REVLANSYS: MISSION AND GNC DESIGN OF TERMINAL ENTRY AND LANDING MISSIONS FOR ADVANCED RE-ENTRY VEHICLES

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ABSTRACT

The ESA REVLANSYS study aims to develop key technologies in the field of Mission Engineering and GNC for autonomous re-entry vehicles, and to derive coherent mission, system and GNC requirements for the specific terminal entry and landing phases. As such, REVLANSYS will provide support to European activities towards an autonomous end-to-end mission for a reusable re-entry system, as the SPACE RIDER, with the objective of performing an end-to-end design of the Terminal Area Energy Management (TAEM), Descent, and landing phases. A preliminary design activity was carried out to evaluate different solutions, including winged vehicles landing on a runway and lifting bodies performing a soft landing with a parafoil. A Multidisciplinary-Design Analysis and Optimization process (MDA-MDO) has been implemented as the instrument to evaluate the performance of the different concepts as a function of key design parameters, and produce optimized solutions that have been traded-off to identify the best option for a detailed Mission and GNC design. A Guidance method has been developed to provide trajectory generation capability from TAEM until landing, and a hybrid Navigation system has been tailored. Mission and GNC performance have therefore been assessed in terms of flying qualities, trajectory, Guidance and Navigation, considering a high fidelity simulation environment adapted to the TAEM and landing scenario. This study resulted in the design of a Mission and GNC solution for the terminal entry and landing phases of a return mission, consistent with the overall mission needs. Also, it allowed identifying the capabilities of the detailed design solution, and the possible limitations and improvements that are necessary to achieve a complete and robust mission and GNC design. Thanks to the knowledge gained during the project, DEIMOS Space Romania (DMR) is now capable of offering Mission Engineering and autonomous GNC solutions for future European re-entry missions.
This paper presents the activities carried out and the results obtained in the study, focusing on the detailed design phase.

KEYWORDS: *Air Transport Systems, Avionics, Flight Physics, Guidance Navigation and Control, Mission Design, Space Systems.*

NOMENCLATURE

AEDB - Aerodynamic database
AoA - Angle of attack
ARD - Atmospheric re-entry demonstrator
ATcoeff - Normalised coefficient of initial alongtrack
A&L - Approach and landing
CRcoeff - Normalised coefficient of initial crossrange
CoG - Centre of gravity
COTS - Commercial off the shelf
EMC - Energy Management Circle
FADS - Flush air data sensing system
FES - Functional engineering simulator

FQA - Flight qualities analysis
D - Drag
DRS - Descent and recovery system
G&N - Guidance and navigation
GNC - Guidance navigation and control
GNSS - Global navigation satellite system
GPS - Global positioning system
HAC - Heading Alignment Cone
HDGcoeff - Normalised coefficient of initial Heading
HW - Hardware
IEKF - *Iterative extended Kalman filter*
IMU - Inertial measurements unit
INS - Inertial navigation system
IXV - Intermediate experimental vehicle
KF - Kalman filter
L - Lift
MCC - Mission control centre
MCI - Mass centre of gravity inertia
MDA - Multi disciplinary design analysis
MDO - Multi disciplinary design optimisation
NOTAM - Notice to airmen
PFD - Parafoil deployment
RCS - Reaction Control System
SGRA - Sequential gradient restoration algorithm
SW - Software
TAEM - Terminal area energy management
TEP - TAEM entry point
TDW - Touchdown
TM - Telemetry
3DOF - Three degrees of freedom
M_{RTG} - Range gain

1 INTRODUCTION

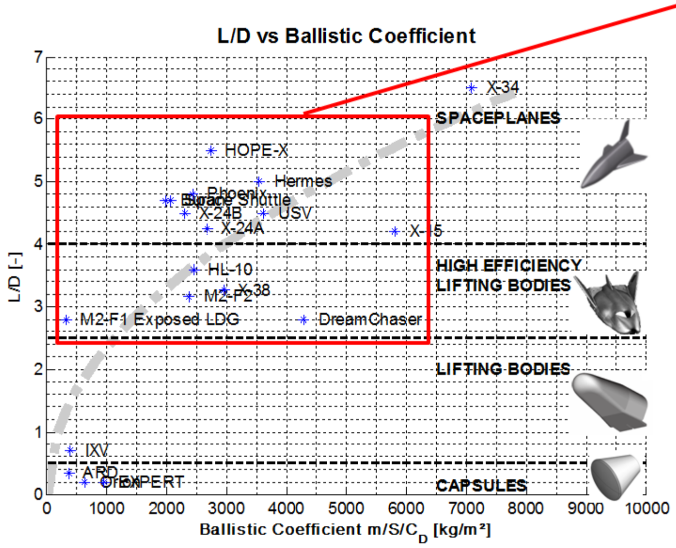
Europe has been very active in the last decades in the field of investigation and development of re-entry technologies. The European most relevant programs include different vehicles, from capsules (the Atmospheric Re-entry Demonstrator, ARD, launched in 1998 [1]), to biconic (the European eXPErimental Re-entry Test-bed, eXpert, pending launcher selection), to the more advanced lifting body Intermediate eXperimental Vehicle (IXV, that performed a flawless re-entry mission on Feb 11th 2015 [2]). In particular, IXV allowed in-flight testing of critical technologies like TPS, structures, aerodynamics, and GNC with a combined flap and RCS control. These European programs focused on high speed re-entry flight (up to transonic). In other European activities aspects of the TAEM and landing problem have been considered, but these have not reached a high maturity level or have had a limited scope. Upcoming European programs will however focus on these flight phases. In particular, IXV is being followed by the development of an affordable, reusable end-to-end Integrated Space Transportation System Service (SPACE RIDER), which will fly during the TAEM and landing phases. The REVLANSYS study aims at providing support to European activities towards an autonomous end-to-end mission, as in SPACE RIDER for a reusable re-entry system.

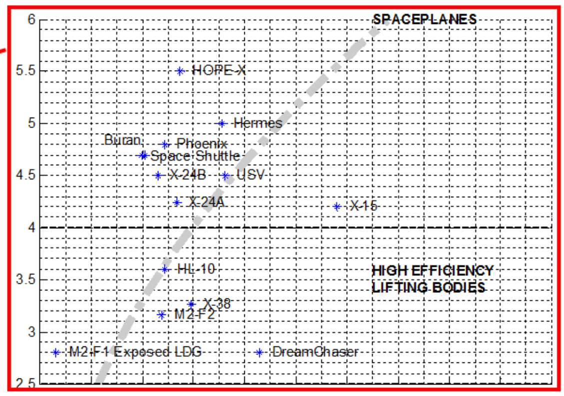
2 STATE OF THE ART AND PRELIMINARY DESIGN

Capsules, Lifting bodies, high efficiency lifting bodies and slender winged bodies, have been developed for decades as re-entry vehicle solutions. Re-entry performance is mainly driven by aerodynamic aspects, which is the result of the vehicle geometry. Different geometries can be compared in terms of the Lift over Drag (L/D) that they are capable of producing, which is directly linked with their trajectory controllability. Capsules or biconic shapes, only with a parachute braking system, do not satisfy the precise landing requirement of a re-usable system. Specific complementary systems need to be designed to overcome aerodynamic limitations of the vehicle with additional non-aerodynamic forces (retro-rockets). On the contrary, a space plane, like the Shuttle Orbiter, is able to achieve a high L/D which in turn enables the vehicle to increase its trajectory control capability. Its demonstrated high accuracy landing capabilities set a top L/D range limit for the range of vehicles shapes of interest in REVLANSYS. Lifting bodies lay in between biconic vehicles and the spaceplanes aerodynamic performance, with hypersonic L/D values in the range of 1 to 2. These enable precise landing capabilities, without the need of a complex spaceplane vehicle geometry, and are therefore of high interest in REVLANSYS.
Figure 1 shows the main vehicles proposed/available in the last decades, divided in four main classes as function of their aerodynamic performance. Although information about many different vehicles are available in the literature, the most interesting solutions for the REVLANSYS study concentrated on Lifting Bodies and High Efficiency Lifting Bodies, like IXV, X-38, or Space Shuttle (Figure 2).

The Intermediate eXperimental Vehicle (IXV) program demonstrated the validity of this lifting body aeroshape to perform a return from orbit, successfully coping with the aero-thermo-mechanical stresses proper of the hypersonic phase, and steering the vehicle during entry to the desired target point for the Descent and recovery system triggering with a high precision (within ±5 km) [1].
NASA-ESA X-38 program [4] was meant to cope with intermediate aerodynamic performance and horizontal landing. To provide the spacecraft with an adequate L/D and control at low speed, a deployable parafoil system was designed The parafoil assures good wind penetration for landing and can be autonomously steered to a pre-determined landing target.
The Space Shuttle [5] was able to perform an horizontal landing on a conventional runway. The Shuttle's TAEM strategy is to fly the vehicle to and around the Heading Alignment Cone (HAC), and afterwards align it, by a straight-line path, with the runway centerline. The success of the Space Shuttle proved the robustness of the re-entry techniques and algorithms developed for this spaceplane.
The detailed analysis of state of the art technology and missions survey led to a system concept trade-off activity to determine the best solutions that would respect criteria such as reusability, precise landing, autonomy, design simplicity, and for which a preliminary design has been produced. Two mission concepts were identified as the most promising solutions (see Figure 3):

- Lifting Body performing a soft landing with a parafoil
- High Efficiency Lifting Body performing a conventional runway landing with gear or skids





Vehicle Class	Description
Capsules	Blunt Ballistic body, limited lifting capabilities L/D up to 0.5
Lifting Bodies	Generate lift from their own shape, their L/D reaches values up to 2.5
High Efficiency Lifting Bodies	Due to their aeroshape, and winglets, reach subsonic L/D values up to 4
Winged Bodies Spaceplane	Winged vehicles generating more lift and able to manoeuvre at lower speed. L/D greater than 4

Figure 1: State of art of entry solutions according to the identified vehicle classes

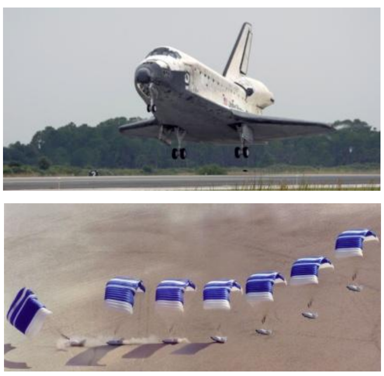


Figure 2: Shuttle and X-38 landing (NASA courtesy)

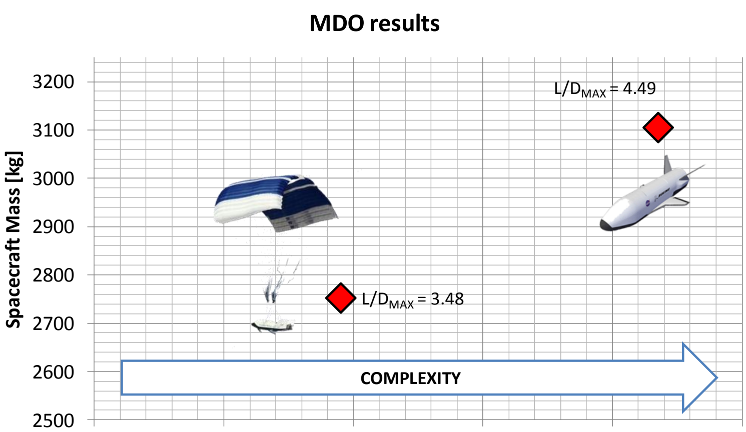


Figure 3: Optimised preliminary design solutions with example aeroshapes

In REVLANSYS, Mission Analysis and System preliminary design is based on a Multi-disciplinary Design Optimisation (MDO) that allows performing the combined mission/system design optimising specific parameters [6] . The MDO relies on a Multi-disciplinary Design Analysis (MDA) core, developed within the study and that allows obtaining reliable predictions of the mission performance, given a system and GNC candidate solutions. Figure 4 shows the MDA-MDO design process defined for REVLANSYS. This process diagram shows the internal design loops identified as red blocks; outputs from a discipline are inputs for the previous one: convergence shall be guaranteed to achieve a coherent design. The classic view also includes the optimization loop on top of the MDA core. For a detailed analysis on the MDA-MDO activity refer to [6].
For the mission design, two different phases were identified:

- Terminal Area Energy Management (TAEM)
- Approach and landing (A&L)

For each phase, the main performances have been assessed depending on several design parameters that allowed exploring in detail the identified mission concepts.

In parallel, the GNC preliminary analysis concentrated on GNC subsystem (modes, phases, HW) and the Guidance and Navigation solutions for autonomous on-board systems. The result at the end of numerous trade-offs on the state of the art in this field culminated in the:

- identification of GNC phases and modes
- selection of most promising G&N solution
- selection of the necessary avionics HW

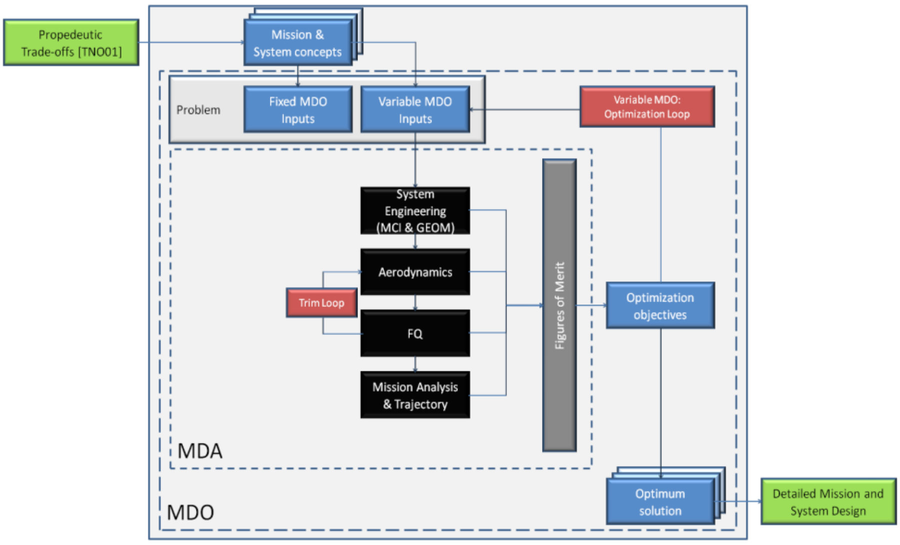


Figure 4: MDA-MDO design process for REVLANSYS.

The MDA-MDO optimisation design process produced optimised preliminary design solutions for both candidate concepts. A quantitative and qualitative comparison and trade-off culminated in the selection of a lifting body, with a soft landing under parafoil, as the most promising solution, for which a detailed Mission and GNC design was performed (see Figure 3). Detailed design process and results are presented in detail in this paper.

3 DETAILED DESIGN: MISSION AND SYSTEM

The results of the MDO activity indicate that a vehicle with similar geometry and aerodynamics to the X-38 is the optimum solution to perform a soft landing under parafoil. Therefore, X-38 aerodynamics was used as representative AEDB. Vehicle and system solutions come from the MDO. Reference mission phases are defined similarly to the X38 mission concept [7], and include:

- TAEM (from TAEM Entry Point until Descent and Recovery System (DRS) triggering)
- Descent (comprising descent under drogue parachute and parafoil unless specified)
- Landing

3.1 Flying Qualities Analysis

As a first step of the detailed Mission and System design, the Flying qualities of the MDO solution are evaluated, in both nominal and dispersed conditions, in order to define a proper entry corridor, design a proper trimline, and assess the trimmability and stability characteristics. The DEIMOS planetary entry toolbox [8] was used to perform the analysis.
The Entry Corridor analysis evaluates the spacecraft performance, either nominal, or with uncertainties, in a carpet plot of Mach and angle of attack, for the TAEM and Landing phases. For each point of the AoA, Mach carpet, a trim routine computes the surfaces deflection (i.e elevator, aileron for both concepts, and rudder for the high efficiency lifting body) able to neglect aerodynamic moments. Once trim is found it is possible to evaluate spacecraft performance such as Static Margin, Lift over Drag, and saturation of control variables. Moreover, it is possible to set expected performance conditions, such as positive static margin, surface deflection between user defined limits, or even values of L/D. The resulting entry corridor is plotted in Figure 5, where the main constraints defining the allowed flight region (i.e. the corridor, highlighted in green) are also reported.
Entry Corridor analysis allows to define a trimline, whose robustness is then tested against uncertainties, at MCI and aerodynamic level. The resulting analysis enables to evaluate with a higher degree of accuracy the effective expected performance throughout the flight, and outlines, if any, zones where control variables are closer to saturation, as well as important performance parameters such as damping, pulsation, time to half/time to double of dutch roll and short period motions. Minimum control on the surfaces and maximization of the control margin (robustness to uncertainties) were the main drivers for the trimline design. Zones of marginal static margin shall be avoided, and Lift over drag shall be maximized.
Figure 6 shows the designed trimline result in terms of AoA-Mach profile with respect to the Static Margin performance. The AoA smoothly reduces towards transonic region to avoid negative static margin. This solution allows obtaining best performance out of the vehicle, and guarantees enough margin with respect to critical zones from an aerodynamic point of view.
The Trim line designed was analysed in dispersed conditions with a 4000 shots Monte Carlo analysis considering uncertainties on trajectory, aerodynamic model and MCI (CoG box). Figure 7 and Figure 8 show an example of the results in terms of elevator deflection and static margin variability (0.5%, 50%, and 99.5% range variability are reported in blue, green, and red respectively, with the associated confidence interval), as a function of Mach number. The Monte Carlo trimline analysis allows to address directly on the expected trimline, instabilities (if any), and margins with respect to surface deflection saturation. The Entry Corridor analysis proved the room for a feasible trimline design, robust to aerodynamic and MCI uncertainties. The results of the trimline Monte Carlo analysis indicated that the vehicle is capable of successfully perform the TAEM phase of the mission down to DRS deployment.

3.2 Reference Scenario Definition

Once the FQA demonstrated the suitability of the system solution to perform as expected in supersonic and transonic regime, a representative reference scenario was defined, to design in detail the TAEM and landing phases for the concept selected.
The vehicle properties (MCI, geometry) were defined by the MDO, as well as the parafoil characteristics (mass, geometry, aerodynamic properties). Reference Mission phases and events are defined in Table 1. For the Pilot and Drogue system parameters no specific design were made, however, a scaling from the original X-38 operational design has been performed to obtain a representative solution for the current system. Santa Maria Airport in the Azores islands is the reference landing site. It represents a feasible European and non-military solution (see section 3.3), currently under evaluation also for return mission under development [9].
The definition of the end-2-end reference trajectory from TEP to touchdown is carried out, with specific objectives and methodologies for each phase.
The TAEM reference trajectory is designed aiming at:

- reaching the drogue deployment conditions with enough margins to allow reliable DRS trigger
- preserving enough trajectory controllability to compensate during TAEM residual dispersions at TEP accumulated during the entry phase

The trimline defined by FQA is flown, and a reference bank angle command, similar to X-38, is designed. Even if influence of the winds during TAEM is limited, Azores is a region with a strong wind activity. Therefore, a wind model is defined providing a global envelope of the expected winds variability considering the annual variation in the region of interest of the winds according to the HWM07. The desired DRS location is thus selected taking into account the wind drift during Descent under drogue.

Moreover, influence of the wind is decisive in the definition of the gliding path under parafoil.

The Descent under parafoil reference trajectory is designed aiming at:

- respecting baseline Guidance strategy for parafoil phase
- compensating the wind effect on the trajectory and minimize the groundspeed at touchdown by landing in a headwind configuration
- finding the shortest path from deployment to touchdown

The X-38 strategy was considered as reference for this phase (see Figure 9). An optimisation method to find the shortest path from an initial position and orientation to a final position and orientation in the presence of a constant wind profile, while Descent under parafoil, was investigated. This method is a Full Optimal Control Problem that involves several parameters (such as minimum time and radius of the Energy Management Circle (EMC)) and control profile (bank profile). The SW used is based on the Sequential Gradient Restoration Algorithm (SGRA), ·[12]·[13]. SGRA is an indirect full optimal control algorithm that allows the optimisation of a control profile along with a determined set of parameters having an effect on the problem under study. The use of this code has a long heritage; however, new features have been included to deal with this specific problem. In particular, winds have a significant impact on the motion of a system controlled by a parafoil, therefore they have been introduced into the re-entry dynamics.

An optimized Descent under parafoil trajectory has been computed from 6 km (parafoil deployment) above ground down to 0.55 km (start of landing flare). Then, the landing phase includes a final flare modeled to simulate the performance of the maneuver during which the parafoil trailing edges are symmetrically deflected in order to decrease the L/D and decrease the co-rotating velocity. The vehicle arrives at approximately 1.1 km from the target in 524 seconds since parafoil deployment. The trajectory respects the X-38 guidance concept – target acquisition circle, EMC entry turn, EMC, followed by EMC exit turn and the final flare. The boundary conditions considered the initial conditions in terms of geodetic altitude, latitude and longitude, co-rotating velocity, flight path angle and heading and the final conditions in terms of altitude, latitude, longitude and heading. The objective function is to minimize the flight time, to respect the X-38 reference trajectory and to reach the final latitude, longitude and heading at the final altitude.

The impact of the winds during the parafoil phase is evident in the velocity (Figure 12), flight path angle (Figure 13), and in the aerodynamic angles profiles (Figure 14 for the angle of attack). In these profiles is remarkable the influence of the winds, especially in the first part of the parafoil Descent, where its magnitude is greater. Although the angle of attack in wind frame are kept at a constant value of 5°, and the flight path angle and velocity are almost only dependant on altitude, in ground frame they present significant variation.

Touchdown occurs at the desired landing site with a horizontal (see Figure 15) and vertical velocity with respect to ground of 14.9 m/s and 6.2 m/s respectively, in line with the predictions obtained using MDA during preliminary design.

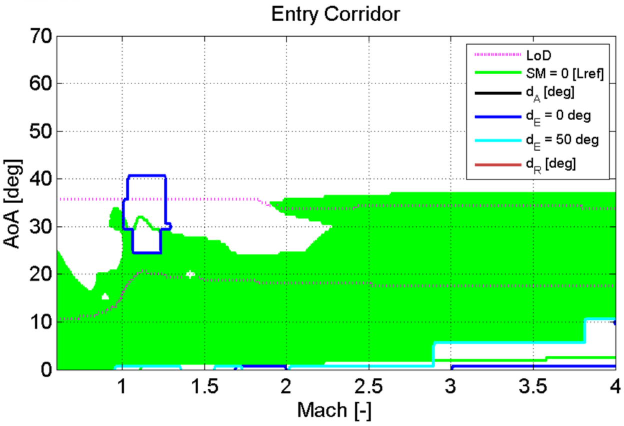


Figure 5: FQA AoA-Mach Entry Corridor (indicated in green) of the REVLANYS vehicle, TAEM phase

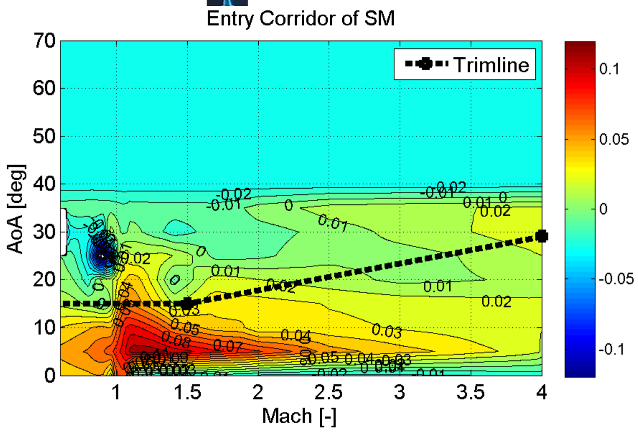


Figure 6: FQA Nominal Trimline and Static Margin performance for the REVLANSYS vehicle, TAEM phase

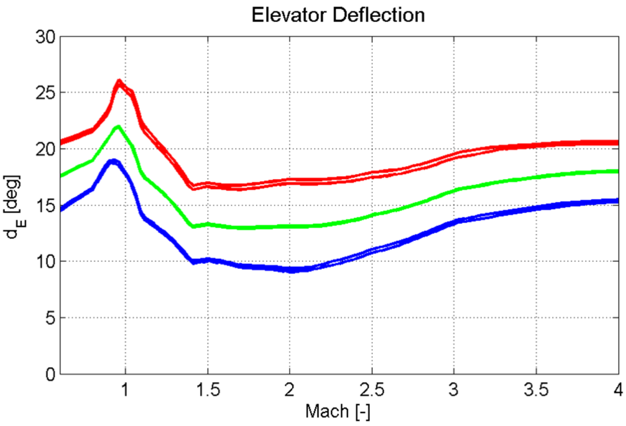


Figure 7: FQA Trimline Elevator Deflection performance versus Mach for the REVLANSYS vehicle, TAEM phase (0.5%tile-blue, 50%tile-green, 99.5%tile-red)

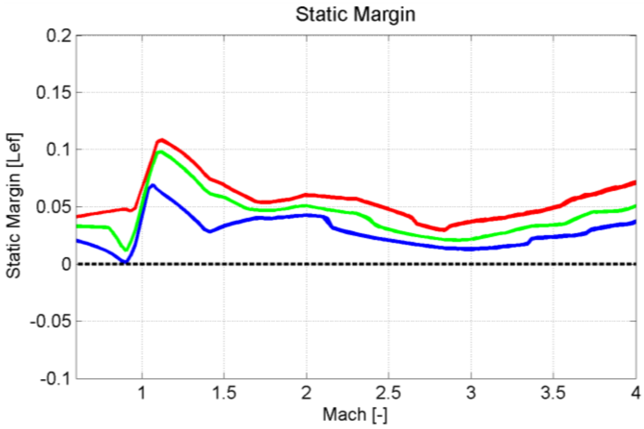


Figure 8: FQA Trimline Static Margin performance versus Mach for the REVLANSYS vehicle, TAEM phase (0.5%tile-blue, 50%tile-green, 99.5%tile-red)

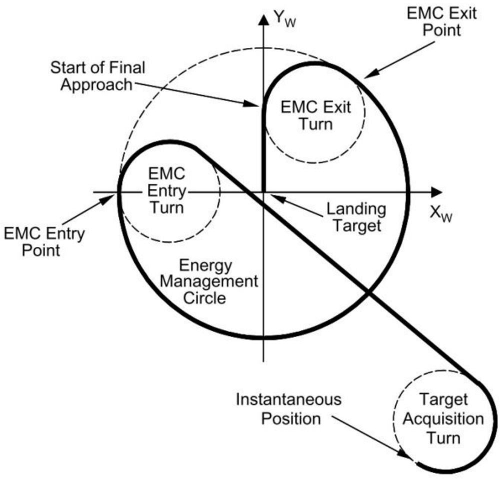


Figure 9: Parafoil Descent and Landing strategy of the X-38 mission (courtesy of [7])

Table 1: Reference Mission phases

Phase	Event	Description
TAEM	TAEM Entry Point	Mach 2.5
Descent	DRS triggering	Mach 0.8
	Pilot deploy	DRS trigger + 0 s
	Drogue deploy	DRS trigger + 4 s
	Drogue dereefing	Altitude = 8 km
	Parafoil deploy	Altitude = 6 km
Landing	Start of landing flare	Altitude = 550 m
	Touchdown	Altitude = 0 m

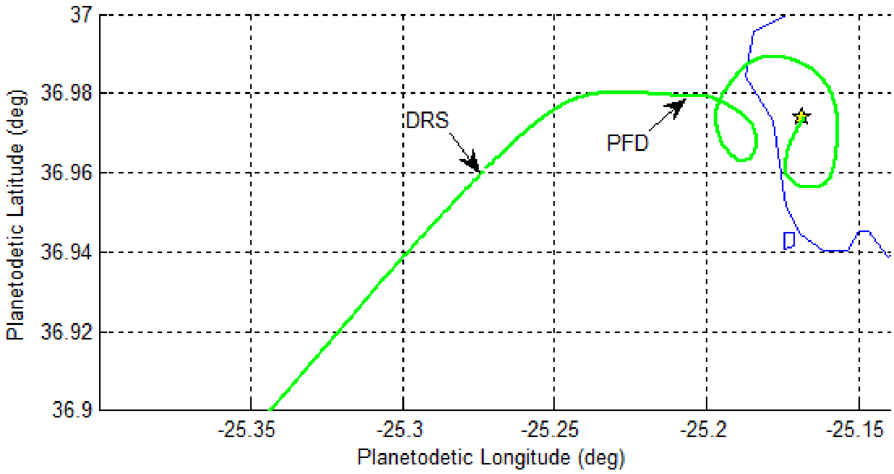


Figure 10: End-2-end Reference trajectory ground track, final TAEM and Descent phases

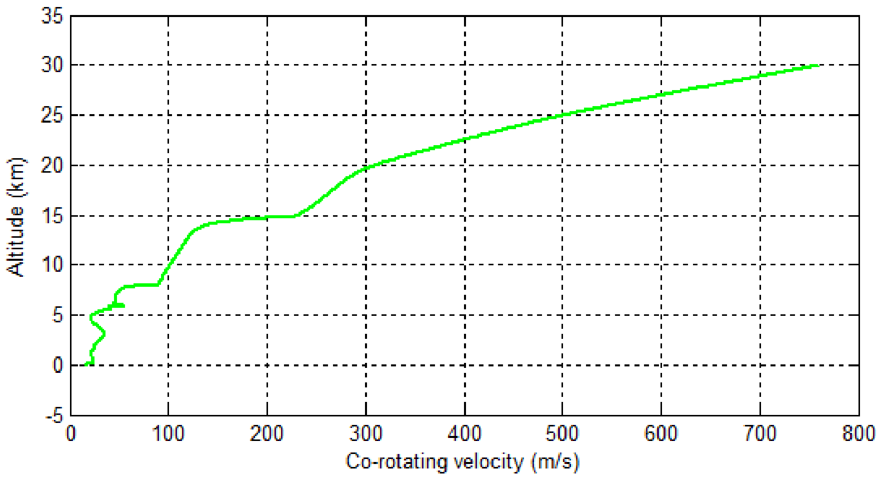


Figure 11: End-2-end Reference trajectory ground track, final TAEM and Descent phases

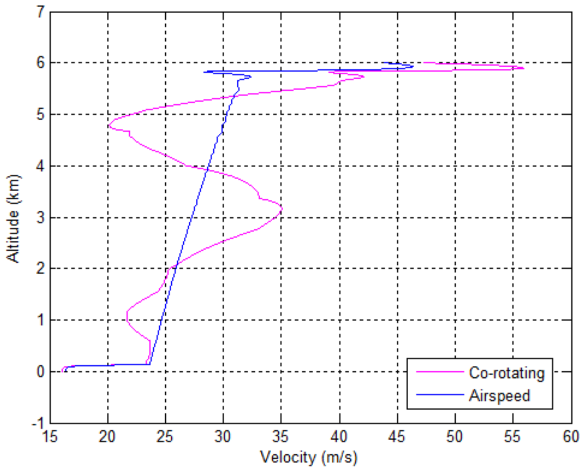


Figure 12: Reference trajectory velocity profiles, Descent under parafoil

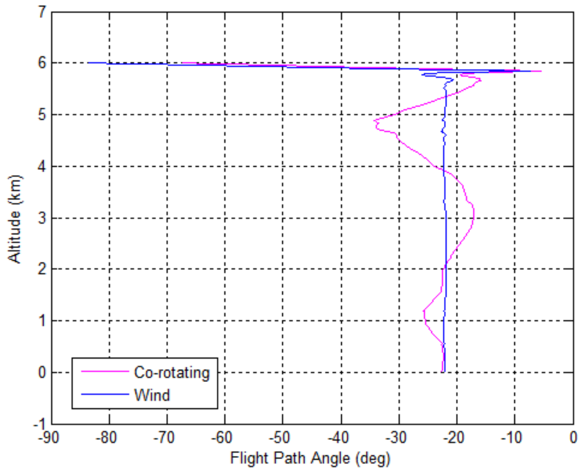


Figure 13: Reference trajectory flight path angle profiles, Descent under parafoil

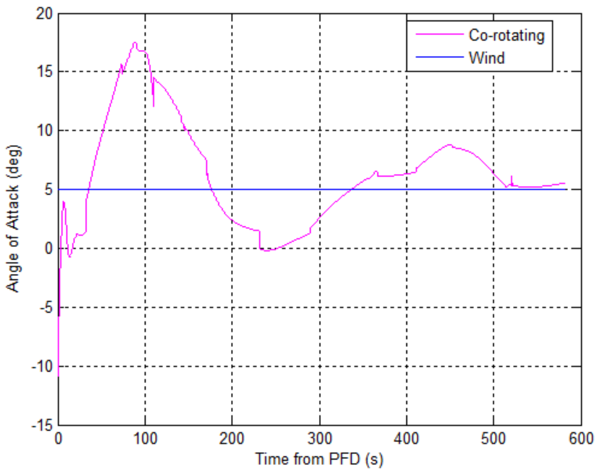


Figure 14: Reference trajectory angle of attack profiles, Descent under Parafoil

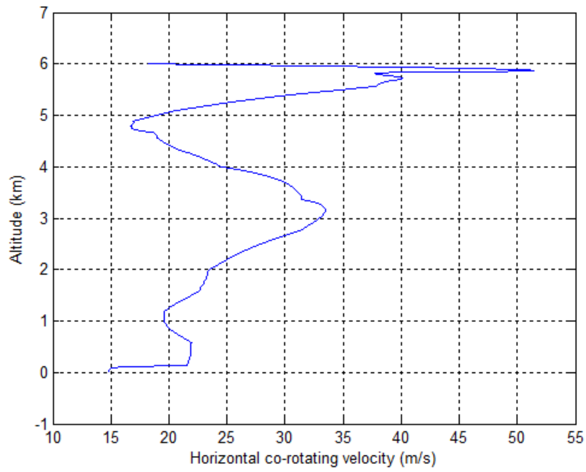


Figure 15: Reference trajectory horizontal velocity wrt ground profile, Descent under Parafoil

3.3 Operational Scenario

An effective space transportation program requires a reliable and efficient ground operations procedure. The Space Shuttle, HL-20, X-15 and IXV missions and flight operations processes have been used as guidelines for the definition of the procedures, schedules and personnel training that will lead to high levels of operational efficiency for the reference scenario defined for the REVLANSYS mission. However, since an unmanned vehicle is considered, a tailoring and a simplification of the Shuttle operations is performed.
In order to execute the necessary operations for the Descent phase, the following resources are needed:

- Processing Facility for vehicle landing
- Mission Control Centre
- Ground Stations
- Communication Network
- Air traffic control facilities
- Recovery accommodations
- Processing Facility for vehicle maintenance

Different criteria were considered for the selection of the landing sites, like: accessibility, facilities available on site, an ESA station (preferred), civil utilisation and a Space Shuttle landing site. For all these reasons, Santa Maria airport in Azores was identified as the baseline landing site (Figure 17). Other airports like Lajes Air base, Kourou airport or Gran Canaria airport are identified as back-up landing sites and constitute the complete landing network.
The Mission Control Centre will coordinate all the activities related to the Descent (see Figure 16). The MCC is interconnected with all the Ground Segment elements, providing coordination and support. It will grant infrastructure, tools and applications to be used for telemetry (TM) monitoring, storage, processing, displaying and detailed trajectory prediction.
The Ground Stations will ensure the tracking of the spacecraft, will receive, locally record telemetry and send requested data, in real-time and off-line mode, to the Mission Control Centre.
The communication network between the MCC and the Ground Stations will be established by satellite links, or if available throughout a dedicated network, like in the case of IXV. The IXV Communication Network [11] was IP based, and relied on Inmarsat satellite to interconnect the MCC with the TM-kit Ground Stations and AsiNet, an Italian Space Agency dedicated network to interconnect ALTEC and Malindi and is presented in Figure 18.
Strict flight rules have to be established, including flight limitations due to weather restrictions, because wind speed, shear and turbulence will have great influence on the parafoil flight capability. Wind data based on balloon measurements that will be launched every hour prior to the flight have to

be collected and used to allow flight and to define the reference wind tables to be loaded on-board for GNC use.
The main aspects taken into consideration by the air traffic management are: NOTAMs, temporary flight restrictions, altitude reservations, special use airspace and tactical approaches.
A safety system process must be defined prior to the flight. For a proper analysis of the spacecraft, first of all different techniques will be established to identify failure modes, subsequent risks and potential errors of the critical systems, performing systems and subsystems. Secondly, the safety system must consist of a validation and verification process for the systems and subsystem hazards.
In the airport premises a staging area for the spacecraft recovery convoy will be identified. Post flight recovery and inspections are an important part of process control. On recovery, a team of engineers will conduct what could be termed as "open assessment," primarily focusing on exterior components.
The maintenance concept should be developed to assure the return of the spacecraft to a state ready to fly. It could be composed of: a complete set of maintenance manuals; technicians with broad-based skills; an integrated maintenance information system that is shared concurrently by all support elements.

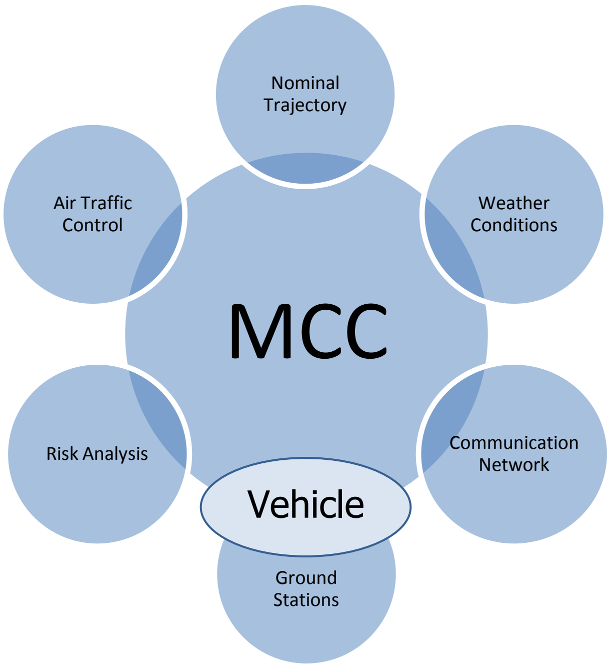


Figure 16: Mission organization architecture

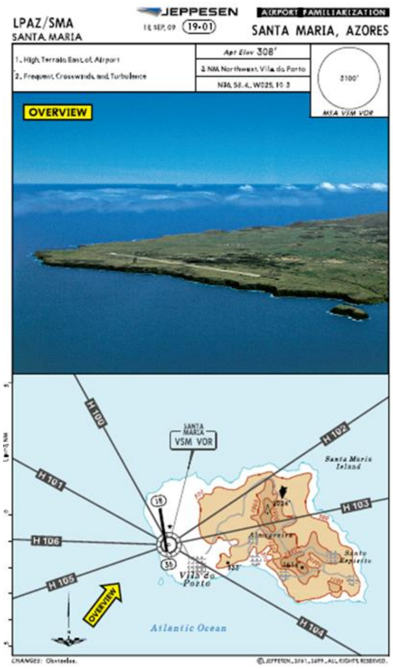


Figure 17: Santa Maria airport map [10]

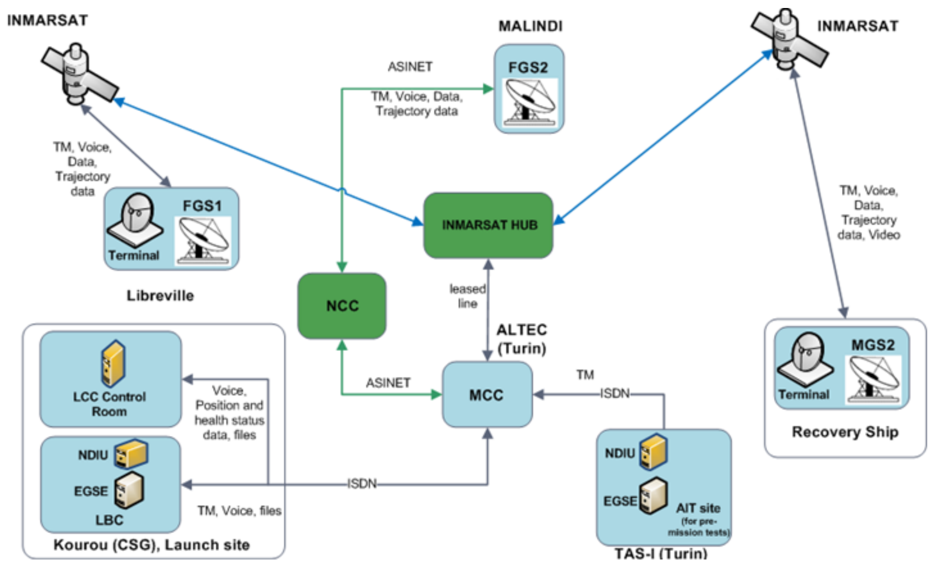


Figure 18: IXV Communication Network [11]

4 DETAILED DESIGN: GNC

On the basis of the final concept defined for the REVLANSYS vehicle, and described before, dedicated GNC has been developed, prototyped, and tested. The overall GNC function is split into the following sub-functions:

- **Navigation:** This consists of a navigation solution served primarily by IMU products and hybridised with a GPS in addition to other sensors (FADS, altimeter).
- **Guidance:** This consists of a guidance algorithm whose aim is to define the re-entry trajectory during re-entry until landing. This serves to ensure the vehicle arrives at the designated landing site, respecting the mission and flight path constraints, and providing the conditions necessary for a parafoil landing concept.
- **Control:** The control algorithm may operate in distinct modes dependent 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.

The modes of the GNC are resumed in Table 2. The GNC design process started with review and trade-off of potential solutions, and that lead to the results through preliminary design, implementation/tailoring and preliminary performance assessment (see Figure 19).
The final solution in terms of Guidance and Navigation includes the following main functionalities, that are explained in detail the next section.

- **Aerosurfaces Guidance**: the guidance is composed by the Trajectory Generator that computes all the trajectory profiles, and the Trajectory Tracker that computes the commands in order to fly the desired trajectory.
- **Chutes Deployment:** starting from the Pilot Deployment, and up to Parafoil Full Deployed, the Guidance is nor actively generating neither tracking the trajectory, the trim angles are the angles that the vehicle has during the Descent.
- **Parafoil Guidance:** the guidance generates directly the command of bank angle with respect to altitude, using a compensation method to take into account the influence of the wind.
- **Landing Flare**: a predefined manoeuvre in order to perform the touchdown respecting strictly the velocity requirements.
- **Re-Entry TAEM Navigation**: the Navigation is estimating the vehicle state under low g conditions with atmosphere forces using the INS/GNSS and FADS sensors.
- **Parafoil Navigation:** the Navigation is estimating the vehicle state under low g conditions with atmosphere forces using the INS/GNSS and FADS sensors.
- **Landing Navigation:** the Navigation is estimating the vehicle state under low g conditions with atmosphere forces. In this phase, GNSS (augmented and/or differential) hybridisation is considered as a possible option to achieve precision landing. At this stage the Navigation is using the data coming from INS/GNSS, FADS and Altimeter sensors.

Parts of the algorithm were inherited from DEIMOS experience in the field, and tailored to the REVLANSYS scenario: the Navigation, and the Trajectory Control (Tracker) function of the Guidance; while in particular the Trajectory Generation function of Guidance was a complete innovative result of this project. Since the control was not within the tasks of REVLANSYS project, its architecture will not be detailed further.

4.1 GNC functional description

Guidance

The architectures of the Trajectory Generation modules of the Guidance are described in Figure 20.

The **TAEM guidance** has to generate the trajectory between the initial state (TEP) and final one (DRS), taking into account the aerodynamic capabilities of the vehicle. The Trajectory Generation module is computing the necessary profiles that will be tracked by the Trajectory Control, which computes the guidance commands (bank and AoA).
The architecture for the Guidance in this part of the flight is represented in Figure 20, left side. The Trajectory Generator is based on a cubic Bezier geometry, that allow a straightforward computation

of the geometric solution, being this curve smooth and analytically computable, for a given trajectory length. Robustness is achieved by taking to account a modulation of the targeted trajectory length with respect to changes in the initial conditions. An appropriate set of gains, modelled as linear functions of the dispersion from the nominal initial condition, is identified:

- Range gain: M_{RTG} is a coefficient that affect the optimal range computation, depending on the initial conditions:

$$\boldsymbol{M_{RTG} = a + b \cdot ATcoeff + c \cdot CRcoeff + d \cdot HDGcoeff}$$

Where a, b, c, d are the gains to be found with the preliminary simulations campaign, and $ATcoeff, CRcoeff, HDGcoeff$ are the normalised initial dispersion from nominal conditions wrt alongtrack, crossrange and heading.

In detail, the Trajectory Generator contains:

- Preprocessor: it settles the system of reference, using NAV information.
- Range Prediction: computes a set of gains based on initial conditions to determine the optimal range to be flown.
- Geometrical Trajectory: computes the 2D trajectory, following the geometry of a Bezier curve.
- Lateral planner: computes heading and heading rate profiles against range to go.

Table 2 GNC and subsystems modes

Mission Phase	GNC Mode	GNC sub systems modes		
		Navigation	Guidance	Control
TAEM	Re-entry	Re-entry TAEM	Aerosurfaces Guidance	Re-entry Aero
Descent	Drogue Chute	Parafoil Navigation	Chutes Deployment	Re-entry Aero
	Parafoil	Parafoil Navigation	Parafoil Guidance	Parafoil Control
Landing	Landing	Landing	Landing flare	Landing

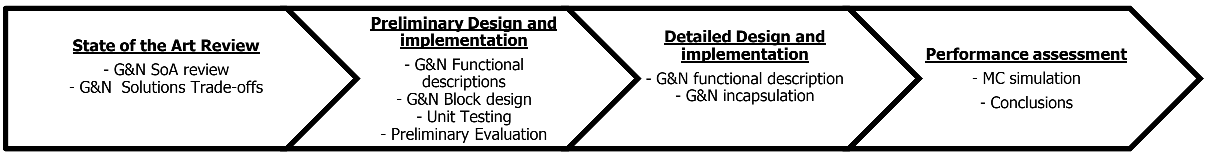


Figure 19 G&N development process

- Longitudinal planner: composed of two main sub-blocks in order to compute Altitude and its derivatives and Velocity and its derivatives against range to go.
- Time predictor: relates range to go and time.
- Profiles converter: converts the range rate profiles in time rate profiles, in order to be compatible with the Tracker block.

The Trajectory Tracker is a tailored trajectory control scheme based on NDI and adapted to the current scenario. It allows computation of the guidance commands tracking the reference solution and knowing the dynamic characteristics of the system.

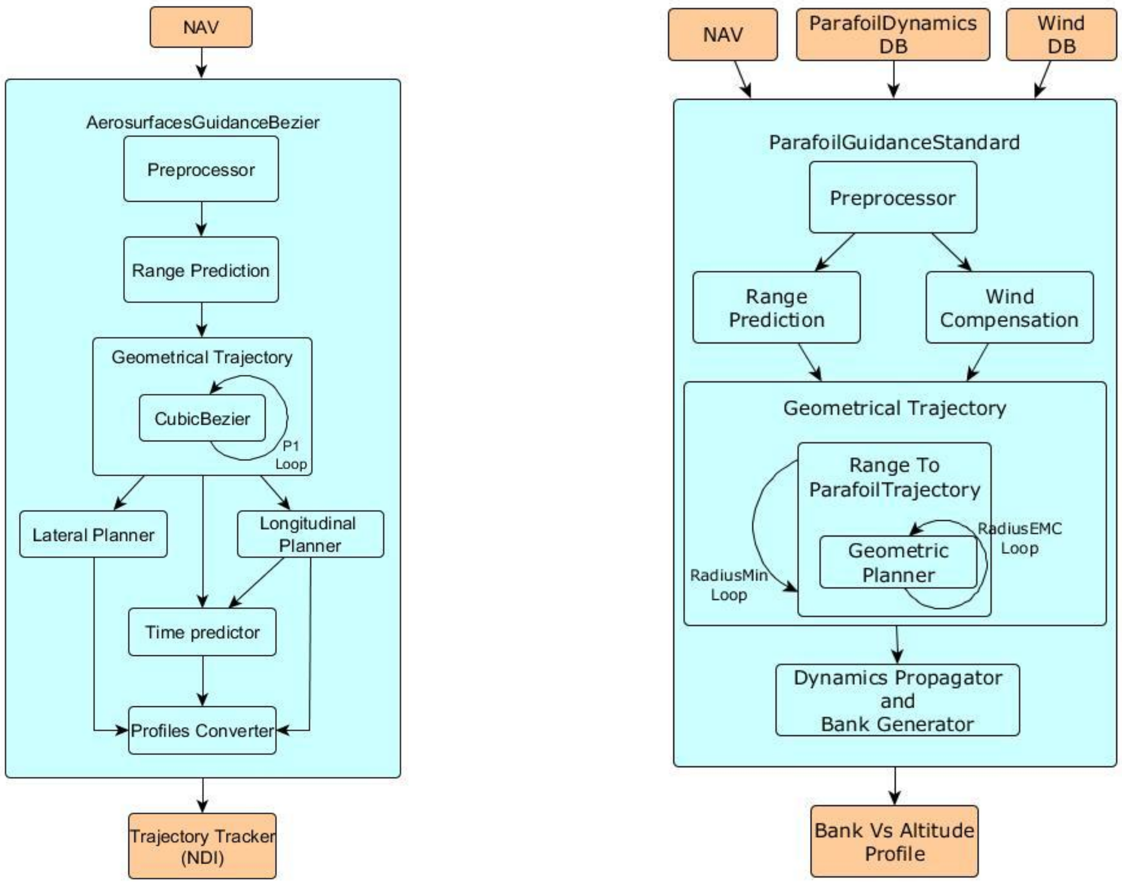


Figure 20 Aerosurfaces Guidance architecture [left], Parafoil Guidance Architecture [right]

The design of the **Parafoil Guidance** concentrated on the Trajectory Generation. The problem to be solved is to generate appropriate bank commands (active control of the angle of attack for trajectory control during glide is considered too complicated and therefore discarded) to guide the vehicle from an initial state (PFD) to the final one (TDW), in position, direction (against the wind) and velocity. The solution is based on a relation between curvature of the trajectory and bank considering other flight parameters associated to the parafoil gliding dynamics. The Parafoil Descent strategy, that is the assumed geometry of the trajectory, is based on the X-38 strategy (Figure 9).
The proposed solution solves the problem of the Trajectory Generation under parafoil in position and direction. A final flare manoeuvre will be performed right before touchdown, in order to further decrease the vertical and horizontal velocity. For performance analysis, this manoeuvre is modelled with a simplified performance model.
Wind compensation is a key factor for a parafoil system and the Guidance needs to take into account the influence of the wind on the trajectory. The wind has been considered as function of altitude, affecting the flight of the system only in the plane parallel to the surface of Earth and containing the vehicle (modelled as a point, CoG). The strategy for wind compensation is based on considering the motion in an air-fixed frame moving with the wind, that will coincide with the target location at touchdown and with the correct orientation to land in headwind.
The architecture for the Guidance in this part of the flight is represented in Figure 20, right side. The Trajectory Generator based on the X-38 Geometry, contains:

- **Preprocessor:** settles the system of reference using NAV information.
- **Range Prediction:** computes the Optimal Range to be flown assuming that longitudinal planning is not affected by bank.
- **Wind Compensation:** computes the necessary corrections needed to compensate the wind.
- **Geometrical Trajectory:** computes the 2D trajectory, using the X-38 geometry.
- **Dynamics Propagator and Bank generator:** computes the bank command using a DB that relates altitude, trajectory curvature and bank.

Navigation
The objective of the Navigation sub-system is to provide an estimation of the current state of the vehicle, in terms of position, velocity and attitude, and the derived products, such as Mach and dynamic pressure. The navigation strategy is naturally linked to the sensors selection. Due to the needs in accuracy the sensors have been chosen to be:

- IMU: LN200S (100 Hz)
- GPS: BAE Systems SpaceNAV receiver (1 Hz)
- FADS: custom (10 Hz)
- Altimeter: custom (10 Hz)

A unique Navigation solution was employed for all the TAEM, Descent, and Landing phases, that is suitable for evaluating the main GNC performance and the accuracy of the mission and GNC solution. This was tailored from available DEIMOS hybrid NAV solution for atmospheric vehicles [14]. The global navigation architecture, shown in Figure 21, is composed by coupled INS/GNSS solution (position, velocity, attitude, bias and scale factor estimation) which is then updated, at relative sensors' frequency, with FADS and ground altimeter measurements (i.e., AoA, AoS, mach, altitude, dynamic pressure, airspeed, etc.). The hybridization of the solution is performed through an iterative extended Kalman filter (IEKF). The IEKF relies on the Kalman filter (KF) algorithm. However, it performs a local linearization of the updating equations in order to meet the linear condition of the KF algorithm. This operation is performed every time a new GNSS measurement is available (i.e. at the frequency of the GNSS receiver).

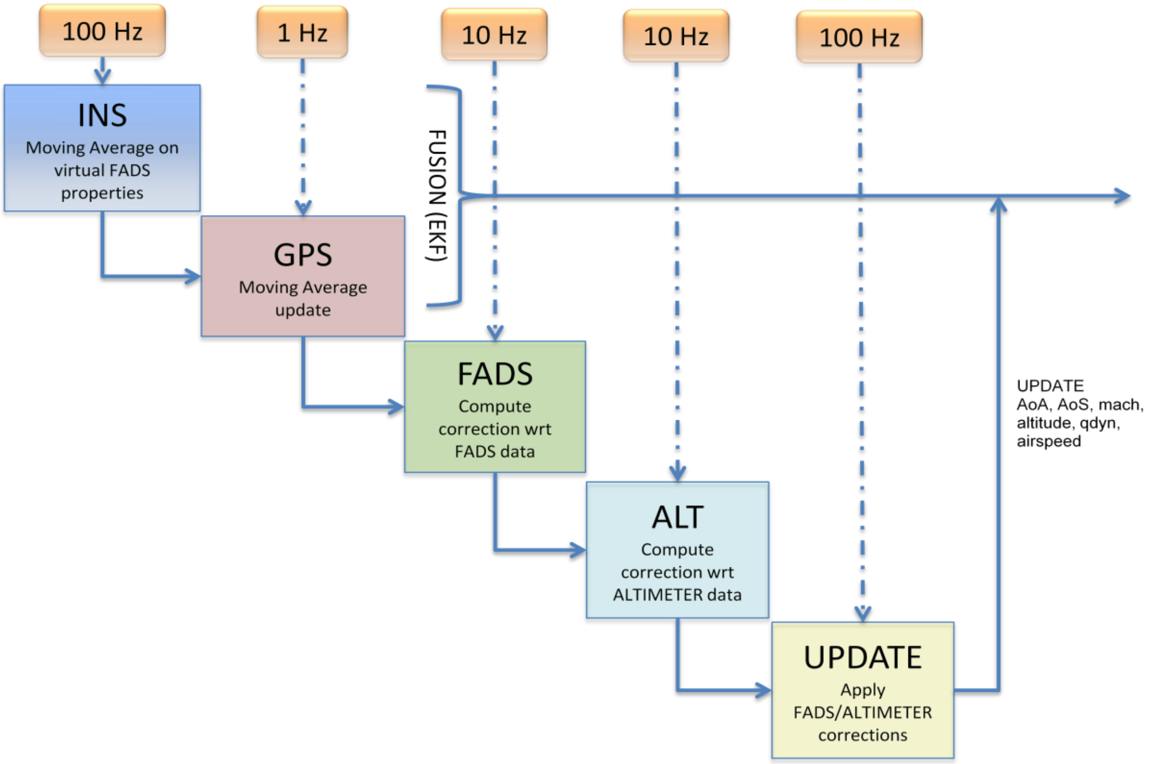


Figure 21 Navigation architecture with loosely coupled INS/GNSS and uncoupled FADS and altimeter

4.2 GNC Performance assessment

The end-2-end reference scenario from TAEM start to touchdown has been defined in section .3.2. Additionally, uncertainties have been included considering heritage from previous studies (e.g. IXV entry GNC performance in terms of position and velocity dispersions at TEP, Table 4) or dispersions associated to vehicle models (aerodynamics, mass, Table 3). Moreover, specific environmental dispersions have been derived considering the annual variability in the Azores region of atmospheric properties and winds, see Figure 22.

A high fidelity 3DOF Functional Engineering Simulator (FES) has been adapted to perform nominal and dispersed trajectories analysis of the REVLANSYS scenario, and evaluate the performance of the prototyped GNC solution. Models for GNSS receiver, class 2 IMU, FADS and altimeter are considered, with uncertainties in the sensors' bias, noise, and scale factor.
A 500 runs Monte Carlo simulation (see Table 3, Table 4 and Figure 22 for dispersions description), from TAEM to Landing, was carried out in order to assess the behaviour of the different GNC methods:

- Trajectory Generation and Tracker of the aerosurface Guidance during the TAEM phase.
- Trajectory Generation method for the parafoil Guidance, tested in:
  - open-loop to verify the capability of identifying a trajectory solution compensating position errors after Parafoil deployment in presence of winds;
  - in closed loop, with a reduced Monte Carlo Campaign (50 shots), to perform a preliminary test on the coupling with the Trajectory Tracker.
- End-2-end Navigation.

The tests performed show how the designed and implemented GNC system is capable to deal with all the last flight phases until TDW (TAEM and A&L), being compliant also with two different vehicle concepts (flight with aerosurfaces or under a parafoil).

TAEM Guidance

During TAEM phase, the Guidance correctly generates Bank and AoA (modulate around the reference trim value, see Figure 25) commands to reach the desired position and achieve the proper conditions for drogue parachute deployment. In terms of position and velocity accuracy at DRS, a clear compensation in crosstrack (Figure 24) and heading error (Figure 23) is observed, while no degradation in the downrange performance. A few outliers exist in the position (see Figure 24) that are those cases either at the limit of controllability (initial heading and position both at the limit of defined dispersions) or due to strong winds; the system is able to compensate with respect to the dispersions, that is particularly important to avoid undesired increase of the footprint during the uncontrolled Descent under drogue. The Guidance algorithm proved to be robust against initial conditions, vehicle, and atmospheric dispersions. The main source of error are the winds, whose compensation was not included in the guidance scheme. Based on the results obtained, wind compensation is recommended and can be included as a further development, mostly reusing the block already developed for the guidance under parafoil. Also, conflicting requirements of limited bank during TAEM and of trajectory controllability affect the performance: during TAEM the capability of compensating position error with a lifting body is limited with respect to more performing vehicles. Nevertheless, the implemented Guidance solution proved successful to achieve the requirements at the end of the TAEM phase, in particular, the targeting of the DRS box for parachute deployment is fully achieved.

Parafoil Guidance

Despite the big initial dispersions that have to be faced during the Parafoil phase, accumulated in the Descent phase under the drogue chute, in which controllability is not feasible, the Trajectory Generation is able to generate feasible and accurate trajectory, as evident in the results both in final heading and position from the Open Loop test campaign (Figure 27, Figure 28). In particular, the wind compensation strategy successfully demonstrates to be effective, not only in position but also with respect to velocity constraints, as maximum final vertical and horizontal velocity, as shown in Table 5. Only two outliers land at less than 1000 m from the target. This results show that the trajectory generation is able to find a trajectory solution in all cases, and the results are therefore promising. The estimated performance of the trajectory Generation for the parafoil phase at touchdown are reported in Table 5. A further test activating the uncertainties in atmosphere, aerodynamics, MCI was carried out coupling the generation method to the Trajectory Tracker adapted from the TAEM phase. Preliminary results show that the Closed Loop Parafoil Guidance is able to correctly steer the vehicle down to the desired landing site with a precision below 200 m. Further analyses, including stress cases, need to be performed to determine the actual performance of the Parafoil Guidance solution, but the results are promising.

E2E Navigation

The Navigation system correctly manages the data filtering between the different sensors, and it is able to correctly estimate the vehicle position (see Figure 26) and velocity. The estimation error is very low (less than 10m / 1m/s) during TAEM, it increases up to 5 time right after drogue deployment, when the dynamics of the drogue release strongly affects the navigation performance, to recover gently after full inflation. The use of the FADS allows an improved and good estimation of the aerodynamic angles (error in AoA, AoS below 1 deg), with a noisy behaviour mainly due to the noisy measurement by the sensor itself. Bank angle estimation, and in general inertial attitude angles estimation, is less accurate, because it is based only on IMU/GNSS data.

Table 3 Aerodynamics and MCI parameters dispersion

Model	Parameter	Value
Vehicle AEDB	CL, CD	Uncertainties defined within the X38 AEDB model
Vehicle MCI	Mass	± 0.5 % (uniform)

Table 4 Initial conditions dispersion at TEP

Parameter	Value
Alongtrack	1 km (3σ)
Crosstrack	1 km (3σ)
HDG	12 deg (3σ)

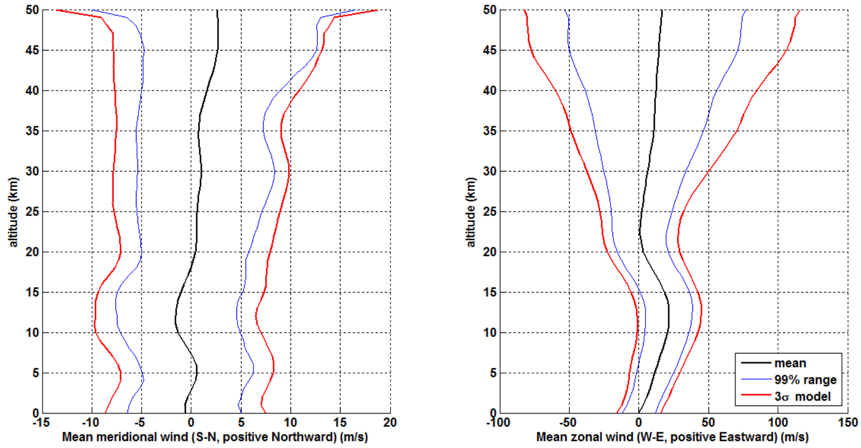


Figure 22 Zonal and Meridional winds dispersion

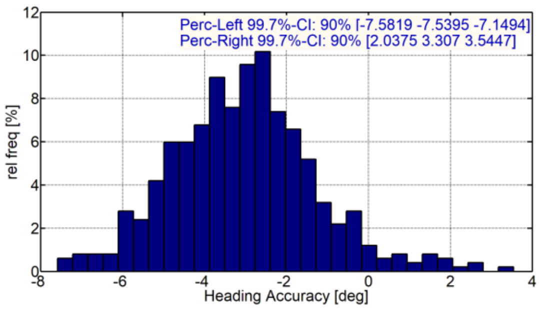


Figure 23 Heading accuracy at the end of TAEM

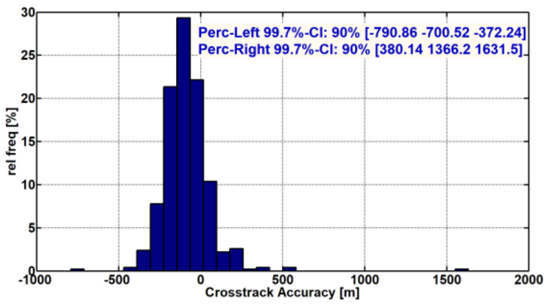


Figure 24 Crosstrack accuracy at the end of TAEM

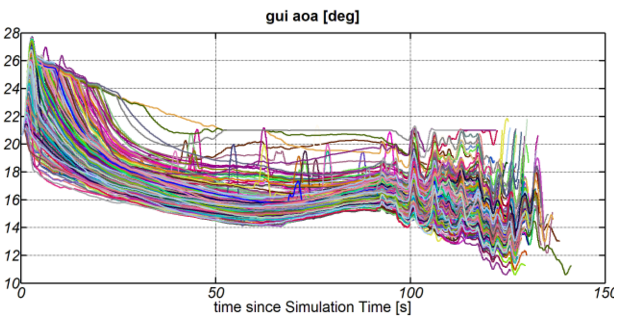


Figure 25 Commanded Angle of Attack during TAEM

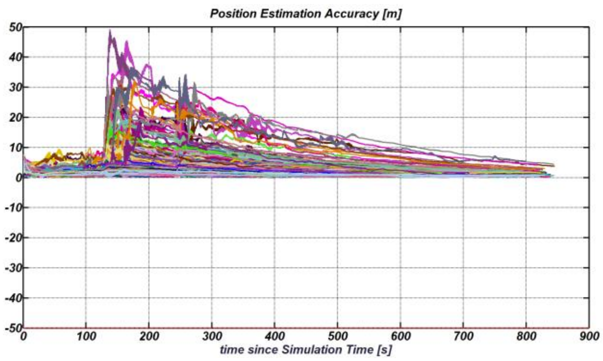


Figure 26 Position estimation accuracy from TEP to touchdown

Table 5 GNC Landing Performance (Open Loop Trajectory Generation test)

Figure of Merit	Performance	
	Requirement	% of shots
Position accuracy at landing	200 m	99.6%
Vertical velocity at landing	9 m/s	100%
Horizontal velocity at landing	18 m/s	100%

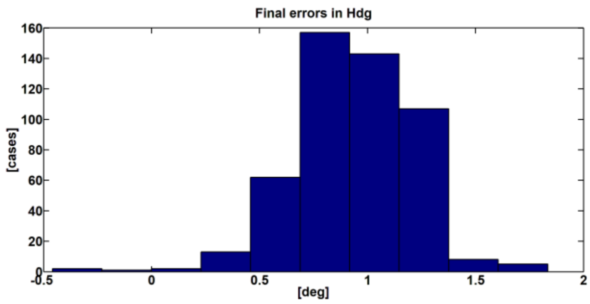


Figure 27 Heading accuracy at TDW (Open Loop Trajectory Generation test)

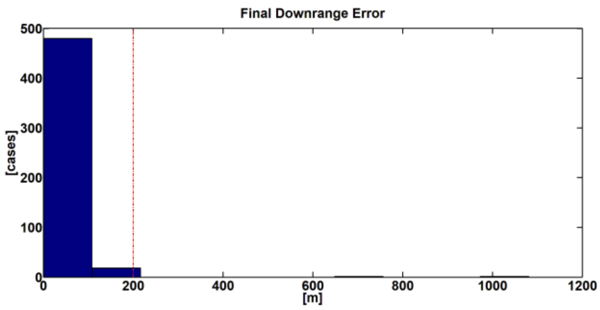


Figure 28 Downrange accuracy at TDW (Open Loop Trajectory Generation test)

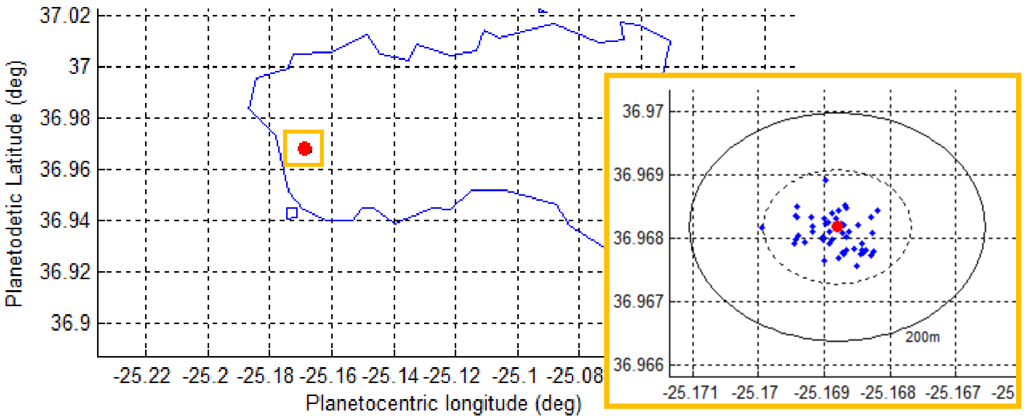


Figure 29 Touchdown accuracy (Closed Loop Parafoil Guidance test)

5 CONCLUSIONS

The REVLANSYS project implemented a coordinate approach for the design of the TAEM and Landing phases of a reusable space re-entry vehicle, including activities in multiple fields as Mission and Flying Qualities Analysis, Aerodynamics, Trajectory Optimization, Guidance and Navigation, HW selection, and generation of requirements. The study demonstrated the feasibility of the design approach:

- the MDA-MDO design approach proved to be a powerful asset to carry out coupled Mission, System and GNC preliminary design for TAEM and Landing.
- FQA and Entry Corridor analysis allowed identifying a realistic trimline, assessing trimmability and stability characteristics in dispersed scenarios, to define a robust reference mission.
- Preliminary GNC modes were defined for multiple mission concepts, detailed Guidance and Navigation algorithms were designed, and potential actuator/sensor configuration selected.
- G&N solution closed loop tests for TAEM and Parafoil phase showed promising performance; Landing phase test showed capability to recover position dispersion and compensate winds.

This study resulted in the design of a Mission and GNC solution for the terminal entry and landing phases of a re-entry mission, consistent with the overall mission needs. It represents a valid basis for further studies regarding TAEM and Landing phases of re-entry vehicles and their application to programmes, such as SPACE RIDER. Further analyses are necessary to reach a fully mature Mission and GNC design. Thanks to the knowledge gained during the project, DEIMOS Space Romania (DMR) is now capable of offering Mission Engineering and autonomous GNC solutions for future European re-entry missions.

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