ROTARY-WING DECELERATORS FOR PROBE DESCENT THROUGH THE ATMOSPHERE OF VENUS

Larry A. Young(1), Geoffrey Briggs(2), Edwin Aiken(3), Greg Pisanich(4)

(1)*Army/NASA Rotorcraft Division, MS 243-12, NASA Ames Research Center, Moffett Field, CA, USA 94035,* *larry.a.young@nasa.gov*
(2)*Center for Mars Exploration, MS 239-20, NASA Ames Research Center, Moffett Field, CA, USA 94035,* *gbriggs@mail.arc.nasa.gov*
(3) *Army/NASA Rotorcraft Division, MS 243-10, NASA Ames Research Center, Moffett Field, CA, USA 94035,* *eaiken@mail.arc.nasa.gov*
(4)*QSS Group, Computational Sciences Division, MS 269-3, NASA Ames Research Center, Moffett Field, CA, USA 94035,* *gp@ptolemy.arc.nasa.gov*

SUMMARY

An innovative concept is proposed for atmospheric entry probe deceleration, wherein one or more deployed rotors (in autorotation or wind-turbine flow states) on the aft end of the probe effect controlled descent. This concept is particularly oriented toward probes intended to land safely on the surface of Venus. Initial work describing a sub-set of engineering studies, simulation, and proof-of-concept prototyping is performed.

1. INTRODUCTION

A NASA-sponsored NRC "Decadal Study" was recently completed [1] wherein solar system exploration priorities were assessed by a broad survey of planetary science requirements. One of the outcomes of this study was the high priority assigned to a probe/lander mission to the surface of Venus to gain an improved understanding (above that attained by the USSR Venera lander missions in the 1980s and the more recent Magellan radar orbiter) of the history of the planet through measurements of the elemental and mineralogical composition of the surface and of surface-atmospheric interactions. Given the young age of most of Venus' surface, special interest focussed on gaining access to the oldest terrains, namely, the highland *tessera.*

In response to the Decadal Study, NASA is initiating the P.I.-led *New Frontiers* Program and at least one Venus atmospheric probe/lander mission is under study in a collaboration between academia, industry and NASA-JPL and NASA-ARC. This mission would ideally build upon the science, and to some degree the technology derived, from the Soviet missions in the 1960's (the Pioneer Venus probes were not designed for landing). The Venera technology -- using bluff-body (flat-plate) decelerators -- provides passive control of the probe descent rate with altitude and thus allows for neither surface hazard avoidance nor precision landing capability (Fig. 1). The Venera technique – and ideally other passive aerodynamic decelerators – are acceptable for lowland sites. The Magellan radar images of the highland tessera indicate that such passive technology will make landing on the tessera very risky because of terrain roughness and steep slopes.

Fig. 1. Venera Flat-Plate Decelerator

Future Venus lander missions call for an active controlled-descent decelerator. In many respects such

To be presented at the 2nd International Planetary Probe Workshop, NASA Ames Research Center, Moffett Field, CA, August 23 - 27, 2004.

control is easier for Venus than for Mars because Venus has a thick atmosphere whose surface pressure of about 90 bars (comparable to pressures a kilometer beneath the surface of our oceans). Such a dense atmosphere makes the use of active aerodynamic decelerators a potentially ideal solution for the descent over highland *tessera*. (The high surface temperatures of Venus do represent a challenge for mission lifetime and for mechanical device actuation and will need to be accounted for in the design process.)

One active aerodynamic controlled-descent concept is the rotary-wing (RW) decelerator (Fig. 2), wherein the autorotating rotors can precisely control both the rate and angle of descent so that hazards can be detected (by optical imaging and laser altimetry) and avoided and so that touchdown can be gentle. These probe autorotating rotors are capable of being slowed down by braking action as well as potentially being able performing a collective pitch-angle step input for the final soft-flare landing maneuver.

2. CONCEPT DESCRIPTION AND PAST WORK

In general, use of active aerodynamic control to perform enhanced planetary probe entry and descent is very desirable characteristic. In particular, use of active aerodynamic control is an essential entry probe attribute to avoid surface hazards during the final stages of landing in unknown and uncertain territory, when there is a high probability of extremely rough terrain. The problem is further compounded with probe thermal management issues for Venus. I.E., it is necessary to provide for high descent speeds through regions of lower-priority interest -- to minimize overall descent time and corresponding heat build-up in the probe's interior -- and to provide for low-speed, a soft landing, and more time on the surface and in the lower atmospheric regions of high-interest. Rotary-wing decelerators potentially promise a satisfactory solution to these problems.

Fig. 2 is an illustration of one approach to implementing a three-rotor RW-decelerator for a Venus probe. Fig. 2 also sequentially depicts (left to right, top to bottom) the release of the probe from the aeroshell, the deployment and full extension of the rotor booms and rotors, and the deployment of landing gear.

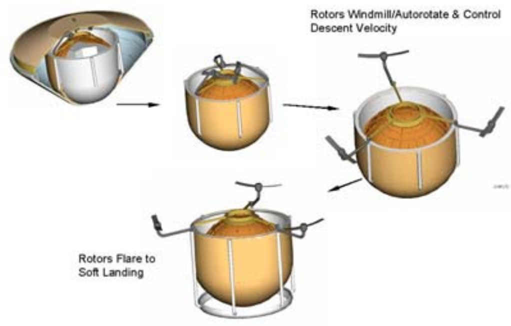

Fig. 2. Rotary-Wing Decelerator for Venus Probe

3. NOTIONAL MISSION & MAXIMIZING SCIENCE RETURN

Researchers [2-9] have previously examined rotor entry decelerators for space mission applications. But none of this past work specifically examined the feasibility of applying this technology to Venus missions. This work does, however, build upon earlier planetary aerial vehicle work by the Army/NASA Rotorcraft Division and the Center for Mars Exploration [10]. The thick surface atmosphere of Venus allows for the usage of very small rotors for deceleration. On the basis of pure aerodynamic deceleration potential, RW-decelerators can at best only match a flat-plate, or bluff body, decelerator – the real advantage of the concept is in the ability to effect controlled-descent (rate and trajectory angle), soft flare landings, and possibly electrical generation during descent. Note that the folding support arms shown in the conceptual sketch of Fig. 2 are perhaps an unnecessary design feature; with typical aeroshell shapes, and the compact rotor sizes of a RW-decelerator, rigid (always deployed) support arms are likely feasible instead.

4. GENERAL TECHNICAL APPROACH

The overall objective of the work is to establish the feasibility of RW-decelerators in terms of performance and cost in comparison to proven Venera-class decelerator technology in the context of providing Venus probes with hazard avoidance and safe landing capability on the ancient Venus highlands.

The problem being pursued has three components:

• First, engineering analysis and simulation to refine the RW-decelerator conceptual design and to identify key technologies that need to be matured/developed.

• Second, proof-of-concept prototyping of small-scale underwater "test articles" employing a multi-rotor RW-decelerator (as a terrestrial surrogate for a Venus atmosphere probe) to demonstrate trim-control laws.

• Third, feasibility demonstrations with a larger underwater surrogate probe (release/submergence of the prototype in a large body of water) of various active controlled-descent, hazard avoidance, and precision "landing" strategies (i.e. implementation of information and control system technologies).

5. DESIGN SPACE AND SIZING ANALYSIS

The design space for the engineering trade studies for the Venus probe RW-decelerator concept is shown in Table 1. All RW-decelerators incorporating one or more rotors are capable of descent rate control. Only decelerator systems with three or more rotors are capable of descent angle/trajectory trim control. All RW-decelerators must incorporate rotor collective pitch-angle step input control to be able to perform a soft flare landing (decelerating to net zero vertical velocity). If some form of rotor collective pitch-angle control is not provided for then some moderate level of landing-gear impact (nonzero vertical velocity) upon surface contact will occur.

Table 1. Design Space

# Rotors	Descent Rate Control	Descent Trajectory Control	Soft Flare Landing	Pitch Control
1	X		X	X
2	X		X	X
3	X	X	X	X
4	X	X	X	X

Employing first-order quasi-steady analysis, Fig. 3 illustrates the first-order influence of rotor size (and number) on probe descent speed, as a function of altitude. For example, a simple estimate of rotor size for a Venus RW-decelerator, for a near-surface design descent speed of 8.5 m/sec for a 200kg probe (sans aeroshell), is 0.42 meters diameter for an individual rotor in a three-rotor decelerator system operating in ideal autorotation (pre-touchdown rotor "flare"). The probe pressure-vessel diameter is assumed to be approximately 0.7 meters. Note, that for the single-rotor case, rotor blade-root cutout is assumed to be equal to the probe pressure vessel diameter, i.e., r_c=D; for all other cases, it is assumed that r_c=0.

As noted earlier, Fig. 3 rotor size estimates were based upon a simple analysis; the details of the analysis are as follows. From [11], for ideal autorotation, the descent speed, V, is given by the approximate expression

$$V \approx b v_h \qquad (1)$$

Where the constant b≈-1.71.

Correspondingly, the ideal hover induced velocity is given by the expression

$$v_h = \sqrt{\frac{T}{2\rho A}} \qquad (2)$$

Where T is the required rotor thrust, A is the rotor disk area ($A = \pi(R^2 - r_c^2)$), and ρ is the atmospheric density at the prescribed probe altitude.

Now, given Eqs. 1 and 2, the rotor size (in terms of R, the rotor radius) can be given in terms of the required (ideal) autorotation descent velocity, V.

$$R = \sqrt{\left(\frac{b^2}{2\pi}\right)\left(\frac{T}{\rho V^2}\right) + r_c^2} \qquad (3)$$

Where, again, r_c is the blade-root cut-out for the rotor(s)

Each rotor will have to provide the following amount of Thrust, T, during descent, recognizing that the entry body in itself will have a drag coefficient of C_D and a frontal area of S.

$$T = \frac{1}{N}\left[mg - \left(\frac{1}{2}\rho V^2\right) C_D S \right] \qquad (4)$$

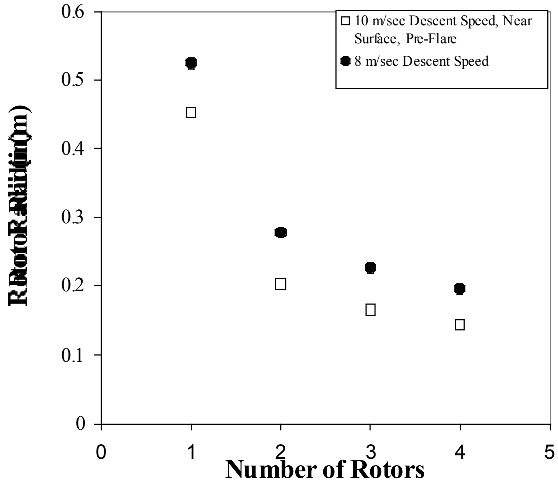

Fig. 3. Rotor Decelerator Size Relative to Autorotation Descent Speeds

Trim control (to vary descent-angle and trajectory) for a four-rotor RW-decelerator is fairly straightforward. Trim for a four-rotor-system simply entails differential rotor braking between the four rotors, note that opposing pairs of rotors spin in opposite directions. Fig. 4 illustrates the connection between the application of rotor differential braking torque and the subsequent resulting (in sequence) reduced rotor thrust, the probe bluff-body angular displacement, and the resulting bluff-body normal- and side-force generation. Symmetry considerations for the four-rotor decelerator system allow for yaw control to be effected in the same manner as the pitch control shown in Fig. 4, merely with an orthogonal pair of rotors, though. For the four-rotor decelerator system, pitch and yaw control are decoupled from each other. Descent rate is influenced to slight degree by pitch and yaw control braking-torque inputs, as they reduce the overall thrust by $2\Delta T$.

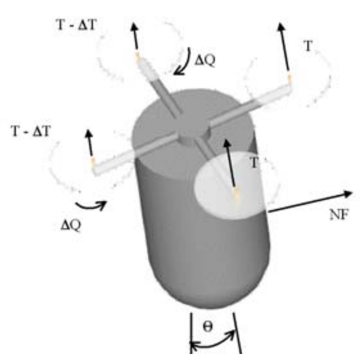

Fig. 4. Four-Rotor (Pitch) Trim Control

Trim control can still be implemented on a three-rotor decelerator system, but it entails a more complex approach. Overall, the three- versus four-rotor decelerator designs have better volume/packaging characteristics while stowed in the entry aeroshell, though.

The final paper will detail the ability to control probe descent angle through rotor braking using first-order quasi-steady analysis and simulation. Rotor autorotation RPM/tip-Mach-number trends, as a function of altitude, will also be presented in the final paper.

6. INITIAL SIMULATION WORK

There are four phases of probe descent with rotary-wing decelerators: 1. release from the entry vehicle aeroshell and initial rotor spin-up and high-speed deceleration of probe, 2. transition phases where the rotor passes through the turbulent and vortex-ring states, 3. low speed and altitude terminal descent, and 4. rotor flare and soft landing. The initial simulation work to be reported in the final paper will focus on the last two stages of probe descent; the majority of discussion in the final paper will be on the demonstration of robust control laws. Future work will couple the basic probe control laws with a high-level closed-loop "autonomous" controller to validate the viability of hazard avoidance and precision landing using a variety of hypothetical sensors and terrain feature-recognition techniques as applied to Venus-representative simulated terrain.

Height-speed curves defining the boundaries of being able to effect a safe "soft flare" landing – given prescribed rotor collective pitch-angle step inputs – will be presented in the final paper.

7. FUTURE SURROGATE PROBE TESTING

The use of underwater submersibles to demonstrate and evaluate teleoperation and robotic technologies for NASA planetary science missions is not a new technical approach. Previous work has been conducted, such as the Ames TROV project [12].

Though Venus's lower atmosphere has pressure levels comparable to the ocean depths on Earth, the analogy between the two is only of limited aerodynamic value. However, there is still considerable value in the possible test and evaluation of surrogate underwater probes for the proof-of-concept testing of descent trim-control laws and terminal stage guidance and navigation and autonomy technologies.

The majority of demonstrations will entail use of small-scale probes that will be released in an artificial pool/tank of water. The test and evaluation team will place artificial hazards (orange markers) at the bottom of the pool (Fig 5). Control of the probe hazard avoidance and precision landing guidance will be provided by using simple optical imagers, existing vision-system software, a pool-side lap-top computer, and radio-frequency (RF) or ultrasound I/O for telemetry and control inputs. The proposed simple vision-system initially to be used in the demonstrations has been previously used for other, similar vehicle guidance projects [13-14]. Additionally, other sensors and systems will be based in part on experience gained in the development of small robotic underwater vehicles. In the final demonstrations the probe will be of larger size and capability and there will be increased realism of terrain hazards at the bottom of the natural body of water (a lake such as Tahoe or Mono where the underwater landscape can be conveniently evaluated prior to field trials.

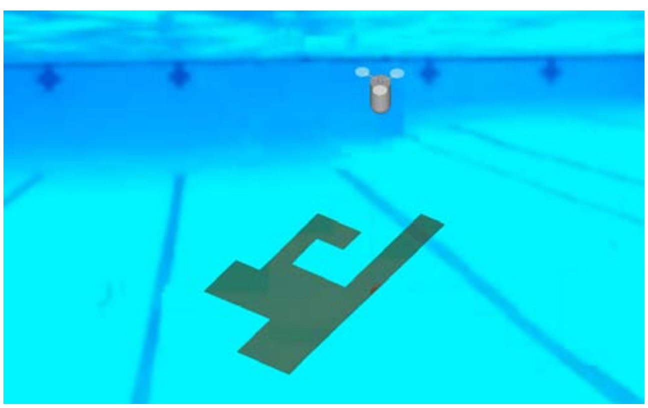

Fig. 5. Small-scale Surrogate Probe Testing

8. CONCLUDING REMARKS

Preliminary work related to the use of rotary-wing decelerators for application to Venus entry-probes/landers has been found to be very promising. Current work is focusing on three areas: conceptual design analysis, probe descent simulation, and developing underwater surrogate probe test articles to validate control law and autonomy efforts.

In addition to specifically, and primarily, examining the RW-decelerator concept, the control technologies developed in parallel with RW-decelerator work are applicable to a general class of active aerodynamic controlled descent for entry-probe/lander problems. This active aerodynamic descent-control work is anticipated to find broad application to a number of priority NASA mission technology needs.

10. ACKNOWLEDGMENTS

The technical work of Jim Kennon, Projects Division, and Corey Ippolito, Computational Sciences Division, is gratefully acknowledged.

11. REFERENCES

1. “New Frontiers in the Solar System: An Integrated Exploration Strategy,” NRC Decadal Study.
2. Levin, A.D. and Smith, R.C., “Experimental Aerodynamics of a Rotor Entry Vehicle,” 3rd AIAA Aerodynamic Decelerator Systems Technology Conference, El Centro, CA, September 23-25, 1968, Technical Report NO. 69-11 April 1969.
3. Iverson, J.D., “The Magnus Rotor as an Aerodynamic Decelerator,”3rd AIAA Aerodynamic Decelerator Systems Technology Conference, El Centro, CA, September 23-25, 1968, Technical Report NO. 69-11 April 1969.
4. Smith, R.C. and Levin, A.D., “The Unpowered Rotor: A Lifting Decelerator for Spacecraft Recovery,” 3rd AIAA Aerodynamic Decelerator Systems Technology Conference, El Centro, CA, September 23-25, 1968, Technical Report NO. 69-11 April 1969.
5. Levin, A. D. and Smith, R. C., “Experimental aerodynamic performance characteristics of a rotor entry vehicle configuration. 1 – Subsonic,” NASA-TN-D-7046, 1971.
6. Levin, A. D. and Smith, R. C., “Experimental aerodynamic performance characteristics of a rotor entry vehicle configuration. 2 – Transonic,” NASA-TN-D-7047, 1971.
7. Levin, A. D. and Smith, R. C., “Experimental aerodynamic performance characteristics of a rotor entry vehicle configuration. 3 – Supersonic,” NASA-TN-D-7048, 1971.
8. Levin, A. D. and Smith, R. C., “An analytical investigation of the aerodynamic and performance

characteristics of an unpowered rotor entry vehicle," NASA-TN-D-4537, 1968.

9. Giansante, N. and Lemnios, A. Z., "The dynamic behavior of rotor entry vehicle configurations. Volume 1 - Equations of motion," NASA-CR-73390, 1968.
10. Young, L.A., Chen, R., Aiken, E., and Briggs. G., "Design Opportunities and Challenges in the Development of Vertical Lift Planetary Aerial Vehicles," American Helicopter Society (AHS) Vertical Lift Aircraft Design Conference, San Francisco, CA, January 2000.
11. Johnson, W., *Helicopter Theory*, Princeton University Press, 1980.
12. Hine, B., Stoker, C., Sims, M., et al, "The Application of Telepresence and Virtual Reality to Subsea Exploration," 2nd Workshop on Mobile Robots for Subsea Environments, Proceedings ROV'94, Monterey, CA, May 1994.
12. Plice, L., Pisanich, G., Lau, B., and Young, L.A., "Biologically Inspired 'Behavioral' Strategies for Autonomous Aerial Explorers on Mars," IEEE Aerospace Conference, Big Sky, MT, March 2003.
13. Pisanich, G., Young, L.A., Plice, L., Ippolito, C., Lau, B., Lee, P., "Initial Efforts towards Mission-Representative Imaging Surveys from Aerial Explorers," SPIE Electronic Imaging Conference, San Jose, CA, January 2004.