AN AIRCRAFT MODEL FOR COMPUTATIONAL SIMULATION

Daniel Baraldi Sesso
Safety Analysis Group (GAS) – Dep. of Computing Engineering and Digital Systems (PCS)
School of Engineering of the University of São Paulo (Poli-USP)
Av. Prof. Luciano Gualberto, Trav. 3, 158 – CEP 05508-010 – São Paulo – SP, Brazil
daniel.baraldi@usp.br

Rafael Yudi Imai
Safety Analysis Group (GAS) – Dep. of Computing Engineering and Digital Systems (PCS)
School of Engineering of the University of São Paulo (Poli-USP)
Av. Prof. Luciano Gualberto, Trav. 3, 158 – CEP 05508-010 – São Paulo – SP, Brazil
rafael.imai@usp.br

Lucio F. Vismari
Safety Analysis Group (GAS) – Dep. of Computing Engineering and Digital Systems (PCS)
School of Engineering of the University of São Paulo (Poli-USP)
Av. Prof. Luciano Gualberto, Trav. 3, 158 – CEP 05508-010 – São Paulo – SP, Brazil
lucio.vismari@usp.br

João Batista Camargo Junior
Safety Analysis Group (GAS) – Dep. of Computing Engineering and Digital Systems (PCS)
School of Engineering of the University of São Paulo (Poli-USP)
Av. Prof. Luciano Gualberto, Trav. 3, 158 – CEP 05508-010 – São Paulo – SP, Brazil
joaocamargo@usp.br

ABSTRACT

This paper presents an aircraft model, programmed in LabVIEW™ language, to be implemented in an air traffic computational simulation environment. This aircraft model, previously described in [1], is part of the modelling of the Air Traffic Management (ATM) system for the safety assessment approach proposed by Vismari and Camargo Junior [2] and extended by [3]. This latter work aims the safety assessment of an ADS-B based ATM system considering data integrity as a relevant factor for safety level.

Besides describing some details regarding the computational implementation of the dynamics and control characteristics of the aircraft, this paper evaluates the results of the tests performed on this model to simulate the behavior of the proposed aircraft model involving several possible maneuvers for the purposes presented in [3], highlighting the model's main features and limitations.

Keywords: Safety, Aircraft, LabVIEW™, Computational Simulation.

1. INTRODUCTION

The International Civil Aviation Organization defines safety as "*the state in which the risk of harm to persons or of property damage is reduced to, and maintained at or below, an acceptable level through a continuing process of hazard identification and risk management*" [4].

Based on this definition and in the global aviation context, the term safety is the feature of a particular system does not causing unacceptable risks of accidents or incidents involving aircraft. Quantitatively, safety is the probability of a system, in a given time, to perform its function or to discontinue it without causing deaths, injuries, environmental and material losses [5].

The growth on air traffic transportation demand from the society are requiring the airspace densification. Aeronautical authorities expedite the process of implementing the new Global Air Traffic Management (GATM) concept for achieving this goal. However, the perception of risk in our society makes air transportation safety requirements to be even higher than current technology so that there is not an increase of the number of accidents. Thus, regarding the adoption of new technologies in airspace, a very careful assessment of their automated systems for navigation, communication and surveillance is needed. Besides the models in the system itself, it is necessary to evaluate their interaction, since, even though each individual part of these presents correct operation, the interaction between them can lead to potentially unsafe situations [6].

In this context, the surveillance system plays a key role for guaranteeing safety in the Air Traffic Management (ATM) System once it is responsible for monitoring the expected and actual trajectories of the aircraft in a given airspace. The adopted surveillance system in the new GATM concept is the Automatic Dependent Surveillance – Broadcast (ADS-B).

There are several possible scenarios for interaction between ADS-B considering parameters of integrity of data. In previous work [2], the impact of ADS-B on air traffic safety was evaluated and compared to systems whose surveillance was primarily based on radar technology. Thus, new parameters available in the ADS-B technology can be considered for evaluating the safety levels of air traffic control, such as the 'projected-profile', a field of ADS-B data package, which was not considered in previous analysis.

In order to maintain uniformity of analysis and to establish a reliable comparison with previous work, the method to be used for the safety evaluation system will be the same proposed and used in [2]. This methodology combines 'absolute' and 'relative' methods defined in [7] in which both quantitative and qualitative analyses are performed in a given system. It assesses whether the safety level is above an acceptable threshold value and also compares the system with another reference system, which is usually a legacy system already tested or in current operation.

To perform this safety assessment, in a previous work of Baraldi Sesso et al. [3] it was proposed an approach based on computational simulation in which the elements of the Air Traffic Control (ATC) architecture, shown in Figure 1, were properly modeled.

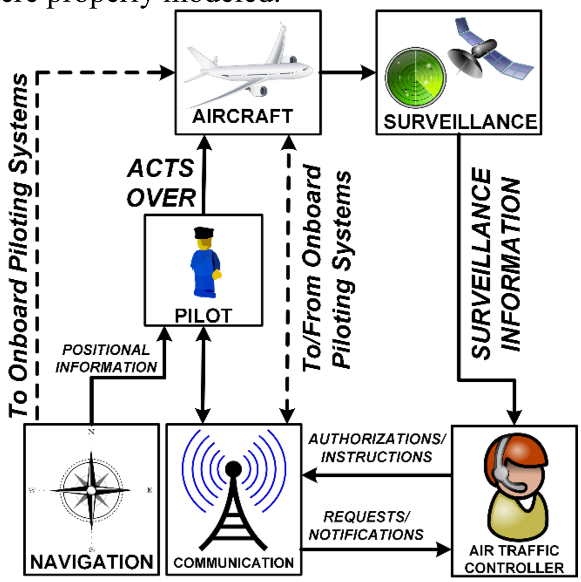

Figure 1: ATC architecture (adapted from [1]**)**

This ATC model was previously developed by Vismari [1] for computational simulation analysis tool based on Petri Nets (SPNP), which used ANSI-C language for implementation. It was proposed in [3] the extension of ATC model adopting new features, specifically positional data integrity parameters, and to adapt it for computer-based simulation of the air traffic environment in LabVIEW™. This paper's focus is specifically over the aircraft model.

Besides the dynamics and control characteristics of the aircraft, this paper evaluates the results of the tests performed on this model presenting its main features and its limitations.

In this work, section 2 briefly presents the methodology to be used for assessing safety considering different scenarios for ATM. In section 3, it is shown the adopted modelling calculation for the aircraft to be simulated in the context of the proposed safety assessment approach. The details of the implementation for the aircraft model are presented in section 4 while the results of its preliminary tests are depictured in section 5. For last, in section 6, we present the concluding remarks.

2. SAFETY ASSESSMENT

The International Civil Aviation Administration (ICAO), describes procedures and parameters to be considered in the airspace planning process, mainly for reducing separation values. Thus, any proposed system shall only be released to commercial operation given that the safety criteria are satisfied [7].

Then, to perform the safety assessment of the adoption of new technologies in the ATC system, Vismari and Camargo Junior [2] proposed a new methodology that combines both ‘Absolute’ and ‘Relative’ methods established by ICAO [7]. In [2], the ATC system’s safety was assessed by modelling the ATC architecture considering two different scenarios. In both, the reference and the proposed ones, Airspace, Aircraft, Pilots, Communication and ATCo models were the same. The differences between the systems lay in the Surveillance and in the Navigation elements (systems related to the ADS-B).

Within the proposed methodology in [2], at least two scenarios must be considered: the reference one and the proposed one.

Extending the study done in [2], it was proposed in [3] the introduction of new features to the previously cited ATC model, more specifically data integrity parameters, and applying the same methodology for safety assessment of this new proposed scenario.

In [3], the reference scenario to be adopted corresponds to the same scenario as that proposed in [2]. From there on, the features previously cited are inserted by modifying or adding elements to those used in [2].

2.1 Computational Model Parameters

In order to evaluate the behavior related to safety (risk of mid-air collision) in air traffic system considering new scenarios such as densification (increased airspace occupation with reduced separations between aircraft) and the introduction of UAS in non-segregated airspace, it is necessary to represent the air traffic control architecture (shown in Figure 2) as a computational model.

The methodology proposed by Vismari and Camargo Junior [2] and already described in [3] is used to design computer models that represent each of the parts described in the system. Figure 2 shows the relationship between each of the model blocks and the parts of the air traffic control architecture. Based on these models, one can computationally simulate several scenarios that comprise the risk of mid-air collision.

For the aircraft block, it can be adopted both models representing manned aircraft (human pilot) or not. Even in manned aircraft it can be used an autopilot system (AP) to control the variables of the aircraft (e.g., pitch, yaw, roll, thrust, among others) from the input data for route correction.

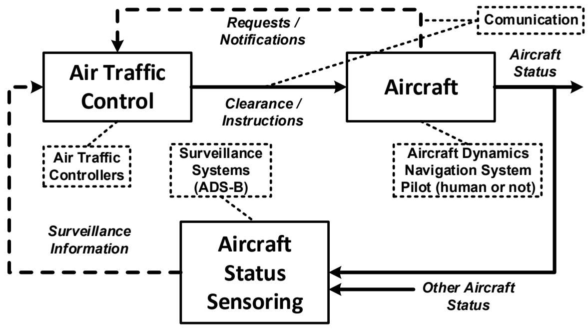

Figure 2: Block Diagram for Computational Modelling of ATC architecture

3. AIRCRAFT MODELLING

Several models have been developed over the past years for computational simulation. One of these classical models is the one proposed by Drela [8] that provides the modelling of the aerodynamics, flight dynamics and control laws of a generic aircraft focusing on its structural issues. Another previous work that can be mentioned is the one developed by Hank [9], which describes the mathematical model and data used to simulate the flying qualities and the characteristics of a Boeing 747 aircraft inserted into NASA FSAA (Flight Simulator for Advanced Aircraft). Although these models are considered quite complete and submit various features of the dynamics of an aircraft, the level of complexity of these represent a major effort to its implementation in computing environment given the ultimate goal of the proposed work in [3]. As BADA [10] provide reliable data for a broader range of aircraft models and simpler calculations, it was adopted herein.

The aircraft model proposed by Glover and Lygeros [11] was specified for computer-based simulation aiming to support the studies in HYBRIDGE project[1]. In their work, an aircraft model was described as a point with mass and energy and its displacement throughout the airspace is based on a set of equations, which calculates both motion and the forces involved with the aircraft dynamics. The three main forces involved are thrust (T), drag (D) and lift (L). Thrust is the force generated by the aircraft engines, while drag and lift are both originated from the aircraft motion through the air.

The equations below are used by the authors to determine the aircraft states [11]:

$$\dot{X} = V \cdot \cos(\psi) \cdot \cos(\gamma) + w_1 \quad (1)$$

$$\dot{Y} = V \cdot \sin(\psi) \cdot \cos(\gamma) + w_2 \quad (2)$$

$$\dot{h} = V \cdot \sin(\gamma) + w_3 \quad (3)$$

Where,

$$\dot{V} = \frac{1}{m} \cdot [(T \cdot \cos(\alpha) - D) - m \cdot g \cdot \sin(\gamma)] \quad (4)$$

$$\dot{\psi} = \frac{1}{m \cdot V} \cdot (L \cdot \sin(\phi) + T \cdot \sin(\alpha) \cdot \sin(\phi)) \quad (5)$$

The states of the model are the horizontal position (X and Y) and altitude (h) of the aircraft, the true airspeed (V), the flight path angle (γ) and the heading angle (ψ). The control inputs to the model are the engine thrust (T), the angle of attack (α) and the bank angle (ϕ), m is the mass of the aircraft and g the gravitational acceleration. In addition, the wind acts as a disturbance affecting the movement and it is represented through its speed vector $W = (w_1, w_2, w_3) \in \mathbf{R}^3$. The effect of inputs such as spoilers, leading edge slats, landing gear, among others are ignored in this particular work [11]

The aircraft model's equating is done according to the procedures specified in the User Manual for the Base of Aircraft Data (BADA) [10]. It aims to ease data generation for testing detection and conflict resolution algorithms. Being the simulation performed from the ATC's perspective, the dynamics presented in an aircraft flight is simplified, allowing the data acquired to be sufficiently realistic for the intended purposes in this research.

Thrust calculation is influenced by the aircraft's altitude (and therefore, by the air density). According to BADA [10], it also depends on factors such as the aircraft engine type (piston, turboprop or jet engines), current TAS (Total Airspeed) and even the International Standard Atmosphere or ISO Standard Atmosphere (ISA) conditions at sea level. At first, the thrust maximum value is calculated, taking into account the aircraft model engine type. It depends, basically, on three coefficients, whose dimensions (units) also vary in the same way.

This maximum value is corrected by means of deviations from the ISA standard temperature at the sea level (which can be found at BADA's Manual). Then, according to the aircraft climbing/acceleration mode or to its flight phase, this pre-processed maximum value is multiplied by operational coefficients that are specific to each aircraft. [10], [11].

Equations (6) and (7) express how the calculation of lift and thrust is performed, according to Glover and Lygeros [11].

$$L = \frac{C_L \cdot S \cdot \rho}{2} \cdot (1 + c \cdot \alpha) \cdot V^2 \quad (6)$$

$$D = \frac{C_D \cdot S \cdot \rho}{2} \cdot (1 + b_1 \cdot \alpha + b_2 \cdot \alpha^2) \cdot V^2 \quad (7)$$

Where S is the surface area of the wings, ρ is the air density (which depends on the altitude) and C_D, C_L, c, b_1, b_2 are aerodynamic lift and drag coefficients whose values generally depend on the phase of the flight (whether the flaps are extended, the landing gear down, etc.)

In (6), a simplifying hypothesis is used. It is assumed that $\alpha = 0$, then, one can conclude that

[1] The Hybridge project was a partnership (ended in 2005) between universities and research institutes in order to develop methods and models to study levels of safety, especially related to air traffic. More information at http://hybridge.nlr.nl/

lift could be calculated as $m \cdot g/cos(\phi)$. As long as the aircraft does not experience vertical acceleration, vertical equilibrium can be assumed and the vertical component of lift must be equal to weight.

Another simplifying hypothesis used for the implementation of the model is the adoption of a constant gravity acceleration. Although gravity varies according to altitude, its difference within a 15 km altitude range is approximately 5 cm/s², thus making it negligible.

It is important to remember that steeper bank angles might result in an altitude loss. BADA limits bank angles at 35° for civilian aircraft, while ICAO [12] standards advise pilots to make turns "at a bank angle of 25° or at a rate of 3°/sec, whichever requires the lesser bank". There are accident records (e.g. Aeroflot flight 593) on which steep bank angles led to loss of control.

The adopted model also allows simulations on the fuel consumption. Whilst fuel weight would represent an important factor in longer flights, the variations of mass caused by fuel consumption for a small distance can be neglected. Among other features presented in [11], the speed schedules and routes with multiple waypoints have not been adopted, once they were not considered vital for the proposed safety assessment approach mentioned in section 2. Instead, the presented model was submitted to a set of focused tests, whose simulation scenarios are based on specific situations that happens during a flight.

4. MODEL IMPLEMENTATION

As the proposed approach in section 2 requires a set of computational simulations to perform the safety assessment of the ATC system, the aircraft model was written in Laboratory Virtual Instrument Engineering Workbench (LabVIEW) language. The programming language used in LabVIEW, also referred to as G[2], is a dataflow programming language. Its execution is determined by the structure of a graphical block diagram (LabVIEW-source code) on which the programmer connects different function-nodes by drawing wires.

The implementation in LabVIEW took advantage on its resources, such as embedded control unit on fields (what helped to detect and avoid errors along the code). Those features helped to process data, as LabVIEW automatically converts values, given that the same wire ends have units of the same type (e.g., feet are converted to meters, as they are both length units).

In order to keep the ease of the code interpretation, formulae found in [10], [11] were divided in three types and reunited in blocks according to this division. The three created blocks are the Flight Dynamics Processing, Coefficient Calculation and Force Calculation block.

Flight Dynamics Processing block aims to calculate and process variables related to the aircraft's movement (e.g., Speed, Position, and Heading Angle). According to Glover and Lygeros [11], the Total Air Speed (TAS) was adopted as the base speed. The Coefficient Calculation block performs calculations to determine coefficient values (e.g., lift and drag coefficients), and the Force Calculation block computes the values of lift, thrust and drag forces. Figure 3 shows the interactions and connections between these three parts.

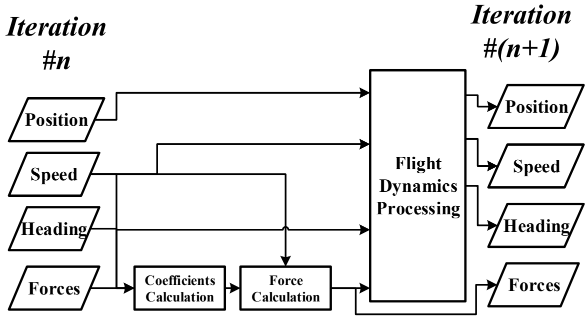

Figure 3: Simulation data flow diagram

Although all of the blocks depend on aircraft data, this linkage was not shown on the diagram for the sake of clarity. The aircraft was abstractly reduced to four variables – Position, Speed, Heading and Forces, and iterations n and $n+1$ intend to show how those variables flow (and also how they are processed) throughout the simulation context.

In order to simulate the aircraft's performance, a standard time interval was adopted. The interval results from the total simulation time divided by the number of points configured. Both of these values can be edited at the simulation

[2] Not to be confused with G-code

configurations (Simulation Initial Data panel, shown in Figure 6). It is important to remark that the interval's length might make the simulation results more or less realistic. Under certain conditions, an interval of 1 s led to a stall condition. While performing tests, we used an interval of 0.1 s, though smaller or larger intervals might be used according to the simulation purpose.

The Virtual Instrument (VI) Hierarchy diagram of the model's implementation in LabVIEW is shown in Figure 5.

The block diagram of the aircraft model VI can be seen in Figure 4.

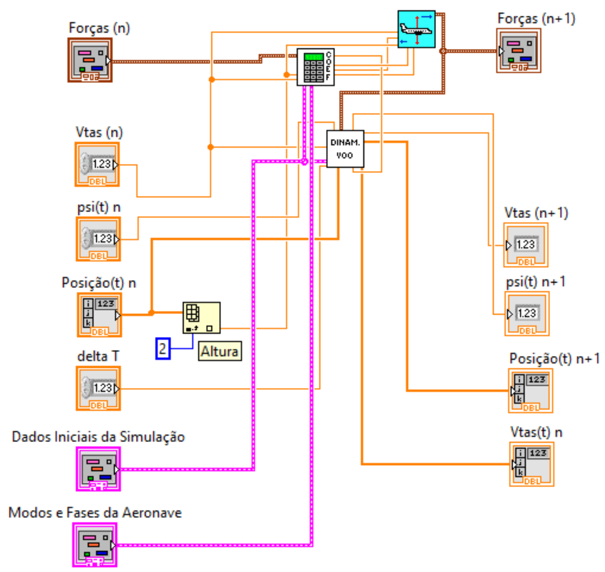

Figure 4: Aircraft Model implementation in LabVIEW

The simulation can be configured by using two blocks in the simulation panel: Simulation Initial Data and Aircraft's Modes and Phases, which are both shown in Figure 6.

For the "*Aircraft's Mode and Phases*" panel, the values that can be set are:

- Flight Phase – Responsible to determine in which of the phases below the aircraft will be simulated. Different selections will alter the value of constants that are used to calculate the aircraft's movement, therefore rendering different behaviors according to the phase.
  - Enroute
  - Approach
  - Landing

Table 1: "Simulation Initial Data" panel fields

Label	*Description*
Constant TAS?	Checked if the aircraft keeps a constant speed.
Aircraft Turning?	Checked if a horizontal maneuver is being simulated.
Initial Position	Initial position of the aircraft.
Dots	Number of dots to be calculated and plotted.
Starting Time	Starting time of the simulation. Used always as 0 s.
Ending Time	Ending time of the simulation. Time interval established by calculating the starting time and the number of dots.
TAS Value	Initial value of the aircraft's TAS (Total Air Speed)
Initial Heading	Initial heading angle (also used as Ψ)
AOA	Angle of Attack.
Bank Angle	Bank angle assumed by the aircraft.
Wind Speed	Wind speed value. Disregarded on the tests.
Wind Direction	Wind direction adopted.

- Accel Mode – Determines how the aircraft is changing (if it is) its velocity. The selection made here, together with data from other fields, will be used to model thrust and other factors that affect the aircraft speed.
  - Acc (accelerating)
  - Cruise
  - Deceleration
- Climb Mode – Determines the vertical attitude of the aircraft. Those configurations will mostly affect the thrust computation.
  - Climb
  - Level
  - Descent

In addition, it is possible to configure the initial values related to the aircraft performance on the "*Simulation Initial Data*" panel. Units, where applying, are shown at the side of the respective field. The description of the input fields can be seen on Table 1

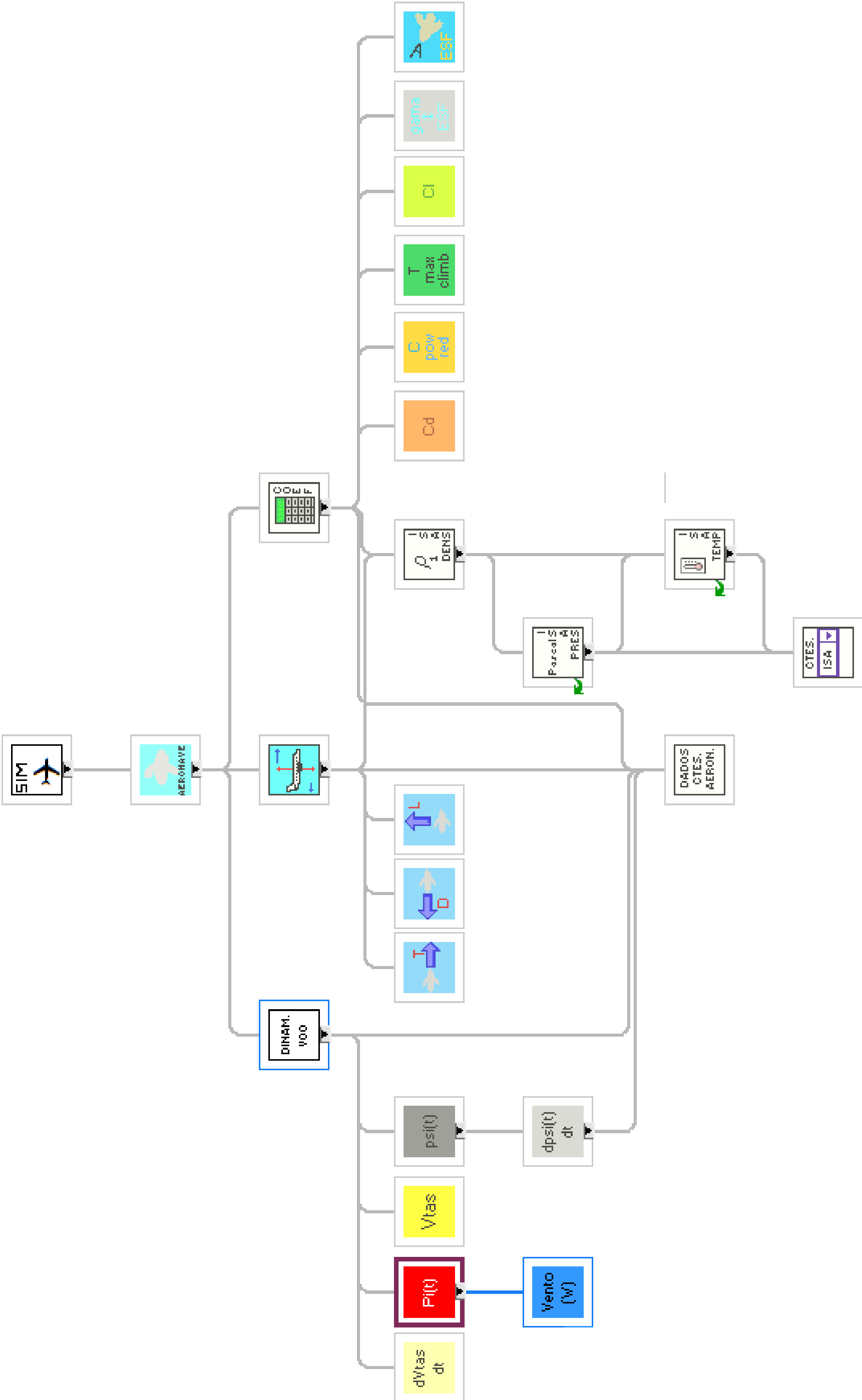

Figure 5: VI Hierarchy Diagram

The other fields in the front panel are used only for programming purposes of development and final adjustments. The aircraft's flight path is plotted in two graphs, one of them being a 3D-graph (useful for situations that involve an altitude variation). During tests, circular trajectories appeared often ellipsoidal. Eventual distortions of the route can be caused by differences between the vertical and horizontal axis scales.

5. AIRCRAFT MODEL TESTS' RESULTS

In order to demonstrate the results of the model, a set of seven test scenarios were performed, involving usual conditions and operations. Common initial values between the seven tests can be seen on Table 2.

Table 2: Initial conditions for the tests

Condition	*Value*
Heading	0°
TAS	440 kt, (≈ 814 km/h).
ISA Temp.	288.15 K (at the sea level)
ISA Atmospheric Pressure	101,325 Pa
ISA Air Density	1.225 kg/m³
Wind Speed	0
AOA	0°
Coordinates	(0 ,0, 10000) m, unless otherwise stated.

The conditions and parameters used in each of the seven different simulated scenarios are the following:

1) Aircraft cruising, constant TAS, 20 º bank angle, time needed to perform a ¼ circumference.
2) Aircraft cruising, constant TAS, 20 º bank angle, time needed to perform the entire circular trajectory.
3) Aircraft climbing, 20 º bank angle, constant TAS, initial position (0, 0, 8000), 30 s test.
4) Aircraft climbing, 20 º bank angle, accelerating with the same conditions as stated in item 3.
5) Aircraft descending, 20 º bank angle, with the same conditions as stated in item 3.
6) Aircraft descending, 20 º bank angle, accelerating with the same conditions as stated in item 3.
7) Aircraft cruising, constant TAS, performing a predefined route.

The aircraft data used for simulation correspond to the Airbus A320, one of the most common commercial jets, retrieved from [10]. The speed adopted as default was 440 kt, which is close to the TAS speed cited in A320 BADA PTF (Performance Table File).

Speed schedules proved to be an important feature for simulation purposes as longer simulation times were tested, mostly for their absence led to miscalculations and anomalous behavior. For instance, the model was able to climb up to its cruising altitude, given that a constant TAS was adopted. Attempts to do a similar maneuver while accelerating made the aircraft to climb only 1500 m above its original altitude and stay there with a speed above 500 kt, even in the case of a take-off at the sea level, what is clearly unrealistic. As drag is proportional to the square of TAS, it has quickly matched the produced thrust, forcing the aircraft to stay in a situation analog to cruising.

5.1 Scenario #1

The conditions and parameters for this scenario simulation are: aircraft cruising, constant TAS, 20º bank angle, time needed to perform a quarter of circumference.

In the given conditions, the turning radius is approximately 14.3 km. A quarter of circumference of such radius has a length of 22.45 km. Therefore, the simulation time for the given length at a speed of 440 kt (≈ 814 km/h) would be a little less than 100 s. According to the 0.1 s time interval, 1000 dots will be plotted.

Figure 7 shows the simulated aircraft trajectory under these conditions.

5.2 Scenario #2

The conditions and parameters for this scenario simulation are: aircraft cruising, constant TAS, 20º bank angle, time needed to perform the entire circular trajectory.

According to the calculations previously made, the aircraft would need close to 400 s to perform a full circular trajectory under the same conditions.

At the end of the simulation, the aircraft had a 1.5º heading, what is a reasonable result if rounding errors are taken into consideration.

Figure 8 shows the simulated aircraft trajectory under these conditions.

5.3 Scenario #3

The conditions and parameters for this scenario simulation are: aircraft climbing, 20º bank angle, constant TAS, initial position (0, 0, 8000), 30-second test.

The final vertical speed obtained was 2.05 m/s, which is approximately 403 ft/min.

Figure 9 shows the simulated aircraft trajectory under these conditions.

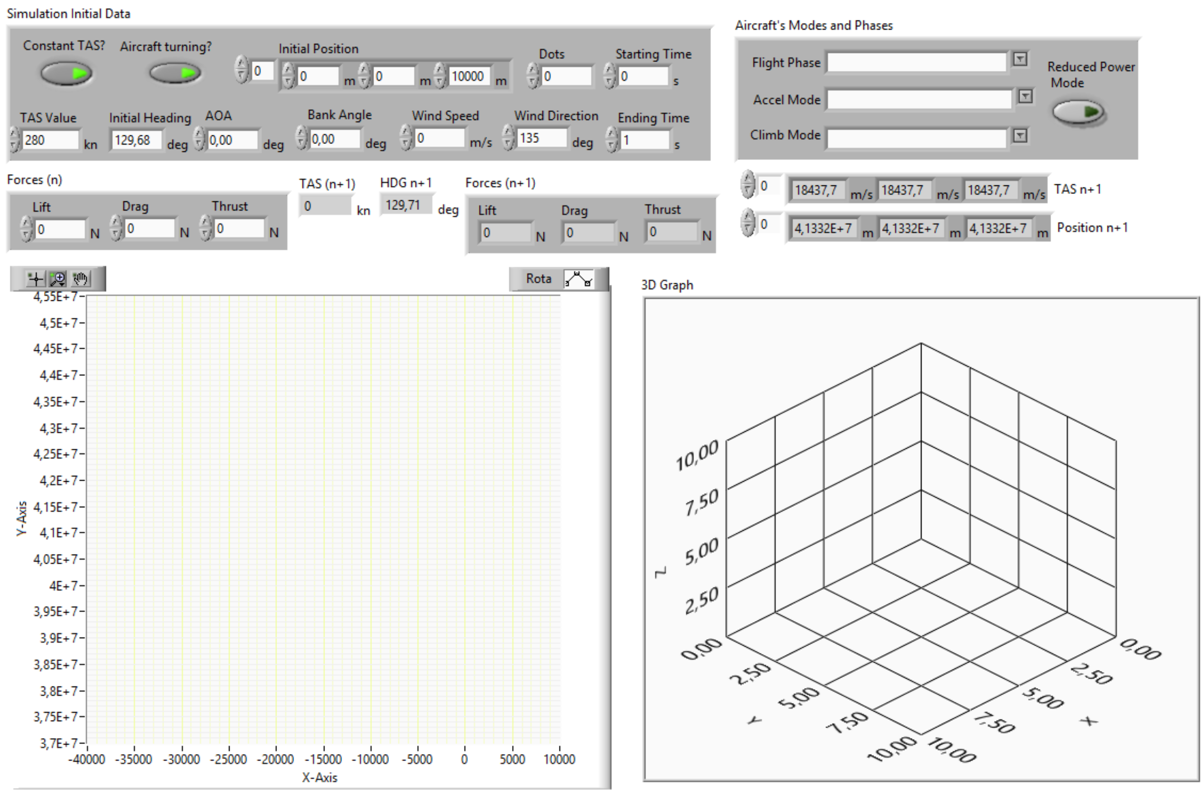

Figure 6: Aircraft Model Simulation Panel (Implementation in LabVIEW)

5.4 Scenario #4

The conditions and parameters for this scenario simulation are: aircraft climbing, 20º bank angle, accelerating, initial position (0, 0, 8000), 30-second test.

This is an example of anomalous behavior that might be caused by the absence of speed schedules or by the Energy Share Factor (ESF) simplification. ESF is obtained through specific formulae, being after all given in function of the Mach number. Formulae used to calculate ESF, as seen in BADA manual [10], are divided in conditions regarding on CAS (Calibrated Air Speed) behavior and the aircraft altitude.

Figure 10 shows the simulated aircraft trajectory under these conditions.

5.5 Scenario #5

The conditions and parameters for this scenario simulation are: aircraft descending, 20° bank angle, initial position (0, 0, 8000), 30-second test.

The final speed computed was 426 kt, while the final vertical speed was -12.1 m/s, which is approximately -2400 ft/min.

The speed was reduced while the aircraft has descended. This behavior was expected in accordance to the determined test conditions. Tests conducted in similar conditions outside setting the aircraft to decelerate led to a smaller final speed with a third from the final vertical speed.

Figure 11 shows the simulated aircraft trajectory under these conditions.

5.6 Scenario #6

The conditions and parameters for this scenario simulation are: aircraft descending, 20° bank angle, accelerating, initial position (0, 0, 8000), 30-second test

The obtained final speed was 426 kt and the final vertical speed -12 m/s, which is approximately -2300 ft/min.

Although the aircraft has slowed down, the vertical speed has increased with the acceleration. This might be caused by an implementation error or even by not adopting the use of speed schedules.

Figure 12 shows the simulated aircraft trajectory under these conditions.

5.7 Scenario #7

The conditions and parameters for this scenario simulation are: aircraft cruising, 800-second test, constant TAS. In this scenario, the aircraft will follow a simple route, consisting of keeping a constant heading on 100 s and making a 20° bank turn in 100 s. Repeating those steps four times will render a trajectory shaped like a square with round edges, standing on its initial position.

Figure 13 shows the simulated aircraft trajectory under these conditions. The trajectory gap in the lower left corner is caused by rounding up the time demanded to each step. Despite of this, the maneuverability of the aircraft model is still shown.

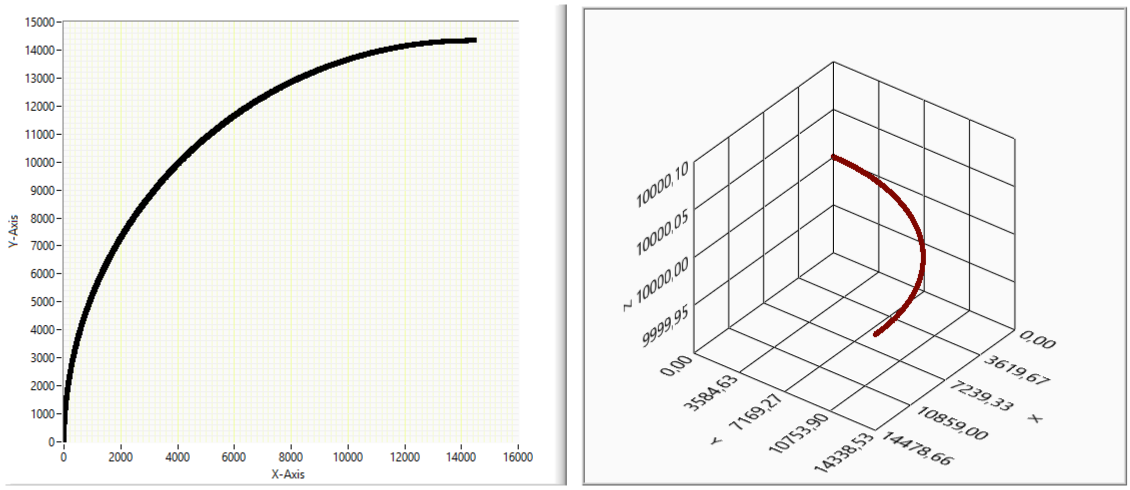

Figure 7: Aircraft Model trajectory obtained for test scenario #1

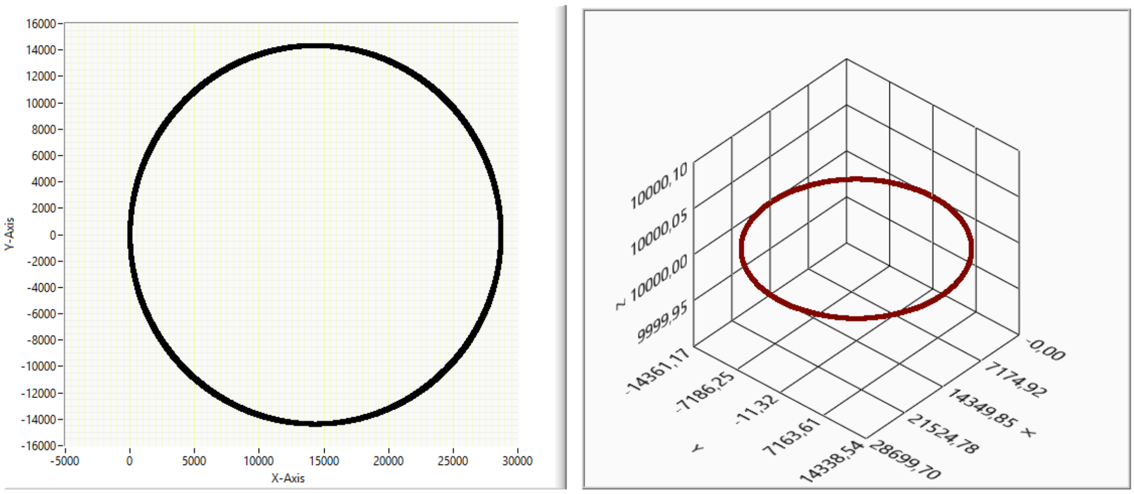

Figure 8: Aircraft Model trajectory obtained for test scenario #2

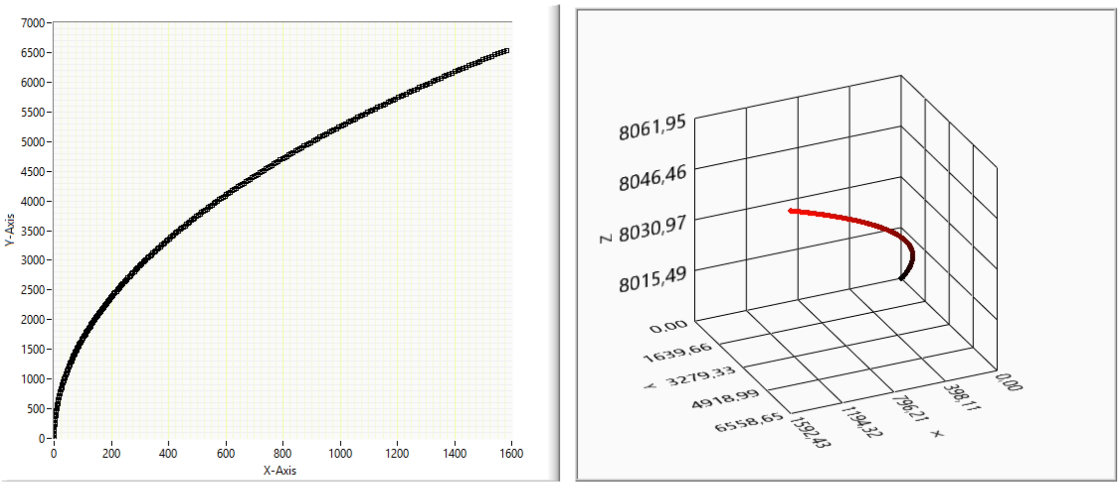

Figure 9: Aircraft Model trajectory obtained for test scenario #3

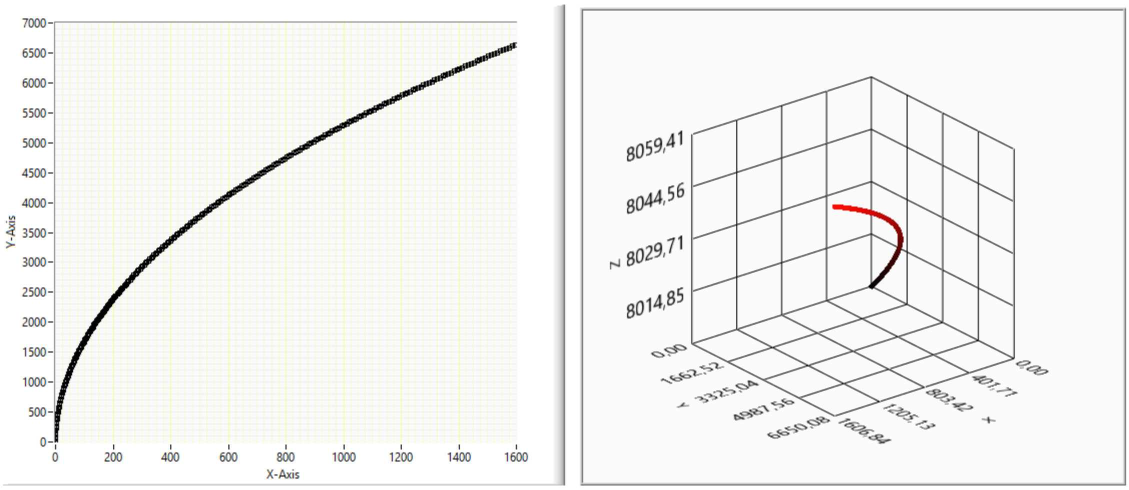

Figure 10: Aircraft Model trajectory obtained for test scenario #4

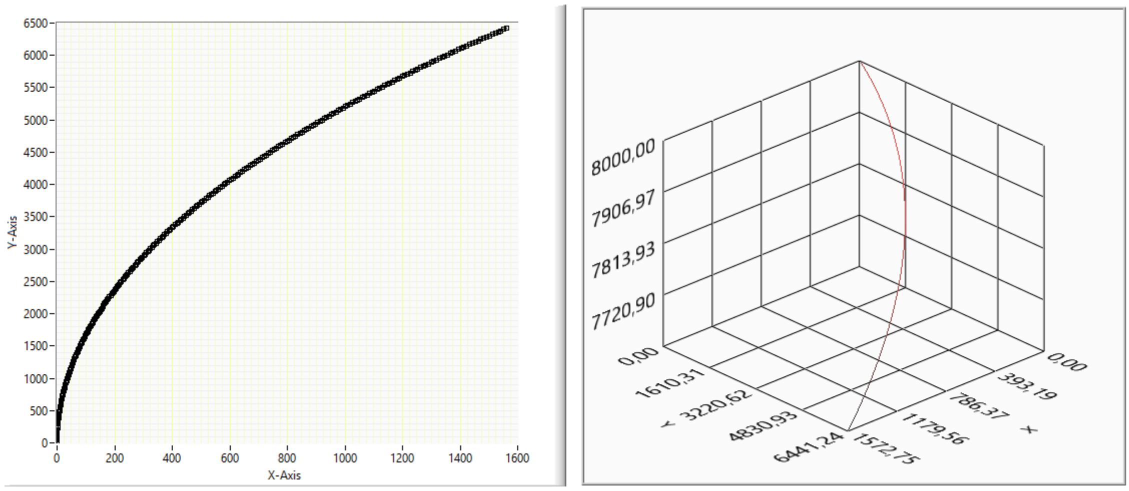

Figure 11: Aircraft Model trajectory obtained for test scenario #5

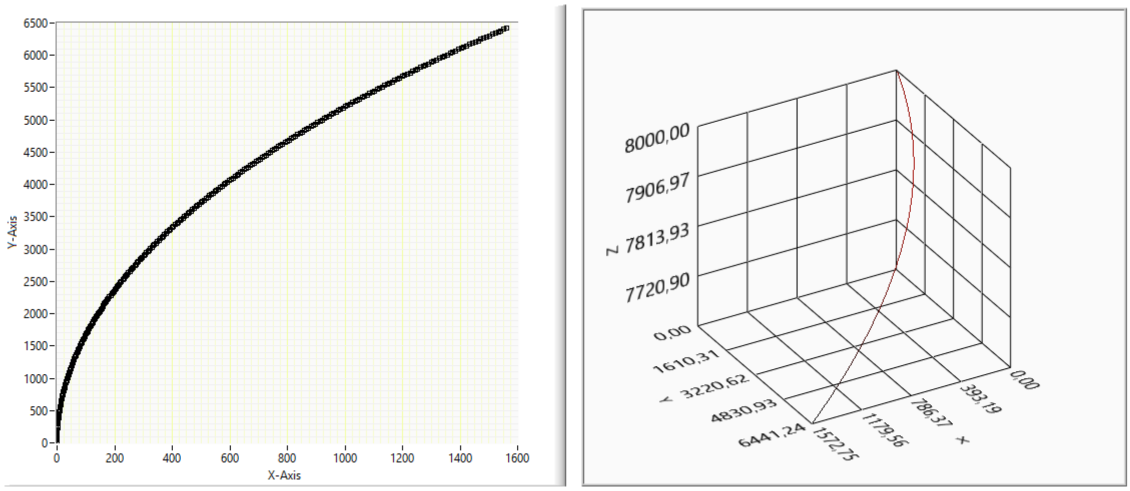

Figure 12: Aircraft Model trajectory obtained for test scenario #6

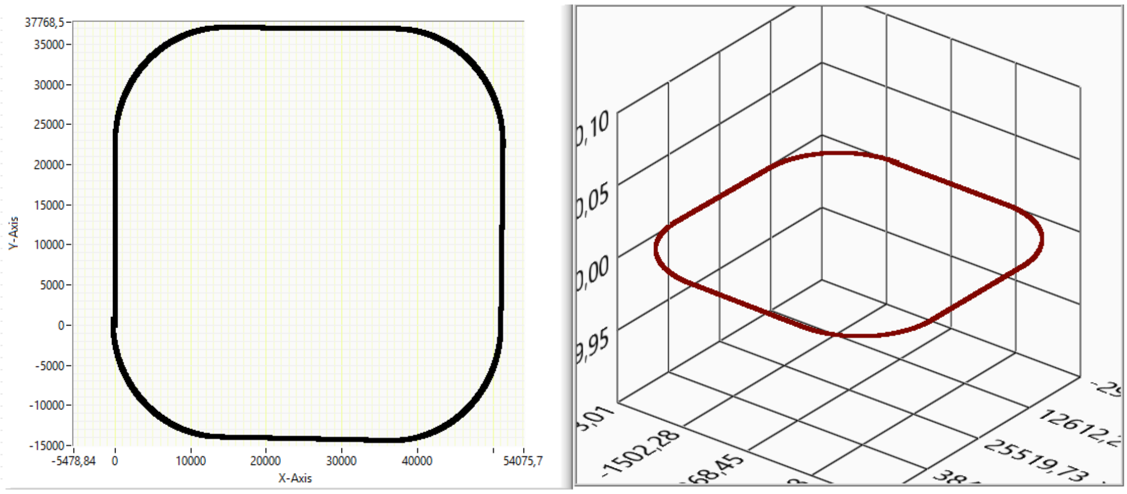

Figure 13: Aircraft Model trajectory obtained for test scenario #7

6. CONCLUDING REMARKS

This paper presents an aircraft model, programmed in LabVIEW language, to be used for computational simulation of an air traffic environment. This aircraft model is part of the modelling of the Air Traffic Management (ATM) system for the safety assessment approach proposed by Vismari and Camargo Junior [2] and extended by [3]. This proposed approach is based on computational simulation in which the elements of the Air Traffic Control (ATC) architecture were functionally modeled. The goal is to assess safety of an ADS-B based ATM system considering data integrity as a relevant factor for safety level.

The model described in this work presents the basic dynamics and control characteristics of the aircraft, an Airbus A320.

The results showed that, for the main maneuvers of an aircraft (climb, cruise and descending movements), the trajectories and parameters obtained satisfactorily matches the expected ones if compared to an actual aircraft.

The main goal of the proposed work of Baraldi Sesso et al. [3] is to assess safety through a comparison between different scenarios of an Air Traffic Management (ATM) environment. Intending to maintain uniformity of analyzes the flight maneuvers of the aircraft are the same in all considered scenarios. In this context, the aircraft model described in this paper presents itself as adequate for such purpose.

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