DOI: 10.13009/EUCASS2019-1016

8th european conference for aeronautics and space sciences (eucass)

The Design of the GNC of the Re-entry Module of Space Rider

F. Cacciatore, R. Haya Ramos*, L. Tarabini Castellani*, A. Figueroa*, J. Veenman*, S. Ramírez**
**SENER Aerospace, Calle Severo Ochoa 4 (PTM), Tres Cantos, 28760, Spain, francesco.cacciatore@sener.es*

*C. Recupero**, M. Kerr***
*** DEIMOS Space S.L.U., Ronda de Poniente 19, Tres Cantos, 28760, Spain,, cristina.recupero@deimos-space.com*

*J.A. Béjar****
**** GMV, Calle Isaac Newton 11 (PTM), Tres Cantos, 28760, Spain, jabejar@gmv.com*

Abstract
Based on the Intermediate eXperimental Vehicle (IXV) and VEGA success and assets, a programme called Space Rider (SR) was proposed to develop an affordable and sustainable reusable European space transportation system to enable routine "access to" and "return from" space, operating in-orbit, de-orbiting, re-entering, landing on ground, being re-launched after limited refurbishment. This paper presents the status of the SR GNC subsystem, featuring two novel phases with respect to IXV: Terminal Area Energy Management and Descent and Landing under parafoil. The mission is currently in phase C, heading towards CDR within the end of 2019.

1. Introduction

Space Rider (SR) is the name of the reusable European space transportation system. will perform serve as platform for in-orbit operation, experimentation and demonstration for applications like micro-gravity experiments, orbit applications and In-Orbit Demonstration and validation of technologies. These technologies suitable for demonstration inside Space Rider cover a wide spectrum of possibilities: from Earth science to planetary Exploration. As the IXV precursor was, the re-entry module itself is a test bed for entry technologies. The project is currently running Phase C heading towards Critical Design Review (CDR) by the end of the year.
Space Rider vehicle is composed by an AVUM Orbital Module (AOM) and a Re-entry Module (RM). The RM of Space Rider is based on the shape of the Intermediate eXperimental Vehicle (IXV), which was successfully flown in February 2015. The Guidance, Navigation and Control (GNC) of the Re-entry Module controls in closed-loop the flight of the vehicle from the separation in orbit from the AOM down to precision landing on ground. The RM mission phases include the orbital coasting up to the Entry Interface Point (EIP), the hypersonic entry flight, the transonic pass (TAEM, Terminal Area Energy Management), the descent under parachutes and the approach and landing using a guided parafoil.
The evolution from the IXV system to the Space Rider RM System presents multiple synergies, like the reuse of the same aerodynamic shape for re-entry but also clear challenges, like the 2 months duration in orbit and the reuse for 6 (maiden plus 5 additional) flights. Compared to IXV, The increased vehicle functionality translates into an increase of the number of GNC functions needed to meet the mission and system objectives. Moreover, the operational nature of the mission stresses all subsystems in terms of reliability, verification, validation and reusability and the GNC is not an exception. As in IXV, full autonomy of the re-entry mission is mandatory, i.e. without ground telecommanding after the separation from the AOM.
This paper presents the status of the design of the RM Guidance, Navigation and Control subsystem, which covers several domains. The systems engineering handles the overall requirements engineering and the definition of the functional architecture, the operational architecture, i.e. the modes and the physical architecture using a model based system engineering approach. Another domain is the identification of requirements, selection and trade-off of candidate units for sensors (IMU, GNSS, Radar altimeter) and actuators (Reaction Control System, elevons and parafoil winches) considering not only performance aspects but mainly qualification status. This activity has been conducted with close interaction with the RM system team due to the strong implications in terms of layout, budgets and programmatic.
In terms of algorithms, heritage in the coasting and entry phase from IXV has been maximized and the modifications required to cope with the Space Rider mission identified. Algorithms have been extended to cover the transonic phase that was not addressed in IXV. The approach and landing under parafoil is a brand new phase in which the guidance

DOI: 10.13009/EUCASS2019-1016

provides the trajectory commands from 6 km altitude to the attitude control to steer the parafoil within the arrival corridor to meet the landing site with an accuracy better than 150 m at touchdown. The Failure Detection, Identification and Recovery (FDIR) subsystem is a new functionality implemented in the Re-entry Module to cope with the operational nature of the mission. The main challenge for the FDIR comes from the time-critial nature of the return mission, as once the de-orbit is commanded the sequence down to landing does not allow for typical spacecraft-like safe modes.
The approach for the Verification and Validation, covering from functional to real time test and drop-test will be presented.

2. Space Rider Re-Entry Module Mission

Space Rider will be launched from Kourou on-board the VEGA-C launcher. The target orbits for injection cover from Equatorial up to Sun-synchronous orbits depending on the payload needs. The vehicle is composed of two modules: The AVUM Orbital Module, which is a modified version of the VEGA-C upper stage (AVUM+) and the Re-entry Module, which is a modified version of IXV equipped with a cargo bay to embark on payloads.
The composite AOM+RM will stay in orbit for at least 2 months at an altitude of 400 km. Focussing on the re-entry mission (Figure 1), the RM will be deorbited by the AOM at the end of the operational mission. Soon after the de-orbiting burn, the RM will separate from the AOM. RM will perform an orbital coasting and an atmospheric re-entry to decelerate from hypersonic to supersonics in a similar fashion as done in IXV. During the TAEM phase the vehicle will cross the transonic and will prepare for the deployment of the subsonic parachute at around Mach 0.75. Subsequently, at an altitude of 6 km, a parafoil will be deployed and the vehicle will be actively guided towards a dedicated landing site to perform precision landing.

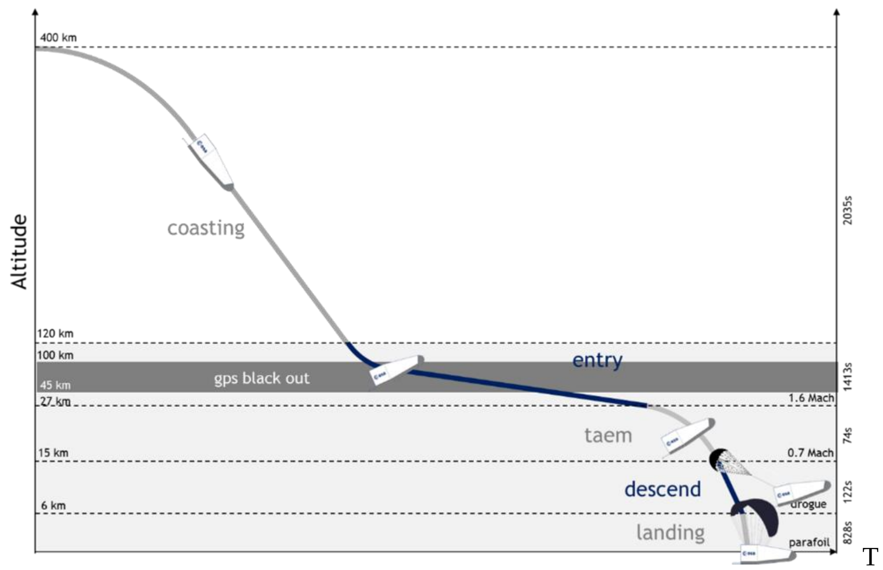

Figure 1: Space Rider re-entry module flight phases (not to scale)

3. GNC Requirements and Challenges

The heritage from IXV drives the design of the Re-entry Module of Space Rider to limit the development cost and reduce risks. However, the wider mission and application scope of Space Rider requires an evolution of several subsystems or the inclusion of new ones.
In the particular area of GNC the main requirements and challenges are:

- Operational vehicle with a reusability of 6 flights.
- The GNC as pilot of the vehicle to ensure achievement of the in-flight objectives and safe recovery.
- 2 months in orbit before re-entry.
- Wide envelope of re-entry trajectories to cover multiple missions: inclinations from equatorial to polar and return landing sites located at equatorial and mid latitudes.
- Wide envelope of mass among the different missions: from fully loaded cargo bay to empty cargo bay.
- Re-use of coasting and entry GNC from IXV taking into account the modifications due to updated avionics.
- One-Failure Tolerance.

DOI: 10.13009/EUCASS2019-1016

- Flight through the transonic phase for subsonic parachute deployment.
- Aerodynamics during TAEM challenged by blunt body nature of the shape, vehicle stiffness and limited trajectory authority (low L/D).
- Operation of the Reaction Control System (RCS) besides the elevons until low altitudes (~15 km).
- Accurate navigation down to landing to support the new phases: TAEM and Descent & Landing.
- Navigation initialization in orbit before separation.
- On-board Air Data System (ADS) replaced by updates of the o/b wind table
- Precision landing under parafoil (< 150m in 99.5%ile).
- Soft landing on ground, i.e. with low vertical velocity at touchdown.
- Autonomous operation.
- Implementation of Failure Detection, Isolation and Recovery (FDIR) for all mission phases High degree of parameterization for missionization.
- Multimodal operational architecture to cover 4 different phases: Coasting, Entry, TAEM and Descent and Landing.
- Design to cost

4. GNC Physical Architecture

Table 1 shows a summary of the sensors and actuators onboard the SR-RM.

Table 1: summary of sensors and actuators required by RM GNC

Type	Unit	Number
Sensor	GPS	2
	IMU	2
	Radar altimeter	2
	Star Tracker	2 (on AOM before separation)
Actuator	Elevon	2
	Thrusters	4
	Parafoil	1

In the Space Rider RM a GNSS receiver of the same characteristics as the one used in IXV is required; since this sensors drives the required horizontal accuracy at landing, two redundant units are employed. The postflight of IXV has shown a reduced GNSS blackout period (between 81 and 60 km), which ensures the reacquisition of the GNSS well in advance to the end of the entry phase, improving the accuracy of the aerodynamic angles estimation. Another GNSS partial loss or degraded performance might happen during TAEM, due to the vibration environment.
Two IMUs with 1553Bus interfaces in hot-redundancy are selected, to be hybridized with the GNSS receiver during the TAEM and Descent & Landing phase. Hybridization is will improve the required attitude accuracy to counteract the IMU accumulated errors.
The radar altimeter provides submetric height accuracy to support the final approach and the flare maneuver, which is critical to keep the vertical velocity at touchdown within landing gear limits. Two redundant equipment with aeronautical heritage have been selected.
Winds need to be known on-board during the TAEM due to the narrow corridor during the transonic phase and for the triggering of the parachute. During the approach and landing wind knowledge is also required to ensure headwind landing. The required accuracy can be achieved with pre-loaded wind tables updated using balloons and local data.
The star trackers are used in orbit by the AOM Navigation function to ensure high accuracy attitude estimation. There are used before the separation, either directly or through the AOM navigation solution to initialize the RM Navigation function before the de-orbit maneuver. They are not/cannot be used as part of the RM GNC sensor suite during the re-entry.
The same elevons as in IXV will be mounted with a revised mechanical design and the same electromechanical linear actuator with no redundancy.
In terms of thrusters, following the lessons learned from IXV flight some modifications have been introduced. In particular, the position has been shifted and the tilt angle changed with respect to the back cover to minimize the residual torques. In addition, even if the thruster unit is the same as in IXV, the inlet pressure rating has been reduced to avoid over actuation and to reduce the Minimum Impulse Bit (MiB) in orbit. The feasibility of these modifications requested by the RM GNC has been confirmed at system level and hence baselined for Space Rider. Figure 2 shows the reduction in the coupling between roll and yaw torque during the coasting phase using the new RCS layout. At

DOI: 10.13009/EUCASS2019-1016

current stage, the operation of the thruster at low altitude compared with IXV, i.e. at higher ambient pressure, has been confirmed.

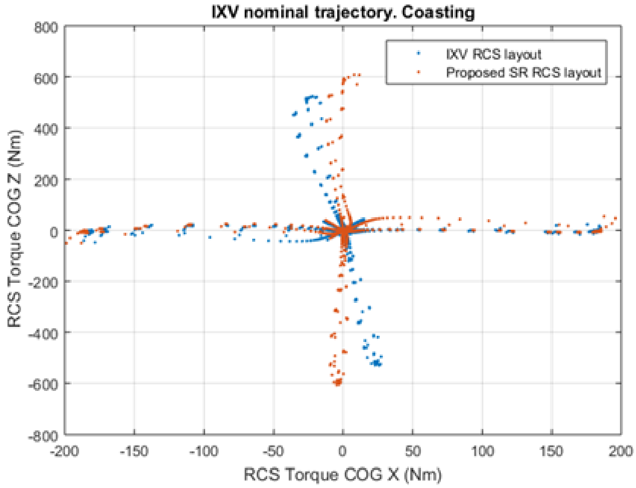

Figure 2: Yaw and roll coupling during coasting: IXV RCS layout vs proposed Space Rider RCS layout

5. GNC Functional Architecture

The SR GNC functional architecture is presented in Figure 3. This functional architecture is inherited from the IXV architecture and extended to cover the new phases (TAEM and Descent & Landing) and new functionalities (FDIR). The GNC is composed of the core functions Guidance, Navigation and Control and the GNC Manager functions:

- **Navigation:** this function consists of a navigation position and attitude estimate solution served primarily by IMU products fused with a GNSS and a radar altimeter.
- **Guidance:** this function consists of a guidance algorithm whose aim is to define the trajectory during entry and TAEM until chute opening and during the approach and landing under parafoil to perform precision landing.
- **Control:** the control algorithm may operate in distinct modes dependent on the GNC phase and available actuators. In general, the control tracks the guidance trajectory and ensures a stable attitude, using the effective actuators for the phase.
- **GNC Manager:** the GNC manager receives flags from the Mission Vehicle Management (MVM), manage the execution of the Guidance Navigation and Control functions and reports the execution to the MVM. The GNC Manager includes the following major subfunctions as depicted in Figure 4:
- **Flight Management**: this function is in charge of analyzing both the internal status and data from all the other functions, performing the RM GNC modes manager, and interfacing with the MVM.
- **Event Triggering**: this function is in charge of triggering of events (i.e. parachute deployment and parafoil deployment).
- **FDIR Management**: this function is in charge of performing the monitoring at RM GNC level for FDI, and coordinates recovery actions at the RM GNC level. The function interfaces with MVM and FM & triggering, which are considered to provide the system level FDIR information and actions. The FDIR Management will not interface directly with the on-board units for their FDIR info, provided instead through MVM and FM.

DOI: 10.13009/EUCASS2019-1016

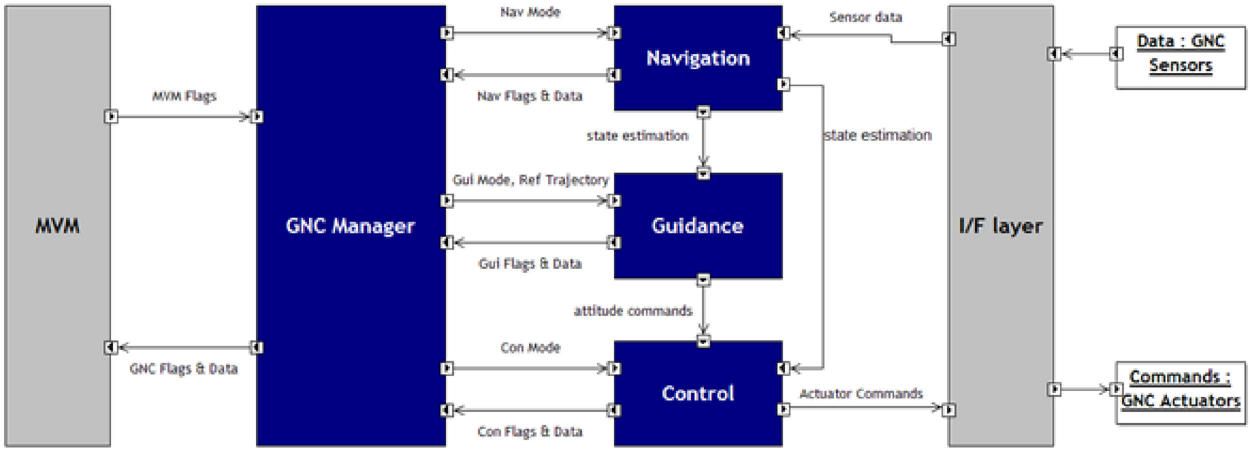

Figure 3: RM GNC functional architecture

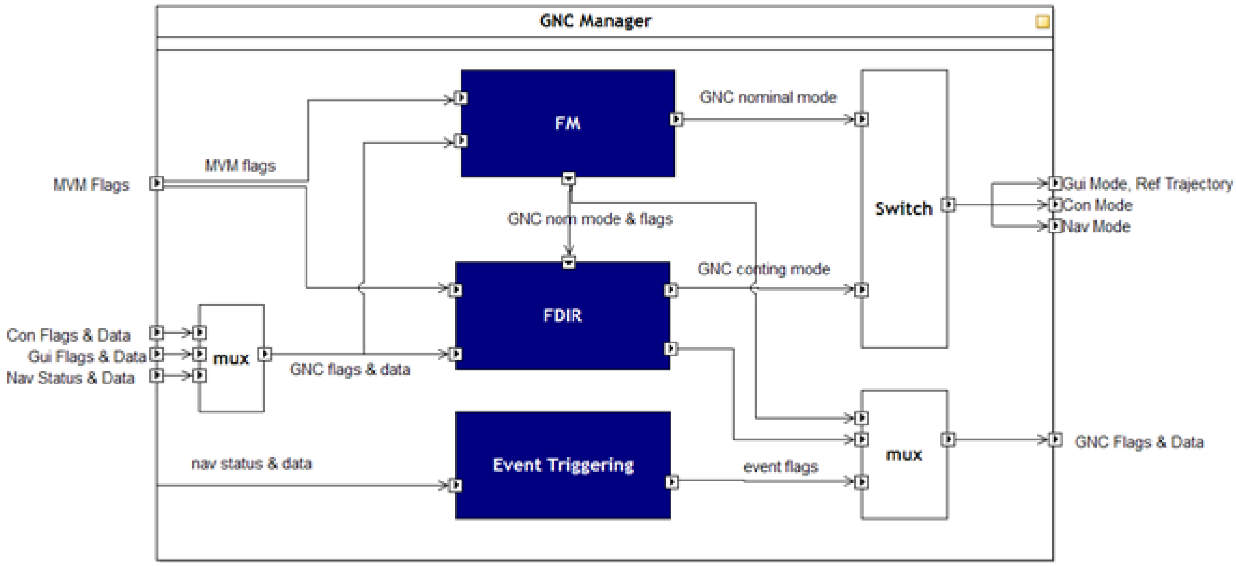

Figure 4: GNC Manager components and internal interfaces

6. GNC Modes

After the separation of the RM from the AOM, the SR GNC starts autonomously the operation to bring safely the Space Rider Re-Entry vehicle to the landing site. The Space Rider Ground Segment activity is mainly limited to the monitoring of the received telemetry and to providing to the vehicle updates of the on-board wind parameters.
The following modes are defined for the SR-RM GNC:

- Pre Separation Mode (PSM)
- Coasting Mode (COM)
- Entry Mode (ENT)
- Terminal Area Energy Management Mode (TAEM)
- Descent and Landing or Parafoil GNC Mode (DLM or PGNC)

Therefore, the RM GNC modes are executed in waterfall sequence starting from the separation AOM separation up to the landing, implying that once the re-entry phase starts it is not possible to put it on stand-by (i.e. no safe mode, for mode reconfiguration can be executed). Table 2 reports the map of the RM GNC Modes, Sub-Modes and the functions activated for each mode.

Table 2: RM GNC modes, submodes and functions

Mode	Submode	Functions
Pre-separation	Navigation initialisation	G: None N: NAV init C: None
Coasting	Attitude Control Low Precision	G: Orbital N: Orbital C: Att Ctrl LP
	Attitude Control High Precision	G: Orbital N: Orbital C: Att Ctrl HP
Entry	Re-entry Off-line	G: Entry OL N: Entry C: Entry Control LP
	Transition LP to HP	G: Entry OL N: Entry C: Entry Control HP
	Re-entry On-line	G:Entry CL N: Entry C: Entry Control HP
TAEM	TAEM On-line	G: TAEM CL N: HYB C: TAEM Control HP
	TAEM Pre-chute	G: Pre-release N: HYB C: TAEM Control HP
Descent and Landing	Descent	G: None N: HYB OL C: None
	Approach and Landing	G: A&L CL N: HYB +RADAR C: A&L CL

6.1. Pre-Separation Mode

PSM is entered upon TC reception. The prerequisite for the execution of this GNC mode is that the IMU, GNSS and STR sensor (located on the AOM) are active and providing time tagged data to the GNC. Calibration is performed on the nominal and redundant IMU using nominal and redundant GNSS sensors.

The PSM is mainly aimed at initializing the GNC Flight Manager and Navigation. For this purpose, it will execute the following tasks: i) collect the measurements of the sensors of the SR-RM and SR-AOM for a predefined time; ii) compute the calibration parameters (mainly of the IMUs) required by the navigation function, accounting for sensors' delays; iii) perform the navigation function, making use of the calibrated SR IMU and GNSS. The mode is exited at the separation of the RM from the AOM.

6.2. Coasting Mode

The COM is continuous and once initiated the transitions occurs autonomously. The GNC algorithm concepts from IXV are considered to be fully applicable for Space Rider in the Coasting phase. They can be extended and adapted for use in the COM Space Rider GNC mode. The main differences wrt the IXV are dure to:

- Consideration of the FDIR function
- Differences in the priming strategy wrt IXV
- Shorter orbital arc
- Higher system inertia leading to a longer duty cycle (beneficial)
- Reduction of residual forces and torques due to the RCS layout proposed for SR (modified wrt IXV)
- Space Rider coasting Navigation will run at 20 Hz and not at 2 Hz.

DOI: 10.13009/EUCASS2019-1016

After separation from the AOM, and availability of the RCS, a low-precision attitude control mode is activated until an altitude of 175km. This is followed by high-precision attitude control from am altitude of 175km down to 120km altitude. The coasting mode exit condition is triggered when the vehicle reaches 120km of altitude.
In order to reach the Entry Interface with the correct attitude the COM guidance function will interpolate a predefined attitude quaternion profile, for the computation of the reference orientation of the vehicle during the ballistic arc. The navigation function will run at 20Hz and will make use of IMU measurements at 200 Hz and GNSS ones at 1 Hz. A ballistic navigation based only on position and velocity propagation (discarding accelerometer measurements) will be used when the non-gravitational acceleration derived from IMU measurements is below a certain threshold. The inertial navigation is activated when the estimated acceleration trespasses/exceeds the pre-established threshold in order to take into account the effect of maneuvers. Once accepted as valid the GNSS measurements will be employed in order to reset/reinitialize the position-velocity estimation. The GNSS measurements are checked for validity by comparing their propagated covariance with the inertial navigation expected error. IMU measurements are also used to compute the SR-RM attitude.

6.3. Entry Mode

Given the similarity of the GNC requirements for the re-entry phase between IXV and Space Rider, no major changes are found in the Space Rider Entry Guidance and Control functions. The IXV re-entry Guidance and Control concept is applicable to the Space Rider Entry GNC for the hyper/supersonic flight phases, down to Mach 1.6.
The Entry navigation function is similar to the Coasting one. During Entry, in addition, drag-derived altitude measurements are used to update the inertial navigation in the range in which they can improve the solution.
Changes and revisions impacting the Entry GNC algorithms are limited to:

- The inclusion of a switching strategy between the different GNC functions;
- I/F adaptation;
- New modes strategy definition;
- FDIR scenarios to be taken into account;
- Missionization of the Guidance.

The requirement for One-Failure-Tolerance drives the need for FDIR capabilities and for some reconfiguration capabilities, which are taken into account in the Navigation, Guidance and Control functions.

6.4. TAEM Mode

The Terminal Area Energy Management phase is one of the most important ones of the Space Rider GNC. This flight phase was not flown by IXV, and it is characterized by an aerodynamic regime which is highly complex and difficult to model and characterize. The TAEM GNC is developed under responsibility of Elecnor-DEIMOS, and has been one of the focal points of activity during the project work in Phase B and C.

The guidance concept of the TAEM Mode makes use of a trajectory generator and a trajectory tracker (Figure 5), as proven in IXV. The trajectory tracker performs tracking of a reference trajectory in both position and velocity, to command the TAEM Control, while the trajectory generator relies on an offline strategy. The objective of the TAEM guidance in this phase is to steer the vehicle toward the desired target point for parachute triggering, and to limit the heading dispersion, in order to align the vehicle to the desired direction for parachute triggering and by also respecting trajectory constraints.
The trajectory generation function provides the reference trajectory from an offline pre-computed lookup table interpolated using the Mach number as independent variable. The trajectory is stored in terms of Position/Velocity and trimline AoA profiles. The reference state needed by the trajectory tracker is composed by the reference position in local reference frame (East-North-Up), its first and second derivative with respect to time (velocity and acceleration in the local relative frame), and the reference angle of attack.
Trajectory tracking algorithm couples the 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. A formulation based on non-linear dynamic inversion (NDI) principles allows the computation of the guidance commands, making use of the extensive heritage and simplicity of this algorithm approach. An NDI-like approach is also used in the Re-entry phase, with IXV heritage. The bank angle is the main command, and is the only command needed to track the reference trajectory. A complete analytical formulation is used to compute the reference command. No on-line optimization is required.
After trajectory tracking, the Flight Control System (FCS) Command Generation function filters the desired bank command depending on possible limitations (e.g. rate limitations) coming from the Control. It also computes the

DOI: 10.13009/EUCASS2019-1016

reference AoA command, based on the trimline, in order to track the desired aerodynamic state computed by the tracker.

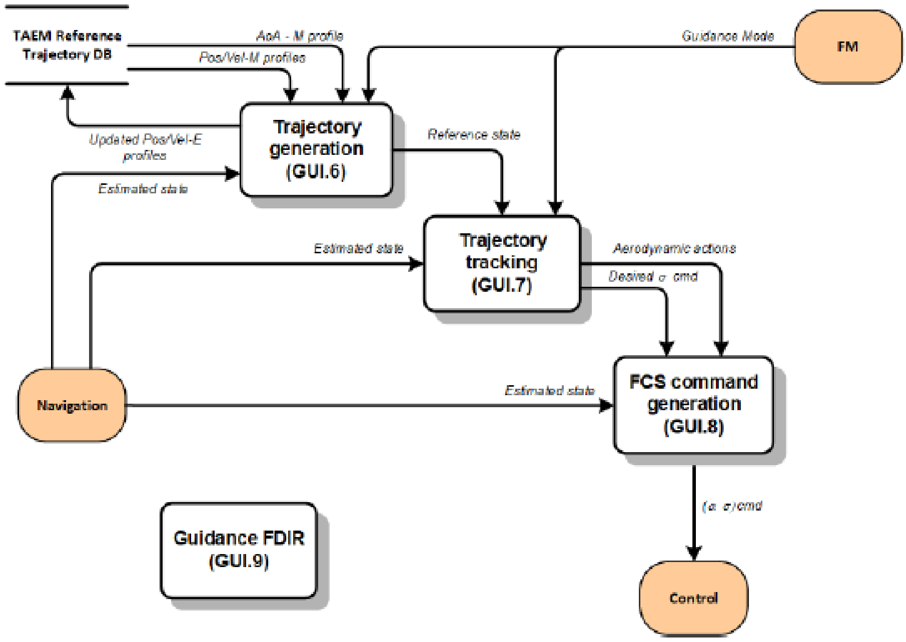

Figure 5: Functional architecture of the Closed-loop TAEM Guidance (Elecnor-DEIMOS)

The objective of the TAEM navigation function is to provide an estimation of the current state of the vehicle, in terms of position, velocity, attitude, and also the necessary derived products, such as angle of attack, sideslip, bank, body angular rates, Mach, drag, lift, velocity and dynamic pressure.
The baseline approach is a Navigation solution for both attitude and translational states, using a coupled system, in which the INS algorithm is hybridized through a filter, using the observations provided by the IMU and GNSS receiver. An Inertial Navigation System function inertially propagates the IMU measurements for both attitude and translational state (position and velocity). The gravitational acceleration is computed in order to update the velocity and position of the vehicle. This function computes also the state of the vehicle in spherical coordinates. Eventually a covariance matrix of the state is computed, as it will be used inside the GPS filter function. The Inertial Navigation System makes use of a strapdown mechanization of the equations of motion based on the midpoint method, propagated in ECI Frame. The GPS filter function within the TAEM Navigation receives the GPS Position, Velocity and Time (PVT) measurements, together with the navigation estimated state computed by INS function, and pass them to a filter to improve the estimation of the navigation state. The GPS filter relies on ordinary Extended Kalman Filter algorithm. An on-board wind table is used to estimate the wind experienced by the vehicle and compute air-derived properties as aerodynamic angles, velocity, dynamic pressure, Mach, etc. Finally, a state fusion function applies filters to output variables to TAEM Guidance and Control functions.

The baseline approach for the TAEM Control is the reuse of the IXV Re-entry controller, further adapted and modified to be suitable for the TAEM mission phase in order to exploit as much as possible the IXV heritage. The TAEM Control includes the hybridization approach for the RCS and ASCS (flaps); the RCS actuator is required in order to permit bank tracking with turn coordination and rejection of disturbances.
The control function in this mode has separate feedforward open-loop and feedback closed-loop components.
The feedforward component provides the actuator command necessary to perform the large bank maneuvers during the atmospheric flight (coordinated turns), used to achieve the translational trajectory corrections requested by the guidance function. This feedforward control is based on an inverted linear model of the vehicle. It works in an open loop fashion with regards to the controlled variables, but makes use of some flight conditions, such as Mach, dynamic pressure, velocity, lift acceleration and flight path angle. Onboard lookup tables are used to estimate the stability derivatives of the vehicle during the flight required by the linear plant inversion.
For the feedback controller, although the design is fully coupled, due to the use of different estimated states the implementation of this element can be shown by separation of the longitudinal controller from the lateral/directional controller.
The longitudinal control law computes the desired Elevator deflection (or RCS moment), based on the commanded and the estimated variables

DOI: 10.13009/EUCASS2019-1016

$$\delta_e(s) = K_{q,i}^{long}(s)\big(\alpha_c(s) - \alpha_m(s)\big) + K_{\alpha,i}^{long}(s)\big(q_c(s) - q_m(s)\big) \quad \textbf{(1)}$$

For the design of the controllers $K_{q,i}^{long}$ and $K_{\alpha,i}^{long}(s)$, the plant is linearized at given points, i, within the trajectory and, for each LTI plant, a controller is synthesized based on robust control theory.
The approach for the lateral/directional control law design is similar to the one derived for the longitudinal dynamics. The lateral/directional controller is a MIMO one, as the lateral and directional dynamics are strongly coupled. Also in this case the plant is linearized at given points, i, within the trajectory, and a controller is synthesized based on robust control theory, but in this case considering the different transfer functions of the MIMO system.
A controller switching scheduling approach is adopted in which the different synthesized controllers are scheduled based on the estimated velocity interval at each time.
The feedback control loop is fed by a Trim Computation function, which provides the aerodynamic actuators trim profile based on the current flight conditions. It is implemented in open-loop based on stored loop-up-tables. Further trim errors will be corrected by the feedback control.
The control actions coming from the Feed Forward, Trim Computation and Feedback, are distributed between the elevons and the RCS by a specific Control Allocation function. The rationale for this allocation is based on the concept of maximizing the use of the elevons against the RCS whenever possible due to its accuracy and efficiency, and the need to limit the consumption of RCS fuel. Control allocation is only applicable for control around the Pitch and Roll axes, where Flaps can actuate. Control around Yaw will always be performed by the use of RCS. The total control action is summed and distributed to virtual elevon and aileron controls; when these virtual actuators are saturated, the remaining action is distributed to the RCS taking into account the relative gain ratio between flap and thrusters efficiency (depending on flight conditions, and precomputed offline).
The functional architecture of TAEM control is shown in Figure 6.

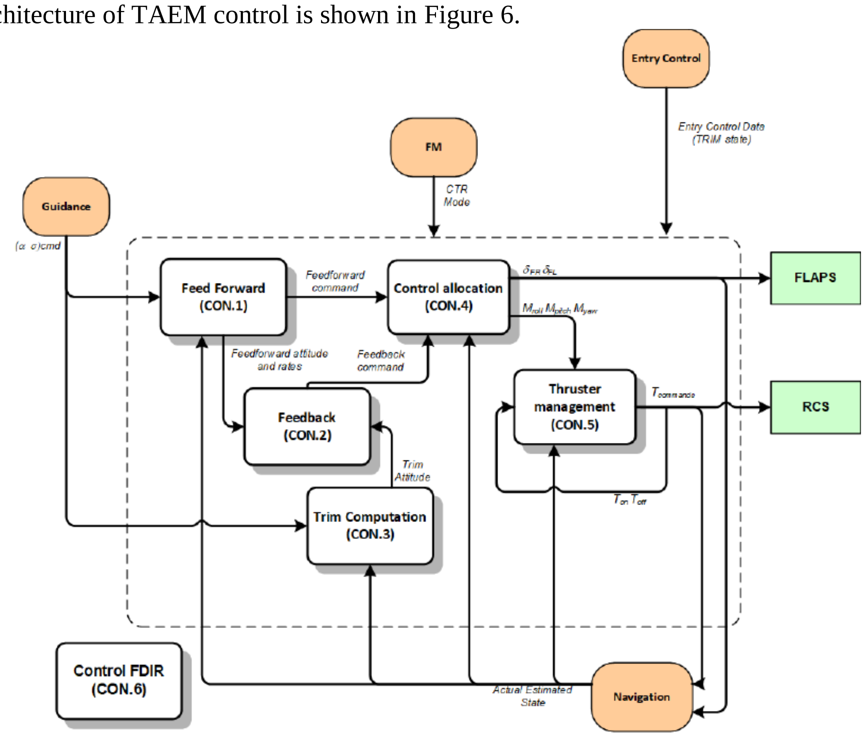

Figure 6: TAEM Control functional architecture (Elecnor-DEIMOS)

The drogue chute triggering event falls within the Entry and TAEM GNC phase. The DRS (Descent and Recovery System) triggering algorithm concept from IXV is considered to be applicable to Space Rider, for what concerns the triggering of the subsonic drogue sequence at the end of the TAEM phase, after being adapted and extended, taking into account the DRS box constraints for the chute chosen for Space Rider.
The DRS Triggering TG1 algorithm includes MAIN and ULTIMATE logics. The MAIN logic triggers the start of the DRS sequence in nominal conditions. The arming logic has been adapted to the Space Rider trajectory, and the triggering logic has been adapted to the current baseline DRS target Mach defined for Space Rider.
An ULTIMATE logic, available as needed and not currently activated, to trigger the DRS in case of failure in the MAIN chain. The drogue triggering main logic has an arming stage, ensuring nominal navigation performances, sufficient time from EIP and enter in the pre-release mode. The main trigger stage is based on a combination of Mach number and Dynamic pressure.

DOI: 10.13009/EUCASS2019-1016

6.5. Parafoil-GNC (Descent and Landing) Mode

The Parafoil GNC (also indicated as Descent and Landing) mode is started at the end of the drogue triggering, and is in charge of the flight phase under parafoil, from deployment of the parafoil itself, until landing is detected.
This mode shall compensate for the dispersion at the be-ginning of the descent accumulated during hypersonic and supersonic phases and shall ensure a soft landing and safe ground roll with no lateral loads. Wind management is one of the main challenges due to the lack of a dedicated Air Data System. Thus, adaptiveness and prediction are key elements in the GNC design.
The Parafoil GNC (PGNC) design is based on a two control loops approach (inner and outer), where the inner loop commands the required vehicle attitude to tack the guidance profile and the outer loop sends the control surfaces deflection commands to the parafoil lines to obtain the required turn and descent rates.
The guidance in this mode is based on the definition of Waypoints (WPs) and follows common phases from Parafoil Air Drop Systems guidance literature. To base the strategy on the selection of opportune WPs is suitable for Space Rider program since it allows splitting the energy management into two phases in order to satisfy safety constraints. A first waypoint, WP1, is foreseen in order to lose if necessary the excess energy (altitude) after deployment and trim, staying above the maximum height of the flyable zone for landing. The second waypoint, WP2, is placed close to the landing zone, and it is employed to descend down to the altitude required to start the terminal guidance that will lead to the landing site and to the execution of the flare maneuver to achieve touchdown.
The guidance logic is independent from WPs in the sense that the guidance algorithm does not need dedicated solutions if WPs locations change. In this way, WPs can be selected taking into account the wind conditions of the landing area and the safety constraints, and the guidance will still be valid without changes.
The trajectory is planned in the horizontal plane and the influence of wind is removed by working in a wind-fixed coordinate frame; this allows simplifying the guidance planning and control effort, but implies the “deformation” on the trajectory when it is observed from a fixed frame relative to the ground.
The summary of the PGNC guidance sub-phases are shown in Figure 7 and are as follows:

- **Trim**: remove residuals after parafoil stabilization and perform system identification.
- **Waypoint (WP) acquisition**: turn to acquire the track toward the first waypoint.
- **Loiter**: descent down to the maximum safety altitude allowed to enter into the landing site area.
- **Homing**: turn to acquire the track toward the second waypoint.
- **Energy management**: descent to acquire the condition for the terminal guidance.
- **Terminal guidance**: traffic pattern to turn from downwind conditions to final approach headwind composed of 3 sub-phases:
    - Downwind: downwind leg.
    - Base: turn from downwind to final conditions.
    - Final: stabilized descent targeting the designated landing point.
- **Flare**: maneuver to control the vertical velocity during touchdown.

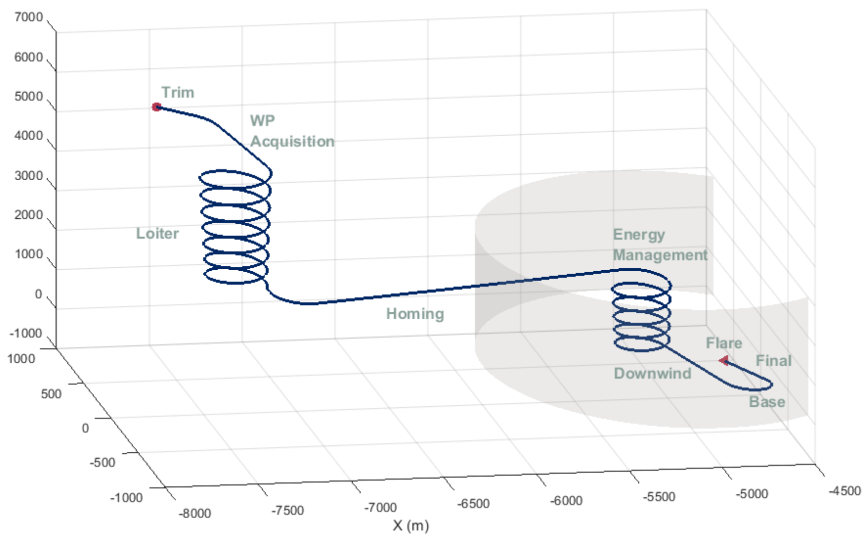

Figure 7: PGNC Guidance scheme

DOI: 10.13009/EUCASS2019-1016

The guidance is designed in order to arrive close to the target areas (WP2 and landing site) as soon as possible, lose energy close to the target points and correct for the uncertainties during the terminal phase, while approaching the desired landing point. The guidance logic of each phases is described below.

Trim

After drogue parachute release and parafoil deployment, the GNC waits for system stabilization and identifies the main system parameters. When conditions for stability are satisfied (e.g. angular rates below a defined threshold) guidance switches from Trim to WP acquisition.

Waypoint acquisition

The objective of this phase is to guide the system from wherever the trim of the system is completed to the first WP. Provided that the system has enough energy to acquire this WP, the time employed to arrive is not critical. For this reason, the course error will be corrected by applying a constant yaw rate until the difference between the target heading and the current heading (based on wind-fixed coordinates) falls below a predefined threshold.

Once the difference enters this band, a closed-loop guidance function will correct the small deviations with respect to the target heading. This logic simplifies the control effort, allows to select a suitable turn rate and is accurate enough for this phase. The formulation of the guidance is in wind-fixed coordinates. It should be remarked that uncertainties coming from wind knowledge have limited impact since the mission of this phase is to lose height before entering the flyable zone near the landing site.

Loiter

Once the desired course is acquired, the system flies towards the WP1. When its distance to the WP is equal to a design value, guidance commands:

A δ degrees left turn at constant yaw rate. Selecting the proper yaw rate, the vehicle acquires the tangent direction of the cylinder in which it will descent.

Constant right turn rate in order to descent following a helix. The commanded heading rate is related with the radius of the helix as follows:

$$\dot{\chi} = \frac{V_h}{R_{WP}} \quad (2)$$

where $\dot{\chi}$ is the heading or turn rate, V_h is the projection of airspeed on the horizontal plane and R_{WP} is the radius of the helix around WP1.

The exit conditions from the Loiter phase are:

1. the airspeed shall point towards the landing point
2. the current altitude is such that, after completing a turn, the final altitude would be below the one needed to reach the landing site,

If both conditions are met, then SR must exit the helix and enter into homing.

Homing

Homing is the phase connecting WP1 with the WP2 and thus the landing site. It is a combination of WP acquisition and helix acquisition.

The guidance commands the heading and heading rate to acquire the track to the landing site. Homing finishes by performing a maneuver equivalent to the loiter helix acquisition in order to enter in the Energy Management (WP2) phase.

Energy Management and Terminal Guidance

The objective of Energy Management phase is to reduce the altitude of SR system close to the landing site. It consists, again, in describing a helix at WP2, close to the landing point. EM finishes when the altitude of SR is enough to perform the turn to base to face the final approach upwind, in order to reduce the system velocity with respect to ground. Therefore, it is critical to exit the turn to base with the airspeed aligned to the wind speed but with the opposite orientation.

During the final approach, the GNC will correct the misalignment to the wind at the beginning of the sub-phase and to conduct a range control in order to improve the landing accuracy. Finally, when the system is a few meters above the terrain, the flare maneuver is triggered to reduce the impact velocity and satisfy the landing conditions.

Figure 9 shows horizontal and 3D views of an example of PGNC trajectory to Kourou.

DOI: 10.13009/EUCASS2019-1016

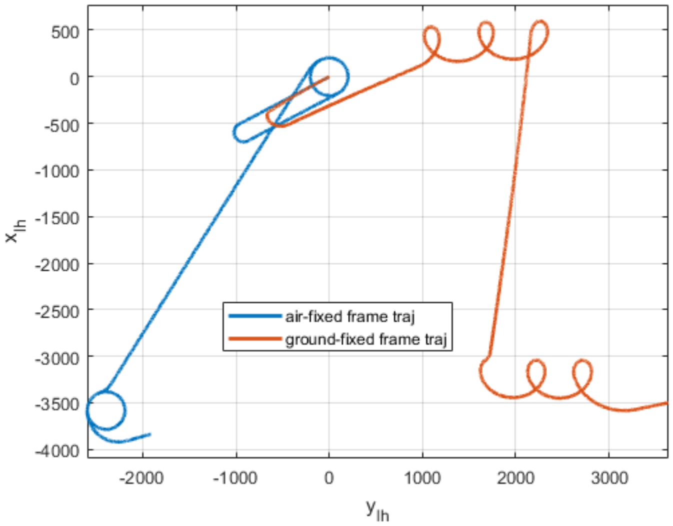

Figure 8: PGNC Guidance strategy - Horizontal view

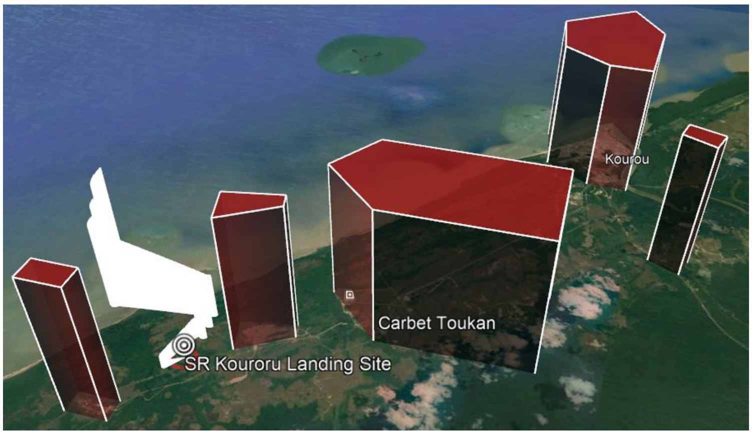

Figure 9: PGNC Guidance strategy 3D view

The main purpose of the Descent and Landing (D&L) Navigation function is to provide the estimates of position, velocity and attitude (which can be turned into several derived parameters, e.g. Mach number, aerodynamic angles, body angular rates, body accelerations), using the outputs of the selected navigation sensors.
The approach in the D&L Navigation function consists of a hybrid navigation, using the IMU measurements to propagate inertially the navigation solution, and GNSS measurements when available to improve the solution (i.e. correct the navigation states).
The IMU Pre-processing receives the IMU measurements that have been stored in a buffer from the last Navigation cycle, and prepares this data to be used at each Navigation cycle. As the IMU is providing measurements at 200 Hz and the D&L navigation runs at 20 Hz, the buffer in the OBSW will provide 10 consecutive IMU measurements at each Navigation cycle.
The GNSS position and velocity in ECEF, necessary in the Kalman Filter, are taken directly from the GNSS receiver processor, and transformed into ECI reference frame. After that, these measurements are corrected in order to take into account the delay in the produced GNSS observables. This correction is performed by extrapolating the position and velocity provided by the GNSS to the current navigation epoch. This extrapolation is performed using the states of the inertial navigation system at the current navigation epoch and at the GNSS time-tag.
At the end of the re-entry, just before the landing, the altimeter measurements are needed to provide better altitude estimation in order to trigger the flare and improve the landing approach if possible. In fact notice that the GNSS will provide measurements with respect to the WGS84 ellipsoid, while the altimeter will allow estimating the altitude with respect to the local terrain, which is required for a successful flare.
The current D&L Navigation runs at 20Hz.

DOI: 10.13009/EUCASS2019-1016

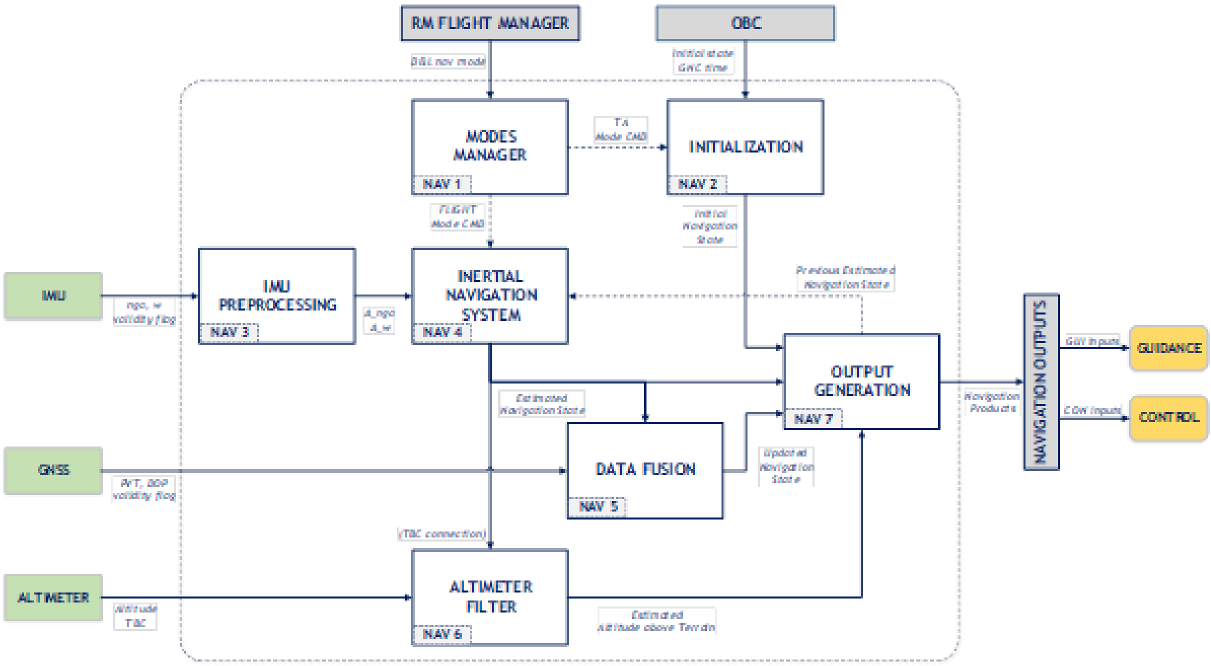

Figure 10: Space Rider RM PGNC Navigation functional architecture

The PGNC control is based on two loops: an outer loop on trajectory control, to correct for heading and attitude error, and an inner loop to compute the parafoil symmetric and asymmetric strokes required to obtain the heading rate and flight path angle requested by the outer loop. The functional architecture of the PGNC control is shown in Figure 11.

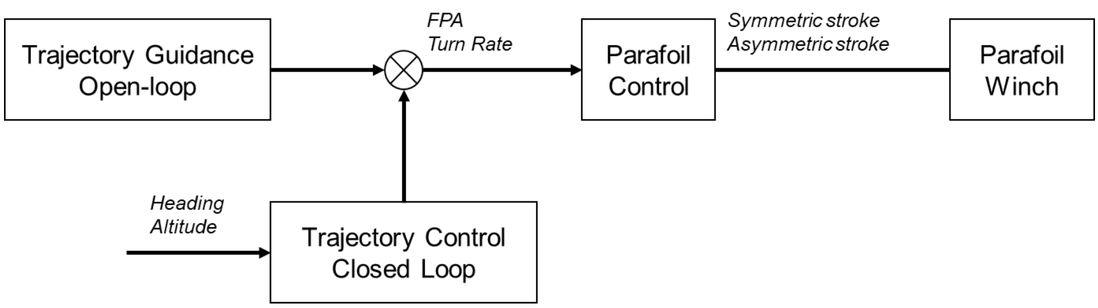

Figure 11: PGNC control functional architecture

The PGNC control is formulated based on a linear parameter varying plant (LPV) plant which is obtained by linearizing the equations of motion of a about a rotating reference frame. Based on this linearization, it is possible to design a feedback control law based on H_∞-techniques, which maps the turn-rate error (i.e. commanded minus estimated) into asymmetric deflection stroke of the parafoil. In the same fashion a controller was designed for the Flight Path Angle (FPA) control, which tracks the reference FPA by commanding symmetric stroke deflections of the parafoil lines.
The closed-loop trajectory control (outer loop) is employed in the final leg of the terminal guidance leading to the flare, in order to ensure the correct heading and altitude (or, distance to landing point at which the flare altitude is reached).
The inner loop for parafoil control features a decoupled turn rate and FPA controls. These control channels act both on the parafoil line strokes, and are combined only in the terminal guidance leg up to flare.
For the inner loop, in order to allow controlling the trajectory FPA (i.e. both increasing and decreasing it), a symmetric stroke of 30% is commanded as operation reference. Here the transition from null symmetric stroke to the 30% reference stroke is commanded slowly enough to ensure that transient effects are minimized.

DOI: 10.13009/EUCASS2019-1016

7. FDIR

FDIR Management is the GNC component in charge of implementing the FDIR functionality in the Space Rider Re-entry Module GNC subsystem. It is in charge of monitoring the GNC subsystem, not only the different GNC components, i.e. Guidance, Navigation and Control; but also the sensors and actuators from the GNC point of view in order to support the system FDIR. This monitoring is intended for the detection and identification of failures, the application of pre-defined recoveries at GNC subsystem level and reporting of them to System.
The GNC FDIR functionality is mainly focused on the monitoring of GNC sensors and actuators available during the different phases of the SR RM mission.
While there is a dedicated FDIR Management in the GNC, some of the FDIR functionality will be allocated in the GNC functions, to reduce the complexity of data exchange between functions, and provide the GNC functions quicker access to the measurement data (without having to process them through the FDIR Management, which would add delays to the measurement data). This FDIR functionality in the GNC functions will be limited to sensor and actuator monitoring, measurement validity checks, command validity checks and checks regarding data provided by other GNC functions.
Sensors and actuators do not have a direct interface to the FDIR Management. Management and then recoveries based on unit reset or reconfiguration shall be managed by System based on GNC FDIR outcomes.
Recovery actions are constrained by the type of mission, and phases and by the available sensors and actuators. Due to the nature of the mission, autonomous re-entry, descent and landing vehicle, some of the recovery levels will not be applicable during certain phases of the mission. This is constrained by the time criticality of certain phases.
IMU and Altimetry sensors are in hot redundancy, and GNSS will be in "warm" redundancy. For such sensors during the re-entry, descent and landing the switch to redundant unit could be considered as recovery action.
The parafoil actuators are not redundant, and as such, any failure regarding this element shall be evaluated by the FDIR, and a restart commanded. If after the mitigation actions are taken, the parafoil is still failing (due to an incomplete opening or failed restart of the parafoil control unit) the unit shall be declared unhealthy, and the failure elevated to System. As an informative note, the action to take regarding any failure of the parafoil system has potential Safety related implications, and as such, ground operators will be standing by to command the actuation of Parafoil bridles cutters if deemed necessary.
RCS thrusters and vehicle elevons no redundancy is considered and therefore, the recovery actions to be proposed could be based on unit reset, if possible and feasible.
The FDIR Management component takes into account the implementation of the FDIR based on 4 main hierarchical levels (Level 0, Level 1a, Level 1b and Level 2) characterized by the recovery action proposed, as follows:

- **L0 No Recovery Action**: Unit or function is capable of autonomous failure detection and recovery.
- **L1a-Unit/function recovery by FDIR**: Either by reset or re-initialization of the unit or function.
- **L1b-Unit substitution or reconfiguration**: Whenever a unit or function is not responding a redundant unit is used instead.
- **L2-System Recovery**: System and Spacecraft mode change to contingency mode.

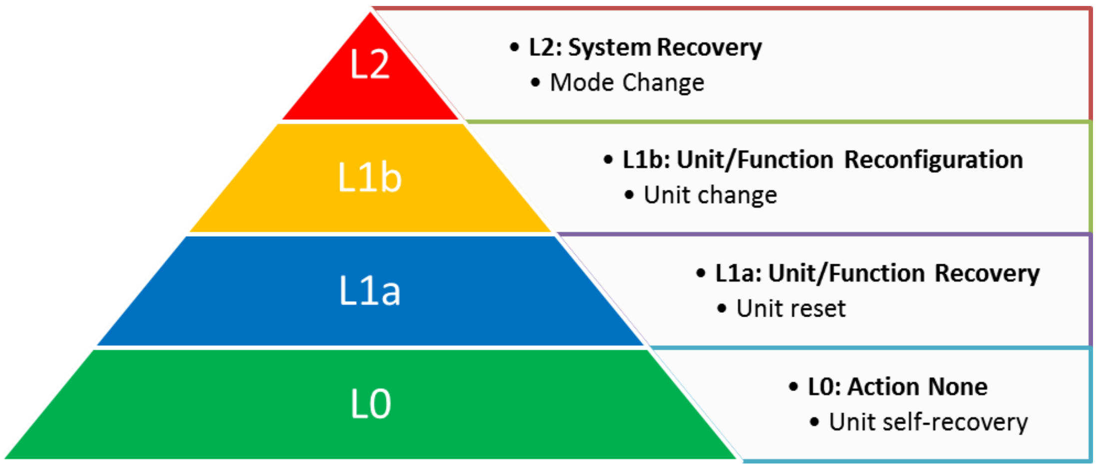

Figure 3 1 FDIR General Approach (GMV)

8. Acknowledgments

This work has been carried out in the frame of the Space Rider programme of the European Space Agency with Thales Alenia Space Italia and Avio as Prime contractors. In this context, SENER is the lead contractor for the Re-entry Module GNC with GMV (Spain) and Elecnor-DEIMOS (Spain and Portugal) as subcontractors.

9. References

[1] G. Tumino et al, The IXV experience, from the mission conception to the flight results, Acta Astronautica 124 (2016) 53–66

[2] V. Marco et al, The IXV guidance, navigation and control subsystem: Development, verification and performances, Acta Astronautica 124 (2016) 2–17

[3] R. Haya, V. Marco and M. Kerr, Flight Demonstration of Re-Entry GNC in the Intermediate eXperimental Vehicle (IXV), Advances in the Astronautical Sciences. Guidance, Navigation, and Control 2017, Volume: 159, AAS 17-092

[4] R. Haya et al, Design Of The Pinpoint Landing GNC Of Space Rider, IPPW 2019 International Planetary Probe Workshop 2019, Oxford, UK

[5] R. Haya et al, Re-Entry GNC Concept For A Reusable Orbital Platform (Space Rider), 69th International Astronautical Congress, Bremen, Germany, IAC-18,D2,5,2,x48560

[6] R. Haya et al, Systems engineering for the GNC of the Re-entry Module of Space Rider, HiSST: International Conference on High-Speed Vehicle Science Technology 26–29 November 2018, Moscow, Russia

[7] R. Haya et al, Mission And Gnc Challenges From Ixv To Space Rider, The 14th International Planetary Probe Workshop (IPPW-14)