Martian surface after controlled-flight has been demonstrated. It is a desired objective to demonstrate a restart and second takeoff and landing following the required soft landing.

- Photographic images taken in flight and post-soft-landing will be transferred via vehicle telemetry to a lander or an orbiter for storage and transfer to Earth Ground Control. Flight profile and vehicle status telemetry should also be transferred from the Martian autonomous rotorcraft to the lander or an orbiter.

- Flight/Mission Package 'Avionics' including camera, sensors and telemetry shall be assumed to be no more than 10% of vehicle mass

- Martian autonomous rotorcraft will be capable of sustaining continuous full sensor and data relay power consumption (first order power consumption estimate to be made as a part of vehicle design) for four (4) hours after separation from the lander and 3 1/2 hours after demonstration of soft-landing.

- The air vehicle must be autonomously deployed from the Mars lander. Complete vehicle autonomy must be demonstrated after release from the lander; only passive telemetry will be received from the Martian autonomous rotorcraft.

- Auxiliary (nonflight) systems on the lander can be used to assemble/deploy the Martian autonomous rotorcraft and/or fuel, power, or spin-up the rotor(s).

- The vehicle must be capable of sustained hovering flight for no less than one minute duration.

- Maximum Mars entry acceleration to be assumed to be 100 m/sec^2

Exceptional design study papers from the participating universities were received. The winning teams of this competition will be announced at the 57th Annual Forum of the American Helicopter Society in Washington, DC.

A follow-on NASA-sponsored student design competition is currently in the planning stage and will focus on a vertical lift vehicle for Titan. It is likely that the following nominal mission and design requirements will be proposed to the competing student teams:

> Assume it is the year 2016. Twelve years after the successful exploration of the upper atmosphere of Titan by the Cassini/Huygens mission -- six years of engineering development followed by six years of transit to Saturn from Earth -- an orbiter satellite and aeroshell entry vehicle arrive at Titan for the long awaited follow-up mission. The orbiter will execute detailed lidar/radar mapping of Titan. The lander besides carrying its own complement of sophisticated instruments will also act as a transport carrier, launch platform, and home base for a small robotic vertical lift planetary aerial vehicle. This aerial platform will be used on a number missions/flights over several weeks to complete a detailed survey of terrain (both solid and, potentially, liquid (methane) surfaces) measured in area over several hundred square

kilometers. Communication between the aerial vehicle and the lander and Earth is maintained by the orbiter satellite.

Specific design requirements will likely consist of the following:

- A minimum total vehicle range of 300 km while carrying a 10% payload fraction is required.

- Maximum cruise altitude is 2km; high-altitude cruise leg of mission will comprise less 50% of total mission range; remaining 50% of flight is at low altitude (less than 500 meters) and low-speed.

- Vertical take-off and landing capability is required for the vehicle design.

- A mid-mission hover out-of-ground effect for one minute is required, followed by a mid-mission vertical landing and take-off.

- Assume a maximum of 5m/sec gusts in hover and low-speed flight.

- There is no maximum speed requirement. Range and payload are more critical design goals.

- Vehicle should be capable of propulsion system shutdown, and restart, upon landing mid-mission. Auxiliary power source should be capable of supporting vehicle stand-by flight systems and science payload for four hours at the mid-mission remote site.

- There is a requirement for multiple flights/missions with the aerial vehicle. Therefore, the vehicle must be capable of returning to the lander and refueling or recharging for subsequent flights/missions

- Maximum vehicle gross weight to be less than 100kg (mass).

- Vehicle should be capable of landing on both solid, uneven (icy) surfaces and liquid (methane) pools; this will impact concepts for vehicle landing gear design. Assume that the solid surface for vehicle remote-site landing will include surface debris of 0.03 cubic meters. Vehicle will hover over and land on a lander platform when returning post-mission/flight.

- The vehicle must be capable of autonomous flight and take-off and landing

- The aerial vehicle must be capable of successful enduring a maximum aeroshell entry deceleration of 100 m/sec^2.

- Flight/Mission Package 'Avionics' including computer, sensors and telemetry shall be assumed to be no more than 10% of vehicle

- Auxiliary (nonflight) systems on the lander can be used to assemble/deploy the Titan vertical lift aerial vehicle and/or fuel, power, or spin-up the rotor(s)/propulsion system.

Program advocacy will be as important an element for the successful development of vertical lift planetary aerial vehicles as any given technical accomplishment. Therefore, public and educational outreach efforts are crucial to the ultimate viability of planetary aerial vehicles.

Back On Earth (Technology Transfer Opportunities)

Why should the vertical flight community be interested in promoting and participating in the study and, perhaps, the ultimate development of vertical lift planetary aerial vehicles? There are several reasons. First of all, PAV advanced autonomous software/hardware technology would be applicable to terrestrial UAV's (fig. 21). Technologies developed for PAVs – including microelectronics/sensors and lightweight power sources/systems such as fuel cells and advanced batteries -- could be applicable to Micro Air Vehicles (MAVs).

Programmatically, vertical lift PAV development will promote a strong working relationship between NASA Aeronautics, Space, and Information Technology programs. And finally, as previously noted, the development and use of vertical lift planetary aerial vehicles for Mars, Titan, and Venus exploration would considerably enhance public and educational outreach and positive awareness for the rotary-wing community and terrestrial rotorcraft applications/missions.

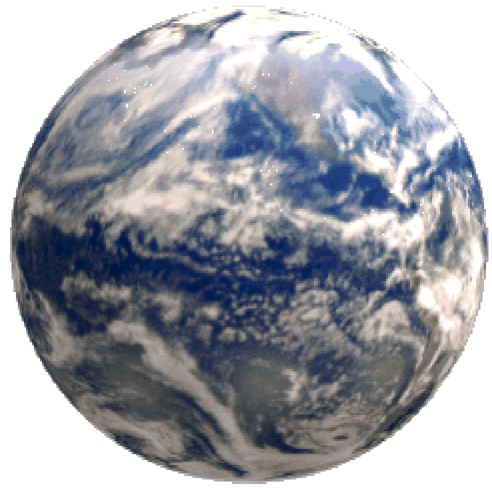


Fig. 21 – Planet Earth (Realizing Technology Benefits Back Home)

Concluding Remarks

Initial work to date suggests that vertical lift planetary aerial vehicles are potentially feasible. Such vertical lift planetary aerial vehicles have tremendous potential to support NASA planetary science and exploration programs. Vertical lift planetary aerial vehicles – if ultimately proven to be feasible -- will be employed in both purely robotic missions, or as 'astronaut agents' for manned planetary expeditions. In particular, Martian autonomous rotorcraft being used in 'scout' and/or utility roles would enable fundamental scientific quests such as the 'hunt for water' and the search for life. With research into and development of such vehicles there are tremendous outreach possibilities for the rotorcraft community. Further, there are significant potential technology transfer opportunities for terrestrial rotorcraft applications.

Three notional vehicle concepts were briefly examined in this paper. These vehicle concepts reflect the breadth of powered/vertical lift and rotary-wing technologies that could be applied to support planetary science missions. This insight is particularly appropriate to highlight during the Year 2000 International Powered Lift Conference.

In conclusion, autonomous vertical lift planetary aerial vehicles can potentially play a vital future role in the exploration of the solar system. A considerable amount of work lies ahead to develop such vehicles. A modest level of effort continues to be sustained within the Rotorcraft Division at NASA Ames Research Center to define and develop the technologies necessary for vertical lift planetary aerial vehicles.

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