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Mission Analysis, GNC and ATD for Reusable Launch Vehicles within ASCenSIon: multi-orbit multi-payload injection, re-entry and safe disposal

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Abstract

Reusable Launch Vehicles (RLVs) are not only key for an economically and ecologically sustainable space access but also represent a paramount innovation towards the increasing demand for smaller satellites and mega-constellations. In order to ensure Europe's independent space access capabilities, ASCenSIon (Advancing Space Access Capabilities - Reusability and Multiple Satellite Injection) is born as an innovative training network with fifteen Early Stage Researchers, ten beneficiaries, and fourteen partner organisations across Europe. This paper provides an overview of the mission, ranging from the ascent to the re-entry of the reusable stages and including the multi-orbit injection and the safe disposal. A special focus is put on the activities developed within ASCenSIon regarding Mission Analysis (MA), Guidance Navigation and Control (GNC) and Aerothermodynamics (ATD). The foreseen methods, approaches and goals of the project are presented. These topics require innovation within and a high level of collaboration due to their interconnection. The pre-flight design capability drives the necessity of a MA and GNC missionisation tool coupled with ATD software to test/explore re-entry solutions. Such a reliable and efficient tool will require the development of GNC algorithms for the re-entry of the launcher. Additionally, specific challenges of trajectory optimization for RLVs are addressed, such as integrated multi-disciplinary vehicle design and trajectory analysis, fast and reliable on-board methods. The results of this study are subsequently used to develop the controlled strategy. Moreover, to perform the novel multi-orbit multi-payload injection. This activity is followed by the development of, a GNC architecture capable of optimally steering the vehicle towards a targeted landing site under precision and soft-landing constraints. In addition, ATD affects the mission profile at multiple phases and needs to be considered at each design step. Due to complexity and limited computational resources during the preliminary design phase, surrogate models with low response times are required to predict wall heat fluxes along the considered trajectories based on the pressure topology. The complete profile is wrapped up with the Post Mission Disposal strategies to be used by the launchers in order to ensure the compliance with the space debris mitigation guidelines, as well as preliminary reliability aspects of these strategies. The paper provides a preliminary analysis of the discussed topics and their interconnections within the work-frame of ASCenSIon paving the way towards the development of novel cutting-edge technologies for RLVs.

Keywords: Reusable Launch Vehicles, Guidance, Navigation & Control, Reliability, Aerothermodynamics, Multidisciplinary Analysis & Control, Post Mission Disposal, Re-entry

Acronyms/Abbreviations

ASCenSIon	Advancing Space Access Capabilities - Reusability and Multiple Satellite Injection
ATD	Aerothermodynamics
CFD	Computational Fluid Dynamics
GEO	Geostationary Orbit
GNC	Guidance, Navigation & Control
HTHL	Horizontal Take-off Horizontal Landing
HTVL	Horizontal Take-off Vertical Landing
IADC	Inter-Agency Space Debris Coordination Committee
LEO	Low Earth Orbit
MA	Mission Analysis
MDAO	Multidisciplinary Design Analysis and Optimization
NLP	Nonlinear Programming
OCP	Optimal Control Problem
PMD	Post Mission Disposal

RLVs	Reusable Launch Vehicles
RCS	Reaction Control System
SSTO	Single Stage to Orbit
TSP	Travelling Salesman Problem
TSTO	Two Stage to Orbit
VTHL	Vertical Take-off Horizontal Landing
VTVL	Vertical Take-off Vertical Landing
TVC	Thrust Vector Control
XDSM	eXtended Design Structure Matrix

1. Introduction

In the last decade, private US companies have revolutionized space access. While the Space Shuttle, developed in the 1980's, was not competitive enough compared to existing expendable rockets, SpaceX has demonstrated the technical feasibility and cost effectiveness of Reusable Launch Vehicles (RLVs) with the first successful recovery and reuse of a Falcon 9 first stage in 2017. With the ever-increasing demand for smaller satellites and mega-constellations, they have become essential for accessing space at lower cost. ASCenSIon (Advancing Space Access Capabilities - Reusability and Multiple Satellite Injection) is initiated as an innovative training network with fifteen Early-Stage Researchers, ten beneficiaries, and fourteen partner organisations across Europe, to study the critical technologies needed to develop a RLV capable of injecting multiple payloads into multiple orbits. More particularly, this paper provides an overview of the challenges and interactions between selected fields of research within the ASCenSIon project. Aiming to enable the RLV flight, the mission profile is analysed from the ascent to the re-entry of the reusable stages and including the multi-orbit injection and the safe disposal. Among these fields of research involved, Aerothermodynamics (ATD), Mission Analysis (MA) and Guidance, Navigation & Control (GNC) are studied in this paper.

The study of ATD focuses on ensuring the integrity of the RLV during ascent and descent to enable its reusability. Because the prediction of surface heat fluxes requires significant computational resources, models with low response times are required to integrate the results in the design process in collaboration with system design aspects and GNC. It is also important to study the interactions between optimal design of RLV, branching trajectories and other system aspects for early launcher synthesis. Advanced techniques as Multidisciplinary Design Analysis and Optimization (MDAO) can not only improve trajectory design but can leverage on the different interactions between trajectory performance, GNC, aerothermodynamics, reliability, and other considerations to produce optimal launcher configurations. Particularly, the challenging aspect of the pre-flight capability enforces the need of an efficient missionisation strategy for the re-entry, needed both to tailor the MA and GNC solution for one particular mission and to provide a single solution qualified for multiple missions. Additionally, the GNC strategy for multi-orbit injection is designed such that it complies with the space debris mitigation guidelines. An overview of the definition of the guiding trajectory that ensures the optimal insertion of different payloads into their respective operational orbits is provided, including the final disposal manoeuvre. The modelling of the reliability of the Post Mission Disposal (PMD) strategy also helps to ensure the compliance with these guidelines.

2. Aerothermodynamics modelling for reusable launch vehicles

As mentioned, an ATD analysis is critical to ensure the reusability of the recovered Reusable Launch Vehicles (RLV). For this, the prediction of the thermal loads and surface heat flux is essential in order to determine the re-entry corridor (see Sec. 4.2), feasible design choices (see Sec. 3) and the required thermal protection system.

Wall heat fluxes are determined with Computational Fluid Dynamics (CFD) simulations, which require significant computational resources. Therefore, especially during the pre-design phase it is not feasible to simulate complete trajectories for multiple shapes with CFD tools due to expensive computational time and cost. Consequently, only characteristic points on the trajectory can be studied. Furthermore, the domain of ATD is a multi-physical domain where complex phenomena such as shock-shock interactions occur, and which requires trade-offs between different disciplines for the re-entry of the RLV. As a result, models with low response times are required. They must be capable to predict the heat flux during pre-design phases quickly and with sufficient accuracy to be integrated in the design process in collaboration with GNC optimisation and system design aspects.

2.1. Current models to analyse the heat load

Apart from CFD calculations, which provide a detailed overview of the heat flux distribution on the vehicle's surface, more simplistic approaches exist. Several simplified equations provide an estimation of the stagnation point heat flux as well as wall heat flux distribution on the vehicle. The stagnation point correlations are often based on simplified boundary layer equations. Examples of such models are the equations from Fay and Riddell [1] and the more simplified equation from Sutton Graves [2] or Detra [3] providing estimations for the convective-diffusive stagnation point heating. A further equation for the stagnation point on a fully catalytic wall is provided by Vérant-Lepage (optimized Kemp heating formulation) [4]. Those rely on the (equivalent) curvature radius and are limited in their applicability regarding full sized industrial designs and regarding their practical usage for non-catalytic walls due to the required parameters. Based on these estimations at the stagnation point the distribution on the surface can be determined, for example, with the Vérant-Lefrancois model [5]. This equation uses the stagnation heat flux, the pressure ratio between the pressure calculated at each point on the surface and the pressure in the stagnation point as well as the local curvature in relation to the nose radius. Unfortunately, this kind of model is not able to calculate local peaks in heat flux induced by complex phenomena such as shock-shock interactions. For the heat flux emitted from the radiative shock layer the Tauber –Sutton [6] and the Martin models [7] provide an equation valid for the stagnation point based on equilibrium shock theory.

2.2. Development of an analytical model to determine the heat flux

In order to advance Europe's pre-design heat flux prediction capabilities, the development of a surrogate model capable of predicting wall heat fluxes within a short time frame is envisioned. Additionally, the surrogate model should capture more complex viscous interactions not captured by current re-entry codes such as ONERA's ARES code. The prediction relies on the patterns provided by the pressure topology given by fast Euler simulations. Such as the Vérant-Lefrancois model, this surrogate model takes advantage of the similar effects we observe on the evolution of the heat flux and pressure profile on the surface. Different machine learning techniques such as a Gaussian process or a neural network will be investigated for this tool.

The following section provides an overview of the structure of the preliminary created surrogate model. In order to predict the wall heat flux on the surface of a given vehicle, at a given flight point, the hereafter steps are required.

Once the surrogate model is trained, the following input/output process is envisioned (see Fig. 1). For a given flight configuration (Attitude: AoA, SSA, Flight point: altitude and associated atmospheric properties, Mach number/velocity) and vehicle design, Euler calculations are performed to obtain the pressure distribution and its gradient on the surface of the object. This will serve as the only input and is the most time-consuming step. These values for the pressure and pressure gradient at each grid point are then transformed to dimensionless variables, which will serve as inputs for the model. Based on this information the surrogate model produces will give the dimensionless heat flux, which then provides the foundation for the prediction for the heat flux. The steps to obtain dimensionless variables are performed within the code of the surrogate model. It is important to note that the surrogate model will not be given any information regarding the shape of the vehicle; this information is solely required for the CFD Euler calculations. The surrogate model considers the data points just as a combination of four (non-) independent input quantities (pressure, pressure gradient in three dimensions) to predict the output variable: the heat flux.

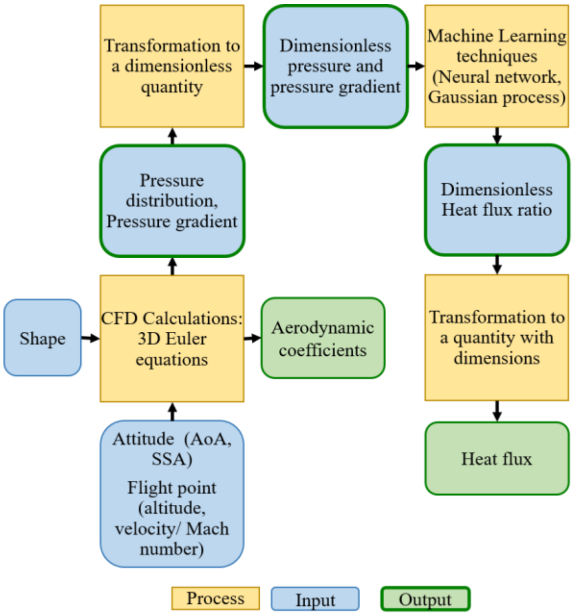

Fig. 1. Visualisation of the structure and variable flow of the surrogate model

To achieve those objectives, the first step is the validation of CFD simulation of the critical phenomena induced by reusable launch concepts using ONERA's in-house multi-physics solver CEDRE [8]. Then, using CEDRE, an exhaustive ATD database (wall pressure and heat flux distributions) for future launcher concepts is built and analysed. Those computations are performed for significant flight points extracted from the optimized trajectories.

In order to make the surrogate model applicable for a variety of vehicle shapes and trajectory points, the ATD database must include a wide range of shapes, trajectory points and different critical phenomena. Regarding the flight points, different points on the ascent and decent trajectory will be chosen, with a focus on different re-entry points with higher expected heat loads e.g. due higher speeds. Since the flight trajectory is also strongly affected by a choice between a Two Stage to Orbit (TSTO) or Single Stage to Orbit (SSTO) configuration and the return mode (VTVL – Vertical Take-off Vertical Landing; VTHL – Vertical Take-off Horizontal Landing; HTHL – Horizontal Take-off Horizontal Landing; HTVL – Horizontal Take-off Vertical Landing), a combination of those parameters will be reflected in the ATD database. A further interesting case for the ATD database

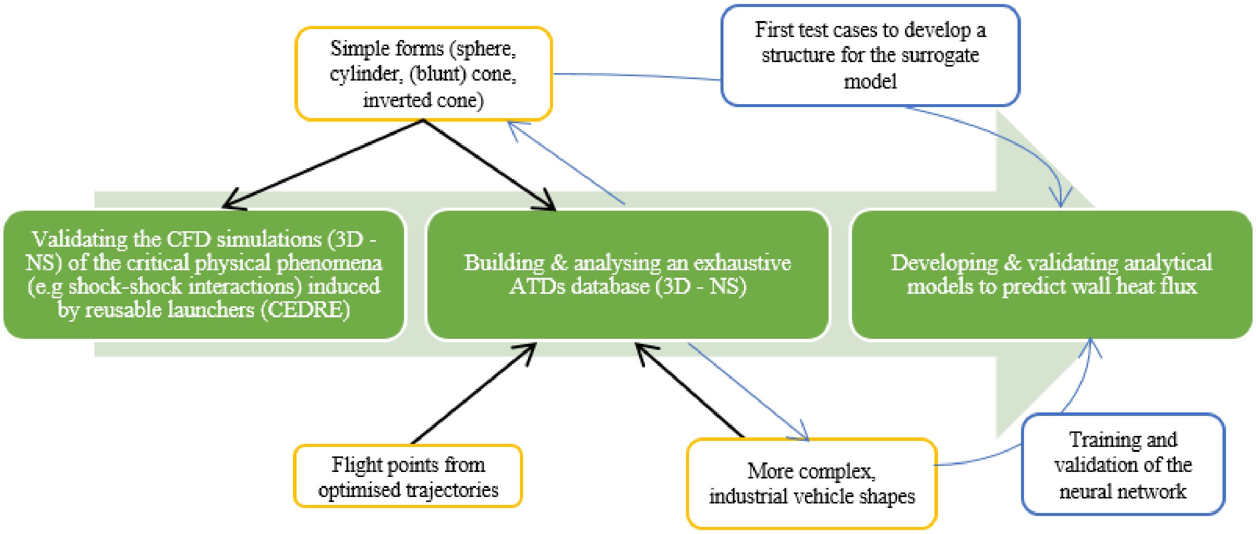

Fig. 2. Schematic illustration of the development process

is a TSTO configuration where one vehicle sits on top of the other during the launch phase, e.g. Space Shuttle or SpaceLiner [9], and which leads to critical phenomena such as shock-shock interactions between the vehicles.

2.3. Future work

The foreseen procedure to develop this model is illustrated in Fig. 2. The two major steps to develop the surrogate model are to expand and built the ATD database and to train and adapt the Machine Learning method. Three dimensional Navier-Stokes CFD simulations are performed with simple forms and compared to literature data to determine a set of valid parameters (e.g. numeric models, grid properties) for the CFD calculations which are able to well capture the relevant phenomena occurring during re-entry (e.g. shock-shock interactions, shock-boundary layer interactions). In order to prove the general approach and discover the underlying challenges, the surrogate model is firstly trained with data from simple forms and is improved and adapted in dependence of further data obtained with structures that are more complex. The preliminary results for simple shapes show promising results.

Regarding the training of the model, several different models will be compared using different hyperparameters. Investigated models include a model based on a Gaussian process, Neural network, and simple regression models. In order to obtain a reliant model a rich ATD database is required.

As explained, the aerothermal loads are strongly affected by the vehicles shape and trajectory. Therefore, interactions with the work performed at Politecnico di Milano, regarding the trajectory planning for the re-entry, are necessary. Furthermore, collaboration with the DLR Bremen is foreseen to integrate the ATD analysis in the design process.

3. Trajectory Optimization and Multi-disciplinary design analysis & optimization for RLVs

Reusable launch vehicles flights are highly demanding as they fly through all atmospheric layers, reach orbit, and return safely. This is further complicated for multi-stage launchers, where mission operations must focus their attention on two or more vehicles flying simultaneously in branching trajectories.

Simulation capabilities and trajectory optimization allow mission designers to assemble the most successful mission which does not only meet all constraints from the diverse phases, but can also complete the mission with optimal propellant. In the next sections, trajectory optimization within MDAO is reviewed along with prospects of future work in ASCenSIon.

3.1. Trajectory optimization of RLVs

Trajectory optimization can be represented mathematically as a subclass of Optimal Control Problems (OCP). These consist of optimization problems minimising an index given some dynamics, certain states, control, and parameters, and path and even constraints.

Various approaches exist to solve optimal control problems, from problem specific indirect methods [10, 11] to direct methods suitable for Non-linear Programming (NLP) [12]. Several techniques as single shooting, multiple shooting and direct collocation based on explicit and implicit dynamics integration exist for the transcription process [13], with the later capable of leveraging on pseudo-spectral methods [14, 15]. To solve the transcribed problem, gradient based local, heuristic based global and hybrid optimization approaches can be used.

Several challenges remain for the development of robust and fast trajectory optimization capabilities for reusable launchers. Several approaches exist to include uncertainty in the optimization process to obtain robust and reliable optimums [16, 17, 18]. Mission analysis approaches are also being integrated with GNC activities as described in Sec. 4.1. For example, novel algorithms as convex optimization for trajectory optimization are being developed which exploit the problem structure to obtain optimal solutions in polynomial time [19, 20, 21, 22]. This is further explored in Sec. 4.2.

Furthermore, recent progress in the field of MDAO has also shown advantages for the treatment of multi-branch trajectories. As RLVs emerged, RLV trajectories were designed by adapting legacy software used for expendable launchers and the space shuttle. To do this, iterative techniques were developed where the recovery trajectory was optimized separately from the ascent problem based on the separation conditions and iterations were performed to adjust the recovery propellant required. This can be seen in Fig. 4, an eXtended Design Structure Matrix (XDSM) [23] adapted for a trajectory optimization problem of a TSTO launcher with main stage reusability (only data flow is shown). Although this approach could provide feasible solutions, it does not exploit the various trade-offs between the ascent and return profile to achieve a minimum total propellant consumption or maximum payload mass injected.

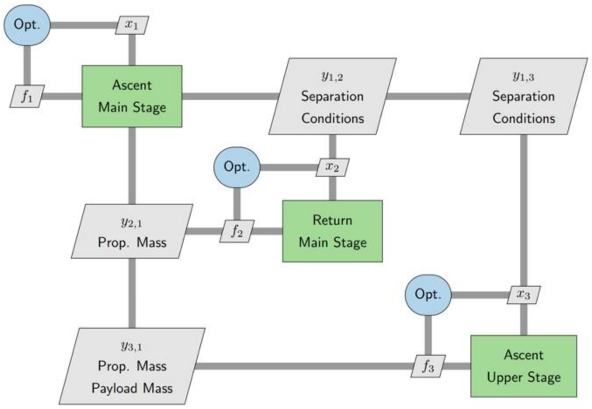

Fig. 3. XDSM diagram for a TSTO trajectory optimisation problem with reusable first stage with a serial analysis. Only data flow is shown. Adapted from [24]

On the other hand, MDAO strategies can be applied to exploit these synergies through a system level optimizer, as seen in a multi-discipline feasible formulation shown in Fig. 4. Ledsinger et al. [24] performed a comparison of various multi-disciplinary design optimization architectures for a TSTO with reusable first stage and compared it with a serial trajectory design showing increased performance. A similar strategy was also employed by Balesdent et al. [25] considering further disciplines and performing a breakdown based on stage flights.

Techniques to obtain system sensitivities in the presence if subsystem solvers as used for MDAO [26] can also enhance problem convergence. The use of the Unified Derivative Equations [27] combining analytical direct, adjoint methods with advanced numerical complex step methods can decrease the number of calculations significantly while increasing accuracy of gradient based algorithms compared to the classical use of finite differences [28]. Falck et al. [29] formulated optimal control in the context of MDAO with implicit pseudo-spectral methods and the integration of various techniques to compute the problem derivatives efficiently.

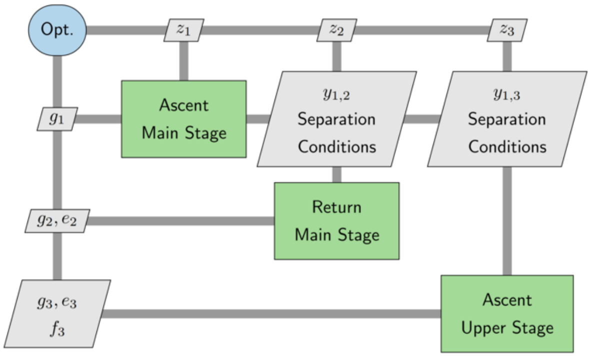

Fig. 4. XDSM diagram for a TSTO trajectory optimization problem within a single level multi-disciplinary feasible formulation. Only data flow is shown. Adapted from [24]

3.2. *Future work*

In DLR-SART, a stepwise gradient based single shooting approach is currently used with Tosca [30]. Within ASCenSIon, the goal is to expand these capabilities to address the specific challenges of multi-branch trajectory optimization considering different reusability options. The methodologies on trajectory optimization for performance estimation and MDAO will be further expanded to the systematic analysis of RLVs considering the interaction with structures, aerothermodynamics and other design disciplines while addressing challenges of monolithic and multi-level architectures. In addition, costs and reliability considerations as used in previous studies for expendable launchers [31] and SSTOs [32] will be further explored. These are further described in an accompanying conference publication on reusability aspects of main stages [33].

4. MA & GNC for re-entry

In this section, first the concept of missionisation for re-entry vehicles is presented. Second, the main aspects for the design of the GNC architecture for RLVs are reported.

4.1. MA & GNC missionisation for re-entry vehicles

The re-flight capability drives the necessity of a MA and GNC missionisation of the solutions for re-entry vehicles. Even if in the literature a clear definition of the word missionisation does not exist, a classical view of missionisation of the MA and the GNC is the recurrent activity to tailor the MA and GNC solution to one particular mission. More in general, missionisation is the adaptation of the spacecraft to the customer's mission. This definition derives from several fields of space technologies. From the launch vehicle perspective, missionisation is the set of activities to be performed to adapt the space launcher to any specific launch and demonstrate reliability of all operations. These operations consider the design of the trajectory, the system engineering analysis, the configuration management, the control of the process, and the data handling of the whole process [34].

An idea of missionisation has been found also in the mission analysis and trajectory design of the Space Shuttle. For each flight, the reference profile, the drag profile in this case, was adapted by tailoring the coefficient of the functions used to design the reference profile itself [35].

More in general, the missionisation process considers all the phases from the preliminary studies to the flight-software acceptance and the running in the correspondent facility. The linking point among these three approaches is the development and the update of the reference solution for a specific mission.

Within the project ASCenSIon, missionisation has a dual purpose. The first one follows the classical viewpoint, addressing the tailoring and the updating of the MA and GNC solution with respect to specific mission challenges. The second aim is the identification of common feasible design space domain for multiple missions, so the assessment of the mission capabilities for a single GNC solution. The missionisation will play a crucial role in the reusability of a space vehicle, where multiple flights are addressed, indeed the final goal is the minimisation of the tailoring effort by updating the MA and GNC solution and by having already qualified solutions, during the mission design phase.

Hence, the development of a missionisation process and tool which reduces the tailoring effort for each mission is addressed within the project. The process aims at identifying the MA and GNC parameters which allow to have robust re-entry trajectories and affect the solution and the performance of the mission. These variables must be systematically categorized by defining the set of optimum invariant and variant MA and GNC parameters. The missionisation tool aims at obtaining an optimized mission solution and a set of feasible multiple missions with respect to these parameters.

4.1.1. High-Level Architecture of the missionisation tool

In this section, an overview of the preliminary high-level architecture of the tool is presented. The tool is constituted by three main modules: the user interface, the design module and the missionisation layer.

The user interface aims at building the problem that the user wants to study. It will allow to set-up all the parameters related to the environment, the vehicle and the boundary conditions. A crucial point will be the arrangement of the optimization variables for both the missionisation layer and the trajectory optimization discipline, if needed. Another task of this module will be the selection of the type of analysis that the tool must perform, as the missionisation has two purposes within this project.

The core of the software is the design module. It is divided into two submodules: the Mission Analysis submodule and the GNC submodule.

The Mission Analysis submodule is constituted by the disciplines needed to compute the mission capabilities of the vehicle or to update the reference mission profile.

For the first scope, several disciplines have been considered:

- Flying Qualities Analysis, which allows to compute in which domain the vehicle can fly in a trimmed and stable configuration.
- Entry Corridor Analysis, which allows to compute the domain in which the vehicle can fly without violating the aerothermal-mechanical constraints.
- Footprint Analysis, which allows to compute the range capabilities of the vehicle, and therefore the capability to reach a given landing site.

Each discipline can be seen as a black box which depends on a set of parameters that can be changed or kept fixed. The varying ones will be tuned and optimized by the missionisation layer for evaluating the mission capabilities of a specified vehicle.

For the second goal, a multiphase trajectory optimization would be considered, in order to compute an end-to-end mission profile. A critical point will be the definition of the cost function and the control and the optimization variables. Also in this case, some parameters can be entered in the optimization performed by the missionisation layer.

A fundamental step is to identify the interactions between the disciplines and the presence of loops among them.

The GNC submodule is relevant when the update of the reference mission profile is considered. Indeed, when the tool is used to compute the common feasible design space, the GNC is seen only as variables that can be used to control the vehicle (e.g. angle-of-attack, bank angle, thrust, etc.). In the case in which a new reference is generated, the GNC submodule has the following tasks:

- Translation of the reference profiles coming from the optimization into parameters (for instance, splines) that can be read by the specified GNC subsystem of the vehicle. This action is reflected into the tuning of the parameters used to map the references.
- Evaluation of the performance of the GNC with respect to the design parameters depending on the inputs.

Especially by considering the second task, the GNC module can be seen as a black box, the performance of which depends on some variables that must be tuned and optimized.

The function of tuning and optimizing the identified missionisation parameters is addressed by the missionisation layer. These MA and GNC parameters are for instance the angle-of-attack, the bank angle, the engine performance, the position of the centre of gravity, the aerodynamic database, that can be modified by means of additional drag devices, and mission events. This module aims at building the design space maps or the updated reference while maximizing, or minimizing, an objective function and considering a penalty function (e.g., a function that considers the number of parameters used to get a specific solution). Then, the tool can interface with additional parts such as libraries, a data repository, simulators and a verification module, where a Monte-Carlo analysis could be run. The idea is to implement a general, modular and fast to set-up tool, able to minimize the tailoring effort between each re-flight.

4.1.2. Future work

The main steps to achieve the development of the presented tool and process are the studying of the theory of the re-entry problem, by understanding and implementing the disciplines needed to design a re-entry trajectory and to define common feasible space, and the identification of the design variables. A crucial point is the identification of the possible interactions between these disciplines. Indeed, the missionisation is an MDAO with respect to the identified MA and GNC parameters.

In parallel, the development of a standard structure to identify and organize the parameters must be considered. This structure aims at approaching several re-entry problems in terms of vehicle characteristics and mission profiles in a standard and systematic way. The purpose is to set which parameters and variables must be considered fixed or must be optimized and tuned. This last set of parameters are so-called missionisation parameters.

The missionisation tool can be used to assess real mission scenarios and test GNC algorithms, such as the GNC architecture overviewed in the next subsection, and to assess the mission capabilities of the vehicle by considering its design limits.

4.2. GNC for re-entry vehicles

The atmospheric re-entry, descent and precision soft-landing on Earth is very challenging mainly due to the atmosphere presence which entails uncertainties and nonlinearities, and the fast dynamics involved [36]. Since the last decades, only a few vehicles have succeeded to land safely on Earth: first for capsules during the Apollo era, then with the Space Shuttle which marked the beginning of RLVs and finally for VTVL vehicles. This has been made possible thanks to advanced and adaptive guidance and control methods which, part of a global GNC system, steer the vehicle towards the desired landing site.

In a MDAO framework presented in Sec. 3, where the objective is to find the optimal RLV configuration considering several disciplines, it is not easy to understand the interactions between atmospheric flight mechanics and GNC. Therefore, a complete Six-Degree-of-Freedom (6-DoF) RLV model is described in this paper to highlight the couplings involved.

In fact, one of the specifications for re-entry GNC is the real-time implementation of the developed guidance algorithms. Due to the high computational power needed to solve the highly nonlinear problem, the latter were only solved offline in the past decade, where a reference trajectory was computed on ground with powerful computers. However, convex optimisation techniques have recently enabled the computation of the reference trajectory in real-time, based on the current flight conditions, and its application in a closed-loop fashion. In the meanwhile, advances in robust control methods have allowed to counteract disturbances and uncertainties acting on the vehicle during the descent. A state of the art of guidance and control methods is presented in this paper.

4.2.1. RLV flight mechanics

In this subsection, the flight mechanics involved in the entry, descent and landing of an RLV are displayed. In the atmosphere, the vehicle is subjected to wind, gravity and aerodynamic forces while different actuators correct the trajectory of the vehicle. These building blocks must be accurately modelled with uncertainties in the 6-DoF simulator in order to correctly assess the performance of the GNC system. Fig. 5 depicts them and highlights their interconnections.

Environmental parameters as the gravity field, the atmospheric density, the speed of sound and the pressure, which intervene in the dynamics, can be modelled as function of the altitude or obtained from existing models as the 2008 Earth Gravitational Model (EGM) [37] for the gravity field or the 1976 Committee on Extension to the Standard Atmosphere (COESA) [A3] for the remaining parameters. Still considering the environment in which an RLV is subjected during re-entry, the presence of wind in the terrestrial atmosphere, as well as potential wind gusts cannot be neglected. As an example, the horizontal neutral wind can be modelled with the 2014 Horizontal Wind Model (HWM) [38] while wind gusts can be generated using noise-colouring Dryden filters [39].

Moreover, the vehicle's mass, centre of gravity and inertia vary throughout the descent according to the actual fuel and oxidizer masses and their level in the corresponding tanks. Therefore, they must be constantly calculated online.

The aerodynamic forces and moments generated by the vehicle are not neglected during the terrestrial re-entry (see Sec. 2). They depend on its external shape which define aerodynamic coefficients according to the drag and lift that are created, respectively, but also on the instantaneous dynamic pressure, highly environmentally dependent. More particularly, the aerodynamic coefficients are estimated as function of the aerodynamic angles (angle of attack and sideslip angle) and the Mach number. They are usually computed offline through CFD simulations using the first stage vehicle configuration from 0 to 180 degrees angle of attack, and then linearly interpolated during the descent.

Taking as example the actuation system of a VTVL launcher, the vehicle is usually mainly steered during atmospheric re-entry via Thrust Vector Control (TVC) but also with aerodynamic fins at low thrust and a Reaction Control System (RCS) based on cold gas thrusters at low dynamic pressure [40]. They directly interact with the GNC system using the outputs of the guidance and control algorithms. The TVC actuates by deflecting the engine's nozzle along the two body axes perpendicular to the vehicle's longitudinal axis by certain angles computed by the control algorithm, while adjusting the thrust magnitude according to the result of the guidance algorithm. During the descent, at low (or zero) thrust, the fins are crucial. They are placed above the vehicle's centre of pressure with usually one pair for the pitch motion another pair for the yaw motion. They have a strong dependence on the aerodynamic angles and on the dynamic pressure. Finally, an RCS based on cold gas thrusters is used similarly to the fins in case of low thrust and low fins effectiveness (at low dynamic pressure which corresponds to high altitude with low atmospheric density). The forces and moments generated by the actuators, as well as the aerodynamic ones, the environmental and vehicle parameters are then integrated in the equations of motion that simulate the re-entry of an RLV in an inertial reference frame.

This subsection allows to understand the interactions between the RLV (actuators, structure, aerodynamics involved), the environment and the developed re-entry GNC system, explained in the next subsection.

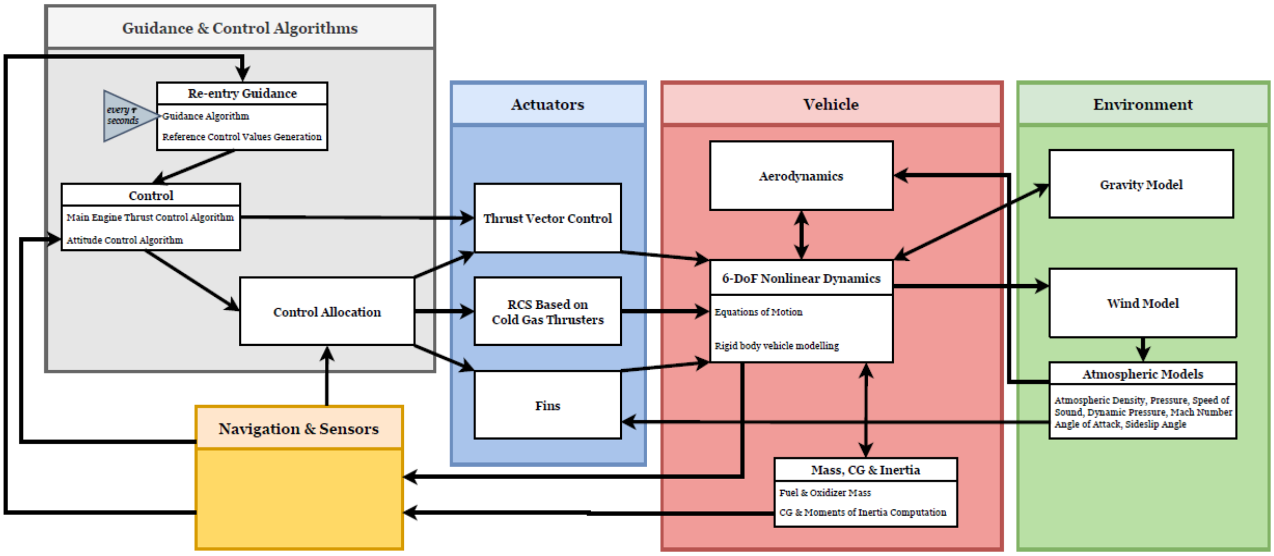

Fig. 5. Building blocks interconnections for an RLV re-entry simulation

4.2.2. Autonomous guidance and robust control design

The previous subsection highlights the importance of the RLV's capability to generate real-time guidance solutions in order to manage the flight mechanics nonlinearities and uncertainties and to enable a soft pinpoint landing. The first family of methods was inherited from the Apollo era, intended for moon landing. A polynomial guidance scheme for the acceleration profile was computed offline according to the initial and final desired positions and velocities [41]. Nevertheless, this method did not consider fuel-optimality, neither allowed for further constraints inclusion. Then, the Space Shuttle entry guidance method used a reference drag-velocity profile to control bank angle and angle of attack during the descent [42], which allowed to better consider the constraints involved (dynamic pressure, heat flux, load factor). However, the recent progresses have shown that convex optimization is the key technology to enable autonomous and onboard real-time trajectory planning and therefore pinpoint landing. It consists of transforming the nonlinear Optimal Control Problem (OCP), defined in terms of propellant consumption, into a convex one, easier and faster to solve. More particularly, the lossless convexification of the non-convex thrust magnitude lower bound constraint first [19], and then further constraints, had made possible the successful pinpoint landing of the Mars Science Laboratory Mission in 2012 and the SpaceX's Falcon 9 in 2015. Since that, research projects and applications have treated this subject and from them, two class of methods can be defined: pseudospectral convex optimization and successive convex optimization. The former transcribes the OCP using nonuniform distributions of discrete nodes and then solves it with convex optimization [20]. The latter iteratively solves convex optimization sub-problems obtained via linearization w.r.t. the previous solution [43]. Liu [44] has extended this method by considering both aerodynamic forces and propulsion as control inputs to gain optimality, whereas Simplício et al. [45] have achieved a trade-off between efficiency and optimality according to the study of the coupled flight mechanics and considered a larger flight envelope encountered by the RLV.

Then, to counteract disturbances from undesired events (e.g. wind gusts), uncertainties and rapid system dynamic, the control system must be able to satisfy strict accuracy requirements while still being robust against parameter dispersions. Classic control linear theory has been deeply exploited in the literature. Winged vehicles have particularly used linear quadratic regulators based on the linearization of the equations of motion and feedback of defined control parameters with gain-scheduling [46]. However, to better address the nonlinearities of the re-entry dynamics and to allow onboard implementation, dynamic-inversion-based techniques and especially sliding-mode control method have been developed [47]. They keep the dynamics in nonlinear form but express them in affine form with respect to the control. These methods, able to deal with off-nominal conditions, are particularly relevant to design a nonlinear control strategy that does not rely on the offline gain scheduling-based synthesis of linear controllers. Nevertheless, all these techniques require an extensive verification and validation campaign with Monte-Carlo analyses, which renders the design process very time and cost consuming. That is why, the H_∞ family of methods, more particularly the *structured* H_∞ technique, is today well studied in both academia and industry [48], while linear parameter varying approach also shows promising results in this direction [49].

4.2.3. Preliminary G&C architecture and future work

This section has explained how a guidance and control architecture interacts with a RLV performing a re-entry into the Earth's atmosphere. A preliminary assessment campaign has been achieved in [50] and allows to point out the more sensitive parameters involved. The guidance and control algorithms used for this study should be extended following the guidelines described in the previous subsection in order to analyse the efficiency of several methods. However, the global architecture must be completed with first, a navigation system, and then, an accurate aerodynamics model, in order to design a powerful tool to synthesize robust GNC for RLVs under precision and soft-landing constraints, depending on the specification of the vehicle itself and its dynamical conditions. This tool will be assessed in a real mission scenario, particularly as part of the missionisation strategy presented in the previous subsection.

5. Multi-orbit multi-payload injection

Another of the characteristics of the new launcher development within ASCenSIon is the possibility of delivering several satellites to differentiated orbits in the same launch. Such interest roots in the increasing number of planned constellation missions as well as the growth in the number of small satellites' launches planned for the near future [51]. Typically, these smaller satellites are launched via piggyback strategies into orbits close to that of a certain primary load, limiting the flexibility of the different missions both in terms of final operational orbit and of scheduling. To counteract these drawbacks, the multi-payload multi-orbit injection capability is proposed. This strategy will allow the upper stage of the launcher to efficiently deliver the different satellites into dedicated orbits, without requiring them to be close to a primary load.

To achieve such capabilities, the launcher must be equipped with a flexible and robust GNC system that can ensure the delivery of all the satellites within industrial requirements. However, the most challenging subsystem is that of the guidance, as the multi-target rendezvous motion of the spaceborne vehicle between different orbits is quite complex. Achieving an optimal trajectory of this nature encompasses two main parts: determining the visiting sequence and optimising the trajectories in-between consecutive orbits. In addition, the whole trajectory must ensure that at the end of the mission, the vehicle is correctly disposed into a certain orbit to comply with the space debris mitigation guidelines.

5.1. The multi-orbit visiting problem

Selecting the ideal sequence of orbit visiting is crucial to achieve the optimal solution, as it determines the transfers performed during the mission, and consequently the cost in terms of fuel consumption and mission time. This part of the guidance to be optimized is a combinatorial problem which presents analogies to the well-known Travelling Salesman Problem (TSP). The solution to this problem is the shortest path which allows the salesman to visit a set of cities once, starting and finishing it at the same location.

However, while similar in nature, there are significant differences that make the multi-payload multi-orbit injection more complex than the typical TSP. On the one hand, the problem under consideration is time-dependent due to the orbital dynamics, which makes the cost of moving between orbits also a function of time. On the other hand, the complete trajectory is not closed, as the vehicle must start at a certain parking orbit (or at the launch location on Earth) and must finish at a disposal orbit to comply with the debris mitigation guidelines.

Several approaches have already been proposed to solve this particular case of time-dependent TSP, although it has been mainly applied to Active Debris Removal and On-Orbit Servicing. The combinatorial nature of the problem suggests the use of an exhaustive search [52] or tree search algorithms [53, 54]. These strategies, however, are limited with respect to the number of possible visiting orbits that they can handle due to the factorial growth of the search space, making computational times unfeasible. To counteract this problem, heuristic algorithms have been used to solve the optimal sequence. These algorithms trade accuracy of the solution with time efficiency, giving sub-optimal results at significantly faster speeds that brute force approaches. Typical algorithms used are the Ant Colony Optimisation [55], the Particle Swarm Optimisation [56], Simulated Annealing [57], or Genetic Algorithms [58].

Most of the proposed solutions, however, do not consider the possibility of having a constant final orbit for the disposal of the vehicle, imposing only the orbits to be visited for operational purposes. The sequence optimisation has been extensively studied in the limited amount of literature related to the multi-rendezvous in space, while the trajectories in between two orbits have been usually simplified, or not considered in the optimisation process, as in the work of Izzo et al. [59]. In most cases an impulsive Hohmann transfer approach is followed, due to its inherently optimality nature. However, for general orbital changes this assumption does not hold and a general Lambert targeting is studied, which is either pre-computed [60] or included in the optimization loop [61].

Most of the presented literature only deals with fuel consumption minimisation as the objective of the optimisation problem. However, when dealing with an upper stage, time is also of utmost importance since customers desire their payloads to be in orbit and operational as soon as possible. A bi-objective formulation of the problem is necessary in which both time and fuel consumption are considered, considering that shorter are achieved through higher fuel consumption, and vice versa. This has been the object of study of previous analysis, such as that of Daneshjou et al. [56].

5.2. GNC system design for multi-payload multi-orbit insertion

The objective of the work to be performed is to develop this new GNC system that would enable the multi-payload multi-orbit injection capability. Such design will be the one that will not only ensure correct deployment of the several satellites, but also the disposal of the vehicle itself after operation, contributing to the efforts of ASCenSIon's objectives within the space debris mitigation activities. The strategy to be followed in order to comply with the mitigation rules, to be decided with the efforts of the mitigation activities of the project, must be included in the mathematical formulation of the problem, which will affect the overall trajectory. In fact, several options can be envisaged, which are discussed in the following section. Stuart et al. [55] considers the solution of the TSP in space with a final disposal re-entry in the transfer sequence.

In this manner, the work to be performed within ASCenSIon will consider the final debris mitigation compliant manoeuvre in the overall visiting sequence, which involves a re-definition of the mathematical formulation for the Mixed Integer Nonlinear Problem including this last transfer as a constraint. It must be noted that, depending on the type of manoeuvre to perform in this last step, time will become of crucial importance, as it must be considered if the vehicle is to be re-entered to ensure safe disposal into uninhabited areas, increasing the complexity and overall mission time-dependency.

It is envisaged that a Hybrid Optimal Control strategy will be used to solve both the combinatorial and the transfer problems. The objective is to reach a flexible optimisation algorithm able to fit any possible orbit required by the customers, followed by a safe manoeuvre to comply with the mitigation guidelines. This way, the trajectory of the upper stage during its operational life will be more realistically studied, ensuring that its disposal is correctly performed by including it in the overall design.

Finally, when dealing with the delivery of an extensive number of satellites, it must be considered that not all of them can be launched in the same vehicle at once. Therefore, a certain planning of the complete mission must be performed in which it is ensured that all of them are delivered within a certain period taking under consideration specific available launch locations on Earth. In such a way, the TSP becomes a multi-salesmen problem with sub-routing in which both the number of salesmen and their path must be minimised, while delivering the complete set of required satellites. This concept has already been studied in previous works, such as the one of Cerf [60], and in fact would be of necessity when developing the complete mission of the newly developed launcher. Each one of these launches would, in turn, need to individually comply with the mitigation guidelines established.

6. Reliability and Safe Disposal

Since the beginning of the space era, the most useful orbits around Earth have been polluted. With almost 30,000 catalogued objects orbiting around Earth, and more than 900,000 objects above 1 cm estimated [61], space missions are at permanent risk. These objects range from defunct satellites and rocket bodies to fragments of collisions or explosions, including even ejecta or NaK leakages from old reactors [63].

The Inter-Agency Space Debris Coordination Committee (IADC) Space Debris Mitigation Guidelines established in 2002 were a good step in the protection of the space environment. These guidelines establish, among other recommendations, the necessity to remove any object from the Low Earth Orbit (LEO) and Geostationary Orbit (GEO) protected regions in less than 25 years from the end of their operational lifetime. Additionally, all on-board energy sources need to be passivated [64]. Thus, all batteries need to be discharged and all the propellant needs to be vented out of the tanks. The clearance from the protected regions and passivation of energy sources is commonly referred to as PMD and it has been shown to be the most effective way to protect the space environment. For instance, Lewis et al. [65] identifies the PMD of constellation satellites and of the launchers used for the deployment as the first two main drivers influencing the impact of large satellite constellations on the space environment.

The successful implementation of the PMD becomes especially important for rocket bodies, being the largest objects that are sent to space and therefore the ones that can cause the biggest harm. Additionally, fragmentation events have historically been related to propulsion causes, mainly due to the large amount of energy stored in propellants [66].

The last aspect to influence a safe disposal of the rocket bodies is the risk that they may pose on ground when they re-enter, as they are usually massive objects which do not completely demise in the atmosphere. However, this paper will focus mainly on the reliability of the PMD, being the risk posed on ground by the re-entry a topic left for future work.

6.1. Current implementation of PMD

The awareness about the importance of the PMD has increased over the years, and the number of launchers that perform it has significantly increased [66].

The preferred disposal method used in the current launch vehicles consists of using their propulsion system to perform a re-entry manoeuvre after the injection of their last payload.

The most obvious reason for this choice is that launchers already incorporate powerful propulsion systems that can be used for the disposal. Any other device would need to be added, increasing the complexity of the design. Additionally, rocket bodies are typically large objects that do not completely demise in the atmosphere during the re-entry. This means that controlled re-entries are required in many cases in order to mitigate the on-ground casualty risk. This implies that devices such as electromagnetic tethers, solar sails, drag-augmentation devices, etc. cannot be used in these vehicles.

This study will therefore consider that the disposal is performed using the propulsion system of the launch vehicle. However, there are still several options to be considered, especially considering the increasing market for smaller systems that may not require a controlled re-entry. These options would include:

- A manoeuvre for a controlled direct re-entry.
- A manoeuvre to lower the perigee in order to achieve an uncontrolled re-entry before the 25 years limit. After this manoeuvre, all on-board energy sources need to be passivated.
- Passivation of all on-board energy sources, when the original orbit is naturally compliant.

6.2. Reliability of the disposal

The first step to improve the reliability of the disposal is to look at past failures, which will help tailoring the reliability efforts. However, the data for failures during the disposal stages is not easily retrievable. However, [67] examines the launch failures occurred over the past 15 years, distinguishing between the ascent and payload injection phases. This data can be used as a reference due to the similarities between the payload injection and the decommissioning phases.

Fig. *6* shows the subsystems that were responsible for the failures occurred during the payload injection phase in the last 15 years. The propulsion subsystem (PROP) was responsible for half of the failures, followed in importance by the Trajectory and Attitude Control System (TACS) with 32%, separation systems (SEP) at 14% and the power storage and distribution system (POW) with 4%.

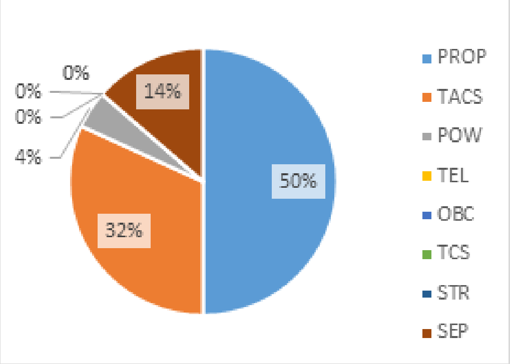

Fig. 6. Subsystem responsible of the failures occurred during the payload injection in the last 15 years [66]

Comparing the payload injection phase with the disposal strategies described in Sec. 6.1 two main differences can be found: firstly, the disposal phase does not require any stage or payload separation and secondly, the passivation processes need to be considered for the disposal phase if a direct re-entry is not conducted. Thus, the failure due to separation systems can be disregarded. It can therefore be inferred that the most important systems to be considered when modelling the reliability of the post mission disposal of launch vehicles are the propulsion system and the TACS. On the other hand, the reliability of the passivation processes also needs to be addressed.

6.3. Future work

The work envisioned for this section includes the modelling of the reliability of the launcher system, focusing on the reliability of the propulsion system, the trajectory and attitude control system and the passivation processes. More particularly, the efforts will be focused on the development of simplified models that can allow to make design choices that will benefit the reliability of the vehicle from early design stages. These simplified models can be included in MDAO methodologies as the one envisaged within ASCenSIon and introduced in Gulczyński et al. [33], which will help ensuring the reliability of the system from early design stages. Finally, the target orbits of the mission and fuel requirements will be considered, in order to find the best solution for the disposal manoeuvre, which will also influence the overall reliability of the disposal. This final disposal manoeuvre will also be included in the multi-orbit injection guidance strategy described in Sec. 5, in order to optimize the overall trajectory.

7. Conclusions

The ASCenSIon project is building knowledge regarding Europe's re-entry capabilities and multi-payload injection. The optimization of flight vehicle's performance with strict aerodynamic, structural, and thermal loads constraints is challenging. The envisioned ATD surrogate model enables a faster interaction loop of aerothermal aspects into the parallel design process of multiple domains. MA & GNC strategies are depicted in this paper to find the best trade-off in meeting these constraints, and enabling advanced guidance and robust control. Moreover, MDAO techniques are used in order to optimize the vehicle's design also regarding cost and reliability aspects. The compliance with the space debris mitigation guidelines is ensured by the study of the reliability of PMD strategies and the integration of the disposal orbit within the guidance solution.

Contributors

Melissa Lantelme carried out the work regarding the ATD analysis. The study on trajectory optimization and MDAO was managed by Guillermo J. Domínguez Calabuig. Jacopo Guadagnini developed the missionisation strategy. Alice De Oliveira guided the GNC re-entry research. Iñigo Alforja Ruiz analysed the challenges of the guidance design for multi-orbit multi-payload injection. Lucía Ayala Fernández conducted the research on reliability and PMD strategies. All of them drafted and organized the manuscript.

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