ABSTRACT

This paper presents the state of the art of the 3D virtual simulator currently under development within the Aerospace Engineering Department of Politecnico di Milano. The simulator has been designed to provide a representation of the real dynamics of Entry vehicle trajectories within a three-dimensional virtual environment. More in details, the two main components of the tool are a lander dynamics module that allows to evaluate the position and the attitude of the vehicle as a function of time given, aerodynamics and controls forces both for the ballistic re-entry and the parachute-deployed phases, and a synthetic environment module.

The tool architecture and software design together with examples which highlight the flexibility of the proposed tool will be presented and discussed in the paper.

1. INTRODUCTION

Present-day and future space exploration programs include the development of planetary re-entry vehicles able to perform precise and safe landing. This is a non-trivial task that requires a closed-loop Guidance, Navigation and Control system based on proprioceptive (like Inertial Measurement Units) and exteroceptive (Radar Doppler Altimeter, cameras) sensors.

In particular, the robotic vision is a complex sensing process. It involves extracting, characterizing and interpreting information from images in order to identify or describe objects in the environment.

The testing of these sophisticated sensors, especially the image processing parts, requires a realistic, large-scale test-bed, representative of the real planet’s surface. Thus considering that virtual simulation is a cost-effective solution to verify and check for system design alternatives, the problem arises from the necessity to model not only the landing vehicle, but also the surrounding environment, in order to evaluate the performances of the surface-relative navigation system.

Several institutions and industries have developed their own Entry Descent and Landing (EDL) graphic simulators, such as the Dynamic Simulator for Entry, Descent and Surface landing (DSENDS) at the JPL [1], the Entry and Guided Landing Environment (EAGLE) by ESA [2] or the Hypersonic Planetary Aeroassist Simulation System (HyperPASS) by Global Aerospace Company [3]. These are proprietary software that commonly rely on third-party programs, such as Matlab®.

The Aerospace Department of the Politecnico di Milano has started the development of a similar tool in order to acquire an independent analysis capacity within such an important field as atmospheric re-entry, gaining at the same time a useful educational tool.

This paper is divided as follows: section 1 gives a brief introduction to planetary re-entry and explains why virtual environments are related to this topic; section 2 and 3 define the mathematical models used to simulate the dynamics together with the hypotheses and assumptions made; section 4 reports a short description of the virtual simulator; section 5 is dedicated to the integration of the EDL tool within the graphic environment and section 6 contains some final remarks and possibly future extensions of this work.

2. EDL MODEL

Describing the re-entry motion it is not a simple task: many variables characterize its dynamic and their exhaustive modelling is very onerous and in most cases not
necessary. So, simplification hypotheses were made in order to reduce the complexity of the model. First of all, a planar motion on the velocity plane has been considered to describe the re-entry vehicle trajectory [4].

The re-entry dynamics has been generically defined using the force equation, that defines the trajectory of the centre of mass, and the moment equation, that deals with the attitude of the vehicle (Eq. 1).

\[
\begin{align*}
& m \frac{dV^I}{dt} = F^I \\
& \frac{dH^I}{dt} = M^I
\end{align*}
\]

(1)

where:
- \( m \) is the mass of the vehicle.
- \( V \) is the velocity vector.
- \( F \) is the vector of forces applied to the vehicle.
- \( H \) is the angular momentum.
- \( M \) is the vector of moment acting on the vehicle.

The superscript in Eq. 1 refers to the Inertial Reference Frame, (X-Y plane on the equatorial plane, the Z-axis is directed towards the North Pole).

Accordingly to the typical mission profile for an EDL system in an atmospheric environment, the landing trajectory has been divided into three phases. Common to each phase are the following considerations:

- A rigid body model has been considered both for the capsule and the parachute.
- The rotation of the planet has been neglected in first approximation to simplify the dynamics. This is an acceptable hypothesis because of the small time of flight.

The equations of centre of mass are solved in the v-frame, whereas the moment equations in a body frame.

The first phase analyses the motion of a capsule from its entrance in the atmosphere entrance to the parachute opening. The vehicle is assumed to have an axial symmetric shape, and to be subjected to aerodynamic \((F_L, F_D)\), gravitational \((F_g)\) and control forces \((T_C)\), and moments \((M_L)\), as depicted in Figure 1.

Figure 1. Phase 1 forces and momentum

The second phase is characterized by a multi body dynamics, in order to describe the motion of both the capsule and the parachute. The equations of motion consider the capsule and the parachute as single objects, while a constraint force has been added to take into account the connection between them. So, the system of equations is the same of Eq. 1, but characterized by a doubling in the state variables number. In addition, the relative distance between capsule and parachute have been added as state variables. Compared to phase 1, the equations of motion are also characterized by:

- The absence of control forces and moments both on the capsule and the parachute.
- The presence of a constraint force acting on the capsule and the parachute.

The parachute has been modelled as a rigid body, using the mathematical model described in [5] that evaluates the physical, aerodynamic, and mass properties of a generic parachute that is supposed to be already deployed when 2nd phase starts.

To take into account aerodynamics, the drag coefficient \((C_d)\) is modelled by the first degree approximation presented in Eq. 2 (where \( \alpha \) is the angle of attack) whereas the lift coefficient is approximated as a perturbation (considering small values as a function of incidence). The pitch moment coefficient is described as a function of the attack angle by using a linear model.

\[
C_d = C_{d0} + C_{d1} \alpha^2
\]

(2)
The mass properties of the parachute may be specified either directly or estimated by using the radii of gyration method, and therefore calculating them through the overall height, span and bridle. To correctly describe the motion of the capsule and the parachute, a constraint force has been added to the equations of motion in order to consider the interaction between the two bodies. The riser attachment points on the vehicle and the parachute are assumed to rotate freely and therefore no torques are transmitted. Under this hypothesis, two models have been used to represent the constraint force between parachute and vehicle (mass-less spring damper and the direct use of the constraint equation). Their equivalence has been successively verified.

A simulator must be able to work with different level of approximation, based on particular requirements defined by the user, so both mathematical models [8, 9] and experimental data fitting [10, 11] have been used to recreate a close to reality atmosphere. The behaviour of an EDL system in an atmospheric environment is strictly connected with the aerodynamic characteristics of the body, thus introducing the critical task of evaluating with good accuracy the aerodynamic coefficients and their uncertainties. There are several methods to estimate the aerodynamic characteristics of a re-entry body:

3. ENVIRONMENTAL MODELS

The description of aerodynamic and gravitational effects is affected both by vehicle’s configuration and by the environment features. The model of the latter must be able to represent the atmosphere, considering the vertical variation of pressure, density and temperature. In addition, there are many additional derived quantities such as speed of sound, molecular mean free path, dynamic viscosity. The gravitational field has been assumed as constant, thus eliminating variations induced by planet’s shape and distance (acceptable hypothesis because of the little duration of a landing and the low magnitude of the gravitational loads with respect to the aerodynamic ones).
• Ground tests in wind tunnel, considering corrections due to the different composition for the atmosphere of the considered planet.
• CFD analysis as in [12] with distinctions between free molecular, transitional and continuum regime.
• Available data from previous missions.

These methods are commonly used together to estimate the aerodynamics of a re-entry body and to study future entry vehicles configurations. Although this approach is the best solution, it requires a large amount of time and resources for dedicate studies, extensive numerical and experimental simulation campaigns. For these reasons, this work relies only on aerodynamic coefficients coming from previous missions. A complete aerodynamic database for a Mars entry capsule is not freely available, so integrated informations coming from different missions have been analysed [12, 13, 14, 15, 16, 17, 18, 19].

4. VIRTUAL SIMULATOR
The virtual simulator has been designed in order to verify how the working environment affects the vehicle’s performances. The development of this tool started independently from the EDL study, thus includes modules that were initially foreseen for mobile robot simulations. To adequately consider the variance in planetary surface properties and the different requirements of land robots and landing vehicles, the simulator is constructed through a modular approach by composing single elements, each dedicated to a specific aspect.

The generation of the surface can be achieved from planetary archives (MOLA), field tests data, height-map from rasterised images (conversion of 2D images into three-dimensional surfaces)[20], generic triangulated meshes, user defined point-clouds and numerical models based either on two-dimensions noise or fractal algorithms [21]. Terrain models can range from limited, almost-flat areas for rovers operations to extended (hundreds of squared kilometres), irregular surfaces characterised by colours and topography variable according to the location.

Figure 3. Simulated Mars

The rock-dedicated module includes models for size-frequency distribution [22], shape and height to width ratio, thus allowing to simulate likely rock-fields whenever accurate data are unavailable in order to keep into account the threat they introduce both for landing spacecraft and planetary rovers.

A typical feature that can be exploited by the lander navigation system to identify its relative position is the existence of impact craters. These structures range from few meters to hundreds of kilometres with class (simple, with or without central dome, multiple concentric rings, non symmetrical) and shape (circular or elliptic) dictated by their age and type of collision that generated them [23].

Variations in lighting conditions are constrained by the planetary celestial mechanics here embedded in a dedicated orbital mechanics module [24, 25] that provides coherent information with the selected environment and sets the position of the Sun with respect to the local horizon as a function of the planetographic coordinates and local time.

As the presence of dark areas within images -taken from the cameras and then elaborated- could lead to an error in the identification of the surrounding environment, the modelling of the cast shadows has been included within the
5. EDL/ENVIRONMENT INTEGRATION

The current version of the simulator is capable to visualize Mars and Earth orbits and a planetary scenario with a rover moving on its surface. With the EDL tool development, a landing scenario is added to the simulator, visualizing the trajectory of the vehicle from its initial orbit down to the planet’s surface. The integration of a synthetic workspace with a simulation of the physic behaviour of the vehicle subsystems grants to evaluate the fallouts of the environment on the design choices, thus providing inputs for the subsequent fulfilment phase as well as for the operation lifetime. An example of such cross influences are the Electrical Power System and the Thermal Analysis and Control, whose boundary conditions result from vehicle’s attitude, position and operative status as well as on local time, Sun position and geographic coordinates.

6. CONCLUSIONS AND FUTURE WORKS

The introduction of virtual visual sensors that are related both to the surrounding space and to the vehicle’s status allows to define and test vision based algorithms, ranging from images analysis and obstacles identification to the integration of the gathered data with the navigation system. All these elements allow the user to exploit the tool in order to test vision based algorithms both for environment reconstruction and navigation, as well as to evaluate environmental effects on the design adopted solutions. Currently the simulation tool is exploited to generate Martian and Lunar-like surfaces for test on rover’s navigation algorithms [26] and stereo vision systems. The ongoing activities include the enhancement of the quality of the virtual environment with a focus on the optimisation of the system performances even with high detailed surfaces and at the same time, the advancement of the subsystems’ definition and refinement.

7. REFERENCES


