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SPACE RIDER: Entry and TAEM G&C of the Future European Reusable Space Transportation System

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Abstract

This paper presents the Space Rider (SR) Entry and TAEM (Terminal Area Energy Management) G&C, at the closure of delta-CDR of the Space Rider ESA program. Space Rider is an ESA development program that aims to provide Europe with an affordable, independent, reusable end-to-end integrated space transportation system for routine access and return from low orbit. It will be used to transport payloads for an array of applications, orbit altitudes and inclinations. The paper presents an overview of the Entry and TAEM G&C Design Definition and Justification, as carried out in the phase C of the Space Rider program, with the Entry and TAEM G&C designed to take the vehicle from hypersonic conditions at the Entry Interface Point (EIP) (~Velocity 7.5km/s, 120km) to subsonic conditions at the parachute release (~Mach 0.73, 16km). The paper provides information on a range of activities for the Entry and TAEM G&C, including: Entry and TAEM G&C requirements evaluation and analysis, Entry and TAEM G&C concept, functional and physical architecture definition and justification, and the assessment of the GNC performance through Monte Carlo simulation campaigns. Most of the Space Rider RM Entry and TAEM Guidance and Control are based on the IXV algorithms. The promising simulation results obtained demonstrate a high level of performance of the Entry and TAEM G&C, as well as robustness against conservative (enlarged) model uncertainties and mission parameters dispersion, providing a solid basis for the Entry and TAEM G&C in subsequent program phases.

Keywords: *Re-entry, TAEM, GNC, Space Rider*

1. Introduction

On February 11 2015, the successful flight of the Intermediate eXperimental Vehicle (IXV) allowed demonstrating the European independent capability to return from space. IXV was a lifting body vehicle with two movable flaps for aerodynamic control that performed a suborbital mission, allowing in-flight demonstration of critical technologies for hypersonic flight conditions and successive re-entry from LEO. After being injected by VEGA in a 400km altitude orbit, IXV performed a successful entry, targeting the desired parachutes triggering conditions at supersonic speed (Mach 1.5), and from there a descent under a two-stage parachute system to a safe splashdown in the Pacific Ocean.

Leveraging on IXV's development, qualification and mission success, intended as an European "intermediate" step toward multiple future space applications, the European Space Agency (ESA) initiated an effort to develop a sustainable reusable European space transportation system in Space Rider, integrated with the VEGA C launcher, currently under development, to enable routine launch and

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return space missions [1]. VEGA C and the Space Rider constitute an Integrated Space Transportation System (ISTS), composed by:

- Module 1 = the Launch and AVUM Orbital Module (AOM), physically consisting of the Vega C launcher with a specifically adapted AVUM, with the latter acting as orbital service module up to de-orbit boost and separation from the Re-entry Module (RM).
- Module 2 = the Re-entry Module (RM), starting its active role at orbit acquisition, performing the in-orbit payload operations with the AOM support, and remaining active until completion of landing on ground.

The Space Rider Re-Entry Module (SR RM, Fig. 1, shown along the AOM) will have a multi-purpose cargo bay able to integrate a number of modular payloads to fulfill multiple mission objectives and to perform experimentation of payloads for multiple space applications. Designed to be an operational demonstrator able to perform 6 missions, Space Rider will have to support orbital operations in multiple orbital scenarios, from SSO to equatorial, deorbit and flight back to Earth with high maneuverability and controllability throughout all flight regimes (i.e. hypersonic, supersonic, transonic, subsonic) to perform a safe and precise soft-landing on ground under parafoil. The vehicle is therefore required to have the flexibility to ensure that environmental and operational unexpected events are mitigated and to guarantee the accomplishment of the mission objectives in compliance to stringent safety constraints in case of failure.

The activity described in this paper has been performed under the Space Rider programme, following the work already performed in the phase B2C [2] and [9], in the re-orientation phase prior to phase D, funded by the European Space Agency. Within this programme, Thales Alenia Space Italia (TASI) and AVIO are Prime contractors of Space Rider, with TASI being responsible for the SR Re-Entry Module (RM), SENER the GNC subsystem Design Authority, in core-team with DEIMOS as responsible for the Entry and TAEM G&C for SR, as part of the overall GNC subsystem activities and as a natural continuation of a role that was successfully executed in IXV ([3],[4]).

Fig. 1 Space Rider Re-Entry module concept (Credits: ESA)

The heritage from IXV for re-entry phase GNC is highly applicable to the Entry G&C for SR RM.

On the other side, the SR mission presents new challenges during the terminal entry phase and requires the development of European capabilities to fly the lifting vehicle aeroshape through the transonic regime up to a subsonic drogue chute, which places constraints and challenges on the GNC and the vehicle's flying qualities during the lower Mach regime from Mach 1.2 to Mach 0.7. The TAEM G&C, specifically designed for controlling the SR RM during such a delicate phase, has been undergoing a detailed design and development process. Several innovations are required for the supersonic, transonic, and subsonic flight phases, especially to develop the TAEM Guidance, to cover the transonic flight regime with the low L/D and limited controllability of the trajectory and the TAEM Controller, to cover the transonic flight regime where the vehicle has limited flying qualities (especially in trim).

Moreover, SR is an operational vehicle, that will support a range of mission types, and the GNC shall provide the capability to robustly steer the vehicle in case of different re-entry configurations or mission profiles. Therefore, both the Entry G&C and the TAEM G&C will also employ an FDIR function to respect the stringent aforementioned safety constraints, which is a new functionality that was not present in IXV.

2. Space Rider Mission and Vehicle

2.1. Space Rider Mission

The current baseline design of the Space Rider Re-entry Module has the same aeroshape and size as the IXV (shown in Fig. 2). The SR RM is a lifting body, having no wings, and provides a lift-to-drag ratio of about 0.7 in the hypersonic regime. With respect to the IXV mission, the SR mission will have to support orbital operations in multiple orbital scenarios, deorbit and re-entry to perform a safe and precise soft-landing on ground under parafoil. In particular (see paper [5] for further details):

- The SR ISTS is launched from Kourou onboard the Vega C launcher and injected into orbit.
- During the orbital phase the SR objective is to accomplish the goals for the specific orbital mission. Target orbits currently considered are circular, have an altitude of 400 km, and with an inclination range from equatorial to medium inclinations (~40 deg), depending on the mission objectives.
- At deorbiting, the SR executes a deorbit boost to target the desired conditions at the EIP. After the deorbit maneuver is completed, the RM separates from the AOM and performs a ballistic coasting phase prior to entry. Attitude control during this orbital phase is carried out by means of the Reaction Control System (RCS). The targeted conditions at the EIP are typical of LEO return missions, with co-rotating velocities beyond 7.4 km/s and nominal altitude 120km.
- The RM then performs a guided gliding re-entry from the EIP until Mach 2.5, when the transition to the TAEM occurs. The TAEM phase objective is to get the vehicle to the desired conditions (position, velocity, attitude) at the DRS triggering.
- At approximately Mach 0.73 the DRS sequence is triggered, and a pilot chute, a conical ribbon drogue, and a Disk-Gap-Band drogue are deployed successively to slow the vehicle down toward the desired conditions for the parafoil deployment, that occurs at an altitude of about 5.5 km and approximately Mach 0.12. The parafoil allows the vehicle to glide with a shallow flight path angle and at the same time to maneuver to reach the desired landing site.
- The flight terminates with an approach and landing phase at the desired landing site. In this phase, the vehicle performs a flare maneuver to achieve the proper touchdown conditions.

The current baseline mission includes a return from a quasi-equatorial, medium inclination orbit (6.2 deg), with the RM in the maximum mass configuration (2850 kg) and landing at Kourou. A backup mission considers a return from a medium inclination orbit (40 deg) and landing at Santa Maria, Azores.

The development and verification of the TAEM GNC was carried out focusing on the baseline mission scenario.

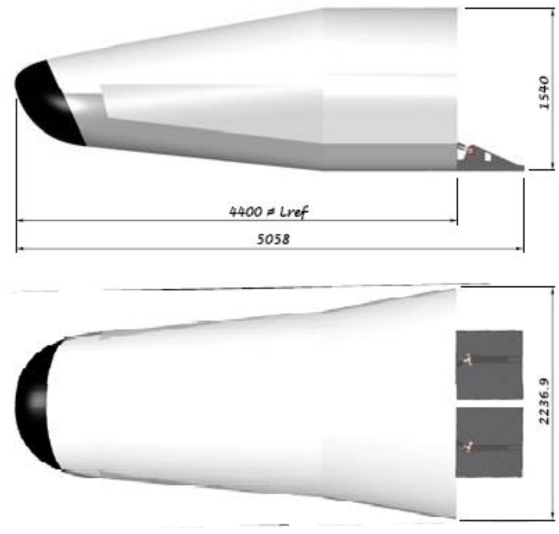

Fig. 2 The IXV/SR RM aeroshape (Credits: TAS)

3. ENTRY G&C overview

During the Phase C of the SR programme, design activities are building on the extensive reuse of the IXV technological solutions, so the Entry G&C design activities have been based on tuning the IXV solution, with upgrades if required to fulfil specific application objectives or to implement IXV lessons learnt.

3.1. Functional Architecture

The ENTRY G&C is split into the following sub-functions:

- **ENTRY Guidance**: This consists of a guidance algorithm that aims to define the re-entry trajectory, based on pre-loaded trajectory profile, during the ENTRY phase, starting at EIP (Entry Interface Point) reaching TEP (TAEM Entry Point) with contained dispersions
- **ENTRY Control**: The control algorithm may operate in distinct modes, depending on the GNC phase and available GNC actuators. In general, the control tracks the guidance trajectory and ensures a stable attitude, using the effective actuators for the phase. This includes the actuator management.

3.2. ENTRY Guidance

The **ENTRY Guidance** is based on the strong heritage from IXV.

The objective of the re-entry guidance sub-function is that the vehicle reaches the desired TAEM interface point, while ensuring its flight within the entry corridor. The ENTRY guidance algorithm will reuse the IXV guidance algorithm, to maximize the IXV heritage, given its flight proven status and the good performance seen in the IXV flight. With respect to IXV, closed loop guidance is extended down to the TAEM interface.

In the Re-entry Guidance function, 2 major sub-modes are implemented:

- **Open Loop Mode**: during the first part of the Entry, the attitude commands follow pre-defined profiles 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, activated based on an estimated drag and energy threshold.

Fig. 3 shows the Closed-Loop ENTRY Guidance functional architecture, composed by the following functional blocks:

- Reference trajectory DB: the re-entry reference trajectory coming from Mission Analysis activities off-line computations is stored within the Guidance Block to be used on-line. The trajectory is described in terms of suitable profiles to be used by the guidance, that is, Drag-Energy and AoA-Mach profiles.

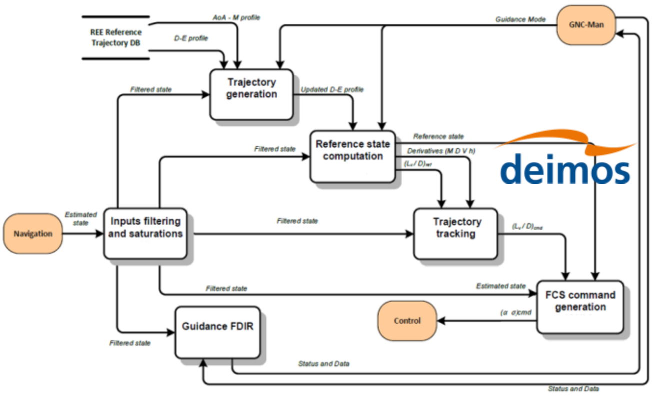

Fig. 3 Functional architecture of the Closed-loop ENTRY Guidance

- Inputs filtering and Saturations: is responsible for obtaining the current vehicle states to be used by the rest of the guidance functions. All the outputs provided by this module are taken directly from the Navigation function and filtered through second order filters to ensure the signals are free from discontinuities and high frequency noise. This function is in common between REE and TAEM, always called before the rest of the Guidance functions, hence there is no need to reinitialize states between the two sub-modes, as the states for the filters are unique and continuous.
- Trajectory generation: this module is responsible for assessing the deviation of the flown trajectory from the reference one due to perturbations and uncertainties, and if this deviation is too large, to update the corresponding D-E and AoA-E profiles to be tracked.

- Reference State Computation: the purpose of this module is to establish the complete desired reference state of the vehicle from the guidance point of view, based on the updated profile computed in the Trajectory Generation module.
- Trajectory tracking: this module is responsible for computing the change in vertical L/D by providing a vertical L/D command, to be able to track the desired reference state (based on the updated profile), considering the current state of the vehicle, as provided by the navigation function.
- FCS command generation: this module translates the L/D command into appropriate commands to the FCS in terms of aerodynamic angles, considering also cross-range constraints.
- Guidance FDIR: provides the low level local FDIR monitoring and recovery actions for the Guidance.

3.3. ENTRY Control

The baseline approach for the ENTRY Control is the reuse and adaptation of the IXV Re-entry controller for the re-entry flight phase.

The objective of the re-entry control function is to actuate the vehicle such that its attitude is stable and follows the attitude commands issued by the re-entry guidance, within a given accuracy, as specified by the control requirements, from the EIP to desired TAEM interface point. This must be done over the full set of flight conditions from EIP to TEP (Mach 30 to Mach 2.5) and respecting the actuator limitations and constraints.

The Control algorithm in REE sub-mode, is strongly based on IXV heritage, and it is further 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.

Based on the mentioned principles, the ENTRY Control will have 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 design is based on control engineering principles, leading to low order controllers, suitable for low latency OBC execution.
- The feedback controller includes integration action in pitch and roll to compensate 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. The complete MIMO control algorithm is designed for the vehicle, including all dynamic couplings.
- The control design tries to maximize the use of the aerodynamic surfaces, and only when these cannot be used because of efficiency or saturation, the RCS actuation is included. 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.
- Control is scheduled by interpolation of its gains, leading to a simple and robust scheduling process that adapts to the actual flying conditions.

Fig. 4 represents the functional architecture of ENTRY control, which is composed of five different sub-functions:

- Feed forward: this function processes the guidance commands and converts them into the reference profiles for the actuator commands, the angular rates and the aerodynamic angles required to track the guidance commanded attitude. These profiles are computed using linearized models of the nominal vehicle aerodynamics and the nominal vehicle MCI properties. This component is mainly employed to execute any rapid, large angle bank maneuvers commanded by guidance. Further deviations between the reference profiles and the estimated state will be corrected by the feedback control.

- Feedback: this function implements the attitude state feedback loops of the controller. They are needed to compensate the effect of uncertainties, perturbations, modeling errors and steady state errors that cannot be handled by the open-loop feed forward and trim computation functions.
- Trim computation: this function has the purpose to provide the aerodynamic actuators trim profile based on the current flight conditions to achieve the trim in Pitch and Roll. The trim strategy, with corresponding deflections, is computed off-line for the nominal vehicle configuration case based on the current flight conditions and stored on-line as look-up-tables as function of the airspeed velocity. Any error resulting from the imperfect vehicle knowledge and the inherent vehicle trim variation with MCI and aerodynamic variations are corrected by the feedback module.
- Inputs filtering and saturations: This function is responsible of obtaining the current vehicle states to be used by the rest of the control functions. All outputs provided by this module are taken directly from the Navigation function and filtered through second order filters to ensure the signals are free from discontinuities and high frequency noise.
- Control allocation: this function combines the different control action contributions from the feed forward, trim, and feedback functions, and allocates the resulting control action to the available actuators in terms of desired deflections for the flaps and desired torque for the RCS.
- Thrusters management: this function translates the desired torque allocated to the RCS by the Control Allocation module, into corresponding commands to each of the thrusters, taking into account the thrusters mounting, their performance in current operation conditions, their firing logic and their physical operational constraints.
- RCS model: is responsible for the on-board estimation of the nominal thrust provided by each thruster given the atmospheric pressure and an onboard model of the tank. The nominal thrust is used by the Thruster Management to compute the RCS PWM.
- Control FDIR: This module provides the low-level local FDIR monitoring and recovery actions for the Control.

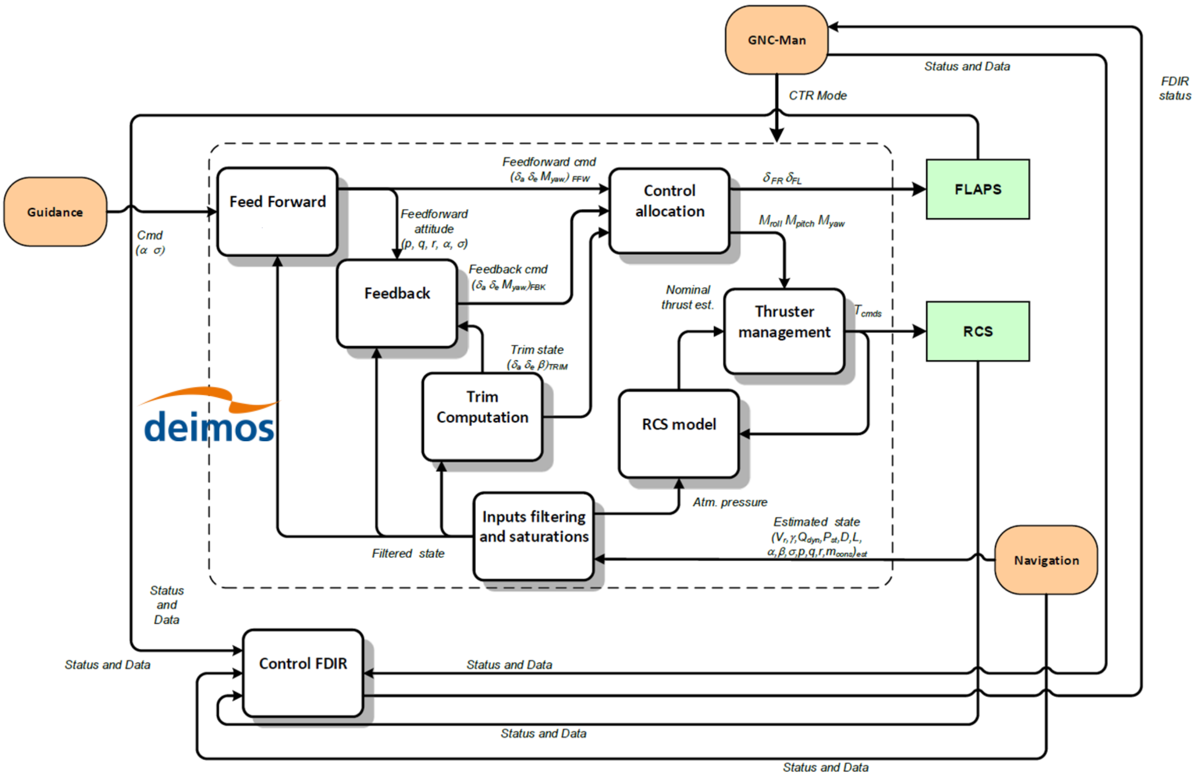

Fig. 4 Functional architecture of the ENTRY Control

4. TAEM G&C overview

The TAEM G&C, new with respect to IXV, has been undergoing a detailed design and development process, leading to the solution hereafter described.

4.1. Functional Architecture

The TAEM G&C is split into the following sub-functions:

- **TAEM Guidance**: This consists of a guidance algorithm that aims to define the re-entry trajectory during the TAEM phase and until chute opening, based on pre-loaded trajectory profile. This ensures the vehicle arrives at chute conditions, satisfying the mission and flight path constraints, and the safety constraints.
- **TAEM Control**: The control algorithm tracks the guidance trajectory and ensures a stable attitude, using the effective actuators for the phase. This includes the actuator management.

4.2. TAEM Guidance

The **TAEM Guidance** operates in closed-loop and, similarly to the IXV Re-entry Guidance, it involves a trajectory generator function and a trajectory tracker. For the trajectory tracker, a well-proven approach and structure is chosen [7], that performs tracking of a reference trajectory in position and velocity, to generate the commands for the control.

For the trajectory generator, it is chosen an *Offline Strategy* in which a reference trajectory is retrieved from a LUT. No on-line optimisation is required. Mach is taken as the independent variable of the guidance scheme, as directly linked to the aerodynamic performance of the vehicle in such a delicate phase (supersonic, transonic, subsonic). Therefore, the reference trajectory defines the desired position and velocity state vectors as a function of Mach, in a local horizontal system, centred at the target point.

The trajectory tracking algorithm formulation is based on non-linear dynamic inversion (NDI) principles that allows the computation of the guidance commands, making use of the extensive heritage and simplicity of this algorithm approach (see, e.g. [3][7][8]). A low-order state (PID-like) tracking is used to compute the Guidance action, in which the tracking of the in-plane motion and the lateral motion is coupled. The bank angle is the main trajectory control command, while angle-of-attack modulation can be activated, if needed, in case of strong deviations with respect to the reference profile. A complete analytical formulation is used to compute the reference command. No on-line optimisation is required.

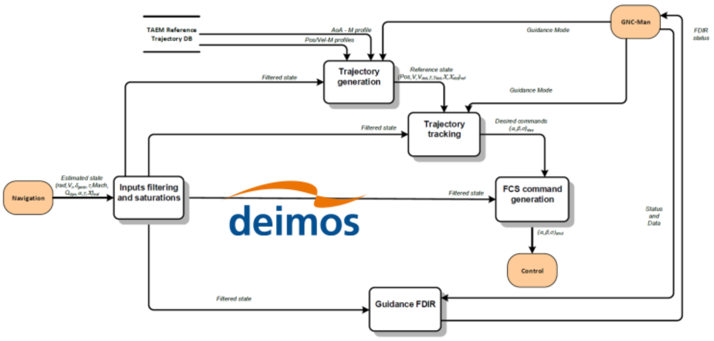

Fig. 5 Functional architecture of the Closed-loop TAEM Guidance

Fig. 5 shows the Closed-Loop TAEM Guidance functional architecture, composed by the following functional blocks:

- Reference trajectory DB: stores the reference trajectory coming from Mission Analysis, in terms of suitable profiles to be used by the Guidance, that is, Position/Velocity and trimline AoA profiles as function of Mach.
- Trajectory generation: computes the reference state to be tracked based on the reference trajectory.
- Inputs filtering and saturations: This function is the same described and used in ENTRY.
- Trajectory tracking: is responsible for computing the desired bank angle needed to track the desired reference state, considering the current estimation, as provided by the Navigation. It computes also the desired aerodynamic state, and provides the reference AoA and AoS commands, based on the trimline.
- FCS command generation: filters the desired bank command depending on possible limitations (e.g. rate limitations) due to requirements.
- Guidance FDIR: provides the low level local FDIR monitoring and recovery actions for the Guidance.

4.3. TAEM Control

The objective of the control function during TAEM is to actuate the vehicle such that its attitude is stable and tracks the attitude commands issued by the guidance, within a given accuracy, as specified by the control requirements, from the EIP to the drogue deployment. This must be done over the full set of flight conditions (e.g., Mach 2.5, down to Mach 0.73) and respecting the actuator limitations and constraints.

The baseline approach for the **TAEM Control** is based on the same principles of the IXV re-entry controller for the Entry phase, given its flight proven status and the good performance seen in the phase B2C [9]. This includes the hybridization approach for the RCS and ASCS (flaps). Notably, while the TAEM flight phase is short in time compared to the entry flight phase of IXV, the RCS actuator is still required, to allow bank tracking with turn coordination and the rejection of disturbances.

Based on the mentioned principles, the TAEM Control will have the following relevant features:

- Separation of feed-forward open-loop and feedback closed-loop components. The 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 design is guided by control engineering principles and follows a systematic approach based on a design process aimed to achieve control robustness and performances, while also ensuring the satisfaction of the requirements.
- 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 and fully exploiting the set of sensor measurements available. Note that control justification is done for the complete controller without decoupling.
- The Control design aims to maximize the use of the aerodynamic surfaces, and only when these cannot be used because of efficiency or saturation, the RCS actuation is included. The exception is the yaw channel, where only the RCS has the required actuation authority.
- Within the Control, the AoS commanded by the Guidance is adapted, based on the natural trim of the vehicle, to avoid an unnecessary control effort against a natural stable condition, which depends on the particular aerodynamic operating point.
- Below about 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, leading to a simple and robust scheduling process, as was done in IXV.

Fig. 6 represents the functional architecture of TAEM control, which is composed of five different sub-functions:

- Feed forward: this function is the same described in ENTRY, exploiting IXV heritage and ensuring continuity between the two phases.
- Feedback: this function implements the attitude state feedback loops of the controller. They are needed to compensate the effect of uncertainties, perturbations, modeling errors and steady state errors that cannot be handled by the open-loop feed forward and trim computation functions. It is the core of the control algorithm, and is different from the Entry one as TAEM flight phase requires more robust approach to encompass the delicate transonic phase. It is structured to be 2DoF (independent reference and measurement channels), improving robustness. In addition, the lateral TAEM controller feedback transfer function does not employ the lag-filters on the AoS channel, unlike the Entry controller. A simpler pure PID structure is found sufficient to comply with the performance requirements of this phase, while providing increased robustness and improved stability margins (critical for the TAEM phase).
- Trim computation: this function is the same described in ENTRY, exploiting IXV heritage and ensuring continuity between the two phases.
- Inputs filtering and saturations: is the same described in ENTRY, exploiting IXV heritage and ensuring continuity between the two phases.
- Control allocation: is the same described in ENTRY, exploiting IXV heritage and ensuring continuity between the two phases.
- Thrusters management: is the same described in ENTRY, exploiting IXV heritage and ensuring continuity between the two phases.
- RCS model: is the same described in ENTRY, exploiting IXV heritage and ensuring continuity between the two phases.
- Control FDIR: This module provides the low-level local FDIR monitoring and recovery actions for the Control.

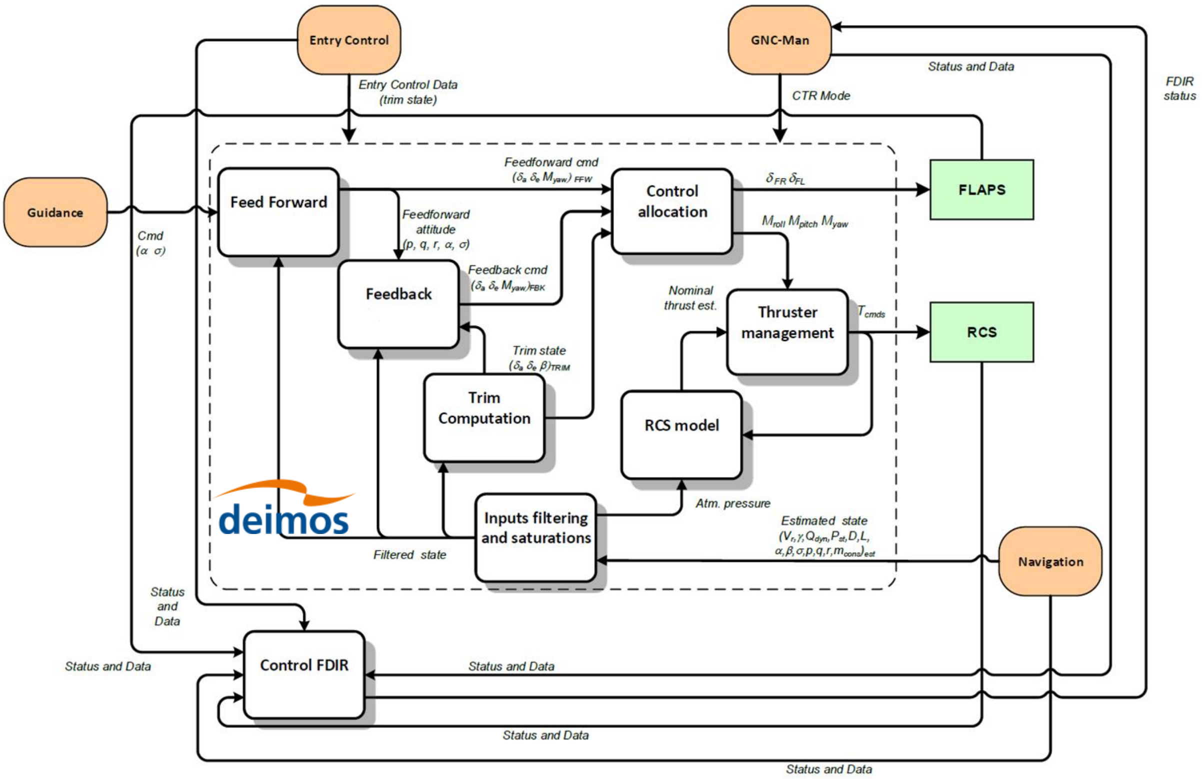

Fig. 6 Functional architecture of the TAEM Control

5. Triggering Algorithms

The Descent System of Space Rider is a multistage system composed of a pilot chute, a Conical Ribbon drogue, a Disk-Gap-Bank drogue, and a parafoil.

DEIMOS Space is in charge of the design of the Drogue System triggering algorithm and Parafoil triggering algorithm:

- **Drogue System (DRS) Triggering**: It aims at triggering the subsonic pilot chute deployment within the chute box conditions at the end of the TAEM phase.
- **Parafoil (PF) Triggering**: It aims at triggering the parafoil deployment within the proper altitude box conditions.

5.1. DRS Triggering

The DRS triggering algorithm concept from IXV [3], based on a MAIN and a ULTIMATE logic, is considered to be applicable to Space Rider. It has been adapted and extended for use in the Entry and TAEM GNC, considering the DRS box constraints for the chute chosen for Space Rider.

The DRS Triggering algorithm logic, reported in Fig. 7, includes:

- The MAIN logic has the aim to trigger the start of the DRS sequence in nominal conditions. The triggering logic has been adapted to the current baseline DRS target Mach defined for Space Rider. Triggering criteria is based on targeting the Target Mach number.
- An ULTIMATE logic is always active as a backup, continuously monitors the estimated altitude, forcing the triggering of the DRS in case a limit altitude is reached while the MAIN chain has not been activated.

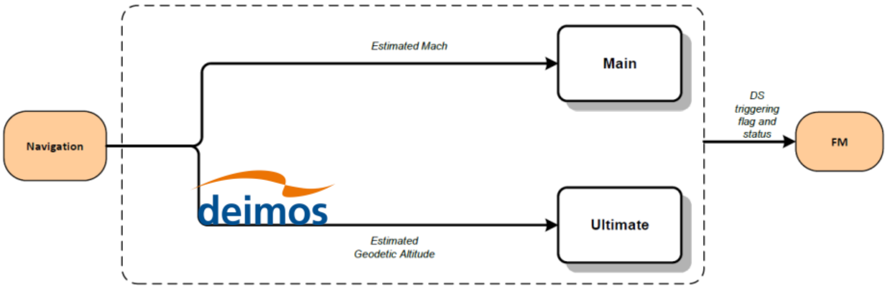

Fig. 7 Functional architecture of the DRS triggering algorithm

5.2. PF Triggering

The PF Triggering algorithm concept is based on similar principles used for the DRS Triggering, based on a MAIN and ULTIMATE logic.

The PF Triggering algorithm logic, reported in Fig. 8, includes:

- A MAIN logic to trigger the Parafoil deployment in nominal conditions. The triggering logic has been adapted to the current baseline PF target altitude defined for Space Rider.
- An ULTIMATE logic is always active as a backup, based on a timer computing the elapsed time since Drogue deployment and forcing the Parafoil deployment if the time threshold is reached while the MAIN chain has not been activated.

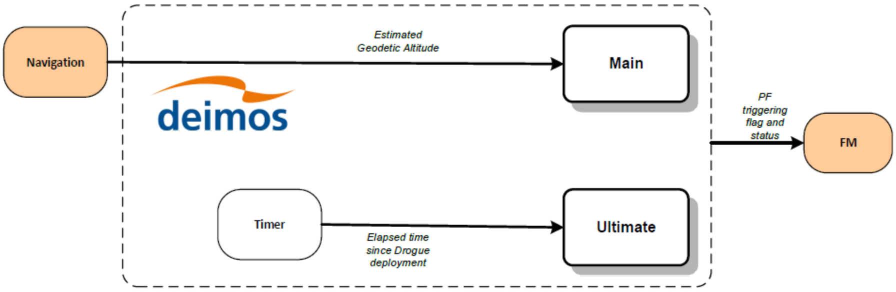

Fig. 8 Functional architecture of the PF triggering algorithm

6. Performance Assessment

The testing of the proposed ENTRY and TAEM G&C solution has been carried out in the Space Rider baseline scenario (maximum mass configuration, quasi-equatorial return to Kourou). The GNC algorithms have been implemented and adapted to the Space Rider scenario in a Functional Engineering Simulator (FES), derived from the DEIMOS IXV FES [6], which exploits the unique heritage of the DEIMOS IXV FES, both its DDV (Design, Development and Validation) and its models.

A 350 shots Monte Carlo simulation campaign was carried out using the FES, to preliminarily verify the performance of the ENTRY and TAEM GNC solutions in an End2End trajectory. This considered all the relevant mission and vehicle features for TAEM GNC, including the dispersions on initial conditions at AVUM Separation, MCI (Mass, CoG and Inertia), aerodynamics, environment (atmosphere and winds), and the sensors and actuator performance. The assessment showed very good results, with an overview of the results shown in Fig. 9 to Fig. 16.

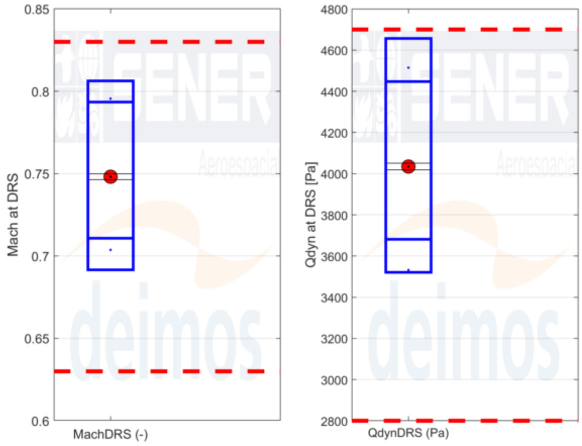

Fig. 9 Mach and dynamic pressure dispersions at target DRS event

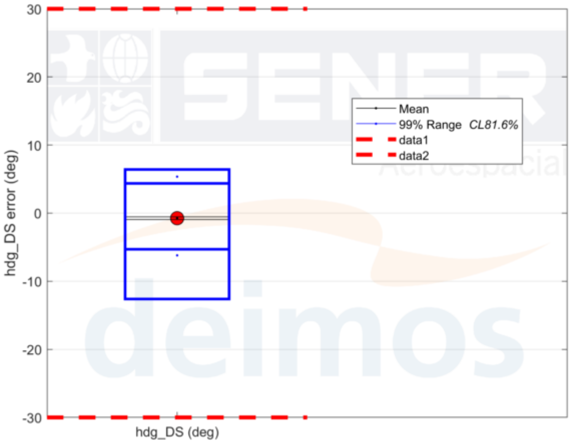

Fig. 10 Heading angle (deg) relative dispersion at target DRS event

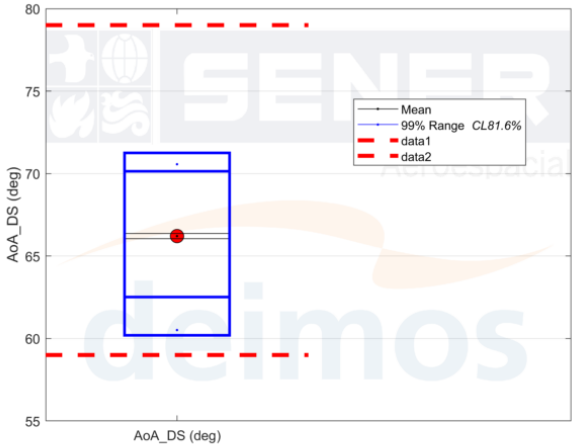

Fig. 11 AoA dispersion at target DRS event

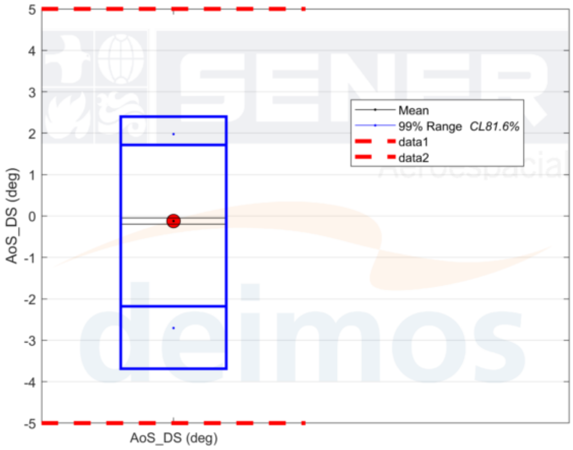

Fig. 12 AoS dispersion at target DRS event

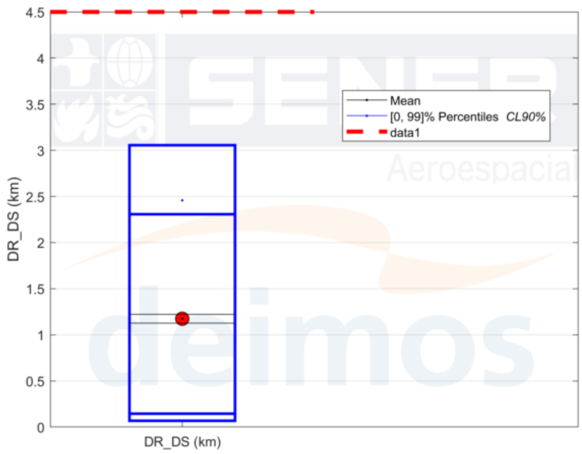

Fig. 13 Downrange accuracy dispersions at target DRS event

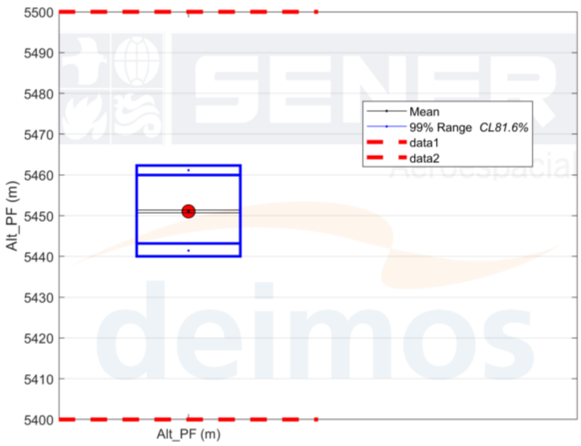

Fig. 14 Altitude accuracy dispersion at target PF triggering event

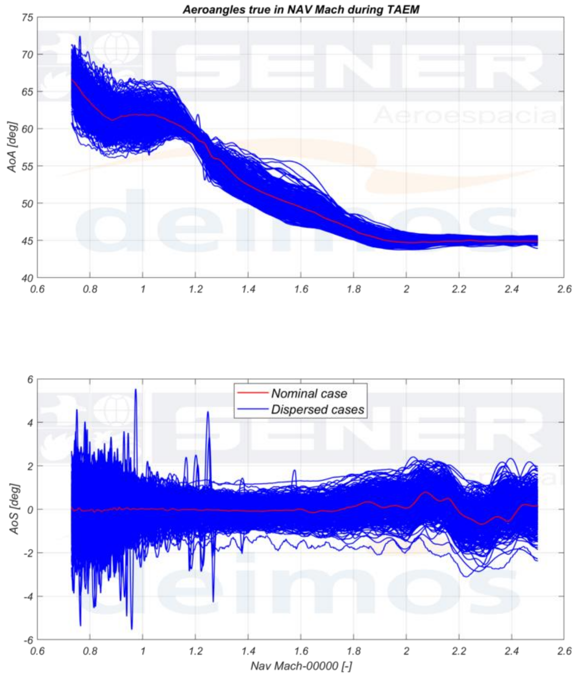

Fig. 15 True Aeroangles vs Estimated Mach number during TAEM

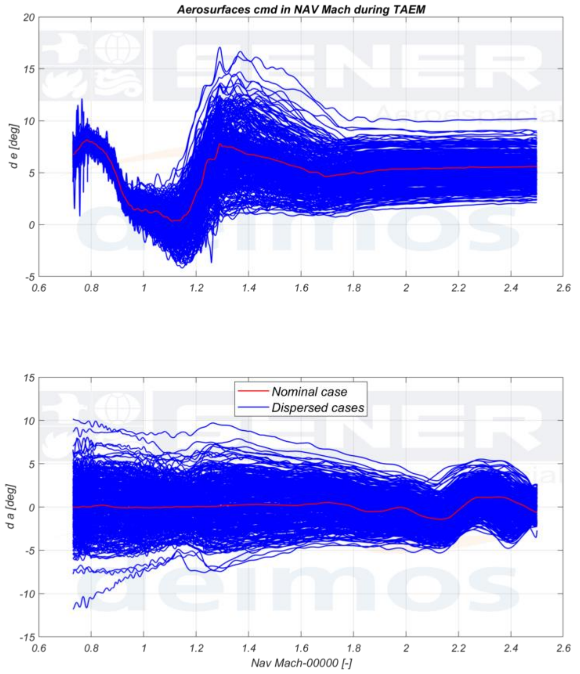

Fig. 16 Elevon and Aileron deflections vs Estimated Mach number during TAEM

7. Conclusions

The results confirm that the ENTRY and TAEM G&C solution developed for the SR mission fully allows the trajectory and vehicle control for the considered scenario and meets the ENTRY and TAEM G&C requirements specified for the CDR design status. Hence, **the ENTRY and TAEM G&C concept is shown to meet the Space Rider mission/system needs from GNC** at the GNC delta-CDR status, in nominal (no-failure) conditions, providing performance acceptable and compliant to mission needs.

In particular, the ENTRY Guidance can successfully steer the vehicle from EIP to TEP, while the TAEM Guidance is able to compensate dispersions at TEP and successfully steer the vehicle to the desired conditions at DRS and PF triggering events. The ENTRY and TAEM Controllers are capable of maintaining the stability of the vehicle throughout the ENTRY and TAEM flight, tracking the Guidance commands, including through the lower subsonic regime down to Mach 0.73, where the vehicle stability corridor is small, and the flying qualities are reduced.

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