Aerobot Dynamics Simulations for Planetary Exploration of Titan

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Abstract: A future mission to return to Titan after Cassini/Huygens has now a really high priority for planetary exploration. Recent Cassini discoveries have revolutionized our understanding of the Titan system and its potential for harboring the ingredients necessary for life. These discoveries reveal that Titan is one of the most exciting places in the solar system; data show a complex environment, both for the atmosphere and for the surface. The data obtained, enriched by continuing observations from the Cassini spacecraft, show hydrocarbon lakes, river channels and drainage basins, sand dunes, cryovolcanos and sierras. All these features demonstrate that dynamic processes are present on Titan and have raised the scientific interest in a follow-up mission to Titan. A robotic lighter-than-air vehicle has been suggested as a possible platform for an extensive exploration of the moon. NASA centers and universities around the US, as well as the European Space Agency, are studying the possibility of sending, as part of the next mission to this giant moon of Saturn, a hot-air balloon or similar for further and more in-depth exploration. Recent studies on airships have demonstrated the high capability of airships to be considered as scientific platforms for extended explorations, both in space and time, on planets with atmosphere. Here we analyse the dynamics of the airship in response of the encountered Titan's environment. Possible trajectories for an extended survey of the moon are investigated; these allow us to have a precise quantitative analysis of the energy necessary for a journey on the moon. Analysis on stability is performed in order to check the possible scientific slot windows available for investigations. A 1.2 km x 1.4 km region is selected as baseline: time necessary for performing a complete survey is investigated. Investigations are conducted both in a quiet situation with no wind and in wind conditions. Trajectories are followed with airship at 1.5, 3, 5 and 7 m/s velocities; surface science (< 100 m) scenarios are proposed. Considered winds are in the range 0.0 − 1 m/s parallel and orthogonal to the ground track.

Keywords: Airship, titan, exploration, simulator, dynamics.

1. INTRODUCTION

Exploration of the planets and moons of the Solar System has up to now relied on remote sensing from Earth, fly-by probes, orbiters, landers and rovers. Today mobility is a key requirement because enables extensive geographical coverage and in-situ science. In this context robotic lighter-than-air (LTA) vehicles are a possible platform for the exploration of planets and moons with an atmosphere, such as Venus, Mars, Titan and the gas giants. NASA's 2006 Solar System Exploration Roadmap clearly states [1]:

> A dedicated Titan orbiter or lighter than air cruise vehicle to observe more closely and continuously the surface of this complex world to find and explore such sites would be a better way to observe potential surface changes associated with geologic activity.

And further clarifies the scientific importance of such a mission [1]:

> This important opportunity to study a fourth planetary body with an actively evolving and complex climate can be realized through orbital and lighter-than-air platform observations of surface geology (including a search for fields of impact craters with a size distribution inconsistent with the present day atmospheric thickness), examination of regionally varying erosional features and organic deposits, sampling of selected sites to assess organic deposits for chemical signatures of varying atmospheric methane to nitrogen ratios, and relative age dating of organic, cryovolcanic, and impact related deposits.

An airship can provide the low-altitude coverage of a wide area of the moon or the planet for a long duration mission (months or even years) with a very low power consumption respect to conventional aircrafts or orbiters. Furthermore airships can identify scientifically interesting sites and reach them, thanks to their higher mobility compared to balloons, which are, for their nature, passive vehicles. A detailed analysis of advantages of Airship w.r.t. other aerial vehicles for planetary exploration is presented in [2].

Cassini/Huygens instruments have uncovered a very complex world with various surface and crustal processes including lakes and seas and fluvial erosive features: large-scale drainage patterns and flow directions of Titans channels and rivers have been pictured by Huygens during 2005 descent [3]; the observed channels have shown a large-scale flow pattern often several hundreds of kilometres in length with valley widths of up to 3 km across and depth of several hundred meters [4]. Lakes have also been definitively

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identified in [5] and [6]. Other features like cryovolcanos have shown a living world [7]; evidence for surface morphology changes on the surface reveal active phenomenas [8]. Mountains and channels (width 1 km) have been identified from measurements of Cassini's Visual and Infrared Mapping Spectrometer (VIMS) instruments [9] and sand dunes (with size and spacing between 1 -3 km and height of about 150 m) have been observed in [10-12].

These different structures on Titan demonstrate that mobility will be a key point for future missions in order to cover wide areas on the surface that will allow the analysis of different regions (liquid, solid and mixed). Furthermore the seasonal variations in Titan's atmosphere [13] and surface morphology suggest that future in-situ mission must be on-site for several months, or maybe years. Airships have been demonstrated to be perfect platforms for long duration missions on Earth and are suitable for future missions on Titan. Moreover aerobots could also be used to transport and deploy science packages or release micro-rovers at different geographically separated sites. In this context a Titan aerobot probe has been proposed as a vehicle that uses wind currents to explore the moon by taking advantage of Titans unique atmosphere. The probe would have the capability to fly to points while simultaneously mapping Titans surface; it would also be able to stationkeep. Besides wind profiling, surface and atmospheric observations, and atmospheric composition testing, the aerobot would also have the capability to collect samples from the surface without landing; failure control strategies have been proposed and tested [14].

Since the late 70's LTA systems have been suggested for Titan [15]; airship concepts were explored in two separate NASA Visions Mission studies, by JPL and NASA Langley groups respectively [16, 17]. At JPL, Hall has also presented a complete design and component testing of an aerobot that would be capable of global in-situ exploration of Titan [18]. For an extended review of balloon concepts for Titan see [19]. A Titan montgolfiere aerial vehicle has been proposed (as part of the Titan Saturn System ESA Mission - TSSM) for a circumnavigation of Titan at a latitude of 20° and at altitudes of 10 km for a minimum of 6 months [20] with instruments that would provide high-resolution vistas and make compositional measurements of the surface, detailed sounding of the subsurface, crustal layering, and chemical measurements of aerosols.

Airship models have been widely published in literature in the last decades (see for example [21-23]), but none of the models presented have been tested in a planet rather than Earth; our work extends the simulations on Saturn's moon in order to verify stability and consumption for space exploration. In fact, up to now only qualitative analyses on the power budget needed for a Titan Aerobot mission have been performed [18, 24]; the present work can be considered a first step in the quantitative analysis of the necessary power sources for a long duration Titan mission. A complete aerodynamic model of an airship has been developed and a test case run in a Titan environment. Preliminary analysis, not presented in this paper, conducted with our model confirm a 15.4 N thrust necessary for a cruise at 4 m/s as described in [16].

Several patents have been registered in the last decades for different airships' application. Specifically related to space and to energy budget is Electrically Powered Spacecraft/Airship [25] in which a spacecraft uses microwave energy from the planet surface or outer space in order to supply electric power to the onboard systems. Airships that use solar power have also been proposed; it is the case of Transformable airship [26] where the longitudinal dimension of the airship can be changed in order to collect more or less energy from the sun. These inventions are in the direction of transporting as less as possible energy from Earth (propeller or batteries) and are in line with our project to know, as precisely as possible, in designing the mission, the amount of energy necessary when on the moon's surface; in fact, less mass to launch corresponds to a less expensive mission.

Other interesting patents present means for controlling the lift, and so the altitude, of an airship using active systems not related to main thruster [27, 28]; these patents describe the possibility of changing the internal embodies of an airship. The applications could really be used in a planetary airship, and act as a backup solution for conventional thruster systems for altitude control of airships. The simulator developed by our group can easily calculate the energy necessary for an altitude variations of several tens/hundreds of meters and compare the result with a lift control using the systems proposed by the described patent.

2. AIRSHIP DYNAMICS

The Airship Flight System Simulator that has been developed includes:

1. system model, containing aerodynamics and airship actuators;
2. control system in a physic based Titan environment;

The kinematic and dynamic equations of the model are discussed extensively in [29, 30] and are presented here only for completeness. We define a body frame fixed in the center of volume (COV) of the airship and an inertial frame fixed w.r.t. Titan. The equations of motion for dynamics and kinematics in the body frame could be written respectively as:

$$M\dot{\vec{v}} + C(\vec{v})\vec{v} = \vec{\tau}$$

$$\dot{\vec{\eta}} = J\vec{v}$$

where $\vec{v}$ = [u, v, w, p, q, r] is the body fixed linear and angular velocity vector and $\vec{\eta}$ = [x, y, z, φ, θ, ψ] is the inertial position and angles vector.

$$J = \begin{bmatrix} {}^{b}R_{i} & \vec{0}_{3x3} \\ \vec{0}_{3x3} & \vec{E}(\phi,\vartheta,\psi) \end{bmatrix}$$

J is the Jacobian that describes the transformation between body and inertial frames.

$$M = M_{RB} + M_{A} \text{ and } C(\vec{v}) = C_{RB}(\vec{v}) + C_{A}(\vec{v})$$

where M_{RB} and M_{A} are the 6 x 6 vehicle generalised mass and added mass matrices; and

$\vec{\tau} = \vec{\tau}_B + \vec{\tau}_P + \vec{\tau}_A + \vec{\tau}_G$

where

$\vec{\tau}_G$ = generalized gravity force vector;

$\vec{\tau}_A$ = generalized aerodynamic force vector;

$\vec{\tau}_P$ = generalized propulsion force vector;

$\vec{\tau}_B$ = generalized buoyancy force vector.

2.1. Wind

Huygens mission showed that near surface winds are weak and should not have a great influence in airship dynamics [3]; nevertheless in this paragraph it is shown how the wind-induced force and moment have an impact on airship dynamics and must be included in the equation of motion. The method is based on the assumption that the equation of motion can be represented in terms of *relative velocity*

$\vec{v}_r = \vec{v} - \vec{v}_w$

where $\vec{v}_w = [u_c, v_c, w_c, 0, 0, 0]$ is the vector of irrotational body fixed wind velocity.

Let $[u_c^i, v_c^i, w_c^i]$ be the Titan (inertial) fixed wind velocity vector, in the body frame it will be

${}^b v_w = {}^b R_i \, {}^i v_w$

Considering constant the body-fixed wind velocity or at least slowly-varying such that the following equation is valid

$\dot{\vec{v}}_w = 0 \Rightarrow \dot{\vec{v}}_r = \dot{\vec{v}}$

Hence the non linear relative equations of motion take the form

$$M\dot{\vec{v}} + C(\vec{v}_r)\vec{v}_r = \vec{\tau}_B + \vec{\tau}_P + \vec{\tau}_A(\vec{v}_r) + \vec{\tau}_G$$
$$\dot{\vec{\eta}} = J\vec{v}$$

3. TITAN'S ENVIRONMENT

Our knowledge and understanding of Titan, Saturn's largest moon, has increased significantly as a result of measurements obtained from the Cassini spacecraft following its orbital insertion around Saturn on June 30, 2004 and even more recently with the measurements obtained during the descent of the Huygens probe through the atmosphere and onto the surface of Titan on January 14, 2005. Titan's atmosphere is ideally suited for atmospheric flight; with its low gravity and the high atmospheric density, flight is readily achieved.

Simulations on Titan environment presented in this section are based on the following hypotheses:

- the air density and the dynamic viscosity are supposed altitude dependent [31];

$\rho = 5.4627 - 0.21851h + 0.00294h^2 - 1.2054 \cdot 10{-}5h^3$ [kg/m^3]

$\mu = 6.43{\cdot}10{-}6{-}1.52{\cdot}10{-}7h{+}1.03{\cdot}10{-}8h^2{-}3.28{\cdot}10{-}8h^3$ [kg/m·s]

- the wind is supposed to act continuously in one direction (longitudinal titan wind) with velocities in the range 0.0−1.5 m/s;
- no atmosphere turbulence is considered;
- the Reynolds number is considered constant, $6.67 \cdot 10^7$;

Simulated trajectories are based on:

- vehicle altitude at 30 m;
- take off phase is not considered, the vehicle starts with the cruise velocity in the range 1.5−7.0m/s;
- airship uses rudders to turn.

Generally weak winds ($|v| < 1$ m/s) were seen in the lowest 5 km of descent [32] raising the interesting possibility of a more Earth-like weather regime within Titans lower troposphere; for this reason only winds up to 1 m/s are considered.

4. AIRSHIP MODEL

The vehicle is shown in Fig. (**1**). The physical characteristics of the airship are reported below. Straight flight performed with our model showed a similar behaviour as described in the NASA's report [16] but a 90° turn with 150 m radius was not possible with NASA's original airship so the fins have been reshaped in order to have a wider rudder area (0.5 m higher and 0.5 m longer) for better control issues.

The Airship is designed as an ellipsoid with length of 17.5 m and max diameter of 3.5 m; total mass and volume of the Airship are respectively 48.13 kg and 86.43 m3. The gondola dimensions and weight are: 1.5 x 1.5 x 3 m and 194.25 kg respectively. The Airship is filled with Helium gas with the density that the gas should have on the surface of Titan, $\rho_{He} = 0.6$ kg/m3.

The control feedback acts on:

- the main thruster for longitudinal motion;
- the tilt engine which can turn the main thruster up to a maximum angle of 20°;
- pitch and yaw rudders, placed on the fins.

5. CONTROL STRATEGY

A crucial aspect of an autonomous flight for an airship is the control of the desired path. A simple PD control strategy has been implemented; an orienteering strategy has been selected: way points are sequentially placed in the environment (with specified position and target velocities). Feedback is controlled *via* the state errors with respect to the planned positions and velocities. The linear error vector is composed by the X-velocity, the yaw angle between the airship X-axis and the way point X-axis, the pitch angle between the airship Z-axis and the way point Z-axis, and the Z-velocity in the body frame. Other possible linear error vectors can be selected (e.g. position instead of linear velocity) as in [29] and [33]. This strategy allows to design intersecting loops that cover both portions of known and unknown environment in successive passages (see Fig. **3**).

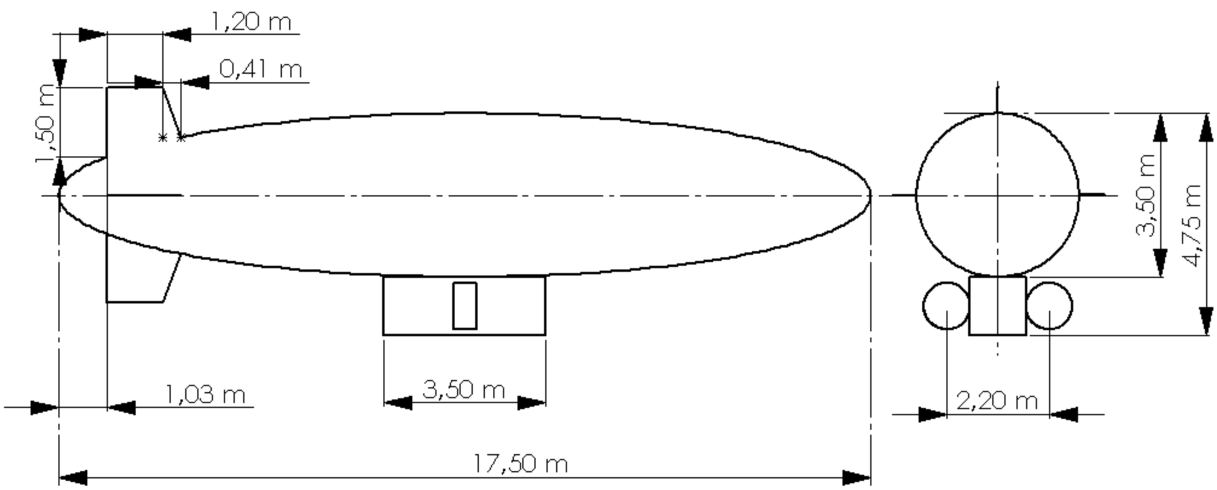

Fig. (1). Titan airship setup.

Error vectors are:

$$\delta X(t) = \left[\delta v_x(t), \delta\vartheta(t), \delta\phi(t), \delta v_z(t)\right]$$

$$\delta\dot{X}(t) = \left[\delta\dot{v}_x(t), \delta q(t), \delta r(t), \delta\dot{v}_z(t)\right]$$

where

$$\delta\dot{v}_{x,z}(t) = \frac{v_{x,z}(t) - v_{x,z}(t-\Delta t)}{\Delta t}$$

Table 1. PD Gains. Proportional and Derivative Gains Control Velocity Along Vehicle X-Axis, Pitch, Yaw and Z Inertial Altitude and their Variations

Gains	K_P				K_D			
	v_x	ϑ	φ	z	$\dot{v}_x$	$\dot{\vartheta}$	$\dot{\varphi}$	$\dot{z}$
	400	150	-20	1	200	100	20	-00.01.00

The input control vector is given by

$$\vec{u}(t) = K_P \delta\vec{X}(t) + K_D \delta\dot{\vec{X}}(t)$$

where $\mathbf{K_P}$ and $\mathbf{K_D}$ are the proportional and derivative control matrices.

The controller's proportional and derivative gains are obtained by trial and error and are presented in Table **1**.

For each control element we define a saturation value (Table **2**) such that

$$|u_i(t)| < u_{i,sat}$$

In order to make the response of the control not impulsive the outputs of the control system are processed by a shaping filter to smooth the control response. The shaping filter processes the control output following the model described by the differential equation

$$\frac{dg(t)}{dt} = -\alpha\left[g(t) - w(t)\right]$$

where w(t) is the input function, and $\alpha = 1/\tau$ where τ is the time constant. To implement the filter in a discrete time system we have to discretised the above equation

$$g_{k+1} = -\Delta t\alpha\left(g_k - w_k\right) + g_k$$

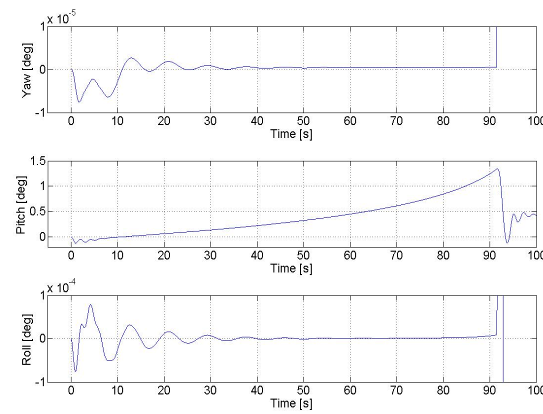

Fig. (2). Attitude stability during straight flight with airship velocity v=5.0 m/s. Pitch angle is increasing due to the PD controller strategy adopted (for explanation see §6).

Table 2. Saturation Level for Control Items

Control Element	Saturation Level
Main Thruster	200 N
Main Thruster rotation	20°
Yaw rudder	30°
Pitch rudder	30°

A qualitative stability analysis has been performed: airship dynamics is very slow and a simple PD law has been demonstrated to be sufficient for a good attitude control (see Fig. **2**): yaw and roll angles are maintained below 10^{-4} degrees for a straight flight; a more detailed and quantitative

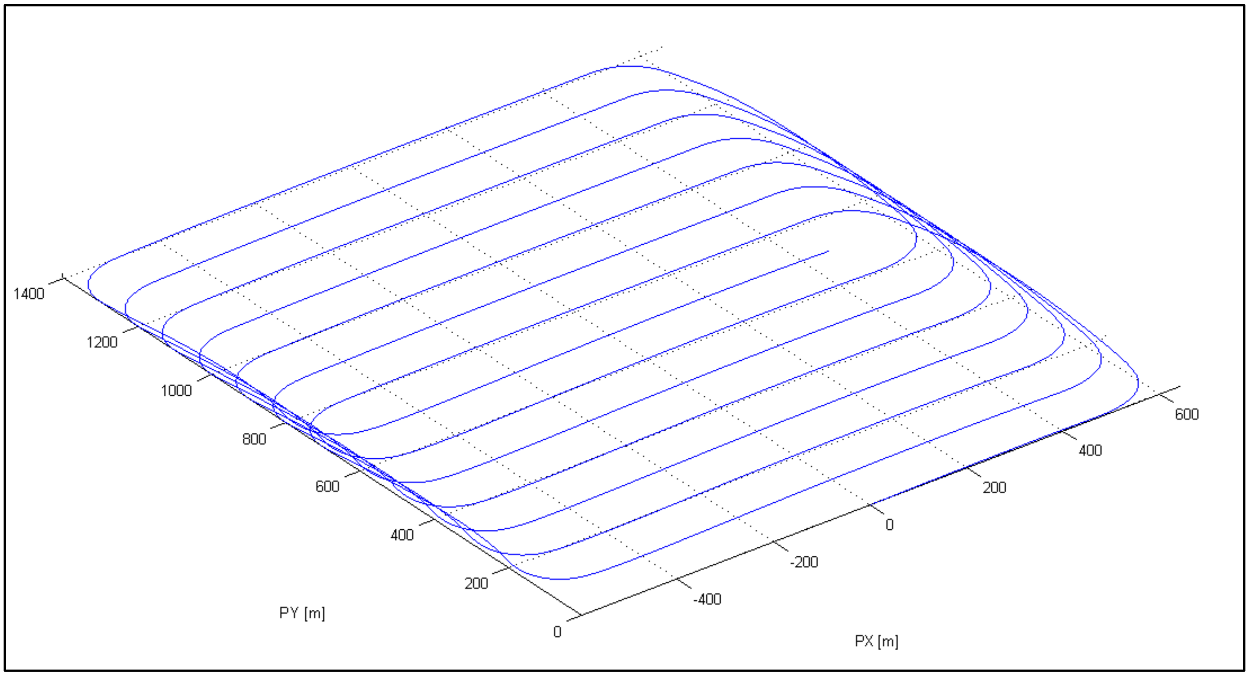

Fig. (3). Full area covered. Velocity of airship v=5.0 m/s and tail wind w=1.0 m/s parallel to X direction.

stability analysis is under investigation but is not scope of this paper.

6. SIMULATION RESULTS

Several sequences of simulations have been conducted; with quiescent atmosphere and winds. A 1200x1400 m area has been considered as baseline for analysis and the airship trajectory begins at an altitude of 30 m. Wider areas will be covered considering sequences of smaller areas exploration phases; no analysis has, up to now, been performed considering significant variations in altitude; landing and take off, and investigations of canyons are still under analysis. The 100 m separation of tracks in Y direction has been selected for a ground coverage with 50% overlapping of the field of view (FOV) with the onboard navigation instruments. The system is completely independent and is able to navigate over the selected area with vision based SLAM techniques that allows autonomous navigation and control.

The control strategy (see §5) is developed in order to maintain the desired velocity along the entire track; tests have been performed in the range [1.5−7] m/s.

The waypoints have a smaller spacing in the curves and are very well separated along the straight lines.

It is possible to observe that as the velocity increases the pitch angle decreases (see Fig. **4**), this is due to the control strategy adopted that calculates the necessary thrust for maintaining the velocity considering the distance at which it is from the desired point: higher the velocity more efficient are the tail rudders and less angle must be used for the rudders.

It must be underlined that the efficiency of the tail rudders is very poor at low velocities and, consequently, instability is higher (max pitch angle is around 18 degrees for a 1.0 m/s wind with a cruise velocity of 1.5 m/s - extreme case). At low cruise velocities the higher the wind the higher the maximum pitch angle and the bigger the differences between the different wind conditions. This difference decreases at higher velocities because the dynamics is much less sensitive to weak winds.

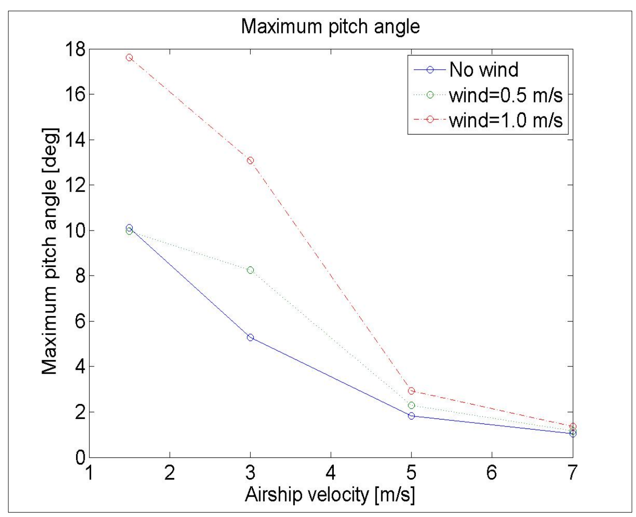

Fig. (4). Max pitch angle.

A similar observation can be done for the maximum roll angle (see Fig. **5**); the higher the velocity the higher the roll angles. The maximum roll angles have been measured in the curve section; this is due to the control strategy that imposes to the airship to maintain the desired velocity so a small thrust in the orthogonal direction w.r.t. velocity direction causes a higher moment at higher velocities. It can be observed that in this case the difference of maximum roll angles is similar at different velocities for different wind velocities.

Through simulation it has been observed that due to the lower gravity on Titan than on Earth higher pitch and roll angle have been observed because the restoring gravitational moment is less efficient. The adopted strategy allows to control the cruise velocity very efficiently: variations in velocity are less than 0.1 m/s and the total time for full coverage of the entire area is independent to variations of the weak winds velocities measured on Titan at low altitudes (0.3 to 1.0 m/s have been measured by Huygens [3]) (see Fig. **6**).

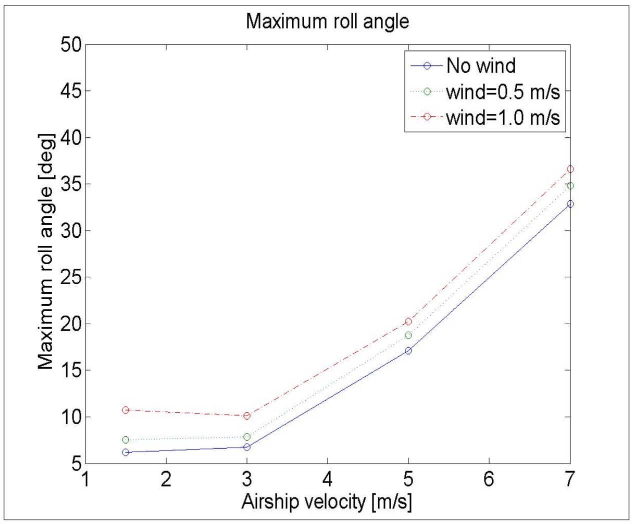

Fig. (5). Max roll angle.

At 7 m/s the 1.7 km^2 area is entirely covered in less than 1.5 hours; this information will be used when developing the scientific usage for the onboard experiments and when defining the communication strategy with the orbiter for data exchange.

A trade off must then be performed for the selection of the cruise velocity: higher the velocity, lower the time for area coverage but, as expected, significantly higher is the total energy needed for completing the trajectory (see Fig. **7**).

The measured energy profiles will contribute to the planning of emergency strategies if some unexpected event happens (high winds, storm, etc.) or if there are some critical tasks to be performed in collaboration with the orbital relay (e.g. orbiter passage over the airship). The energy budget is then critical for planning the lifetime of the airship mission: it allows to calculate more precisely the amount of energy necessary for navigation and the total energy that must be generated on board the airship (for example by RTGs).

Another aspect that can be observed from the simulation is that there is a different response of the system depending on the wind direction; in fact, after a left turn with tail wind the maximum deviation from the expected path is around 38 m while, after a left turn with facing wind, the maximum deviation is less than 29 m (see Fig. **8**). In the first case the wind contribution is in the same direction as the airship velocity while in the latter the wind has to override first the airship velocity and then it pushes it in the opposite direction.

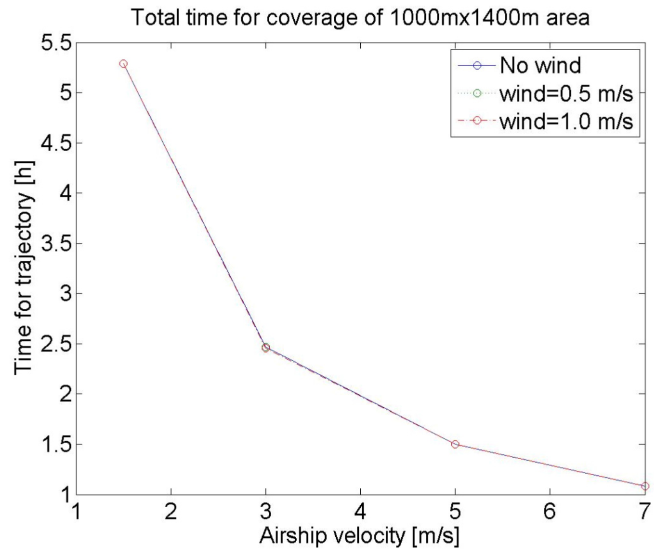

Fig. (6). Total time for area coverage at different velocities and low surface winds.

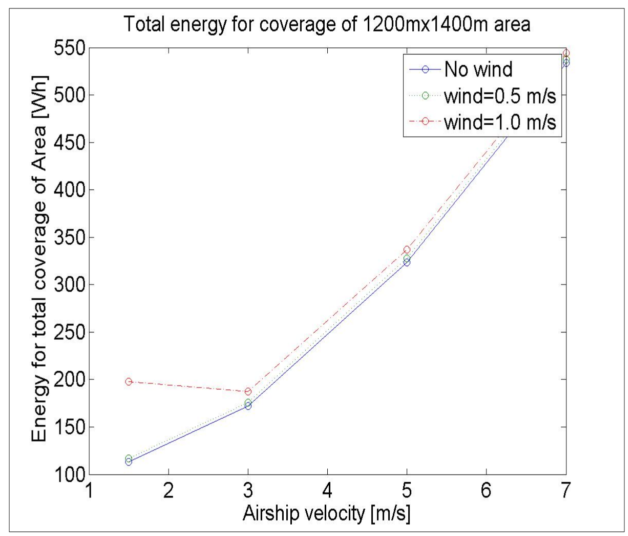

Fig. (7). Total Energy consumption of main thruster for area coverage.

7. CONCLUSIONS

We have presented the simulation results of significant dynamics parameters (mainly pitch and roll angles) of an airship in response of the encountered environment of Titan. Due to the lower gravity w.r.t. Earth, pitch and roll angles are higher than angles measured in simulation for a terrestrial airship with same control strategy adopted. An orienteering waypoint control strategy for possible trajectories for an extended survey of the planet are performed considering a baseline area of 1.2 x 1.4 km.

Investigations have been conducted both in a quiet situation with no wind and in low wind conditions (up to 1.0 m/s); higher wind conditions have not been investigated yet but seem to be unusual on the surface of Titan. This work outlines how the selection of the cruise velocity and the maximum desired angles for attitude are extremely important when designing the science operations plan due to the fact

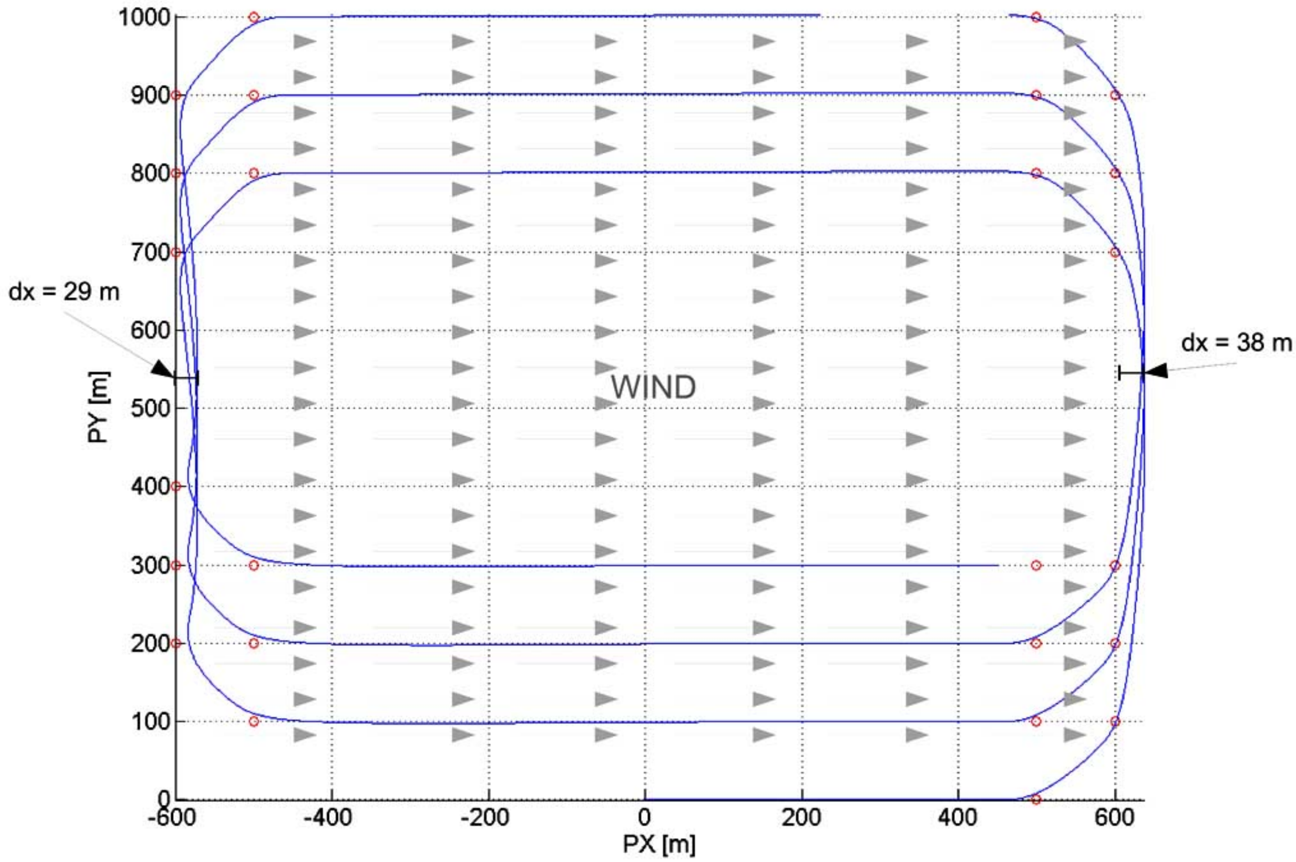

Fig. (8). Ground track with velocity of airship v=5.0 m/s and tail wind.

that dynamics has a significant impact on the possible performances of the on-board instruments. The stability of the airship and low power consumption show the efficiency of this type of airborne platforms for planetary exploration. The analysis show which is the necessary energy for a journey on the planet.

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