ROTARY WING DECELERATOR USE ON TITAN

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ABSTRACT

Rotary wing decelerator (RWD) systems were compared against other methods of atmospheric deceleration and were determined to show significant potential for application to a system requiring controlled descent, low-velocity landing, and atmospheric research capability on Titan. Design space exploration and down-selection results in a system with a single rotor utilizing cyclic pitch control.

Models were developed for selection of a RWD descent system for use on Titan and to determine the relationships between the key design parameters of such a system and the time of descent. The possibility of extracting power from the system during descent was also investigated.

1. INTRODUCTION

The ongoing Cassini mission to Saturn is considered one of the most successful international collaborations in the history of space exploration. The mission included the Huygens probe, which landed on the surface of Saturn's largest moon, Titan, in 2005, generating a huge amount of scientific interest in further exploration of Titan. Huygens brought its power source with it in the form of batteries, which limited its operational lifetime to about six hours, nearly half of which was spent in atmospheric descent.

Titan's dense nitrogen atmosphere, methane hydrological cycle, and presence of water make it an especially interesting subject of study for atmospheric and planetary scientists. Huygens' success, combined with other recent findings, such as possible plate tectonics and cryovolcanism, provide justification for a return mission to study Titan's atmosphere and surface.

A vehicle for such a return mission would greatly benefit from a descent system that can provide landing site selection, low-velocity touchdown, and power generation capabilities, while also providing a platform for atmospheric research. This paper provides a comparison of various atmospheric deceleration technologies for possible inclusion on a future mission to Titan based on their potentials for providing heading control, a soft landing, and power generation during descent, and shows a rotary wing decelerator (RWD) system to be of significant merit. A preliminary design of such a system is offered, as well as basic performance figures.

A rotary wing decelerator system uses rotating blades, like those on a helicopter, spinning in autorotation to slow a descending vehicle down. The rotor is allowed to spin freely as the vehicle descends, which induces a large amount of drag. When the vehicle nears the surface, the pitch of the blades can be reversed, harnessing the momentum to generate lift for a low-velocity or zero-velocity touchdown on the planetary surface. Versions of such systems are typical in manned helicopter systems, where they are used for emergency landings in the event of engine failure.

2. ATMOSPHERIC DECELERATION METHOD SELECTION

For the purposes of this study, the goals of an atmospheric descent and landing system are low cost and weight, controllable descent and landing site selection, zero- or low-velocity touchdown, and power generation capability. Such a system should also provide a suitable platform for atmospheric research during the descent phase of the mission across all altitude ranges.

Five atmospheric descent techniques were compared on their abilities to fulfill the requirements given above for a mission to Titan, relative to the capability provided by a parachute. These techniques were to use deployable surfaces to increase drag, a controllable parachute, retro thrusters, and an RWD system. The absence of a descent system was also included for purposes of comparison. A standard parachute was taken as the baseline system, as such a system was successfully employed on Huygens.

Table 1: Comparison of Descent Technologies

Concept	Parachute (Baseline)	None	Drag Surfaces	Controllable Parachute	Retro Thrusters	Rotary Wing Decelerator
Cost	0	+	+	–	–	–
Weight	0	+	+	–	–	–
Controllability	0	0	0	+	+	+
Landing Speed	0	–	–	0	+	+
Power Gen.	0	–	–	0	0	+
Atm. Research	0	–	–	0	0	+
Total	0	-1	-1	-1	0	+2

The results of this comparison are shown in Fig. 1, and clearly show an RWD system to be of significant merit. Stepping through the study, we see that this indication is not without justification. First off, the comparison shows that an increase in capability is always associated with an increase in both cost and system weight, which was expected. The weight of an RWD system for a 2000 lb probe has been estimated at 10-15% of the gross vehicle weight.

What is surprising, however, is that the controllable parachute adds very little capability for the increase in power and mass required by the added navigation sensors and mechanical actuators. Further augmenting such a system with retro thrusters, as are often used for Mars descent and landing, comes at an additional mass and cost penalty while serving only to reduce landing speed (while also disturbing the landing site). Huygens' final landing speed using only a parachute was about 5 m/s, so it is difficult to make case for retro thrusters solely on the grounds of increasing controllability or reducing landing speed.

By adding a rotor to the system, there is a capability increase in all four areas. An RWD system offers the capability of a precise, zero-velocity landing. The system can generate power for its navigation sensors and atmospheric research during the descent by attaching a generator to the free-spinning rotor. An RWD system can additionally increase atmospheric research capability by varying its rate of descent and slowing down during its traverse through key regions of the atmosphere, such as the tropopause.

3. BASICS OF RWD SYSTEMS

There are many variations on RWD systems available, but all follow the same general sequence of events during descent. First, the vehicle enters the Titanian atmosphere and is slowed to approximately Mach 1.5, similar to Huygens' entry. At this point, the RWD system's protective cover is released, automatically deploying the rotors. As soon as they are deployed, the rotor (or rotors, if more than one are used) enter stall, behaving similarly to flat-plate drag surfaces. This slows the vehicle, and the rotors will soon de-stall and begin to rotate, gaining and storing momentum. Around this time, the vehicle slows further to about Mach 0.6 and the heat shield is released from the vehicle, allowing atmospheric data collection to begin.

The probe can now apply control actions to the spinning rotor system, inducing a forward glide through the atmosphere as it descends, allowing significant distance to be covered for aerial photography of the surface of the moon. Because the rotor system is more efficient in forward flight, the horizontal glide phase significantly increases the descent time, allowing additional time for data collection. Once the probe is near the surface, the pitch of the blades can be reversed in what is called a "cyclic flare" maneuver, which lasts a total of about five to ten seconds. In this maneuver, he stored momentum of the blade is used to generate lift and enter a slow, tightly controlled descent, at the end of which the probe gently settles on the ground [1-2].

Rotary wing decelerators are not a new topic of study, and research into RWD applications to planetary entry date back to the 1960s, when such systems were envisioned for ground-based recovery systems for Apollo. The most in-depth studies were carried out by the Kaman Aircraft Company, who demonstrated the feasibility of using a single-rotor RWD system, called the Rotochute, for atmospheric recovery systems. They found this system could be successfully deployed at velocities up to their testing limit of Mach 3 [1]. However, parachutes were available and demonstrated reliable, so RWD development slowed significantly.

More recently, RWDs have been reconsidered as a viable alternative to parachute-centric systems. In 2004, Young, et al, proposed an RWD system for atmospheric descent on Venus [3]. In 2005, Hagen proposed the use of a RWD system for NASA's Crew Exploration Vehicle [4]. Even more recently, in 2009, EADS Astrium developed an inflatable RWD system for Martian descent and landing as part of an ESA study [2].

The dense atmosphere (greater than four times that of Earth), low gravity (nearly 1/8th that of Earth), and large atmospheric extent (over 160 km of usable altitude for deceleration and study) combine to make Titan even more ideal than Earth or Mars for the use of such a system. In this paper, we build off these previous studies to present a preliminary design of a RWD system for use on Titan.

4. RWD SYSTEM DRIVER ANALYSIS

Many variations of RWD systems are possible, providing a large design space to work within. The general approach for picking a design was to determine the factors that drive the system as a whole and then combine those factors into a few system architectures. These architectures were then compared against one another on their relative merits, and the best option was selected as the baseline.

First, a list of system characteristics was created, each of which represents a choice between at least two options, which span the design space. From this list of properties, three were determined to be driving properties of the system, while the rest were characterized as "system details." Combinations of these driving properties result in vastly different RWD systems, to which the options can then be applied. Different combinations of the system details can then be applied to these systems based off the system drivers to narrow in on a more specific design for a given application. For the purposes of this paper, the options considered are shown in Table 2, though this preliminary design exploration only involved the system drivers.

Table 2: System Characteristics

System Drivers	**Options**
Rotor Count	One, Two, Three, or Four
Blade Pitch Control	Cyclic Pitch Control, Collective Pitch Control
Heading Control	Pitch Control, Multiple Rotors, Variable CG
System Details	
Blade Count	One, Two, Three, or Four
Blade Size	Cyclic Pitch Control, Collective Pitch Control
Blade Position	Pitch Control, Multiple Rotors, Variable CG
Landing Style	Cyclic Flare, Powered, Vertical
Anti-Torque	Fins, Control Surfaces, Auxillary Rotor
Energy Storage	None, Battery, Capacitor, Flywheel

The three system drivers are the number of rotors, heading control, and blade articulation. The number of rotors is by far the most significant driving property, as varying the rotor count vastly affects the system. One rotor is the most common option, though systems with three or four rotors have been proposed [3]. Using only two rotors complicates the design without providing any significant advantages, as such a system requires aerodynamic control surfaces that would unnecessarily restrict the design and make landing more difficult.

The next system driver was heading control, which can be accomplished using a number of methods, but most notably by using pitch control, a variable center or gravity, multiple rotors, or control surfaces. Control surfaces were ruled out, as they will not be effective during the landing phase of the mission. Varying the relative rotation rates of multiple rotors is by far the simplest option when multiple rotors are already present, so this option was locked in for the case of 3 or 4 rotors. The single rotor case can use either pitch control or vary its center of gravity (CG).

The last system driver was blade pitch control, as RWD systems can use cyclic pitch control, collective pitch control, or rigid blades. Rigid blades do not allow adequate descent rate control, especially during the landing phase, and thus cannot fulfill the system requirements. It only makes sense to use cyclic pitch control if pitch control is being used for heading control, otherwise the cyclic capability serves no purpose.

The resulting set of simplified RWD system drivers can be combined into only four architectures, as shown in Fig. 2.

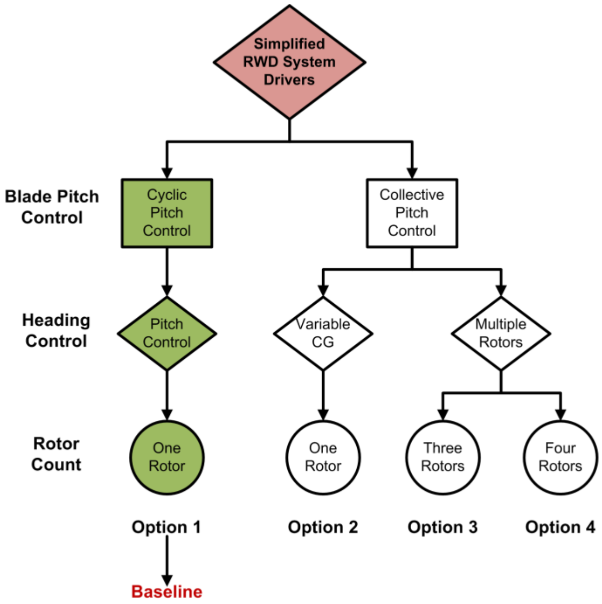

Fig. 1. Architecture Options

The resultant architecture options were then compared based off their relative strengths in four areas: heading control, descent rate control, mechanical complexity, and power generation. Because the four options being compared were inherently different, a few assumptions had to be made. First, multiple rotors with collective pitch control were considered to be roughly equivalent in complexity to one rotor with cyclic pitch control, and second, it was assumed that the power system associated with a single large rotor would be more efficient than a power system associated with multiple smaller rotors. And third, it was assumed that it would be more difficult to control the heading of a three rotor system than a four rotor system.

Table 3: Comparison of RWD Architectures

Concept	Option 1 (Baseline)	Option 2	Option 3	Option 4
Heading Control	0	–	–	0
Descent Rate Control	0	0	0	0
Mech. Complexity	0	–	0	0
Power Generation	0	0	–	–
Total	0	-2	-2	-1

Option 1 was taken as the baseline, and was found to be the best fit for use on Titan. Advantages of this baseline system are numerous. First and foremost, because rotor area is related to diameter squared, one rotor is the most efficient from a mass standpoint. A quad-rotor system requires at least twice the total blade length to achieve equivalent performance. Second, having only one rotor greatly simplifies the vehicle design, rotor packing and deployment, and power generation system. The variable CG control method offers less control capability at the cost of additional mechanical complexity.

5. VEHICLE DESCENT TIME

A model was created to model probe descent time in Titan's troposphere as a function of vehicle mass and diameter. For the purposes of this preliminary design analysis, the system has been simplified to assume purely vertical motion, though autorotational systems are generally more efficient in forward flight. Additionally, the typical drag coefficient for a system in autorotation. C_D=1.23, was held constant throughout the analysis, though it actually will vary based off other factors, such as blade rotation rate. Atmospheric density was assumed to be constant throughout the troposphere, however in reality the density decreases by almost 90% at the tropopause from its 5.75 kg/m3 surface value. An update to this model in the future is planned.

$$\square\square=\square\square+\square\square \quad (1)$$

$$\square\square=18\square\square\square2\square\square\square2 \quad (2a)$$

$$\square\square=\square\square \quad (2b)$$

$$\square\square=\square\square\square\square\square\square\square\square\square\square \quad (2c)$$

The external forces on the vehicle during vertical descent are shown in Fig. 2. Drag force, from the rotor, acts to slow the vehicle. Using a generator to capture some of the energy of the rotor can be modeled as an additional force, acting to reduce drag and increase descent speed.

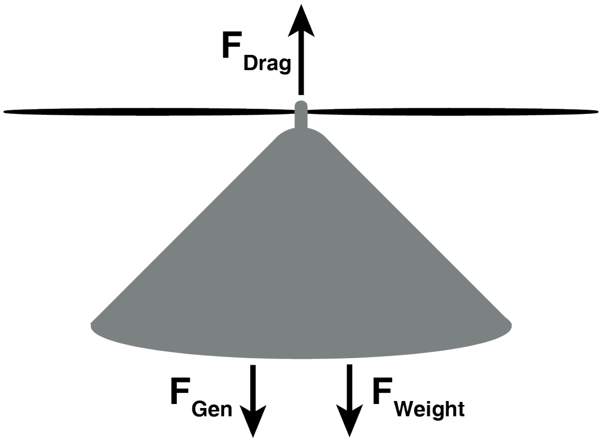

Fig. 2. Forces on RWD System During Descent

$$\square=1\square8\square\square\square\square\square\square \quad (3)$$

During standard descent, the probe will reach a steady state velocity when its drag force equals its weight [5]. From this, a relationship can be derived to determine the required rotor diameter for a given probe mass and desired descent velocity, presented in Eqn. 1. Fig. 3 shows the probe diameter necessary to achieve a desired descent rate on Titan for probe masses equal to or greater than that of Huygens (319 kg).

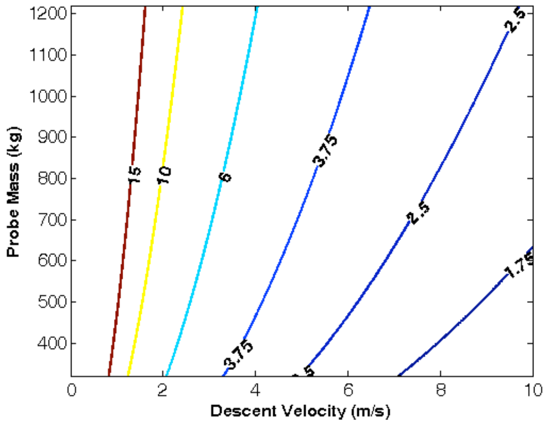

Fig. 3. Rotor diameter as a function of probe mass and desired descent velocity.

As shown by Fig. 3, low descent velocities are associated with large rotor diameters. The simplest rotor is one in which no deployment or unfolding is necessary, however this seriously limits the rotor diameter to something that will fit within a rocket payload fairing, which are typically 5 m in diameter or less. However, a very simple deployment scheme is possible, as shown in Fig. 4, that will deploy automatically upon release of the blades from the sides of the probe. If the main rotor shaft is lengthened, additional increases in rotor diameter are possible. Other strategies for increasing the rotor diameter include using an inflatable rotor [2] or telescoping blades [6].

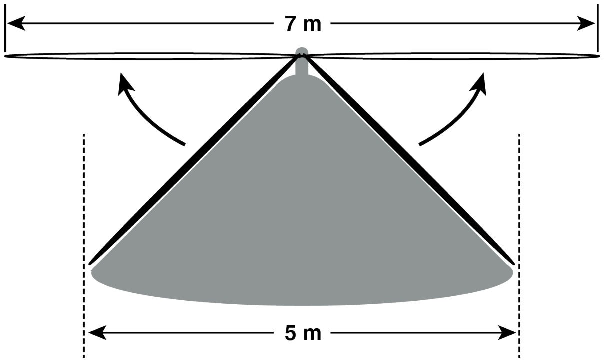

Fig. 4. Rotor deployment permits rigid rotor larger than probe body diameter.

A relationship was then developed to predict the total descent time of the probe based off the size of the diameter, as shown in Eqn. 4. For a constant mass, there is a linear relationship between rotor diameter and descent time, as shown in Fig. 5. Titan's tropospheric extent is 42 km (although the system would deploy at around 160 km, like Huygens' parachute), tropospheric descent times for a 500 kg probe can reach 6 hours with a 7-8 m rotor.

□□□□□□□□□=ℎ□8□□□□□□□ (4)

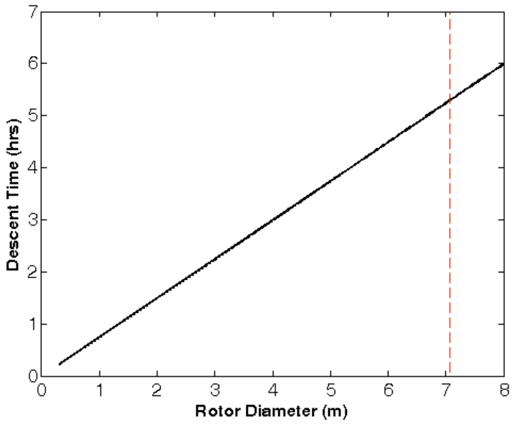

Fig. 5. Descent time as a function of rotor diameter. The dashed line represents the rotor in Fig. 4.

6. POWER GENERATION

It is possible that some of the energy of the descending vehicle could be used to power vehicle sensors, guidance systems, and research packages during descent. However, diverting some of the rotor's power by using a generator will make the rotor less effective at slowing the vehicle, increasing descent velocity and reducing the total descent time. Power output and descent velocity are related in Eqn. 5. However, this method is only a first-order approximation for preliminary mission design purposes, and will only give a reasonable result for small amounts of power extraction.

□=□□(18□□□2□□□2+□□) (5)

Fig. 7 shows the effect of power extraction on descent time for four vehicle configurations. Descent time is much more sensitive to changes in probe diameter than to changes in mass. A heavy vehicle sheds more potential energy as it descends than a light vehicle, so although the heavy vehicle has a shorter descent time in ideal autorotation, its descent time is far less sensitive to power extraction than a lighter vehicle.

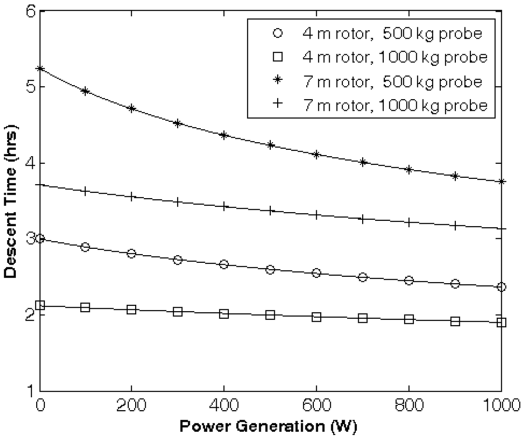

Fig. 6. Vehicle descent times in Titan's troposphere as a function of power being extracted.

7. APPLICATION TO EARTH, MARS, AND VENUS

This model is not specific only to Titan, and descent times can also be calculated for other planets with atmospheres, including Earth, Mars, and Venus. Atmospheric densities, troposphere altitudes, and gravitational constants for these three bodies can be found in Table 4.

Table 4: Properties of Various Solar System Bodies

Planet	Atmospheric Density (kg/m^3)	Tropospheric Extent (km)	g (m/s^2)
Titan	5.75	42	1.345
Earth	1.20	17	9.80
Mars	0.02	40	3.71
Venus	65	65	8.87

Descent times as a function of rotor diameter are plotted in Fig. 7. From this plot it is clear that both Titan and Venus have high potential for long-duration atmospheric descents using relatively small rotor sizes. For a 10 meter rotor, a tropospheric descent on Earth lasts only about half an hour, and only 15 minutes on Mars. This means that RWDs are likely not an ideal platform for atmospheric research in these locations.

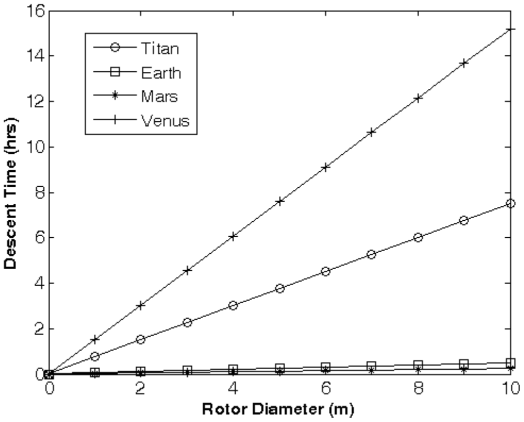

Fig. 7. Descent time as a function of rotor diameter for various solar system bodies. Descent times on Earth and Mars are significantly shorter than those on Venus or Titan.

8. CONCLUDING REMARKS

A rotary wing decelerator system shows great promise for atmospheric descent and landing on Titan, and would serve well as a platform for atmospheric research. A single-rotor system using cyclic pitch control provided the ideal RWD system design for such an application, providing precision landing capability, as well as possibility for utilization of rotor energy for power generation.

Future work will focus on increasing model fidelity, working towards experimental verification of the system presented.

9. ACKNOWLEDGEMENTS

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