Wind-based Navigation of a Hot-Air Balloon on Titan: A Feasibility Study

[1a]Roberto Furfaro, [b]Jonathan I. Lunine, [c]Alberto Elfes, [d]Kim Reh,

[a]Aerospace and Mechanical Engineering Dept., University of Arizona, Tucson, AZ, USA
[b]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, USA
[c]Mobility and Robotic Systems Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA
[d]Strategic Missions and Advanced Concepts Office, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

ABSTRACT

Current analysis of data streamed back to Earth by the Cassini spacecraft features Titan as one of the most exciting places in the solar system. 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 (Montgolfier-type) for further and more in-depth exploration. The basic idea would be to design a reliable, semi-autonomous, and yet cheap Montgolfier capable of using continuous flow of waste heat from a power source to lift the balloon and sustain its altitude in the Titan environment.
In this paper we study the problem of locally navigating a hot-air balloon in the nitrogen-based Titan atmosphere. The basic idea is to define a strategy (i.e. design of a suitable guidance system) that allows autonomous and semi-autonomous navigation of the balloon using the available (and partial) knowledge of the wind structure blowing on the saturnian satellite surface. Starting from first principles we determined the appropriate thermal and dynamical models describing (a) the vertical dynamics of the balloon and (b) the dynamics of the balloon moving on a vertical plane (2-D motion). Next, various non-linear fuzzy-based control strategies have been evaluated, analyzed and implemented in MATLAB to numerically simulate the capability of the system to simultaneously maintain altitude, as well as a scientifically desirable trajectory. We also looked at the ability of the balloon to perform station keeping. The results of the simulation are encouraging and show the effectiveness of such a system to cheaply and effectively perform semi-autonomous exploration of Titan.

Keywords: Titan, Autonomous Exploration, Balloon Dynamics, Fuzzy Controller.

1. INTRODUCTION

Titan is one of the most exciting places in the solar system. Indeed, current analysis of data streamed back to Earth by the Cassini spacecraft reveals Titan to be an extremely complex and diverse planetary body with a dynamic, thick atmosphere and diverse landform structures. Recent radar observations of the saturnian satellite [1] show the presence of dark areas that are most likely to be depressions--lakes--filled with liquid methane. Cassini data show that Titan is home to a large spectrum of Earth-like geological processes ranging from fluvial erosion to formation of dunes to volcanism [2]. Such diverse environment and its connection to astrobiological implications are motivating the interest of both NASA and ESA to pursue future exploration beyond the on-going Cassini mission. The two agencies are pursuing a cooperative study of a future Titan mission that would be launched in the 2015-2022 timeframe. Under the stimulus of the Outer Planet Assessment Group (OPAG) [3] which advocates large-effort flagship missions (>\$2B budget including technology development) designed to optimize the overall science return and to increase the understanding of the outer planets, a Titan mission is top-priority together with a sister mission to Europa.With the overall objective to maximize the scientific mission return for the minimum cost,

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[*] email: robertof@email.arizona.edu, phone: 520-312-7440, web:
http://www.ame.arizona.edu/faculty/furfaro/furfaro.php

NASA and ESA have various options on the table which include a multi-element architecture designed around a combination of orbiter, balloon and lander. The latter might include a mobility solution in a Mars Exploration Rover (MER) fashion. Within such framework, the balloon solution is one of the most attractive. While each of the proposed components has a specific vantage point (e.g. the orbiter would observe the planet on a global scale and the lander/rover would observe and analyze on a local scale), the balloon has both mobility and proximity and thus could represent an excellent stand-alone solution or a component of the overall architecture. Indeed, the thick atmosphere present on Titan (5.9 kg/m3 at surface level) coupled with its low gravity (1.3 m/sec2) make the exploration via flight the natural choice. While airships, airplanes and even helicopters have been considered to accomplish exploration missions, hot-air balloons have marked advantages (e.g. good lift performances of thermally-driven hot-air balloons [4]). Deployment of hot-air balloons on the Titan atmosphere requires navigation capabilities which can be active or passive. On-board active propulsion systems can be used to provide the highest level of balloon controllability but they have the drawback of increasing balloon's mass and power requirements as well as complexity and therefore decreasing mission reliability. On the contrary, passive navigation and guidance aim at exploiting knowledge of wind structures. When coupled with an active vertical control system, the wind prediction can be employed to guide the balloon in desired Titan's regions or maintain a relatively stationary position with relative to the ground ("station-keeping").

In this paper, we explore the possibility of using wind knowledge and active vertical control to perform local navigation during the course of Titan's exploration. After briefly reviewing the planetary environment and a possible hot-air balloon configuration, a simplified thermal and dynamical model is presented. A fuzzy-based system for the control of the balloon vertical motion is designed, analyzed and implemented. The fuzzy logic framework is exploited to design a robust reason-based system capable of dealing with the inherent non-linear equations of motion avoiding the need to any linearization. The vertical controller is the key component of a more comprehensive local navigation/guidance scheme which includes a fuzzy-based trajectory planner and a fuzzy expert system for scientific interpretation of the stream of incoming data for real-time, in-transit autonomous decision. Three modes of operations are implemented and simulated to show the potential of the overall methodology.
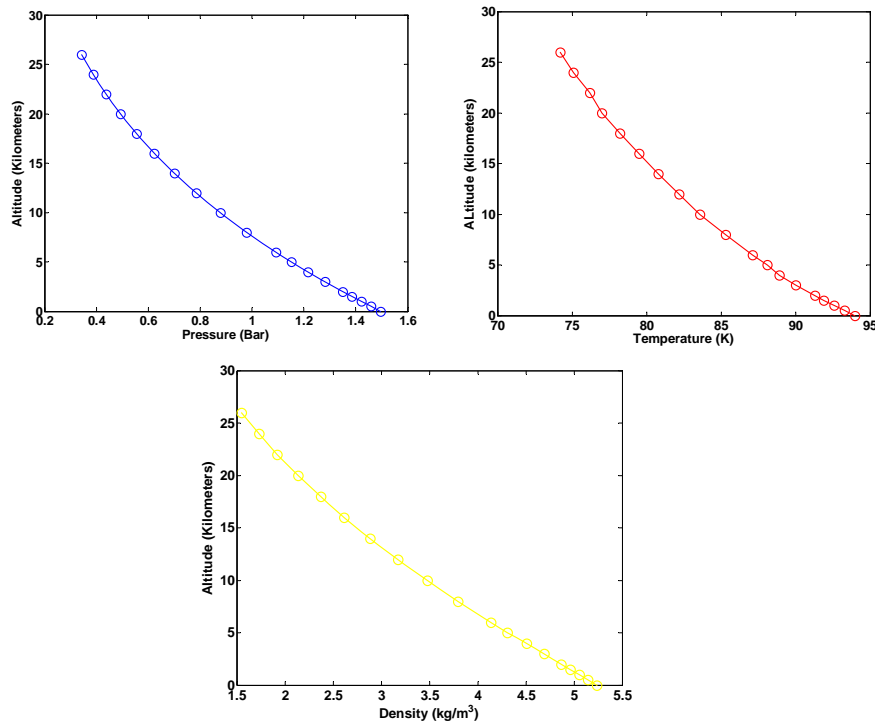

Fig. 1. Pressure, temperature and density as function of the altitude. These data have been measured by the Huygens probe during its descent in the Titan atmosphere.

2. TITAN ENVIRONMENT DESCRIPTION

As previously mentioned, the Titan environment is characterized by a thick atmosphere (i.e. elevated density and pressure) and low temperature. The atmospheric composition is mainly nitrogen (95% at the surface) with a substantial component of methane. Figure 1 shows the density, pressure and temperature profile as measured by the Huygens sensors during its descent [5]. The wind profile was measured by the Huygens Doppler instrument [6] and the Descent Imager [7]. At its entry point (Ls = 300 deg, Lat = 10 deg S), the wind blew the probe first eastward and then northwestward as shown in figure 2a. Global Circulating Model (GCM) [8] predicts westerlies and easterlies over broad regions. If that occurs, wind inversions potentially can be used to effectively control the balloon trajectory for regional/global navigation. In addition to the "zonal" component, the near surface wind structure may be dominated by a "tidal" component due to the effect of the gravitation attraction of Saturn on Titan's atmosphere motion [8]. Figure 2b shows a simple model for the tidal component. It is predicted that the tidal portion of the wind blows eastward or westward with intensity up to 2 m/sec depending of the position of Titan in its orbit around Saturn. Clearly, such a-priori wind knowledge can be exploited for local navigation as well.
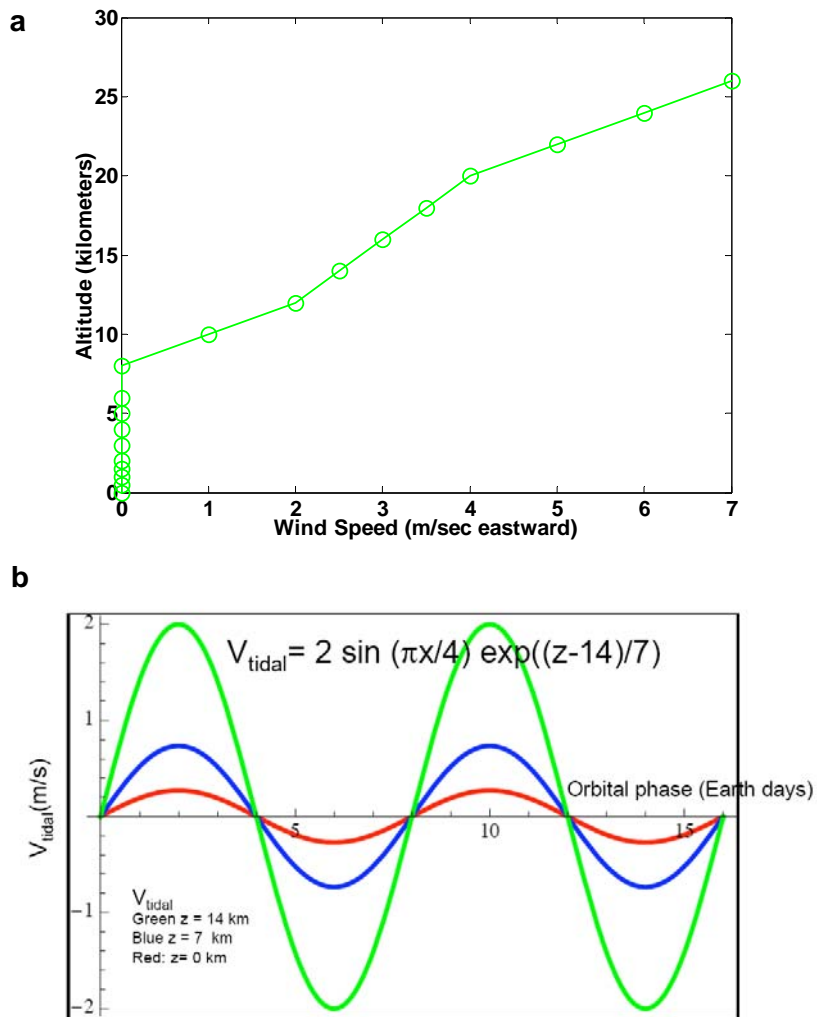

Fig. 2.a) Titan wind (zonal) component as measured by the Huygens probe during its descent (wind was reported blowing eastward), b) Model for Titan's tidal wind component: wind velocity and direction as function of the orbital phase around Saturn.

3. TITAN HOT-AIR BALLOON CONFIGURATION

Despite the fact that hot-air balloons (Montgolfier-type) have a lower specific buoyancy than gas-based (helium of hydrogen) balloons, they tend to perform better when navigating the Titan's environment. It is estimated that because of the extreme conditions of Titan's atmosphere, a hot-air balloon provides equivalent buoyancy with 100 times less power than the analog Earth-based balloon. Considering a class of Radioisotope Power Source (RPS) called Multi-Mission Radioisotope Thermoelectric Generator (MMRTG, weight ~40kg, electric power ~100We (Watts electricity)), we could generate as much as 2000 W of thermal power that can be used as heat source for buoyancy generation. Lorenz [4] estimated that a balloon flying on Titan at 8 km altitude using the available MMRTG would be capable of sustaining a payload of 195 kg. Figure 3 shows the conceptual design of a double-walled Montgolfier for Titan exploration. The preliminary idea would be to install the MMRTG near the neck of the balloon [4] for highest efficiency. Note that in such configuration, the balloon would be equipped with a top venting valve to control the internal gas temperature and therefore the lift level. Indeed, the assembly valve plus motor represents the available mean of actuation for vertical altitude control.
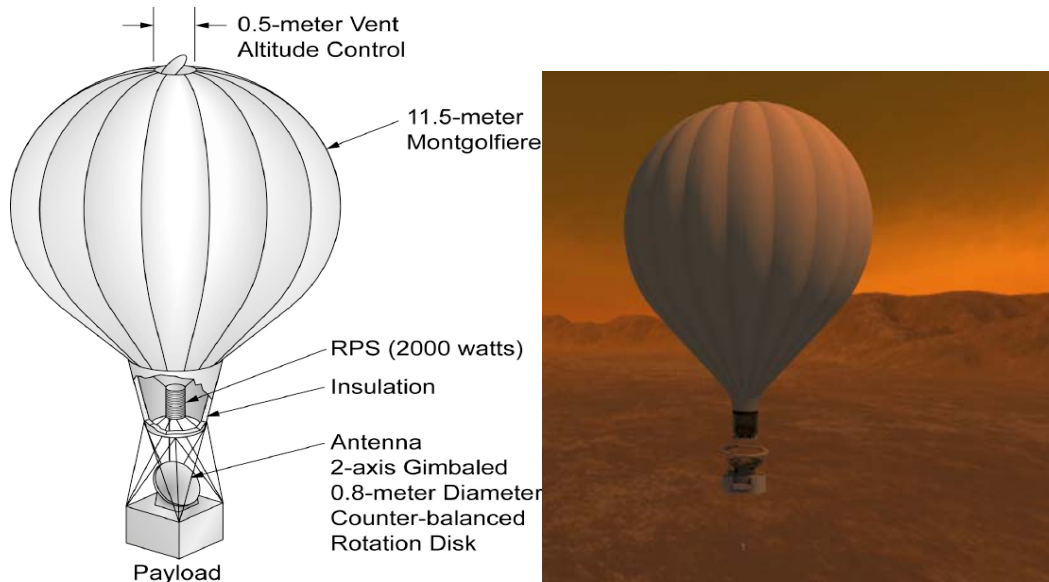

Fig. 3. Conceptual configuration of a Titan hot-air balloon (left). Artistic balloon image (right) courtesy of Tibor Balint (NASA JPL)

4. MODELING VERTICAL AND PLANAR (2-D) BALLOON DYNAMICS

Design and analysis of control strategies for hot-air balloon navigating Titan's environment require the definition of appropriate thermal and dynamical models. Few authors [9], [10] have developed the basic equations of motion describing both vertical and horizontal balloon's displacement as well as the thermal equations describing the gas temperature behavior inside the balloon.

On a very fundamental level, two balance equations are required, i.e. Newton's law and conservation of energy. The vertical acceleration of the balloon is described by the vertical force balance equation. The balloon's lift is function of both gas internal temperature and the surrounding atmosphere's density and temperature. Moreover, Newton's law applied to balloon's motion requires the inclusion of an additional term to account for apparent mass involved in the acceleration process:

$$\left(m_{tot} + C_m \rho_a V\right)\frac{d^2 z}{dt^2} = g\left(\rho_a V - m_{tot}\right) - \frac{1}{2}\rho_a C_D A\left|\frac{dz}{dt}\right|\frac{dz}{dt}$$

(1)

Here, $m_{tot} = m_g + m_f + m_{pay}$ is the total mass, (i.e. sum of the gas mass, film mass and payload mass), V is the internal gas volume, ρ_a is the atmosphere density, C_D is the drag coefficient, A is the balloon cross-section, z is the altitude and g is the gravity (3.41 m/sec^2 for Titan). The internal gas volume is related the other thermodynamic properties according to the following equation:

$$V = \frac{m_g R T_g}{M_a p_a}$$

(2)

Here, M_a is the molecular weight of the gas, R is the universal gas constant, p_a is the atmospheric pressure and T_g is the gas temperature.

The heat balance equation of the balloon (gas plus film) dictates that the global conservation of energy must be ensured, i.e. net flux of thermal energy into and out of the system must be compensated by an internal change of gas temperature:

$$m_g c_{pg} \frac{dT_g}{dt} = \dot{q}_g - \left(\frac{g m_g T_g}{T_a}\right)\frac{dz}{dt} + q_w - u$$

(3)

Here, m_g is the gas mass, c_{pg} is the gas specific heat, T_g is the internal gas temperature, T_a is the atmospheric temperature, $\dot{q}_g$ is the balloon's heat flux, q_w is the heat injected into the system by the balloon's heat source (MMRTG) and u is the amount of heat removed from the system by the venting valve.

At this level of modeling, we ignore the difference of temperature between balloon film and atmospheric temperature and no heat exchange between film and balloon's gas is considered. Moreover, we ignore film convection effects and solar irradiation. The infrared emissivity is included in the model as part of the spectrally integrated emissivity as the radiative cooling is assumed to be the dominant cooling mechanism during the flight. The balloon's heat flux can be expressed as follows:

$$\dot{q}_g = -S \varepsilon_{in} \sigma \left(T_g^4 - T_a^4\right)$$

(4)

Here, $S = 4\pi \check{R}^2$ is the overall balloon surface, $\check{R}$ is the balloon's radius, σ is the Boltzmann constant and ε_{in} is the balloon's spectrally integrated emissivity.

The balloon's motion in the horizontal (x and y) direction is generally caused by wind drag and can be approximated by the following (kinematic) equations:

$$\dot{x} = \lambda w_x$$
$$\dot{y} = \lambda w_y$$

(5)

Here, w_x and w_y are the components of the wind in the x and y directions (horizontal plane), λ is the ratio between absolute balloon speed and wind speed and it is a measure of the drag effect. For our analysis, we assume that λ is unitary.

4.1 State space representation

The thermal and dynamical equations can be put in state-space form, i.e.

$$\underline{\dot{X}}(t) = \underline{F}(X(t), u(t))$$

(6)

Let $X_1 = z$, $X_2 = dz/dt$, $X_3 = T_g$ and $X_4 = x$. The equations become:

$$\dot{X}_1 = X_2$$

$$\dot{X}_2 = \frac{g\left(\rho_a(X_1)V(X_1) - m_{tot}\right) - \tfrac{1}{2}\rho_a(X_1)C_D A |X_2| X_2}{\left(m_{tot} + C_m \rho_a(X_1)V(X_1)\right)}$$

$$\dot{X}_3 = \frac{1}{m_g c_{pg}}\left(\dot{q}_g(X_1, X_3) - \left(\frac{gm_g X_3}{T_a(X_1)}\right)X_2 + u\right)$$

$$\dot{X}_4 = F_{wind}(X_1)$$

$$V(X_1) = \frac{m_g R X_3}{M_a p_a(X_1)}$$

$$\dot{q}_g(X_1, X_3) = -S\varepsilon_{in}\sigma\left(X_3^4 - T(X_1)_a^4\right)$$

(7)

F_{wind} (z) is the function that describes how the wind velocity varies with altitude (see figure 2). It is important to stress out that in our analysis, the motion in the y direction has not been considered. Indeed, in the reminder of the analysis only vertical motion and motion on the vertical plane are considered (2-D model).

5. FUZZY CONTROLLER AND TRAJECTORY PLANNING

The goal of this section is to describe the methodology applied to the analysis and design of a fuzzy-based controller that could be effectively implemented on the on-board micro-processor for autonomous local balloon navigation of the Titan's environment.

The overall navigation/guidance scheme relies on a-priori knowledge of wind structure. After deployment, the balloon is left under the influence of the wind with the only option to control its altitude using an electric motor to open and the close of the venting valve. While the hot-air balloon is pushed back and forth according to the wind direction, it is conceivable that an intelligent change of altitude may be an effective mean to navigate the Titan environment.

During the mission operations, the balloon would be assumed to execute three possible modes:

Mode 1: The balloon would cruise at constant altitude. The wind would blow only in one direction and the control system would be responsible to maintain altitude.

Mode 2: The balloon would cruise at an "intelligent" altitude. In such condition, the wind would blow in one direction but the altitude of the balloon would change according to the input coming from on-board software designed to optimize the altitude depending on the scientific value of the area of interest and safety consideration (guidance scheme).

Mode 3: The balloon would perform a "station-keeping" maneuver. In such mode, the on-board computer would elaborate sensor information and a-priori wind pattern knowledge to evaluate if right conditions exist for maintaining the balloon relatively stationary. If the answer is positive, the controller would execute a station-keeping maneuver.

The key behind the successful execution of the three modes is to design and implement a proper altitude controller. Subsequently and on such premises navigation and guidance scheme can be conceived, designed and implemented.

5.1 Fuzzy logic for balloon altitude control: Design, Analysis and Implementation

The equations of motion, as represented in their state-space form (7), are non-linear. Various approaches to design an altitude feedback control system are available. The most obvious is the linearization approach where the equations are linearized around a reference condition and the classical and/or modern methods of linear control theory are applied to synthesize the controller structure. Clearly, the design works well as long as the system is kept close to the nominal point, i.e. the non-linear effects are negligible. Deviations from the nominal conditions are highly probable since the balloon would be expected to operate in an environment that is highly uncertain and not very well characterized. Methods adapted from general non-

linear theories (e.g. Lyapunov-based design methods) are available but generally more complicated and lack of a comprehensive, well-understood framework. Design techniques based on fuzzy reasoning are our method of choice. In the realm of control theory, fuzzy logic refers to a method to synthesize a controller that makes decisions similar to the way humans do. Introduced first by Zadeh [11], [12], fuzzy logic is a multi-valued logic that operates in contrast with the classical Aristotelian two-value (crisp) logic. In a sense, it can be thought as an extension of the classical logical construction. For example in crisp logic, a number either belongs or does not belong to a set. In fuzzy logic, the definition of fuzzy sets and membership functions [13] allows numbers to have partial membership to the set. Membership functions are functional maps that transform a number into a value between 0 and 1, where 0 means that the variable does not belong to the set while 1 means that the variable belongs to the set. For example, we can state that the "error is high to a degree 0.2" meaning that the error belong to the set "high" with a truth value of 0.2. A fuzzy inference system is comprised of various components. Fuzzification is combined with a set of IF-THEN rules [13] to form the so-called inference engine. An output scheme called de-fuzzification [13] is also required.

The basic fuzzy-controlled feedback system has the same structure as a closed-loop system with the fuzzy controller replacing, for example, the classical Proportional-Integral-Derivative (PID) controller. The overall system accepts desired altitude and vertical velocity as command inputs. Their values are compared with data coming from altitude measurements devices (e.g. radar altimeter), the errors evaluated and fed into a fuzzy controller. The fuzzy controller is comprised of a knowledge-base which contains a set of IF-THEN rules representing the heuristic control action. Figure 4 shows the input membership functions for both altitude error and vertical velocity error. Throughout this work, we use the abbreviations P for positive, Z for zero, N for negative, LP for low positive and LN for low negative. The output membership functions are abbreviated as H for high, M for medium, L for low, VH for very high and VL for very low. The rules for the valve command (angle) are shown in table 1. The first column is the vertical velocity error and the first row is the altitude error.

All rules have the following form:

$$IF\ \Delta z\ is\ X\ AND\ \Delta v\ is\ Y\ THEN\ \alpha\ is\ Z$$

Where X,Y can take any of the possible meaning in the first row/column and Z can take any value in the table (H,M,L,VH,VL). Alpha (α) is the aperture angle of the top venting valve. The assumption is that an electric motor is able to open and close the valve ($\alpha = 0$ deg, valve is completely closed, $\alpha = 90$ deg, vale is completely opened). In our design we ignore the dynamics of the electric motor (and valve mechanical structure as load) and we assume that there is a linear relationship between the expelled thermal energy and the valve angle.
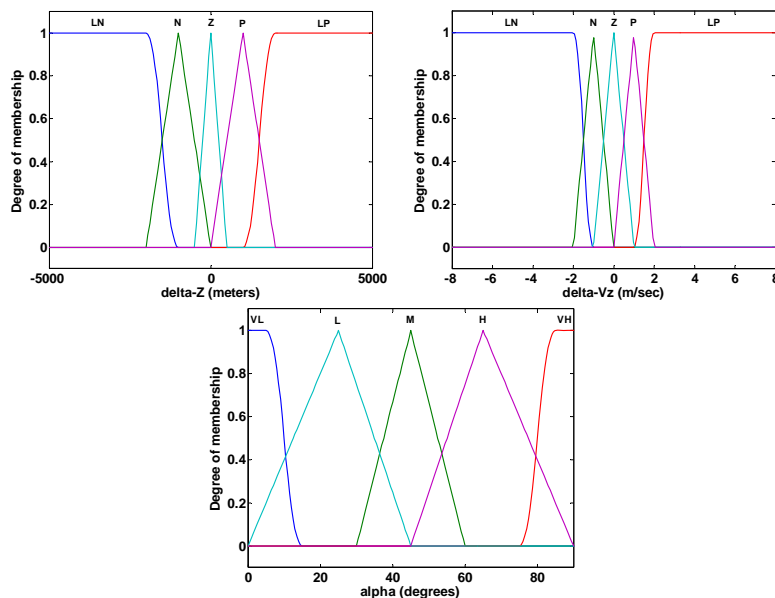
Fig. 4. Selected membership functions for input and output parameters of the vertical fuzzy controller.

As inference method, the product implication is used, i.e. the output membership function is multiplied by the truth value of the relevant rule. Whenever more than one rule is active, the maximum value of aggregation is used. Every rule is concurrently to form the aggregate output profile. The latter is a fuzzy quantity which must be defuzzified to provide a useful crisp value to the actuator (angle). Between various options, the centroidal method [13] has been selected. After the (crisp) control signal is computed, the selected valve angle is input to the balloon dynamical model to simulate its effect on the vertical displacement and velocity.

The outlined fuzzy design is equivalent to implementing a non-linear, reason-based Proportional-Derivative (PD) controller. A separate integral control action has been implemented in a parallel fashion completing the design of what is generally called fuzzy PD+I controller.

The abovementioned fuzzy controller and the balloon equations of motion have been implemented in MATLAB for fast analysis and performance evaluation. Huygens-based measured data have been interpolated and used to simulate Titan's atmosphere. The Fuzzy Logic Toolbox has been used to implement the knowledge-base (IF-THEN rules), the appropriate membership functions, the inference scheme and the fuzzification/defuzzification algorithms. Two simulation scenarios have been considered to analyze the vertical dynamics of the fuzzy-controlled hot-air balloon that would fly in a Titan environment. Both scenarios consider a balloon placed at 6000 m of altitude with zero vertical velocity and initial internal gas temperature of 120 K. The system would be dropped and the controller activated to follow two altitude commands, i.e. 1) maintain a constant altitude of 5000 m, and 2) vary the altitude according to a prescribed time-varying signal.

Figure 5 shows the results of simulation #1. The blue trajectory is the time evolution of the controlled altitude as the balloon would converge to the desired altitude. The control logic is shown to be effective as it would drive the system toward the desired state, i.e. zero vertical velocity and 5000m of altitude. The steady state would be reached after approximately 15,000 sec (~ 4 hours). Clearly, the system's slow response to input altitude commands is caused by first-order delays introduced by the thermodynamic behavior of the balloon internal gas. From a physical point of view, lift is generated by creating buoyancy, i.e. increasing the gas temperature. The energy conservation is described by a first-order ODE temperature equation which represents the heat balance between the MMRTG input heat power and the heat eliminated by the venting valve. Heat would be introduced/expelled into the system at different rates causing the thermal inertia to affect how lift is changed. The designed fuzzy controller would be capable of handling such non-linear effect and it is shown to drive the system to the desired state. Simulation #2 is a more sever test for the fuzzy controller. The system is required to track a change of altitude signal which is assumed to be a sinusoidal function varying between 4000 m and 6000 m with set temporal frequency. Figure 6 reports the simulation results. It is shown that the controller effectively tracks the signal. Starting from the same initial conditions as in simulation #1, the controller opens and closes the valve to track the altitude input. The steady-state tracking would be achieved after approximately 40,000 sec (~ 11 hrs).

5.2 Balloon guidance system: Fuzzy planner

The non-linear fuzzy-based altitude controller would be able to close the loop (feedback) on both altitude and vertical velocity and control the vertical position of the hot-air balloon. Planning the balloon altitude during the wind-based navigation of Titan's environment requires the design ad implementation of an appropriate guidance system. Figure 7 illustrates a possible architecture for the coupled guidance/control system. The balloon would be equipped with a suite of sensors that provide information about the system dynamical state (e.g. altitude, position, wind velocity, horizontal position) plus a set of scientific instruments or payload (e.g. imaging spectrometer, subsurface radar sounding) that would be used to acquire information about the down-looking field. Therefore, the balloon would acquire data while in-transit and a guidance system would decide what is the best flying altitude and/or when is appropriate to attempt a station-keeping maneuver (possible under appropriate local wind conditions). Generally speaking, the more interesting the observed site, the closer the examination is granted. The guidance system is thought to be comprised of two major components, i.e. an intelligent fuzzy-based expert system and a fuzzy planner.

Indeed, the full-scale deployment of a hot-air balloon for Titan exploration requires the design, implementation and integration of an intelligent system. Such a system should be designed to enable fully

automated and comprehensive characterization of an operational area, as well as to integrate existing information with acquired, "in transit" spatial and temporal sensor data, to identify and eventually execute maneuvers to closely inspect the desired locations. Recently, fuzzy-based expert systems have been proposed as integral part of mission architectures for autonomous planetary reconnaissance [14], [15].
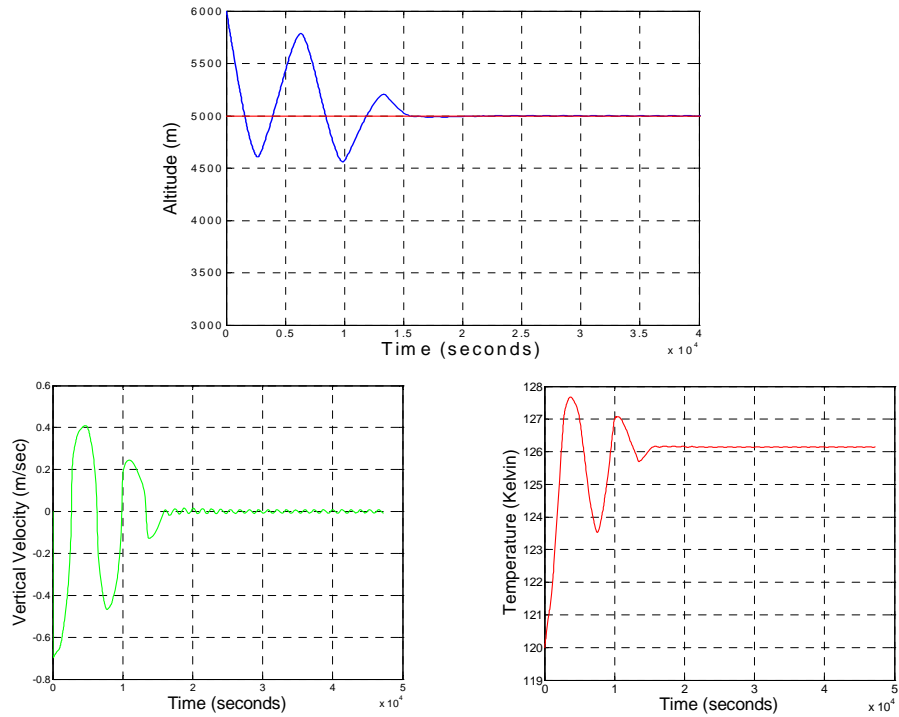

Fig. 5. Controlled vertical balloon trajectory as function of time (blue). The balloon is required to stabilize the system at a prescribed altitude. The bottom panels show vertical velocity and temperature as function of time during the controlled phase.
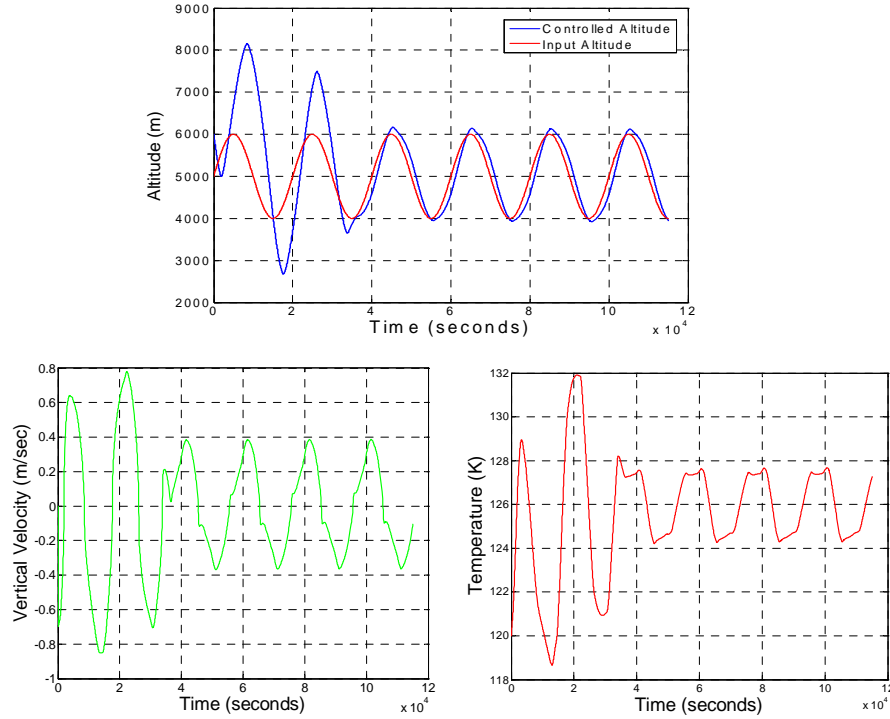
Fig. 6. Controlled vertical balloon trajectory. The top panel highlights the capability of the fuzzy controlled system (blue) to track an input signal (red).

Such systems operate by acquiring the appropriate geomorphologic, topographic, spectral, thermal and elemental data to elaborate the scientific context of the observed locale and provide an autonomous evaluation on the potential for the area to contain valuable scientific information (e.g. harbor life). While details of how such fuzzy experts are designed, implemented and tested can be found elsewhere [14], [15], [16], [17], here we are interested on discussing how such algorithms fit on the overall balloon guidance scheme. Following Figure 7, it is seen that sensor data are forwarded to the fuzzy expert. Data are preprocessed and categorized using appropriate algorithms (e.g. Automatic Global Features Analyzer (AGFA), [18]) to extract a large variety of scientific indicators. A fuzzy inference system is used to reason upon such indicators and determine the potential for scientific discoveries. While the output of fuzzy expert systems can be multiple (e.g. potential for habitability, potential for fluvial processes), in the rest of the discussion, we assume that balloon on-board fuzzy expert outputs what we call "Scientific Interest' (SI), i.e. an index between 0 and 100 that indicates the worthiness of the area to be explored. The SI index is fed to the fuzzy planner. The latter is designed to accept two inputs, the other being the Distance From the Ground (DFG) as measured, for example by a radar altimeter. The fuzzy planner uses the fuzzy logic framework and IF-THEN rules to infer the optimal flying altitude. The latter represents the guidance command tracked by the fuzzy controller. The fuzzy rules composing the knowledge base of the fuzzy planner have the following structure:

IF SI is X and DFG is Y THEN h is Z

Where X,Y and Z can be High (H), Medium (M) and Low (L). Table 2 shows the complete fuzzy knowledge-base employed by the planner. The rules have been defined such that the system always finds a compromise between two opposite requirements, i.e. scientific interest of the observed locale which invokes a closer examination (lower altitude) and balloon safety which generally requires higher flying altitude (i.e. distance from the ground).
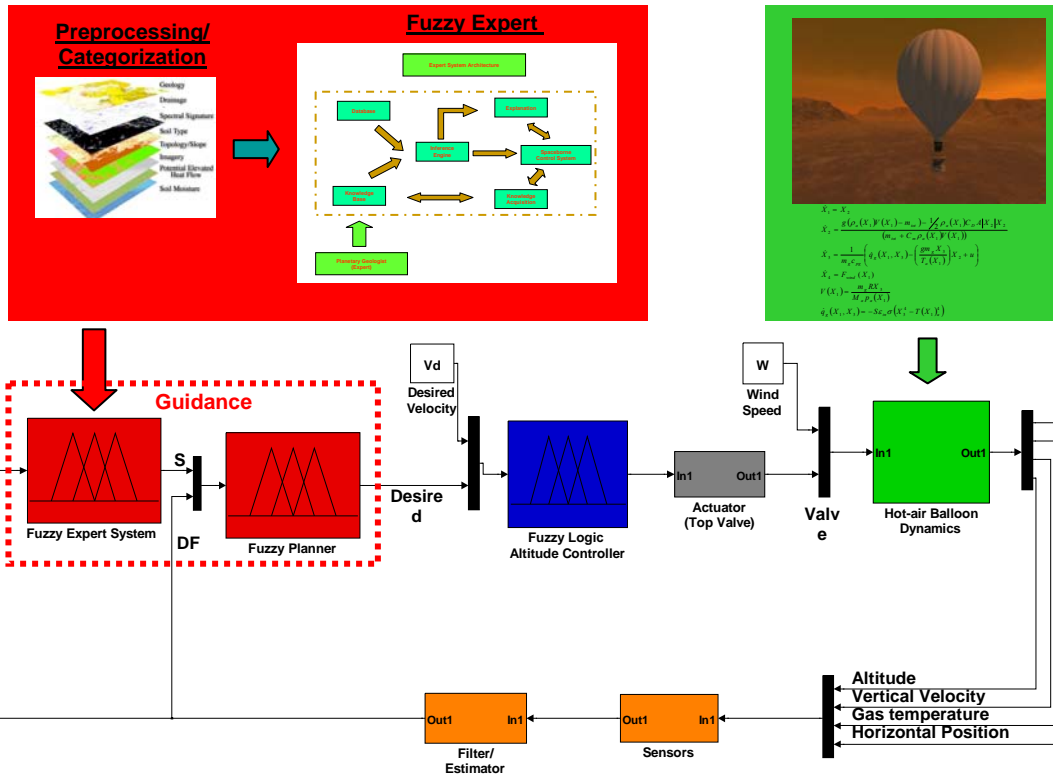
Fig. 7. Fuzzy-based Guidance, Navigation and Control (GNC) scheme for the hot-air Titan balloon.

The fuzzy planner has been designed, implemented and simulated as integral part of the guidance, control and navigation system, i.e. coupled with the fuzzy controller to analyze the overall system performances. A MATLAB simulation has been implemented to show the system behavior (figure 8). In such simulation, the 2-D controlled balloon dynamics is considered. The simulated scenario assumes a constant wind (2 m/sec) continuously blowing eastward. Titan ground topography is assumed to vary periodically as the square of the sine function to simulate mountains and reliefs. For this analysis, the balloon was assumed to be initially located at 6000m with zero vertical velocity and internal gas temperature of 120 K. The balloon is commanded to maintain a constant altitude of 4000 m as it travels for 10,000 m horizontally. After that, the fuzzy planner is activated and the controller is asked to track the guidance command. The SI input parameter is modeled to behave as a square signal function of the horizontal distance traveled by the balloon. The DFG input parameter is evaluated assuming that a radar altimeter is able to instantaneously measure the altitude from the ground (perfect measurements, no noise). Figure 8 shows the results of the simulation. The red line depicts the planned (guidance) command which must be tracked by the balloon (blue line). The simulation shows that the controller is able to track the trajectory defined by the planner showing the feasibility of coupling the two fuzzy systems.
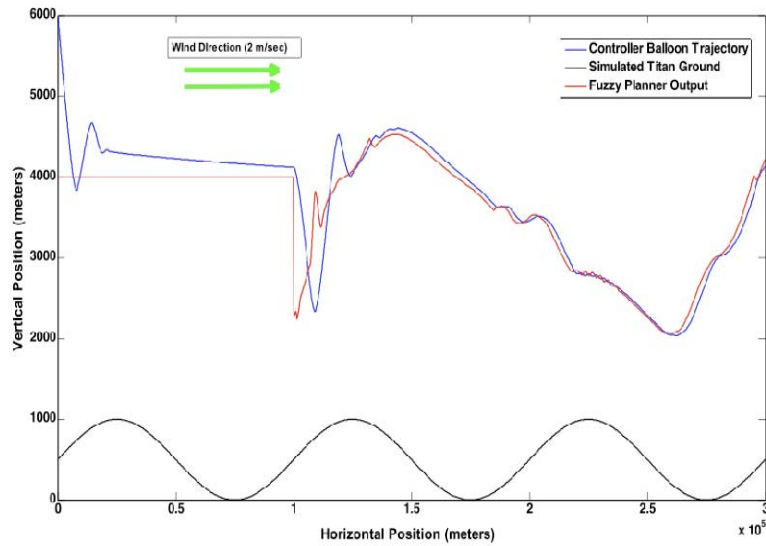
Fig. 8. Coupled guidance and control fuzzy system. The balloon (blue line) is moving following the wind direction (eastward) and track an input command (guidance) determined by the fuzzy planner.

5.3 Fuzzy controller for station-keeping maneuver

In principle, the fuzzy planner can be also used to command local station-keeping maneuvers. Clearly, this is possible only if the wind vertical structure present inversion points. As discussed in the titan environment section, the tidal component is capable of providing wind inversion and the station-keeping maneuver is designed around the assumption that the system is able to determine if and where wind inversion points are located. The guidance and control architecture does not require any special modification to handle this case. If the intelligent system output a very large SI value (close to 100) and if the system is able to predict that wind inversion point are available, the fuzzy planner command a signal in which the altitude is changed to follow a periodic signal.

Figure 9 shows the result of the simulated controlled trajectory for station-keeping maneuver. It is assumed that the wind would blow eastward (+ 2 m/sec intensity) above 5000 m where it has an inversion point. Below that altitude, the wind is assumed to blow westward with intensity of (–) 2 m/sec. For this analysis, initially the balloon located at 7 km with zero vertical velocity and internal gas temperature of 120 K. The balloon is then asked to track an altitude of 6 km. After traveling for 10 km, the scientific interest of the observed areas is large enough that the fuzzy system decides to execute a station-keeping maneuver. The fuzzy planner generates the command to implement the maneuver. As illustrated in figure 9. The amplitude of the maneuver is set to be approximately 20 km. The simulation shows the feasibility of the planned station-keeping.
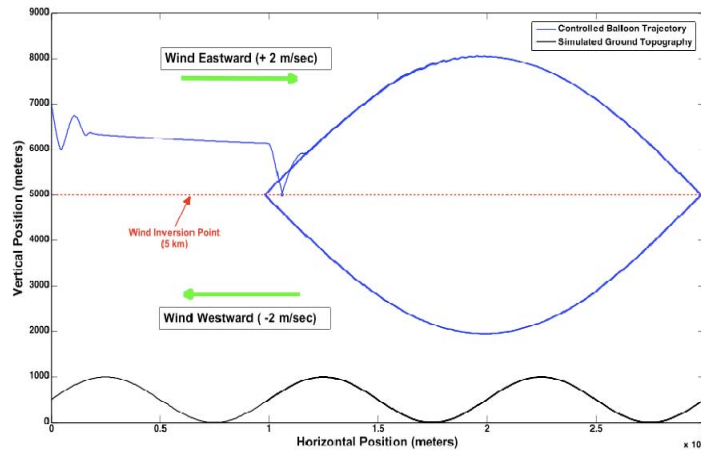
Fig. 6. Controlled vertical balloon trajectory. The top panel highlights the capability of the fuzzy controlled system (blue) to track an input signal (red).

6. CONCLUSIONS AND FUTURE EFFORTS

This paper shows how to approach the design and analysis of the hot-air balloon control and guidance system for Titan exploration. Indeed, this is the first attempt to study the coupled problem aiming at showing feasibility of the selected approach. While chosen design technique may vary, the fuzzy logic-based design has been selected for two reasons: 1) to show that heuristic, reason-based controllers are effective in handling non-linear dynamics without resorting to any linearization and 2) the fuzzy controller is embedded in a fuzzy-based guidance scheme using the same logical framework. Indeed, fuzzy logic has been promising in establishing such AI technique as preferred choice for intelligent, on-board, science-based reasoning to evaluate and understand streams of data acquired by the sensors and to autonomously infer the potential of significant discoveries. Realistic simulations show that local navigation is possible upon wind knowledge and vertical altitude control ability. Intimately connected to the AI decision fuzzy expert, the fuzzy planner appropriately guides the balloon according to the mode of operation, effectively and robustly.

Importantly, this study is a step toward the full-scale design of the controller and guidance system for local and global Titan's navigation. To this end, future efforts would include more extensive tests of the fuzzy controller on more realistic models, including high-fidelity 6-DOF models. The maturity of the guidance system design will follow a parallel track with the development of the appropriate fuzzy expert system for autonomous Titan scientific interpretation. Due to the satellite distance from Earth, autonomous balloon's operations would be critical for effective exploration. Therefore, studies on understanding how AI experts, guidance system and controller interact would be critical for future mission success.

7. ACKNOWLEDGMENT

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