Modelling and Simulation of the Space Rider Re-Entry and TAEM Phases

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Abstract: *The design and Verification &Validation (V&V) of Guidance, Navigation, and Control (GNC) algorithms for reusable re-entry space vehicles represent one of the most challenging aspects of modern aerospace engineering. One of these challenges, which is the focus of this paper, is the modelling and simulation of autonomous flight control systems, particularly the high-dynamic transition from orbital de-orbiting to Terminal Area Energy Management (TAEM) phases. Using Europe's Space Rider as a primary reference, the authors examine the development of a robust simulation environment capable of capturing the complex aerodynamic and atmospheric interactions that occur during the re-entry and parafoil descent phases. The paper details the Model-in-the-Loop (MIL) architecture used to verify the GNC logic, leading into the results of extensive simulation campaigns that validate the algorithms' ability to compensate for mission dispersions and sensor uncertainties. This work is the collaborative result of the European Space Agency (ESA)-led consortium (Thales Alenia Space Italy, SENER Aerospacial and Indra Space), aiming to provide a reliable representative simulation environment for vehicle qualification. Ultimately, the paper demonstrates how the presented simulation technique reduces the reliance on costly physical testing while ensuring the safety and precision required for the next generation of reusable space transportation systems.*

Key Words: *Modelling, Simulation, GNC Algorithms, Re-entry Vehicles, Space Rider, MIL Validation.*

1. INTRODUCTION

The Space Rider (SR) program aims to provide Europe with an affordable and reusable space platform suitable for in-orbit operations, experimentation and demonstration of orbit applications and technologies. The Space Rider vehicle is composed of an AVUM Orbital Module (AOM) and a Re-entry Module (RM). The RM is based on the shape of the Intermediate eXperimental Vehicle (IXV), which was successfully flown in February 2015. Space Rider mission will be launched with VEGA C [1].

This paper presents the SR-FES architecture and validates its performance using the RM GNC subsystem as a high-complexity test case.

The second chapter presents the mission phases, followed by the description of the simulation environment in chapter 3. In chapter 4 we show the high-level architecture and logic of the G&C algorithms, followed by the performance and results in chapter 5. Finally, we present our results in section 6.

2. SYSTEM OVERVIEW & MISSION PROFILE

After over 2 months of in-orbit operations the re-entry phase will start. The mission profile of the RM is depicted in Figure 1 and the main phases are briefly described hereafter:

- **Initialization**: Calibrate/initialize navigation unit using AOM data transfer and initialize navigation. Once the navigation units are ready, the RM detaches from the AOM.
- **Orbital Coasting:** the vehicle attitude is controlled by means of Reaction Control System (RCS) until the Entry Interface Point is reached with the desired attitude conditions. Coasting ends at an altitude of 120 km.
- **Re-Entry:** the vehicle attitude and trajectory are controlled by means of flaps and RCS. This mission phase can be divided into two subphases:
- **Entry:** the vehicle is controlled in hypersonic and supersonic regime to reach beginning of TAEM with the desired conditions. Entry phase ends when the estimated drag is below 0.153 g.
- **TAEM:** Control the vehicle in transonic regime to reach drogue inflation point. TAEM ends when the system reaches Mach 1.2.

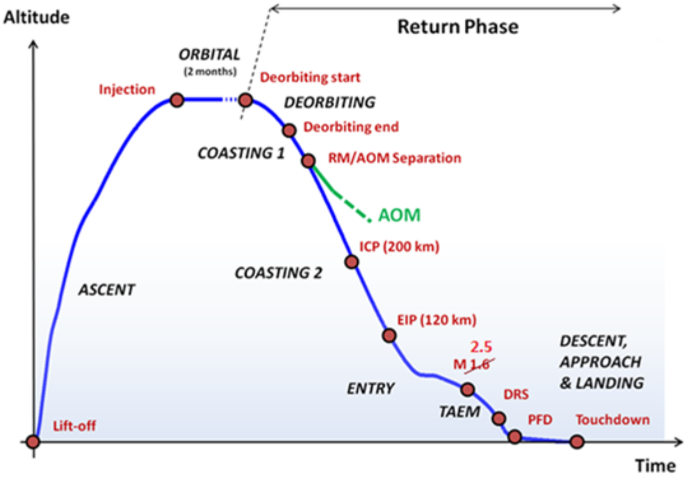

Figure 1: Space Rider mission profile [2]

- **Descent:** Deploy Drogue Release System (DRS) system to slow down system to reach conditions compatible with parafoil flight. The end of this phase is based both on altitude and time, triggered at the parafoil deployment event (6000m).
- **Landing**: Control the vehicle in flight under parafoil to reach ground with proper touchdown conditions and a landing accuracy of 150 meters with respect to the nominal landing point. This phase ends at touchdown.

3. SIMULATION ENVIRONMENT & MIL ARCHITECTURE

All the simulations and analyses are performed in a Functional Engineering Simulator (FES). The SR-FES is a software tool for the functional and performance assessment of the RM GNC sub-system.

The SR-FES is a non-real-time simulator, supporting 6 degrees of freedom (DOF) simulations of the SR RM vehicle, as well as Monte Carlo analyses. The main purpose of the SR-FES is to serve as an representative test and simulation environment for the RM GNC algorithms to be put on-board the SR RM vehicle.

The SR-FES architectural design is largely based on an internal framework called SIMPLAT (Simulation Platform).

The SIMPLAT logic model is outlined in Figure 2. There are six main SW components in architecture:

- Simulation Engine: responsible for the complete definition of a simulation, including the definition of the mission and the configuration of the models to be simulated. It loads the parameters of the mission from the Configuration Data Files (XML files). The parameters of the mission are pre-processed to obtain model and simulation parameters, and the models are configured accordingly by setting their mask parameters. This component also controls the execution of the simulation.
- Simulation Core: it represents where the numerical integration of the system dynamics is carried out. In general, it consists of a Simulink template, which is customized for each operation mode by replacing the applicable models taken from various Simulink libraries.
- Monte Carlo Simulation: comprises several functions that manage the configuration and control of Monte Carlo simulations. It generates perturbed values of the model parameters (applying dispersions and uncertainties) and controls the storage of the raw data so that they can be further processed.
- The Man Machine Interface (MMI): provides user interface functions that give access to the principal functionalities of the simulator, namely simulation, post-processing and visualization. In the case of the GNC FES, the implementation of the MMI is a Graphical User Interface (GUI).
- Visualization: its purpose is to generate graphical representations or plots of the simulation raw data and of the post-processed data (system budgets and Figures of Merit). The graphical outputs will be integrated into the MMI for user convenience.
- Post-Processing: it provides functions for processing the raw data obtained in the simulations. They will compute system budgets and performance indexes.

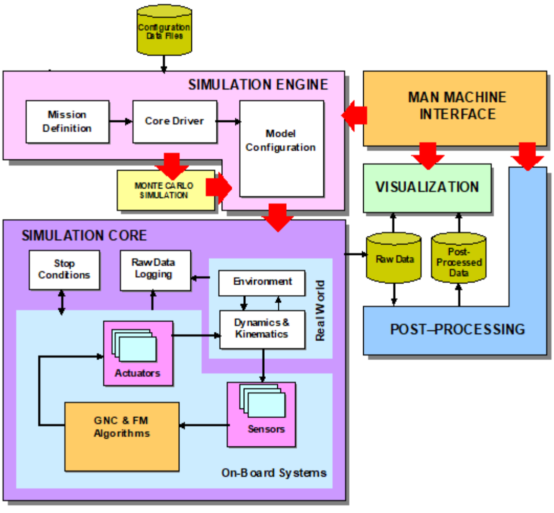

Figure 2: SR FES Logical Model

A screenshot of the simulator model is presented in Figure 3. The main blocks can be observed in this architecture, including the Dynamic and Kinematic Engine (DKE) and GNC blocks, Failure Detection, Isolation, and Recovery (FDIR) for fault detection and injection, the initialization and Raw Data generation blocks.

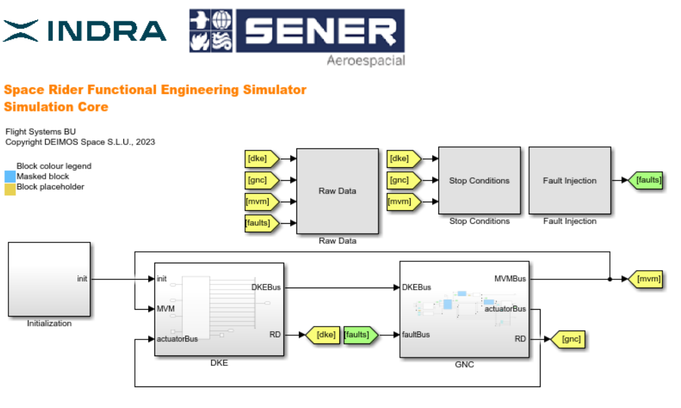

Figure 3: FES simulation interface

4. G&C ALGORITHM DESIGN

This section presents the architecture and design logic of the Guidance and Control algorithms used in the re-entry and TAEM phases.

4.1 Guidance

4.1.1 Entry Guidance

The REE sub-mode Guidance is based on the strong heritage from IXV.

The objective of the re-entry guidance is that the vehicle reaches the desired TAEM interface point, while ensuring its flight within the entry corridor. In the Re-entry Guidance function, two major sub-modes are implemented:

- **Open Loop Mode:** during the first part, the attitude commands are pre-defined until the aerodynamic forces rise to get enough trajectory maneuvering capability.
- **Closed-Loop Mode:** angle of attack and bank angle are commanded as a result of a close loop feedback trajectory control; it is activated based on an estimated drag and energy threshold.

The Re-entry closed loop guidance has the following relevant features:

- **Trajectory generation algorithm features**
  - A reference trajectory computed offline is preloaded on board.
  - Energy is taken as the independent variable of the guidance scheme, for both trajectory generation and trajectory control functions, which give efficient non-simplified formulations.
  - Reference is given as a profile of Drag as a function of Energy.
  - To compensate deviations at the target TAEM interface point a ranging technique is applied, which is based on the update of the nominal drag profile to cope with differences between the on-board estimation of the range-to-go and the available range capability.
  - This Range-to-go prediction is performed considering the complete current drag reference profile and the actual state and is analytically formulated.
- **Trajectory tracking algorithm features**
  - Decoupling between in-plane motion, for the control of the down-range via a PID-like tracking, and Lateral motion, for the control of the cross-range, via the bank reversal technique.
  - Complete analytical formulation used to compute the reference command.
  - The control output is the commanded vertical lift-to-drag ratio (L/D), which is converted into a bank angle command.
  - A modulation into the commanded angle of attack is applicable based on drag deviations with respect to the reference profile, to minimize transient effects during bank reversals and other short term perturbations.
  - Provision to the flight control of reference AoA and bank angle commands. Sideslip is kept by the control around its trimmed position.

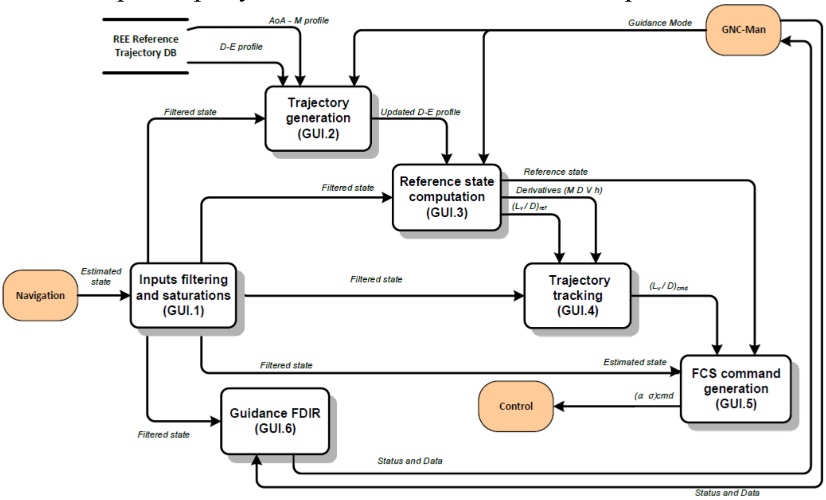

Figure 4: Functional architecture of the Closed-loop Re-entry Guidance [3]

4.1.2 TAEM Guidance

The objective of the TAEM guidance is to steer the vehicle towards the desired target point for parachute triggering, to limit the heading dispersion and to align the vehicle to the desired direction for parachute triggering, by also respecting trajectory constraints.

The TAEM guidance follows a closed loop approach and is characterized by a trajectory generation and a trajectory tracker algorithm:

- **Trajectory generation algorithm:**
  - Reference trajectory is computed, in the form of a Look Up Table output, by considering a fixed reference trajectory computed offline
  - Mach is taken as the independent variable of the guidance scheme
  - The reference trajectory defines the desired position and velocity state vectors as a function of Mach, in a local horizontal system, centered at the target point.
- **Trajectory tracking algorithm features**
  - Coupling between In-plane motion and Lateral motion, controlling the complete position and velocity state via a low state (PID-like) tracking used to compute the Guidance action, as reference to TAEM Control.
  - A formulation based on non-linear dynamic inversion (NDI) allows the computation of the guidance commands.
  - Bank angle is the main command and is the only one available to track the reference trajectory.
  - An analytical formulation is used to compute the reference command. No on-line optimization is performed. [4]

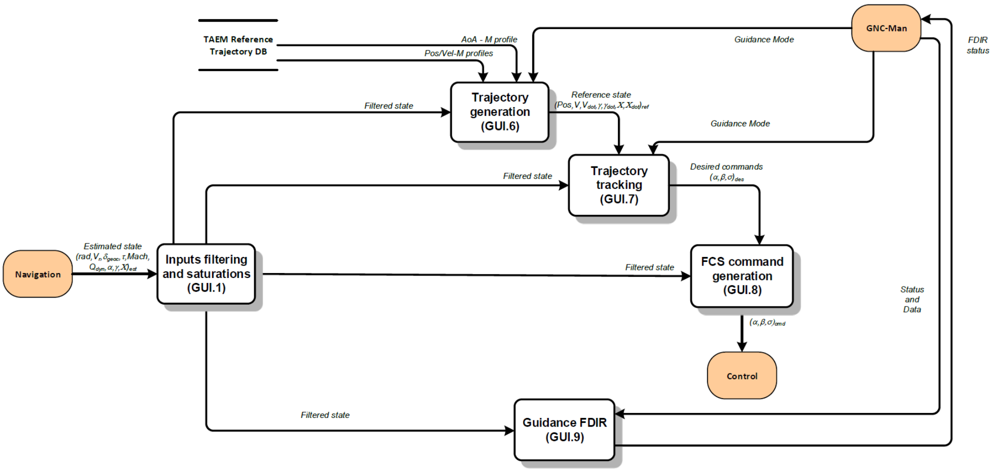

Figure 5: Functional architecture of the Closed-loop TAEM Guidance [3]

4.2 Control

4.2.1 Entry Control

The Reentry Control is inherited from IXV. The spacecraft attitude is controlled over a large velocity range from Entry Interface Point (EIP) to TAEM Entry Point (TEP) (Mach 30 to Mach 2.5), respecting the actuator limitations and constraints. The control algorithm is divided in two sub-modes:

- **Low Performance:** when dynamic pressure is too low and RCS-only are used as actuators.
- **High Performance:** when dynamic pressure is high enough to use the flaps as main roll and pitch actuators, while RCS is used to provide further control authority if needed.

The REE control has the following relevant features:

- Separation of feed-forward open-loop and feedback closed-loop components.
- Feed-forward commands aim to directly implement the vehicle trimming and maneuvering from the guidance commands. Errors due to feed-forward model mismatching, perturbations, and uncertainties are subsequently corrected by the feedback action.
- The feedback controller includes integration action in pitch and roll to compensate for steady state errors from the open loop commands, specifically from the open-loop trim.
- Coupled control design for longitudinal and lateral/directional dynamics. Longitudinal control is implemented as a SISO system and lateral/directional control is implemented as a MIMO system.
- Due to the large variation range of the external conditions, a gain scheduling approach by gain interpolation has been implemented, leading to a simple and robust scheduling process that adapts to the actual flying conditions.
- The control design tries to maximize the use of the aerodynamic surfaces, and only when these cannot be used due to low efficiency or saturation, the RCS is exploited. The exception being the yaw channel, where only RCS actuation is available.
- Within the Control, it is necessary to adapt the AoS command by the Guidance, based on the natural trim of the vehicle, to avoid unnecessary control action against a natural stable condition.

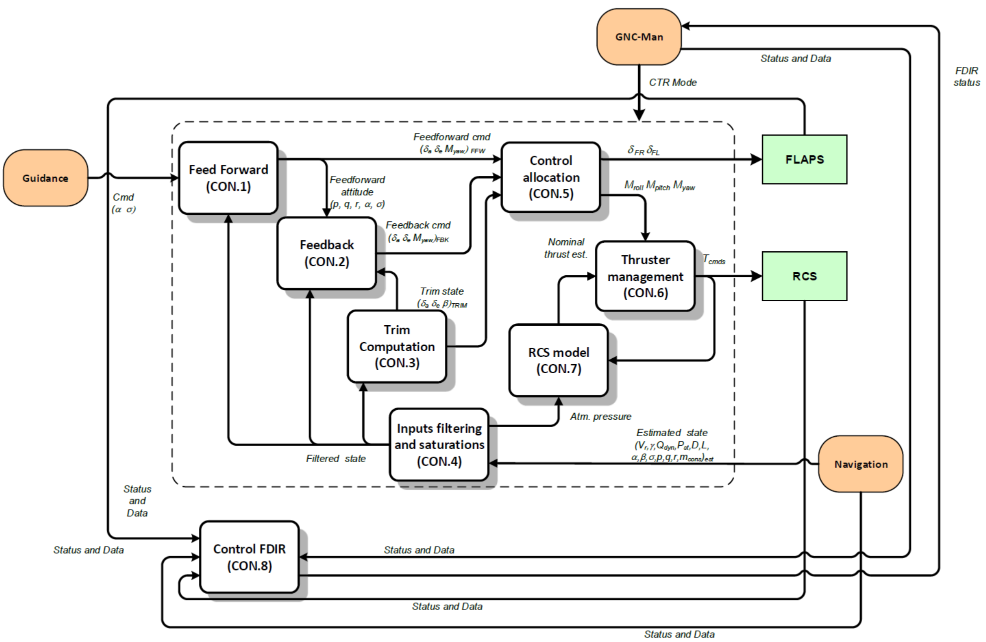

Figure 6: REE Control functional architecture [3]

4.2.2 TAEM Control

The TAEM control reuses the IXV re-entry controller concept and architecture. The control algorithm is divided into two sub-modes:

- **Full Control:** at higher Mach numbers, the trim strategy, as per IXV, consists in using the elevator and the aileron feedback commands to trim the vehicle around the reference AoA and AoS profiles.
- **Longitudinal Trim Inhibited:** below a certain Mach number, a washout filter is employed on the elevator output in order to inhibit the longitudinal trim, allowing additional control authority to compensate for disturbances.

The objective of the TAEM control function is to actuate the vehicle in order to maintain its attitude stable, while rejecting disturbances, and to track the attitude commands issued by the TAEM guidance function, within a given accuracy, as specified by the control requirements.

This must be done over the full set of flight conditions from the TAEM entry point to the drogue deployment (e.g. Mach 2.5, down to Mach 0.73), while respecting the actuator limitations and constraints.

TAEM Control has the following relevant features:

- Separation of feed-forward open-loop and feedback closed-loop components. The feed-forward commands aim to directly implement vehicle trimming and maneuvering from the guidance commands. Errors due to feed-forward model mismatching, perturbations, and uncertainties are subsequently corrected by the feedback action.
- The feedback controller design is guided by the control engineering principles and follows a systematic approach based on a design process aimed at achieving control robustness and performance.
- The feedback controller includes integral actions in AoA and Bank, to compensate steady-state errors and ensure the convergence to zero of the average tracking errors.
- Decoupled control design for longitudinal and lateral/directional dynamics, to minimize complexity. Both longitudinal and lateral/directional controllers are implemented as MIMO systems accounting for all the relevant dynamics.
- As in the Entry controller, the use of the aerodynamic surfaces is maximized, and only when these cannot be used because of efficiency or saturation, the RCS actuation is included.
- The AoS commanded by the Guidance is adapted, based on the natural trim of the vehicle, in order to avoid an unnecessary control effort against a stable natural condition, which depends on the particular aerodynamic operating point. Reference AoS is 0, however dispersed aerodynamic parameters may have a non-zero trim AoS. To reach stable AoS trim, the low frequency component of the AoS error is ignored.
- Below Mach 1.2, the natural longitudinal trim of the vehicle is followed, minimizing the low-frequency control action and allowing for the flaps to be used fundamentally for stabilization purposes, i.e. avoiding saturation conditions due to the excessive effort in the low-frequency tracking of the reference profile.
- The Control is scheduled by linear interpolation of its gains [1].

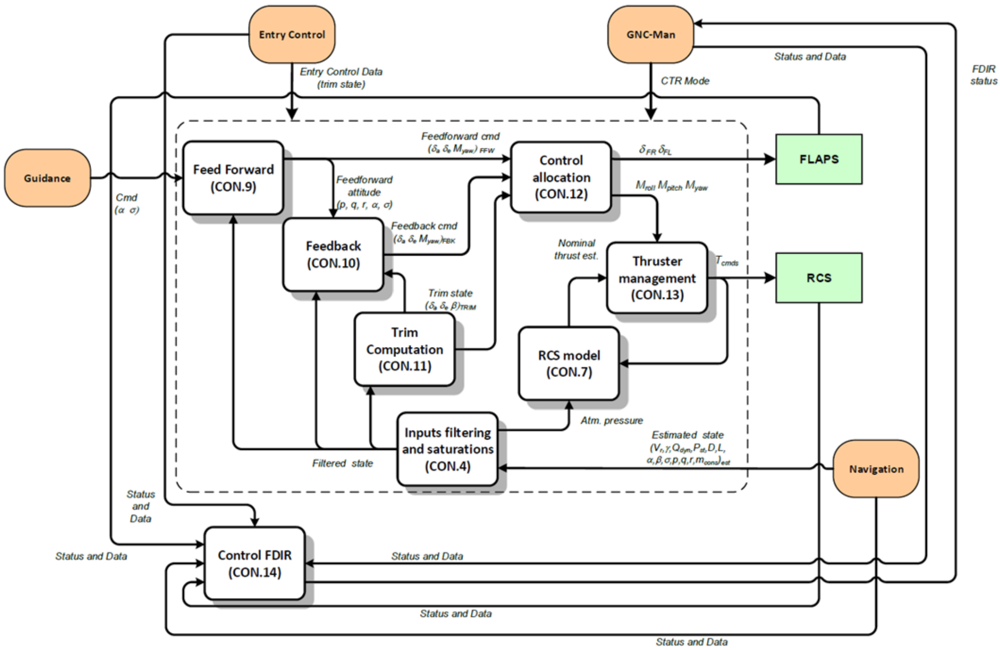

Figure 7: TAEM Control functional architecture [3]

5. SIMULATION RESULTS & PERFORMANCE ANALYSIS

To validate the model, a simulation campaign of 1000 MC shots was performed. The simulation was performed at a minimum (without payload) and on maximum mass (with payload) configurations.

These simulations account for uncertainties in atmospheric density, aerodynamic coefficients, and initial state vectors at the EIP. By testing both minimum and maximum mass configurations, we ensure that the control logic maintains stability across the entire operational envelope of the vehicle.

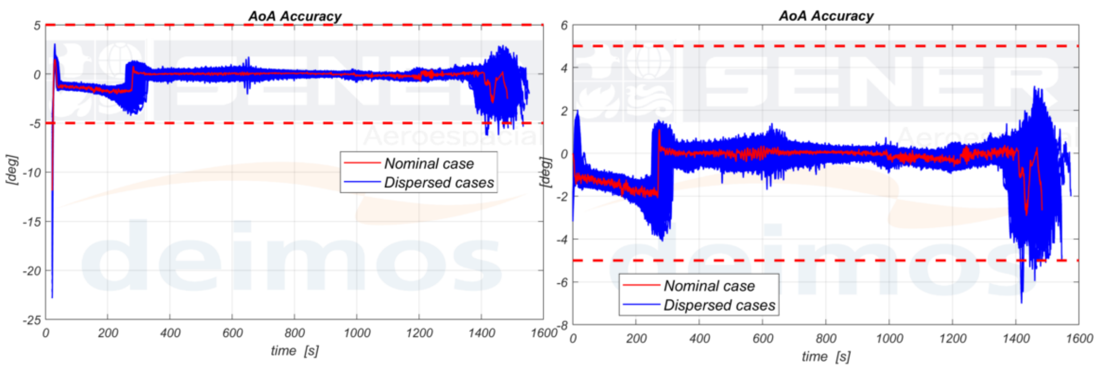

Figure 8: AoA accuracy. a) Max-mass and b) Min-mass configuration

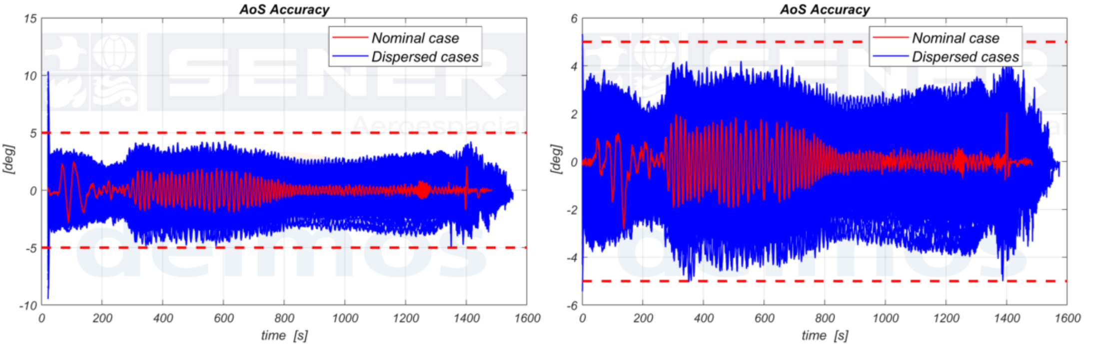

Figure 9: AoS accuracy. a) Max-mass and b) Min-mass configuration

The results for the Angle of Attack and Angle of Sideslip indicate that the vehicle remains well within the prescribed aerodynamic stability margins. The guidance commands are followed with high precision, and any oscillations triggered by atmospheric disturbances are quickly damped by the flight control system.

At this moment, there are several shots that fall outside the imposed limits for the angle of attack, due to extreme combinations of atmospheric dispersions and mass configurations, suggesting that the current control algorithm requires further refinement in these specific high-dynamic pressure regions.

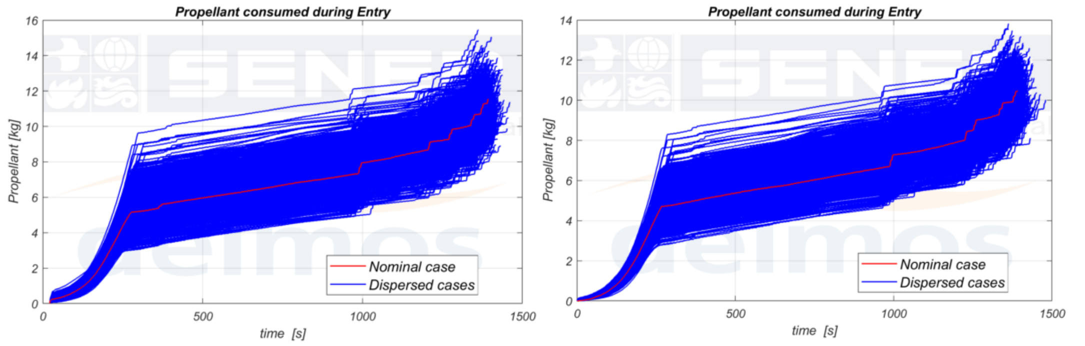

Figure 10: RCS consumed propellant. a) Max-mass and b) Min-mass configuration

The RCS consumed propellant analysis shows that the total fuel mass required for attitude control is within the mission's allocated budget. The distribution of propellant usage across the MC shots confirms that the control laws are optimized for efficiency, avoiding excessive thruster firing while maintaining the necessary pointing accuracy for the de-orbiting and re-entry maneuvers.

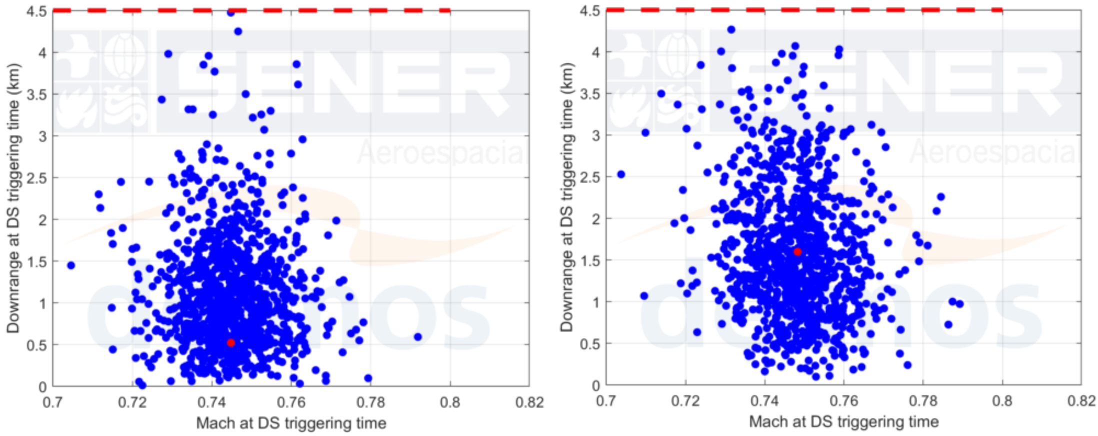

Figure 11: Distance wrt DRS trigerring point. a) Max-mass and b) Min-mass configuration

The distance with respect to the DRS triggering point is a key indicator of the re-entry precision. The simulation results show a tight cluster of triggering points, which ensures that the energy management phase starts at the correct altitude and velocity. Furthermore, the Bank Angle profiles demonstrate smooth transitions during energy management, reflecting a stable modulation of the lift vector to nullify downrange and crossrange errors.

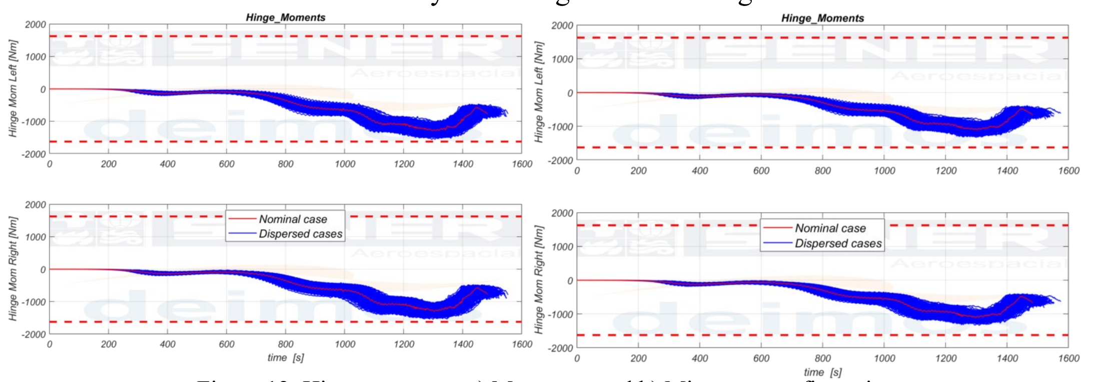

Figure 12: Hinge moments. a) Max-mass and b) Min-mass configuration

The Hinge Moments analysis confirms that the aerodynamic loads on the control surfaces remain within the torque capabilities of the onboard actuators.

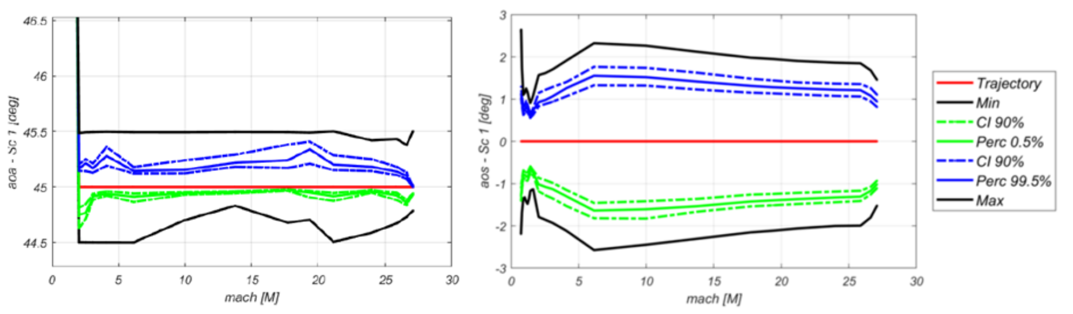

Figure 13: Trimlines for AoA(a) and AoS(b)

The Trimlines for the aerodynamic angles show that the vehicle maintains the values within the limits throughout the descent.

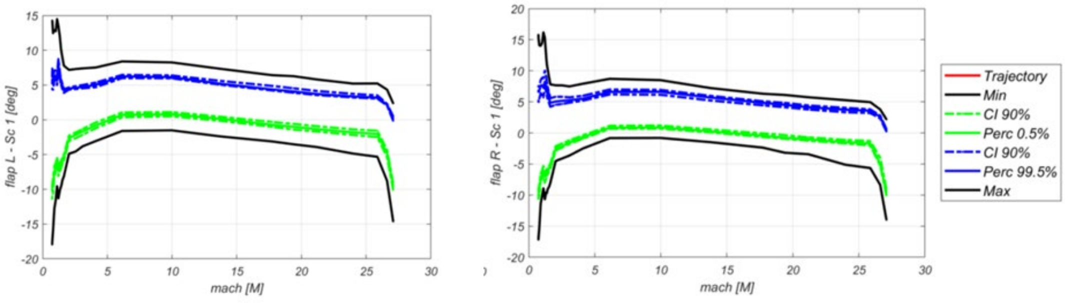

Figure 14: Trimlines for flaps (left and right)

The Trimlines for the left and right flaps indicate that the control surfaces operate within their nominal deflection limits to balance the aerodynamic moments.

The controller synthesis was performed in a decoupled manner, and requirements in the frequency domain were assessed using the decoupled and coupled plant dynamics. The requirements on the stability margins are expressed in a statistical sense. In the following results, the 0.5 percentile and the lower 90% confidence interval will be provided for a more compact view, providing thus a lower statistical bound for the margins.

6. CONCLUSIONS

The MIL simulation campaigns confirm that the G&C algorithms can effectively manage the transition from re-entry to TAEM for Space Rider. Results for the Santa Maria site demonstrate that the control logic remains stable despite atmospheric dispersions and sensor uncertainties.

This validation effort, conducted by the TASI, SENER, and INDRA consortium, ensures the necessary robustness for the flight software. These outcomes serve as the baseline for the upcoming Hardware-in-the-Loop (HIL) phase, marking a critical step toward the vehicle's 2028 maiden flight.

REFERENCES

[1] S. Burlou, I. D. Oprea, A. E. Tarabic, A. M. Stan, M. Marinescu, F. Tache, "Descent and Landing Safety Considerations for Autonomous Guided Systems," in *Aerospatial Conference organised by INCAS proceedings*, Bucharest, Romania, 2024.

[2] I.-D. Oprea, A. Burlou, A.-E. Tarabic, A.-M. Stan, M. Marinescu, F. Tache, G. Guidotti, P. Vernillo, F. Maria Pisano, G. Cuciniello, G. Rufolo, "Mission Analysis and Feasibility Assessment for the System Drop Test of ESA Space Rider Re-entry Module," in *IAC-24,D2,6,x82723 75th International Astronautical Congress (IAC) proceedings*, Milan, Italy, 2024.

[3] J. Cardín, F. Cacciatore, R. Sánchez, J. Veenman, G. Blanco, M. Lucrezia, C. Recupero, V. Fernández, F. Tache, A. Tarabic, A. Cojocaru, D. Bottero, S. Vidano, "Space Rider Re-entry Module: GNC Design and Development for Europe's Reusable Space Transportation System," in *IAC-22-D2.3.2, 73rd International Astronautical Congress (IAC) proceedings*, Paris, France, 2022.

[4] P. Vernillo, G. Rufolo, G. Cuciniello, F. M. Pisano, A. De Fenza, I. Brinza, C. Petre, C. Munteanu, C. Moisoiu, A. Burlou, I. Oprea, A. Tarabic, F. Tache, "System Drop Test for the Validation of Space Rider Descent and Landing Mission Phase: Status of Design and Development Activities," in *IAC-23-D.2.6.4 74th International Astronautical Congress (IAC) proceedings*, Baku, Azerbaijan, 2023.