TITAN BUMBLEBEE: A 1 KG LANDER-LAUNCHED UAV CONCEPT

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A concept for a small (~1 kg) unmanned aerial vehicle (UAV) launched from a lander on Saturn's moon Titan is discussed. This battery-powered vehicle could survey an area of hundreds of square kilometers around the lander over a few hours, providing stereo imagery, boundary-layer meteorological profiles and other data. The cold, thick atmosphere on low-gravity Titan makes a fixed- or moving-wing vehicle easy to fly, but requires substantial energy to keep it warm, a situation similar to terrestrial bumblebees and a similar flight configuration may therefore be appropriate.

Keywords: Titan UAV, Titan surface exploration, Titan aeronautics

1. INTRODUCTION

Saturn's largest moon Titan [1] is one of the easiest places in the solar system for aerodynamic or buoyant flight: it has a thick, cold atmosphere with high molecular weight, and it has a low surface gravity. Titan has a varied landscape featuring lakes filled with liquid hydrocarbons, mountains, river channels, vast seas of organic sand dunes, craters, cryovolcanos and other features. It is an environment abundant in organic materials and thus for prebiotic synthesis. It is thus an attractive target for future solar system exploration, e.g. [2].

There is a very wide space of options for Titan exploration, both in the selection of an overall architecture (e.g. an orbiter with several landers, or an orbiter with a single airship etc.) and in the details of any particular vehicle. A recent NASA Flagship study [3] suggested one near-term architecture that addressed a wide range of scientific goals with balanced risk and cost would include an orbiter, a lander and a large (200 kg) hot-air balloon. Discussions are presently underway with ESA as a potential partner, following the selection of TANDEM (Titan AND Enceladus Mission [4]) for further study under the ESA Cosmic Visions programme.

The thick, cold atmosphere with too little sunlight for solar power forces in-situ vehicles to be logically divided into short-lived (hours) battery-powered systems, or long-lived (years) radioisotope-powered systems. In that context, the author has discussed in a separate paper [5] some options for balloon systems. Sustained heavier-than-air flight is difficult, even in the favourable Titan environment, given the low power:weight (or specific power) of present-day radioisotope power systems (100 W, 20-40 kg). While indeed possible on paper [6, 7], flight at such low power:weight would require rather low wing loading (much like human-powered aircraft on Earth) posing severe structure and deployment challenges [8] and making the vehicle susceptible to gust loads. If higher power:weight radioisotope (or for that matter, reactor) systems were available, then long duration flight would indeed be an attractive proposition at Titan (e.g. [9] discusses a 200kg aeroplane using a novel radioisotope engine to provide the 10-80 kW (thermal) necessary for flight at 5-40 m/s.)

Chemical-powered (battery or internal combustion) aircraft would also work well on Titan, but it is important to consider what scientific measurements can be made with an aircraft which can last only some hours that are not made with lower risk by a lander or an orbiter, which are less burdened by power:weight considerations Obviously, as with a balloon, meteorological measurements and high-resolution imaging of the surface are key possibilities. Some balloon-borne measurements [3] such as subsurface radar sounding may in fact be less attractive from an aeroplane due to the somewhat ungainly antenna required.

Heavier-than-air flight in the absence of a guaranteed safe place to land requires that the vehicle be propelled and under control essentially at all times (although climb-glide strategies are possible). Further, while terrestrial unmanned aerial vehicles (UAVs) have demonstrated impressive capabilities in recent years, the launch/deployment of these vehicles is usually supervised, manual intervention is often possible if automatic control is lost (and autonomous navigation is of course greatly facilitated by the availability of GPS) and replacement or repair is feasible. A Titan aeroplane must be launched or released into the Titan atmosphere unsupervised after 5-10 years of travel in space and a hypersonic entry.

While even the quantitative evaluation of risk and of scientific value are subjective, and the qualitative judgement of a given risk's acceptability is even more so, it seems difficult to envision an aeroplane being the scientific centerpiece of a Titan mission. In this context it is worth recalling that the most novel in-situ space missions that have flown or been attempted (the VEGA balloons, the DS-2 Mars penetrators etc.) have only been able to do so as 'add-on' augmentations to primary missions rather than as the sole elements on which mission success is judged.

It was recognized in the 2007 Titan Flagship study [3], as well as in prior studies [e.g. 2, 10] that deployment of small sub-vehicles of a variety of types from more [2] or less [10] conventional in-situ vehicles at Titan could enhance the total science return, without jeopardizing the central science goals attained by the main platforms. These sub-vehicles could include profiling drop-zondes released from the balloon, or a subsurface 'mole' like that carried on the Beagle 2 lander to Mars, or as we describe here, a small UAV. This could be deployed from a balloon, but since the 2007 Flagship Science Definition Team determined [3] that the lander science is more significant and the platform is of lower risk than the balloon, we consider here launch from the lander. We furthermore assume that the UAV is launched after some weeks of lander operation, as discussed in a later section.

Insofar as the inclusion of an element in a mission is qualitative (news headlines read 'Aeroplane flies on Saturn's Moon Titan', regardless of how large or scientifically significant the aircraft is) we consider a 'minimal' UAV, of mass 1 kg. The incremental cost of such a vehicle could in fact be rather small overall – comparable with a modest scientific instrument. This may allow such a vehicle to be perceived as worth the risk. Larger, more capable vehicles (e.g. 2 kg, 5 kg etc.) could also be considered, but we explore 1kg as a starting point, noting that Titan is an aeronautically-easy environment, that 2 kg UAV's are in routine use on Earth, and that for this application weight-saving measures could be applied that are not economic on mass-produced UAV's.

2. TITAN ENVIRONMENT AND VEHICLE SCOPE

It is important to recognize that the near-surface Titan environment, while facilitating mobility, is challenging from a longevity standpoint. The lack of solar power (insolation at the surface is ~1/1000 of that at Earth) precludes that as a power source, and the thick, cold atmosphere (94K, 1.46 bar pressure) means active heating is required for operations sustained over any period more than a few hours. It will be recalled [11] that the 1.3 m diameter Huygens probe, even though it had a 5 cm thick layer of foam insulation, lost some 400 W heat to the Titan environment after landing. Even with aggressive thermal control measures (which become progressively more difficult for small vehicles, since the surface area:mass ratio is higher at smaller scales, and the penetrations through insulation required for sensors, cabling etc. become proportionately more significant) steady-state operation on Titan's surface may be impossible without many tens of watts of thermal power. It is this thermal power requirement more than anything else that drives the bifurcation of in-situ missions on Titan into short-lived battery vs long-lived RTG systems.

Let us consider the energy available: if we use high-performance primary batteries such as Lithium Thionyl Chloride (the type used on Huygens, Galileo and the DS-2 Mars Microprobes) these have an energy density of 400 Wh-hr/kg, e.g. [12]. Thus our 1 kg UAV with an energy content of 720 kJ, even if half of its mass were allocated to battery, would be able to run at 100 W for 2 hours, or perhaps 20 W for 10 hours. Some tens of watts of power are likely to be required individually for propulsion and thermal power, (see later), so these durations and powers bound the likely design space.

The most evident science results from a small UAV would be high resolution visible or near-infrared images of Titan's surface for a few km around the landing site, together with boundary-layer meteorological profiles (temperature, wind and methane humidity). Instruments to perform these functions would involve only a couple of hundred grams of payload. In essence, the UAV would function much like the small (1-3 kg) hand- or catapult-launched UAVs now used routinely (e.g. [13]) by the military for video and thermal surveillance, for example for perimeter defense at airfields. These vehicles (a selection is listed in Table 1) have a typical endurance of 1hr at speeds of ~20 m/s, a wingspan of 1m and a flight power of ~200 W. The vehicles are flown either by remote control, or by an autopilot following a chain of waypoints with navigation by Global Positioning System (GPS), with video or other data being relayed by line-of-sight radio link to the base station. Some thousands of these systems are in routine use – e.g. the US Marine Corps operates 2000 Dragon Eye UAVs – see Fig. 1. Table 1 summarizes the parameters of some small conventional (aeroplane) UAVs. Comparable capabilities are in fact readily attained with off-the-shelf model aeroplanes with cellphone- or microcontroller-based autopilots [14], and an annual International Aerial Robotics Competition sees undergraduate students develop aircraft that fly autonomously over several kilometers and pick out a designated building and either enter it or deliver a sub-vehicle into it to acquire interior imagery. Thus the technologies to achieve the sort of mission we intend for Titan can be considered rather mature in the terrestrial environment, and only modest adaptation is needed for the Titan environment.

Fig. 1 A Dragon Eye UAV about to be hand-launched during Operation Enduring Freedom in Kuwait in 2003. This vehicle is twice as massive as the concept discussed in this paper. (Photo Credit: US Marine Corps)

Clearly for Titan implementation, certain modifications are entailed. First the flight environment permits a more compact airframe and less energetic propulsion, but with new thermal control demands. Further, since the vehicle is being flown some 9-10 AU from Earth, with a one-way light time of over an hour, earth-based control is impossible. Since there is no GPS constellation at Titan, navigation must be accomplished by other means. A combination of dead reckoning/inertial guidance, optical navigation and/or the use of a lander beacon signal could be used to follow a simple survey flight pattern such as a racetrack or raster pattern, or some sort of spiral.

3. FLIGHT POWER REQUIREMENTS

Let us now consider how far our aircraft may usefully fly and how fast, and what the energy cost of moving our 1kg vehicle around might be. Huygens data [11, 15, 16] and circulation models [e.g. 17] suggest winds in the lowest few kilometers are of the order of 1 m/s or less. Thus to achieve effective penetration of headwinds, a flight velocity of say 4-10 m/s is required. If we adopt a nominal lifetime of 3 hours, this would permit a flightpath of some 40-100

TABLE 1: *UAV Airplanes (Data Compiled from Various Sources).*

UAV	MTOW (kg)	Span (m)	Aspect Ratio	Speed (m/s)	Power (W)	Endurance, comments
Aerovironment WASP	0.17	0.33	3		143	Hand launch >1.5hr
Dragon Eye	2.4	1.14		17		30-60mins
Draper Labs WASP	4	1.22	8	40		1hr. 155mm Gun-launched
EADS DO-MAV	0.5	0.41	3	10		0.5 hr
Aerovironment Black Widow	0.056	0.15	2	15	16	16 mins Flying wing.
Aerovironment Raven	2	1.35	6	14	200	2 hr
EMT Aladin	3	1.5	8	10	300	0.5hr
Cyberflight Bushmaster	2	2	8	35		1.5hr

km. This may be compared with the 1-sigma delivery error ellipse of a Titan lander [3] of ~ 240 x 70 km: a 1 kg UAV can probably therefore fly almost anywhere in the ellipse.

For reference, the horizon at Titan for altitudes of 0.1, 1, and 2 km altitude is 22, 71 and 101 km away respectively (ignoring atmospheric refraction and terrain blocking) so in order to permit line-of-sight communication a maximum distance of a few tens of km, and a total flight path of 100 km or less seems appropriate. (It is assumed that the UAV telemetry is sent to the lander where it is stored for subsequent relay to Earth via an orbiter or Direct-to-Earth link.)

As for propulsion power, small terrestrial UAVs have a power requirement of about 100 W/kg, giving a zeroth-order requirement of 100 W. However, the Titan environment can permit much lower powers than Earth. Its surface gravity is 1.35 ms^{-2}, 1/7th that of Earth means a lower lift force is required for a given mass, while the air density (the air being ~95% molecular nitrogen with ~5% methane and traces of many other organic gases) is 5.3 kgm^{-3}, some 4x higher than Earth and thus the momentum flux to attain lift can be generated more easily with lower speeds. Zubrin [10] even suggested a human equipped with wings could fly under his or her own power. The high density is due in part to the high surface pressure (1.46 bar) but in fact more due to the low surface temperature (94K). The low temperature provides another bonus, in decreasing atmospheric viscosity to increase the Reynolds number for a given size and velocity – wing and rotor performance typically improve at higher Reynolds number.

With conventional scaling, flight power P = DV, where D is the Drag and V the flight velocity. Now $D = (C_D/C_L)W$, where W equals the vehicle weight Mg and C_D and C_L are drag and lift coefficients. The Lift:Drag (L/D) ratio equal to (C_L / C_D), and varies from about 2 for stubby vehicles like Frisbees to well over 10 for aircraft like sailplanes with slender wings.

If vehicle parameters (mass, wing area, L/D) are held constant, then the lower gravity on Titan immediately gives a vehicle a factor of 7 reduction in required power. However, the thicker atmosphere means that a vehicle can fly slower: specifically, $L=0.5S\rho C_L V^2$ where S is the wing area and ρ the air density, so Titan's 4x air density over Earth generates the same dynamic pressure at half the speed. If a 1 kg terrestrial aircraft (with S and C_L fixed) were taken to Titan, the combination of lower lift and higher density means it could sustain level flight at a speed only 20% of that at Earth. Put another way, with P=DV, the 7x reduction in L (and thus D) and the five-fold reduction in required speed allow a given aircraft to remain aloft on Titan with 35x less power than on Earth, suggesting we need only a few watts for flight power.

On the other hand, packaging issues associated with deploying a UAV from a 1-2 m diameter lander on the ground are such that a wingspan rather smaller than the typical terrestrial UAVs (which can be assembled on-site by hand) would be preferred. While folding wings and other deployables are possible, in the interests of simplicity and robustness we consider only fixed monoplane geometries (a biplane or box-wing being a configuration that might merit further study). Furthermore, such a deployment makes vertical takeoff highly desireable, which in turn requires thrust:weight considerably in excess of 1.

We show in a moment that the cruise thrust requirement is in fact rather comparable to the vertical takeoff thrust requirement of ~2 N, and thus the same propulsion system is logically used for both phases of flight. (One could augment thrust briefly at takeoff with rocket boosters like the JATO 'Jet Assisted Take-Off' rocket pods used on some aircraft. However, besides adding complexity and hazard, the efflux from such devices might impinge upon the lander and contaminate the landing site with exhaust chemicals.)

Ignoring vehicle configuration for a moment, if the battery and other systems average to yield a mass density of 1000 kgm^{-3} (a typical value for aerospace and electronic systems) then for a pod with a length:diameter ratio of 3, a 1 kg pod will have a diameter of 7 cm and a length of 21 cm, or a total surface area of 400 cm^2. A spherical pod would have more drag, while a more slender pod would have more surface area over which to lose heat – a shape factor of 3 is a good compromise (A similar problem of trading aerodynamic performance, favoring slender objects, against heat leak, favoring spherical ones, was considered in a previous study of Venus dropzondes [18].) To pull such an area through the air at up to 10m/s will require about 2 N of thrust if we assign an effective drag area of 1000 cm^2 (0.1 m^2) to provide some notional penalty due to instrument apertures, connector protrusions etc. and adopt a drag coefficient of 0.5 typical for a sphere at these Reynolds numbers. This high drag means that a thrust:weight ratio of around 2 is required for cruise as well as takeoff – such high thrust:weight ratios are found in helicopters, aerobatic aircraft and in high-performance jet fighter aircraft.

Thrust represents the product of mass flux and the velocity increment imparted to that air mass flux: it is thus most inexpensively attained (in terms of power) by a large mass flux and a small velocity increment. Where economy or limited power is a consideration (unlike with jet fighters) wings, jets or rotors are made large, as with the large wingspan in sailplanes, large diameter turbofans used in commercial jetliners and so on. We therefore consider the vehicle more like a helicopter than an aeroplane, in that the rotor diameter should be as large as possible, or in practical terms, as large as the vehicle itself, say 25 cm in diameter. Previous work [2, 19] has noted the good performance and utility of vertical-lift vehicles such as tilt-rotors and helicopters for Titan application. Table 2 summarizes the parameters of some small terrestrial UAV rotorcraft.

Tools exist to predict the thrust performance of various rotors at different flight speeds and in different atmospheres. Here we use a web application Javaprop [19] and show results in Fig. 2. We assume no wing lift – the thrust from the rotors is directed vertically downwards at zero-speed liftoff, and progressively rotated to the horizontal at higher speeds to match the changing vector balance between thrust, weight and drag. At a flight speed of 10 m/s, the thrust is directed roughly 45 degrees down and backwards since drag and weight are almost equal.

The total power curve in Fig. 2 is typical of that of helicopters (or, for that matter other high thrust:weight systems such as birds [20]). There are two main components to the total propulsive power – the profile power (due to the drag of pulling the body through the air, which increases with flight speed) and the induced power (that drawn by the rotor itself). The induced power in fact has a minimum with flight speed, as the mass flux into the rotor increases with flight speed, with thrust almost constant, until eventually higher thrust requirements at higher speed overcome thus decline. These effects are discussed in detail in standard texts on helicopter aerodynamics (e.g. [21]).

The details of rotor diameter, blade number, airfoil choice and pitch are all subject to optimization, as is the size and shape of the battery/motor pod, but some modest exploration of the parameter space suggests it is difficult to escape from a power requirement of the order of 5 W for takeoff and low-speed (4 m/s) flight, and 20-25 W for higher-speed flight of 10 m/s. Rotor efficiencies of about 65-75% appear typical for high speed conditions, falling at lower speed, and the power required with these rotor diameters and speed/thrust conditions are actually quite similar for Titan and terrestrial conditions – at high thrust levels the Titan power requirements can be about 20% smaller than for Earth due to the higher air density at Titan. Care would need to be taken in the propeller design that the tip speeds do not approach the speed of sound, which is rather lower (~200 m/s) than at Earth (~340 m/s).

The ab initio estimates of flight power above are reassuringly consistent with a first-order empirical relationship [7] which estimates flight power P (W) as a function of mass M (kg) and speed V (m/s) in planetary environments as $P \sim 11 m^{0.8} V^{0.9} (g_t/g_e)(\rho_t/\rho_e)^{-0.5n}$ where g is gravity (subscript t and e denoting Titan and Earth respectively) and n is an index between 0 and 1 parameterizing the effect of density on propulsive efficiency. For n = 0.1, crudely indicated by the numerical experiments above, for a 1 kg vehicle at 4-10 m/s we find a flight power of 5-12 W. The apparent underestimate of this relationship at the higher speeds is probably because it is based on aircraft of conventional layout, whereas the Titan Bumblebee is rather stubby and thus has higher fuselage drag.

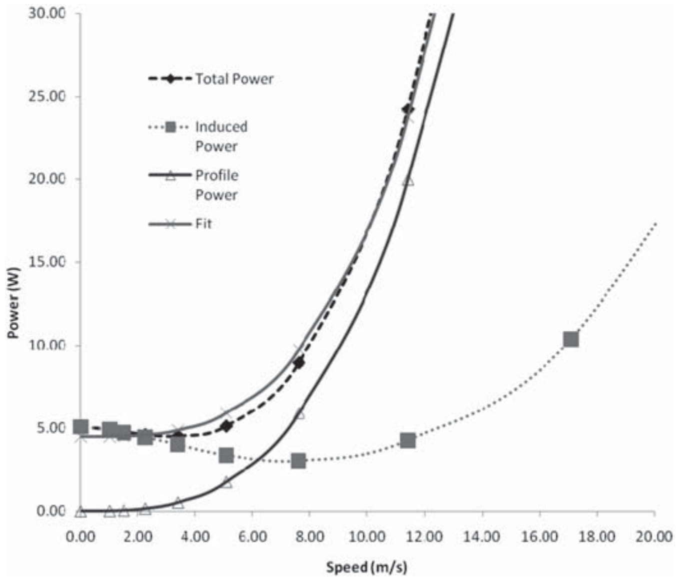

Fig. 2 Flight power requirements for a 1 kg UAV at Titan surface conditions, with a 0.11 m diameter rotor and a 0.1 m^2 drag area. The empirical fit is of the form $P=4.5+0.01V^{3.2}$.

4. THERMAL POWER REQUIREMENTS AND POWER OPTIMIZATION

Having scoped the flight propulsion power requirements, we return to the thermal setting. Consider a 0.5 cm layer of foam insulation with a conductivity of 0.02 $Wm^{-1}K^{-1}$ (equivalent to the performance of the foam used on the Huygens probe [11]). Assuming an operating temperature inside of 294K, there is a 200K temperature difference across the insulation. The heat loss through the insulation is therefore around 30 W. Thicker insulation could of course be used, at the cost of adding more cross-section and thus drag. Since the insulation performance will be compromised by penetrations for instruments and cabling, extreme insulation measures would in any case be futile. We see then that the thermal power requirements are likely to be 10-30 W, or quite comparable with the flight power requirements.

The situation of flying a system in a cold environment, wherein heat dissipated by flight is important in maintaining thermal conditions for operation (rather than the more usual situation where efforts are needed to efficiently reject heat) is an interesting one, confronted by many living things, especially small ones [22]. A particularly appealing example is the Bum-

TABLE 2: *UAV Rotorcraft (Data Compiled from Various Sources).*

UAV	Mass (kg)	Rotor diameter (m)	Speed (m/s)	Power (W)	Endurance (hr)
EMT Fancopter	1.5	0.5			0.5
Singapore Tech Fantail	3	0.29	>30		1
Aurora Goldeneye	0.5		27	3700	
D-STAR Eye-Mav	4.5	0.22	15	1000	
Alcore Maya	2.5	0.32		600	0.5

blebee [23] which has the same vertical take-off requirements as the vehicle discussed in this paper. This insect, which has evolved to exploit alpine and subarctic conditions, has a most unaerodynamic appearance. Certain aspects of Bumblebee behavior are optimized to manage heat, notably a bee will not necessarily empty a flower of nectar. The motivation is as follows: a bee expends only modest energy when gathering nectar at a flower, and thus its internal heat dissipation is low and it cools. Its flight muscles can only function effectively over a certain temperature range, and so a bee must either arrive at a flower, acquire some nectar quickly and move on before it cools too much, or it must expend energy buzzing its wings on the flower in order to warm them up after a longer stay, for example if it emptied the flower. Careful studies have shown that typically the Bumblebee will adopt a more energy-efficient policy of making only short stops such that energy is not expended purely on heating.

While certain other insect species (such as moths) similarly expend energy to warm up muscles for flight, and marine mammals such as seals and dolphins may be playful as a result of their thermal environment (they must be active to stay warm in any case, so the incremental energy cost of play is minimal e.g. [24]) we focus on the Bumblebee as an appealing analog for the vehicle design challenge posed in this paper. A bumblebee has an appreciably nonstreamlined shape and insulating fur, together with high thrust:weight permitting vertical take-off – all features shared by the vehicle presently under discussion.

Returning to the vehicle, we saw above that modest insulation might lead to a need for 30 W of thermal power to maintain steady-state conditions: thicker insulation might drop this by a factor of 2 or so at the cost of perhaps 20% increase in drag area, but further reductions on such a small system are unlikely given the need for instrument penetrations etc.

Usually motors on small aircraft are mounted outside to permit cooling: here we would want in fact to capture this waste heat - electrical motors are typically 90% efficient, so 10% is lost as heat in the windings. Similarly, losses of perhaps 10% of the total electrical requirements may be expected due to internal resistance in the batteries and due to dissipation in the power-conditioning electronics. These unavoidable dissipations in the propulsion and power systems, normally useless, can balance part of the thermal leak to the environment. Unfortunately as we see here, this provides only a few watts of the tens of watts needed. Additional dissipation from other required power drains (e.g. control system, and in particular the power amplifier of the telemetry transmitter) may provide a few additional watts, but it seems likely that some watts to tens of watts of dedicated heating power may be required. Because the thermal power is comparable with the propulsion power, there is (as for dolphins etc.) no advantage in energy terms to flying slowly.

Table 3 shows an example power budget. There are two power columns, one for electrical power, the other for thermal power. Inspection of control system requirements for various small landers and rovers [12] as well as those of homebuilt UAVs [14] suggest only a watt or two are needed for these systems, and payload requirements for imaging are similarly only a few watts. Line of sight video links, and telemetry from small probes [12] typically require only one to a few watts of RF output power, requiring DC power of several watts. Electrical power loads are all equivalent to thermal sources, with the two exceptions of the bulk of the propulsive power (which is exported from the vehicle as kinetic energy of the air in the propeller wake) and that fraction of the transmitter power that is radiated away from the antenna.

TABLE 3: *Example Power Budget. Electrical Power Dissipated in the Control System, Payload and Heaters Translates Directly into Supplied Heat. A Fraction of the Telemetry Power and Motor Power is Converted into Heat in the Transmitter and Motor Respectively, as is a Small Fraction of the Total Electrical Power Which is Dissipated by the Battery's Internal Resistance and Power Conditioning Electronics.*

System	Power (We)	Internal (%)	Dissipation (Wth)
Controls	2	100	2
Payload	2	100	2
Propulsion	10	10	1
Telemetry	6	60	3.6
Heaters	10	100	10
Total Electrical	30	10	3
Total Thermal			21.6

The detailed optimization of the flight speed, power budget, vehicle layout and insulation is likely to be subject to empirical factors (such as heat leak through penetrations, motor dissipation losses, transmitter efficiency etc.) which cannot be explored in detail here. However, it is evident that a spectrum of viable designs exists in the 10m/s and few hour flight time specification discussed previously. As a demonstration, we can show that for some reasonable adopted goals and constraints, an optimum exists in this spectrum. If we consider that transmitter and thermal power require, say 20W, and the propulsive power requirements are of the form $P=A+BV^n$, with A~6W, B=0.01 $W/(m/s)^n$ and n~3 (see Fig. 1), then the energy E required to reach a given distance D is PT, where T is the flight time T=D/V. Thus $E \sim (26/V + 0.01V^2)$, which is a function with a minimum value (see Fig. 3.)

Higher flight speed than the 10 m/s discussed here might be explored, since the energy cost does not increase rapidly with speed, but the line-of-sight communications constraint may make the range improvement of only modest interest since the vehicle would then have to be at an altitude of some kilometers, perhaps higher than might be desired for surface imaging.

5. INTERFACE WITH LANDER

The UAV should provide as few demands and constraints on lander configuration and operations as possible. The UAV is therefore a completely passive attached payload until its deployment. Fortunately, the Titan environment allows high thrust:weight ratios to be obtained, and thus the vehicle can take off vertically, so no deployable launch catapult or similar structure is required. Prior to takeoff, it could be retained on the side of the lander by a clamp and released by a single pyrotechnic or solenoid actuator after its propeller has spun up to high thrust.

A serial datalink from the lander, via a connector with low demate force (or conceivably an optical coupler or Bluetooth-like short-range wireless link) could permit an update to the UAV flight sequence before launch, although a lower-complexity option could omit this feature.

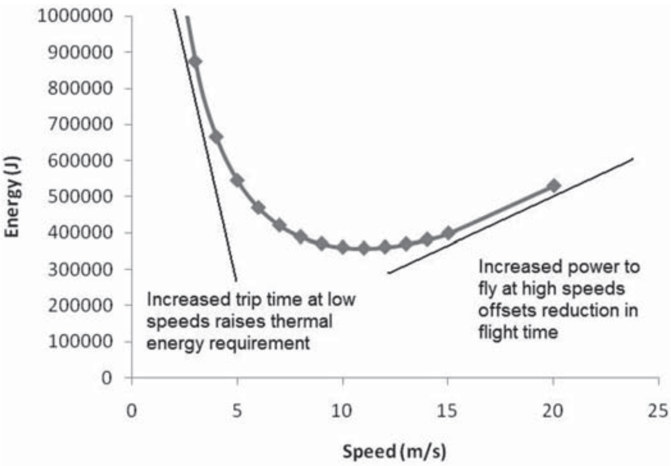

Fig. 3 Energy requirement to fly 100 km given the power requirements in the text. The curve has two asymptotic trends – when thermal energy dominates the total varies as the reciprocal of speed, while at high speeds the propulsive energy dominates and rises slowly with speed. The optimum occurs for roughly a 3-hour flight at a speed of ~10 m/s).

One service the lander should provide is prelaunch heating. Healthy power requires that the battery temperature be around 270-300K, whereas without additional heating, equipment at Titan's surface will rapidly attain the ambient temperature of 94K. The energy required to raise the system temperature from cold-soaked ambient to operational levels is not insignificant (adopting a heat capacity of 1000 $Jkg^{-1}K^{-1}$ and a 1 kg mass, warm-up requires 200 kJ, or some 50 W-hrs). This energy cost is such as to demand an undesirably large fraction of the UAV flight energy budget, but can be provided effectively from the lander instead (we see again the analogy with the preflight warming of a Bumblebee's flight muscles [23]). While tempting to provide a passive heat leak path (e.g. a thermal strap) from the lander to the UAV, recall that the lander thermal design must be robust and efficient both with the UAV present and without - thus in order to avoid complications to the lander's own thermal management, this heating would be best provided electrically. A low-insertion force connector, or perhaps even inductive coupling, would allow a single lander power switch to provide the heating function. Desirably there would be a housekeeping temperature sensor on the UAV able to report the UAV battery temperature to the lander without requiring the UAV itself to be powered-up.

The telemetry feed from the UAV to the lander would be accomplished with a line-of-sight radio link, probably UHF. Omnidirectional antennas on the UAV and the lander avoid the need for any pointing operations.

6. OPERATIONS

It is likely that UAV operation would be deferred to some months after landing. This first ensures that the key lander science (surface chemical sampling, and several Titan day's-worth of meteorology and seismology data) is acquired before the risk of UAV operations (minimal as that is) is engaged. Second, this schedule provides a public relations boost at a stage in the mission when landed operations will have become routine. (In contrast, landing – already an attention-getting event – would be accompanied by the aerocapture arrival of the orbiter, and quite possibly the deployment of a balloon. The UAV's outreach potential would be lost in this media maelstrom.)

Thus, when the decision is made to launch the UAV, there should be some familiarity with the immediate vicinity of the lander (from panoramic camera images), probably some regional context data (from downlooking images acquired by a lander descent camera prior to landing), as well as some meteorological data on the likely windspeed and direction at the surface. These data may recommend some adjustment to the UAV operations, such as direction to a specific target of interest identified in descent camera data or bias in operations to compensate for expected winds.

The heater power supply from the lander would be switched on some hours before takeoff (it is likely that the lander can only support an additional load of a few tens of watts, so more than two hours would be needed). Once comfortable temperatures are attained, the UAV command system can be powered up and any command updates transmitted to it such as trajectory biases as above, or perhaps lander pressure readings if the UAV is to use a pressure sensor as an altimeter.

Once these updates are made and verified, the lander will initiate the launch sequence. The UAV runs its propeller to high power, and the release mechanism is actuated. The UAV climbs away vertically from the lander and then pitches down and throttles back into level flight once the predetermined flight altitude is attained.

The UAV would then perform its preprogrammed flight pattern, with data being streamed in real-time to the lander by UHF link for storage, data compression and selection, and ultimately for relay back to the Earth. No data processing on-board the UAV should be required. The pattern might include a large number of turns and/or changes in altitude.

Depending on the data storage capacity on the lander, the UAV might be programmed to fly for a set duration and then power off to a gliding impact. On the other hand, particularly if the lander data storage permits, it could be simply programmed to fly until battery exhaustion. Logically, to maximize the probability of obtaining at least some data from the UAV, and to minimize the probability of the UAV impacting the lander at the end of flight, an ever-widening spiral flight pattern has a simple appeal. The initial short range would ensure a healthy link margin on the UHF datalink (and, incidentally, prospects for images from the UAV of the lander sitting on the surface, and perhaps its influence on the area around it by digging etc.).

Illumination at Titan's surface is about 1000 times weaker than at Earth (a factor of 100 lower by virtue of the distance from the sun, and another factor of ten or so due to the thick haze in the upper atmosphere). To put this in context, noontime sunlight on Titan is 1000 times brighter than full moonlight on Earth. It may be recalled that the Huygens camera worked quite satisfactorily, and even though angular motions were much higher than had been anticipated, only three out of 600 images were degraded by motion blur [25]. Given the low levels of illumination, the payload might require larger light-gathering optics and/or longer exposures than are typical for the video cameras used on terrestrial UAVs, and the UAV attitude stability may need to be considered in this light.

7. CONCLUSIONS

The thick Titan atmosphere and low gravity makes a small

UAV at that world the easiest (and least expensive) means of flying an aircraft at another world. As a stand-alone platform, even a large aircraft is not able to address the full range of science objectives desired at Titan, but as an inexpensive add-on to a broader architecture in a Flagship mission, a small UAV offers outstanding imaging science potential and enormous public appeal. This paper has outlined a setting in which such a UAV could operate. The technical challenges in such a mission are of great educational value, and require neither new technology nor special facilities to demonstrate, such that it is not inconceivable to implement the UAV as a competed student experiment. University teams could design, build and test prototypes on Earth in a competition, perhaps with demonstration in a low-temperature nitrogen tent, and free-flight tests with uprated engines to compensate for the less easy Earth atmosphere and gravity. The best design could then be flown at Titan.

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