SOFTWARE TOOL FOR SIMULATION OF AIRCRAFT TRAJECTORIES

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Abstract

New concepts in air navigation have been introduced recently. Among others, are the concepts of trajectory optimization, 4D trajectories, RBT (Reference Business Trajectory), TBO (trajectory based operations), CDA (Continuous Descent Approach) and ACDA (Advanced CDA), conflict resolution, arrival time (AMAN), introduction of new aircraft (UAVs, UASs) in air space, etc. Although some of these concepts are new, the future Air Traffic Management will maintain the four ATM key performance areas such as Safety, Capacity, Efficiency, and Environmental impact. So much, the performance of the ATM system is directly related to the accuracy with which the future evolution of the traffic can be predicted. In this sense, future air traffic management will require a variety of support tools to provide suitable help to users and engineers involved in the air space management. Most of these tools are based on an appropriate trajectory prediction module as main component. Therefore, the purposes of these tools are related with testing and evaluation of any air navigation concept before they become fully operative.
The aim of this paper is to provide an overview to the design of a software tool useful to estimate aircraft trajectories adapted to air navigation concepts. Other usage of the tool, like controller design, vertical navigation assessment, procedures validation and hardware and software in the loop are available in the software tool. The paper will show the process followed to design the tool, the software modules needed to perform accurately and the process followed to validate the output data.

1. Introduction

For the next years aircraft are expected to fly optimal trajectories that are defined in the form of several waypoints and some required times of overfly. In order to maintain safety separation and exploit the benefits of these new trajectories (4D-trajectories), aircraft must stay within very small volumes around the reference track. Uncertainties arise when it comes to unpredictable events like for example fast atmospheric changes that may affect the prediction phase of the trajectory. So, all around trajectory prediction and its application to modern aircraft and to new challenges in airspace must be design with enough accuracy.
The simulations activities carry out around trajectory prediction become an important activity on the study of aircraft performance. New tools and software tools are being designing to know the behavior not only of single aircraft but the entire airspace. The impact of parameter variations is another aspect to be included in the simulation tools. This performance will allow to engineers to know the flight deviations at simulation stage.
Some aspects of the future airspace development are based on previous concepts like Continuous Descent Approach [1], and the advanced descent – ACDA [2], [3]. At same time, the responsibles for future airspace and the governments and states are concern by the environment, in order to get a green environment in the airports in near future [4], [5] and [6].
The above mentioned trajectories design represent other research field. Some new concepts are deriving from the airside. The business trajectories, the 4D trajectories, the arrival manager, the departure manager, all of them are changing the future Air Traffic Management (ATM) system [7]. From the point of view of trajectories the problem can be formulated in terms of compliance with objectives in trajectory based operations and with system parameter variations.. These variations can be taken as system perturbations (e.g. atmosphere and winds). Also the type of aircraft must be taken into account ought to varying navigation capabilities and the 4D trajectory tracking mechanism. This will be solved by means of different algorithms and aircraft models.

The purpose of this paper is to give the main guidelines in the development of a suitable software toolbox able to design and flight any aircraft trajectory. This function is going to be reached by means of an appropriate set of software models, related with aircraft, with earth and atmosphere and some mathematical algorithms [8] and [9]. To obtain the mentioned function is needed a set of preliminary data related with aircraft. This leads to some known as aircraft database such us BADA [10]. Other aircraft data are also useful, such as those providing aircraft coefficients. Among possible application of this tool is the development and design of the trajectory module of an arrival manager (AMAN) [11].
The paper is organized as follows. One section is dedicated to explain the general aspects of the software tool and its structure. Sections four and five give information about several mathematical models and about the implementation of the tool. Section six presents the results from some flight simulations performed to check the feasibility of the tool.

2. General Aspects of the Tool

Generally speaking a tool that evaluates the trajectory of any aircraft must have several modules. The most important are the mathematical models for aircraft and any object needed to perform the simulation, the aircraft database and the visualization module.
The first software module for the tool will manage the aircraft performance, the physical environment and the particular inputs to the system as a function of the application. The first one are related with all the parameters related with the aircraft motion, its power plant and the performance of the FCS (Flight Control System), the navigation laws managed by a FMS (Flight Management System) and the equations of motion needed to obtain a desired trajectory. Regarding the physical environment, the weather, earth and geomagnetic models have to be included in the tool. These performances can be considered as perturbations to the system, needed to evaluate real scenarios. Finally the inputs to the system will be adapted to the particular application of the tool.
The aircraft parameters are obtained from specific aircraft database. The function of these databases is to provide available data of aircraft parameters needed to solve the mathematical model of any aircraft. At least, the tool will use aircraft data coming from three databases, BADA, Datcom and one ad-hoc database. Any of them will provide aerodynamic performances, fuel consumption, thrust, drag and weight as main data.
Finally the third component of the tool is the data presentation and visualization to users. This module provides some freedom to the user to select the data needed according to the simulations carried out. The data provided are also used to validate the software tool comparing the information with real data. Some interesting aspects must be outlined in designing a tool with these performances.

- **Aircraft Performance:** The main features of any aircraft flight trajectory are largely determined by the aircraft type and some external perturbations. Performance aircraft data generally are provided by the aircraft manufacturer. Among the aircraft data are speeds and climb and descent gradients. This data are often presented as functions of aircraft weight, atmospheric conditions and establish envelopes for safe flight. Climb and descent speeds as actually flown are dependent not only upon aircraft performance, they may also be limited by flight procedures or by speed restrictions.
- **Navigation:** Navigation information may be an input to the simulation tool, by means of a flight plan data. The route is defined by a sequence of navigation fixes, radio navigational aids, airway intersections, latitude and longitude information of a waypoint or radials and distances relative to a fix. Altitude, departure and destination airports as well as latitudes and longitudes of the navigation fixes that define the route may be obtained from aircraft databases provided by Eurocontrol.
- **Flight Phases:** The purpose of the simulation tool is model any flight phases. Several flight phases may be simulated within the flight model, from take-off roll to final descent and land (Takeoff Roll, Takeoff, Initial Climb, On-Course Climb, Cruise Climb, Cruise, Initial Descent, Approach Descent, Final Descent, Landing). Fixed-wing aircraft are generally assumed to sequentially complete all flight phases, so the purpose of the model will be to allow for variations within certain phases to accommodate higher and lower performing aircraft types or flight at atypical cruising altitudes. The most important flight phases to be silmulated at this phase of the simulation tool are mentioned in the following paragraphs:
    - **Cruise and Climb of an Arbitrary Aircraft:** In the segments known as cruise and climb, the accelerations of airplanes such as jet transports and business jets are relatively small. Hence, the tangential acceleration is neglected in this kind of problems. Some interesting problems can be addressed in this phase, such as those related to distance and time in cruise and the distance, time, and fuel in climb for an arbitrary airplane. Then, the performance of an airplane can be computed for a particular velocity profile, or trajectory optimization can be used to find the optimal velocity profile. This is done by solving for the distance, time, and fuel in terms of the unknown velocity

profile. This problem may be addressed by the application of the optimization theory to find the corresponding optimal velocity profile.

- **Descending Flight:** The importance of the descent segment relies on the application of continous descent approach, in the study of estimated time of arrival, in the simulation of arrival managers, in the application of control theory and many other aspects related with arrival performance. The versatility of simulation tools in this flight phase is very interesting for trajectories design. Another perturbation included in this phase is the wind, that is the atmospheric data. In an aircraft's general state of motion requires adjustments of engine power settings or pilot control inputs. A set of flight parameters are defined for each aircraft type including accelerations, speeds, altitudes, as well as climb and descent gradients. The model may calculate flight progress distances and time by converting all indicated airspeeds to true airspeeds depending on the actual altitude of the aircraft.

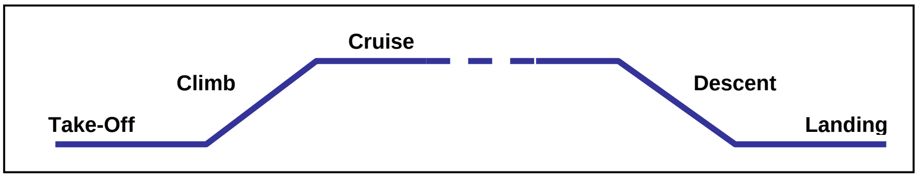

Figure 1: Typical flight phases.

All flight phases require different parameters. These parameters become input data to the simulation model. Some of the necessary parameters are related as follows in function of the cruise and descent flight phases:

- Cruise: Cruise acceleration, Airspeed.
- Descent and approach: Cruise Mach number, Initial descent deceleration, Airspeed, Gradient and altitude, Target speed, Altitude and Distance

3. Toolbox Structure

The general toolbox structure includes all the modules needed to perform aircraft flights and to calculate their trajectories according to system inputs. A real flight system can be reduced to three loops as shows figure 2. The inner loop is related with the control of the aircraft, performing the necessary maneouvers to maintain the aircraft stability. The middle loop is related to the automatic functions of the aircraft managing the data generated in the previous stage. Finally the outer loop is related with the flight management. The flight plan is carried out in the Flight Management System and the data pass to the following step.

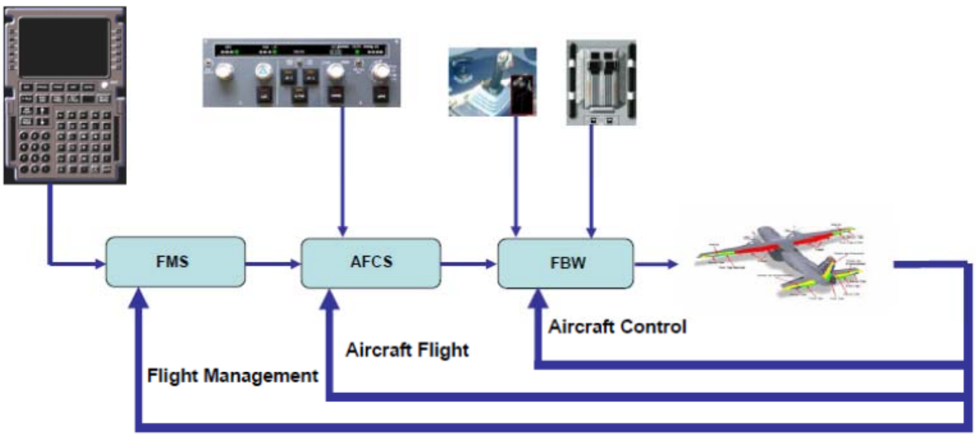

Figure 2: Aircraft simulation based on three loops.

The design of the modules of the toolbox will be introduce in progressive way. The first block to be developed will be the aircraft model, in which are included the actuators transfer functions. The trajectory generator will provide the basic data of any flight. The aircraft dynamics is a general block that includes besides the aircraft model, the needed controllers for any application, based on different and selectable control laws and the aircraft database. The perturbations block includes the wind and earth models, and finally the outputs block groups several types of data representation and visualization. The following figure depicts a vey simplified toolbox structure

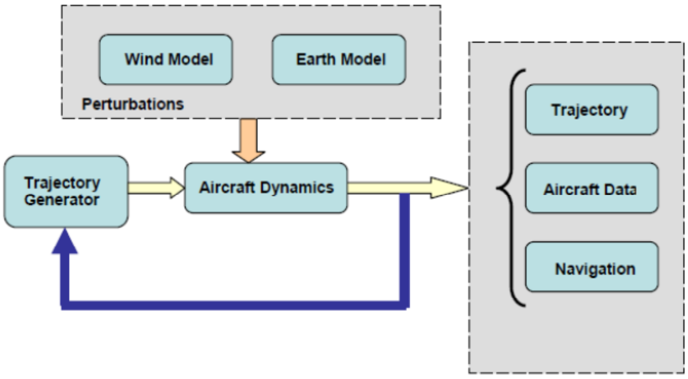

Figure 3: Minimum blocks of the tool simulator.

4. Mathematical Models

The equations of motion constitute the core of the mathematical model of flight dynamics. These equations relate the forces acting on the aircraft to its position, velocity, acceleration and orientation in space. The accuracy of the tool depends on the fidelity of the mathematical models selected for the specific application. The tool is going to work with mathematical models for atmospheric, earth and aircraft. The aircraft mathematical models included in the tool are those related with six and three degrees of freedom, although the point mass model will be used mostly for the trajectory prediction. With several mathematical models will be possible to simulate different navigation scenarios and different flight phases.
As an example of the usage of models, let us considerer the aircraft mathematical model as a six degree of freedom non-linear model of any civil transport aircraft included in the BADA database. The non-linear model can be completed with nonlinearities of actuators and a model of wind disturbances. An aircraft can be modelled as a space state using a point mass model, based on Newtonian dynamics. In this case the aircraft dynamics is represented as a state system space system, where the state vector is given as:

$$x = \begin{bmatrix} V & \alpha & \beta & p & q & r & \theta & \varphi & \psi & X & Y & h \end{bmatrix}^T \tag{1}$$

where V is the aircraft speed,(α, β) are the attack and slip angles respectively, (p, q, r) are the three speed rotation of the aircraft regarding body axes, the symbols (θ, φ, Ψ) are the Euler angles and the position of the aircraft (X, Y, h). Additionally to that, the model includes the needed control inputs, such as engine thrust (T), the bank angle (Φ) and the angle of attack (α) among others.

Another possibility is based on the mathematical model called Total Energy Model (TEM). This model is obtained from the point mass model in which has be taken into account that aircraft operates close trimmed flight conditions (i.e. $\alpha = 0$). The total energy model considers the variation of available energy between the starting point of the procedure and the final is due to the work of external forces that acting on the aircraft and using different variables that define the state of the aircraft and its evolution [2]. The corresponding mathematical equation is:

$$(\boldsymbol{T} - \boldsymbol{D})\boldsymbol{V}_{TAS} = \boldsymbol{m}g\frac{d\boldsymbol{h}}{dt} + mV_{TAS}\frac{d\boldsymbol{V}_{TAS}}{dt} \tag{2}$$

where $\boldsymbol{T}$ is thrust, drag $\boldsymbol{D}$, $\boldsymbol{m}$ the mass of the aircraft, the altitude $\boldsymbol{h}$, $\boldsymbol{g}$ the acceleration due to gravity and $\boldsymbol{V_{TAS}}$ the true air speed. The solution of last equation requires express thrust $\boldsymbol{T}$ and drag $\boldsymbol{D}$ as function of the kinematic variables $\boldsymbol{h}$ and $\boldsymbol{V_{TAS}}$, by using the coefficients collected in the BADA database. With these examples, it is highlighted the freedom of the user to choice the suitable mathematical model for any particular application.

In modeling an aircraft or another flying vehicle for trajectory design or optimization, the following assumptions, usually associated with [12], are common:

- The aircraft is treated as a rigid body with six degrees of freedom. This idealization of actual flight dynamics avoids the consideration of elastic forces and moving aircraft elements.
- It is assumed that earth is flat, that earth rate is constant and zero and that Coriolis accelerations can be neglected to simplify the equations of motion for the aircraft.
- The thrust and the drag forces, as well as the velocity vectors, are assumed parallel with the reference line of the vehicle.
- The lift force is assumed to be orthogonal to the velocity vector and to point upwards in the frame of reference of the vehicle.
- The inertias of a vehicle are assumed negligible.
- The Earth is assumed flat and the gravitational acceleration is assumed constant.

5. Model Overview

The model is a collection of modules, each one performing a specific function. The primary modules are the aircraft actuator and surface command inputs, aircraft mass and geometry modeling, the equations of motion, the atmospheric model, the aerodynamics, the propulsion system, and the observation variable modeling. Each major module is described in the following sections. Figure 4 shows the minimum model blocks to be included in the tool simulator, and how the modules would be connected together with user synthesized control laws to form a complete system model.

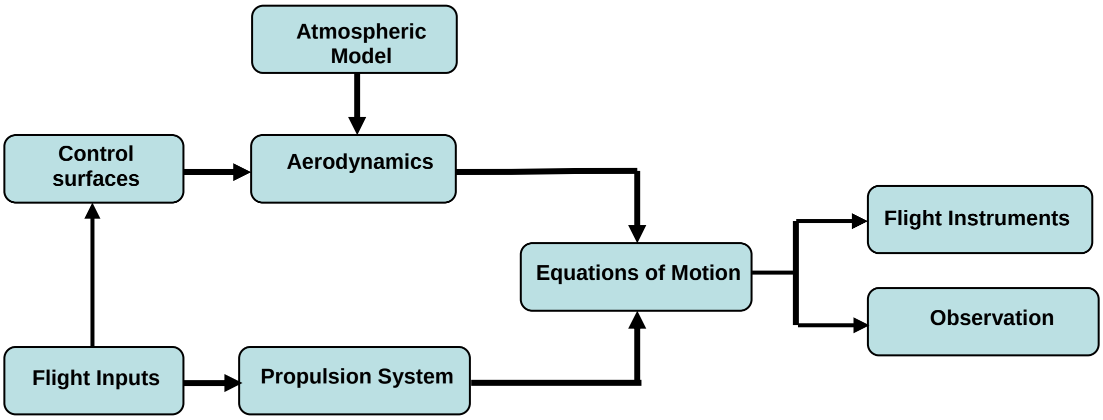

Figure 4: Minimum blocks of the tool simulator.

The functions of these blocks are the next:

- **Flight Inputs:** These inputs represent the desired flight data. These data can be provided by means of ad-hoc script, by means of theoretical trajectory or by means of real flight data or FMS data mode. The main function is to customize through parameter files the flight tests desired.
- **Control Surfaces:** The function of this block is to provide the necessary commands to the aircraft to move the aircraft control surfaces.
- **Aerodynamics:** This block provides the aircraft coefficients to be translate to the equations of motion block. This block needs the date generated in the atmospheric block, among others the wind profiles, taken these data as perturbations to the system.
- **Equations of Motion:** The aerodynamics block models for the full vehicle envelope using multidimensional tables and linear interpolation to form nonlinear function generators. The equations defining the aerodynamic model provide non dimensional forces and moment coefficients. The longitudinal parameters are in the stability axis system: the lateral-directional parameters are given with respect to the body axis system.

- **Propulsion System Model:** The propulsion system model consists of some engine models. The engines block provides the data needed to the mathematical model block. Basically speaking, the engine block provides the thrust to next simulation step
- **The Flight Instruments and Observation blocks:** They are the interface with user. They allows to give information regarding the flight performances and the variables provided by the model. A broad class of parameter is useful for vehicle analysis and control design problems. These variables include the state, time derivatives of state, and control variables. Air-data parameters, accelerations, flight path terms, and other miscellaneous parameters may also be included.

6. Model Implementation

Simulations are essentially obtained by means of computer programs developed in Matlab and Simulink environment. The software implemented integrates the equations of motion and all the others models previously mentioned. They are used to evaluate the flight characteristics of an aircraft according to the inputs to the system.

6.1 Graphical User Interface

The interface between the tool and the user is solve by means of a high level graphical user interface (GUI). This interface allows to users to choose the main aspects related to the scheduled flight. Also this interface, allows to selecting between different aircrafts and different atmospheric environments. The final visualization is chosen by the user according to the kind of simulation performed. Some inputs, outputs and simulation parameters are included in this GUI.

- Inputs: Aircraft type, winds model, airports, flight type, waypoints, take-off and landing airports and aircraft database.
- Aircraft mathematical model: The user will select the mathematical tool to solve the aircraft trajectory. This facility gives the user the possibility of compare results as a function of the test performed.
- Outputs: Some visualization tools are included to give the easy of taking a view of the data generated in the tool. The outputs cover from engineering graphs to aircraft view by means of a commercial flight simulator.

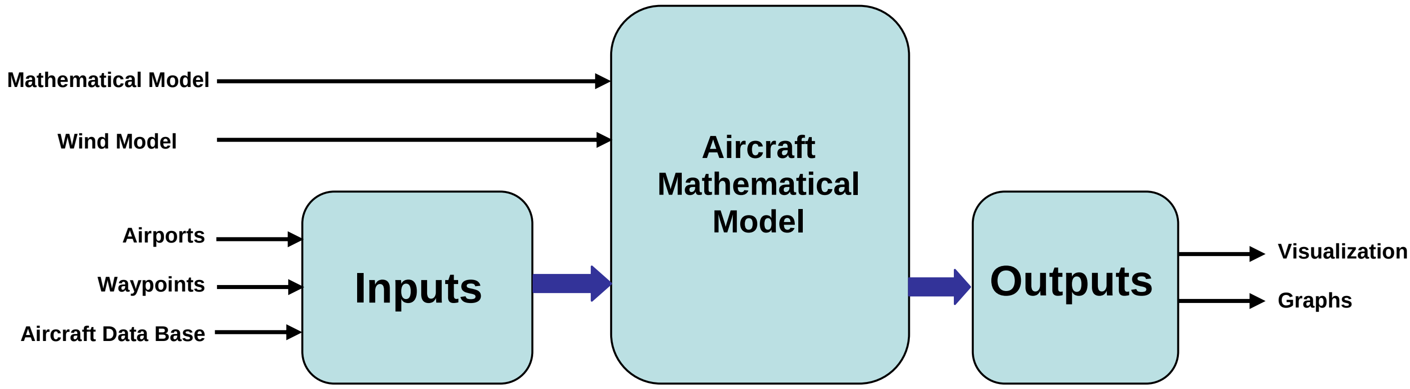

Figure 5: Blocks diagram of the Graphical User Interface

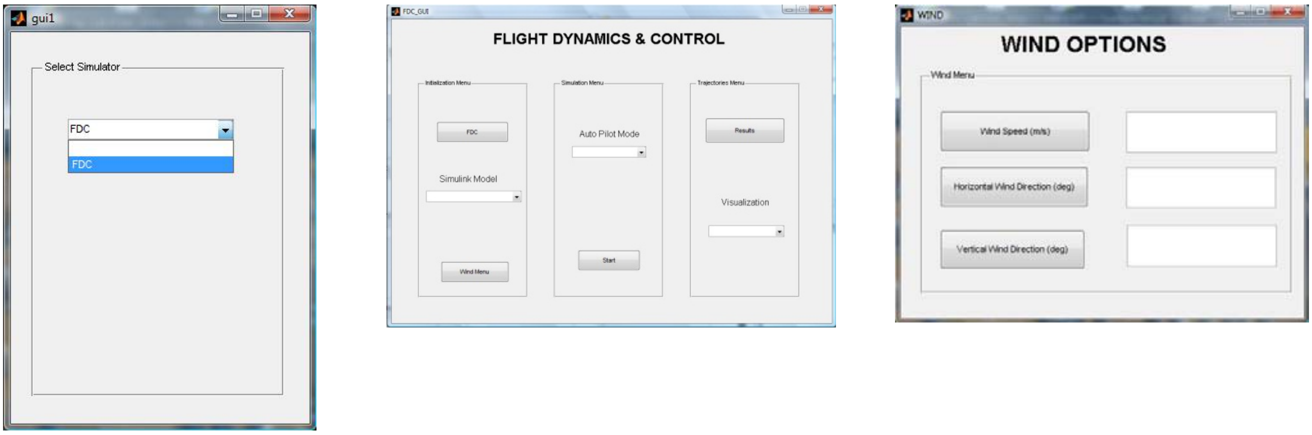

Figure 6: Example of the GUIs

6.2 Some examples of Flight Paths

The final module of the simulation tool is the easy to depict some graphics and some visualization graphs. Here are included some images obtained with the tool performing some flights. As an example the flight paths from Madrid Airport (BRA) to Canary Islands (GDV): Aircraft A-320 is depicted in the following figures.

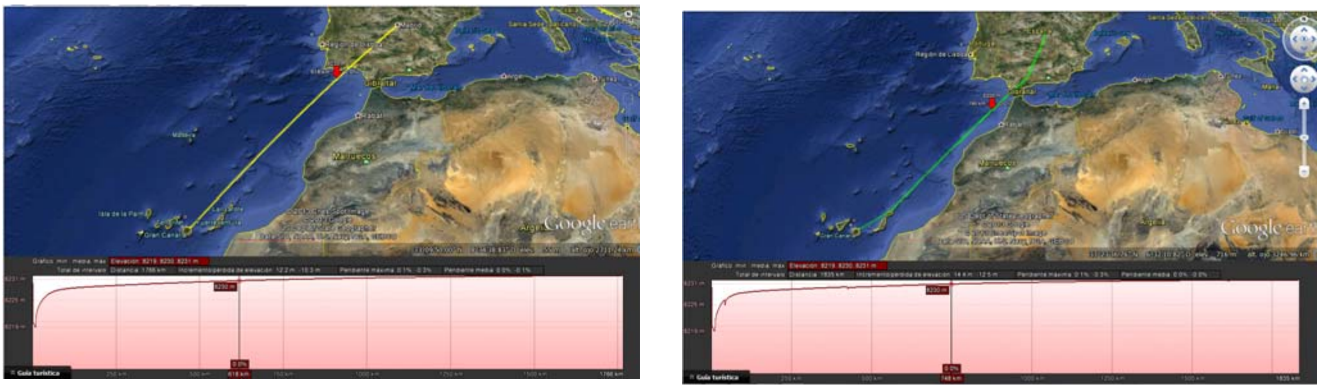

Figure 7: Orthodromic distance (a); waypoints flight path (b)

Figure 8: Comparison of different flight paths

Other visualization modes are related with flight instruments. In this representation of the flight parameter it is possible to check the performance of the flight within flight instruments performances. This kind of visualization is useful in test related with cockpit data.

Figure 9: Example of visualization

Finally, the flight simulation tool depicts engineering data related with flight performances. The engineering data representation is selected by the user by means of Graphical User Interface. The performance of the flights can be validated with real flight data obtained from aircraft FDR.

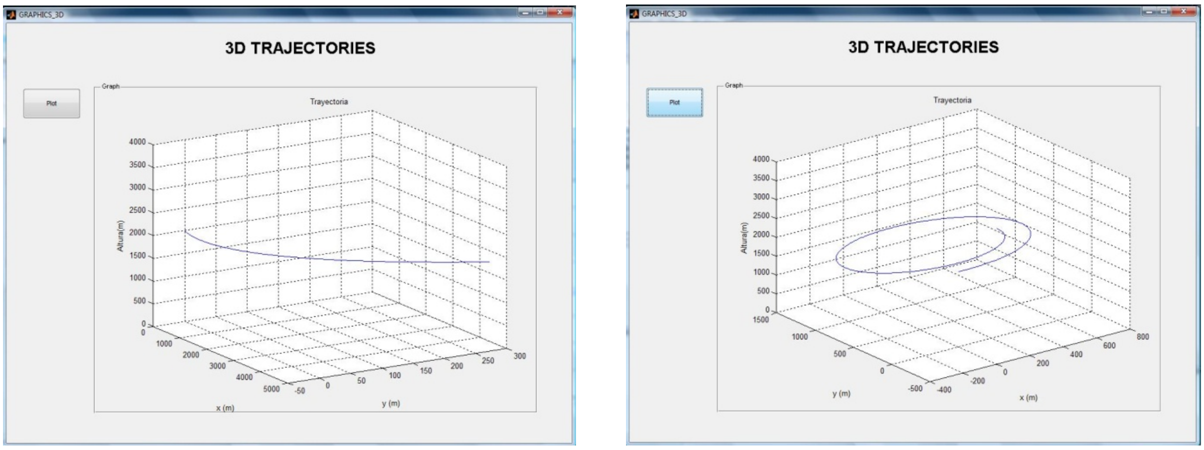

Figure 10: Engineering data graphs

7. Acknowledgments

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8. Conclusions

This paper focused on the main aspects related with the development of a software tool to design and model aircraft trajectories. The necessity of this kind of tools is supported for the new and future challenges introduced in airspace. The aircraft trajectory is model by means of mathematical and data modules included in the tool. The final software tool will allow simulating any aircraft flight phase in order to compute its simulated flight trajectory and to introduce and understand navigation concepts. From the user point of view, we would like to highlight the suitability of this toolbox because of the freedom to select any flight scenario. The software tool allows to the users to choose

different airplanes, different flights conditions and different flight scenarios. Behind the high level managed by the user are the intermediate and low level software. Among these are the aircraft mathematical model, the atmospheric models, wind model and earth model. Other performances related to visualization, engineering data and graphs and other possibilities related with validation data were managed in the software tool.
Among the possible uses of this tool are the development and implementation of some of the SW modules or the current Arrival Mangers (AMAN), the development of HW using the tool as hardware in the loop and the software in loop test to validate specific hardware.

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