OPTIMUM GNC SOLUTIONS FOR THE RECOVERY AND VERTICAL LANDING OF AN ORBITAL LAUNCH VEHICLE

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ABSTRACT

This paper presents the GNC concept solution developed for the recovery and landing of Vertical Take-off Vertical Landing (VTVL) launch vehicles in the context of RETALT (RETro-propulsion Assisted Landing Technologies), a European Union Horizon 2020 project with the objective of investigating and developing launch system reusability technologies based on the use of retro-propulsion. The project aims to increase the Technology Readiness Level (TRL) of the recovery technologies up to 5 for structures and mechanisms, Thermal Protection Systems (TPS), Aerodynamics and Aero-thermodynamics, and up to TRL 3 for GNC. One of the great technical challenges related to the reusability of launchers is the recovery Guidance, Navigation and Control (GNC) system, of which DEIMOS Space is in charge for RETALT. In particular, the design of the powered-descent and landing GNC offers a difficult challenge, since it must allow the system to perform a precision landing in a fast-dynamic environment, with extremely limited fuel margins, and with significant unknown dispersions accumulated during prior phases. To tackle this, state-of-the art algorithms based on hybrid Navigation techniques for state estimation, as well as online convex optimization and successive convexification for the design of the guidance GNC sub-function are explored. The Control algorithm operates in distinct modes dependent on the GNC phase and available GNC actuators, and it is based on modern robust control methods in order to provide analytical guarantees over the control performance in the presence of uncertainties and unmodelled dynamics. The proposed GNC solutions were integrated and tested in a high-fidelity simulator and the performance were preliminary assessed, demonstrating the capability to successfully steer the vehicle to the desired landing site.

Index Terms— GNC, Optimisation, Successive convexification, Hybrid Navigation, Robust Control. RETALT

1. INTRODUCTION

Launch vehicle reusability is currently the most effective way of reducing the cost of access to space, which is a key endeavour to the commercialization of space [1]. Despite this, it remains a great technical challenge, with only two US entities (companies SpaceX and Blue Origin) having developed the necessary technology to carry out routinely successful launcher recovery missions. Both use retro-propulsive vertical landing as the recovery strategy, and both report significant cost savings due to the reusability effort. On the other hand, the European aerospace industry remains largely behind in this effort, risking being far outcompeted if it does not catch up with its US counterparts.

In this context, the main goal of RETALT is to investigate the concept of VTVL Two Stage To Orbit (TSTO) reusable launchers applying retro propulsion combined with aerodynamic control surfaces that is currently dominating the global market. The objective of the GNC design in RETALT is thus to develop key GNC concepts that would enable the recovery of the first stage of the TSTO launcher and target a TRL 3 for the most critical components at the end of the study.

To meet the study objectives, a baseline end-2-end solution is identified for the complete return mission. Critical algorithms are then defined, implemented, and tested, being the powered descent and landing solution the main focus of the development. Although autonomous powered-landing GNC strategies and algorithms have been available from past Moon and Mars robotic landing missions, their direct application to the landing burn of a booster recovery mission is not possible due to the additional difficulties of the present mission. These include a higher Earth gravity and hence faster dynamics, a non-negligible atmosphere and therefore non-negligible aerodynamic forces and winds, and minimal fuel available due to the recovery not being the primary mission. In particular, the guidance function for the present design requires sophisticated state-of-the-art algorithms based on online optimization [2]. The strategy is to formulate an Optimal Control Problem (OCP), and solve it directly in real-time with a numerical optimization solver. The output of the optimization is a landing trajectory and thrust profile that are dynamically feasible, fuel-optimal, and which take into account certain operational and system constrains.

2. REFERENCE MISSION AND CONFIGURATION

The baseline configuration and the main focus of the project and this paper is RETALT1. The vehicle operates similarly to a typical launcher until separation, after which two scenarios for the first stage recovery are considered: Downrange Landing (DRL) and Return to Launch Site (RTLS), illustrated in Figure 2. The latter differs in the use of a post-separation flip manoeuvre and boost-back burn that modifies the ballistic arc to allow a landing at or near the launch site, while the former foresees a landing at sea on a floating barge. Both scenarios employ a re-entry burn, in order to reduce velocity (from hypersonic to high supersonic speed) and dispersions, and an active aerodynamic descent phase enabled by the use of aerodynamic control surfaces (ACS). Finally, the first stage recovery mission ends with an engine-powered descent and pinpoint vertical landing, which slows the vehicle down from low supersonic/transonic velocity to a soft touchdown.

Different configurations were studied for the RETALT1 concept, including interstage petals (IS), planar fins (PF), and grid fins (GF), with the planar fins configuration eventually selected as the baseline [3]. The baseline RETALT1 return configuration is shown in see Figure 1.

The concept configuration of the RETALT1 first stage was designed assuming the use of Vulcain-like engines [4], and has a dry mass of 59.3 tons and 57 tons of propellant available for the return manoeuvres (50 tons plus 7 reserve). The feasibility of the mission solution was assessed by an extensive mission analysis [3], and the validity of the propellant budget confirmed.

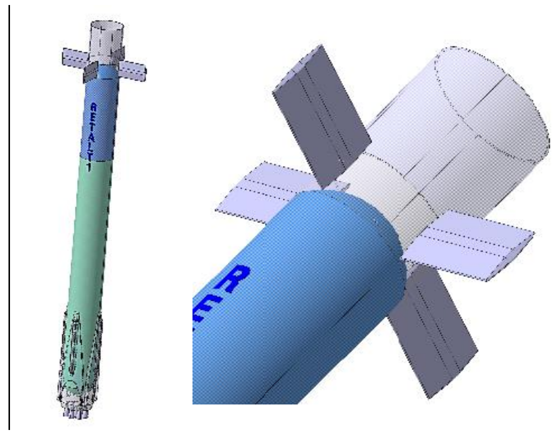

Figure 1 Baseline RETALT1 concept, with planar fins as main aerodynamic actuators [4]

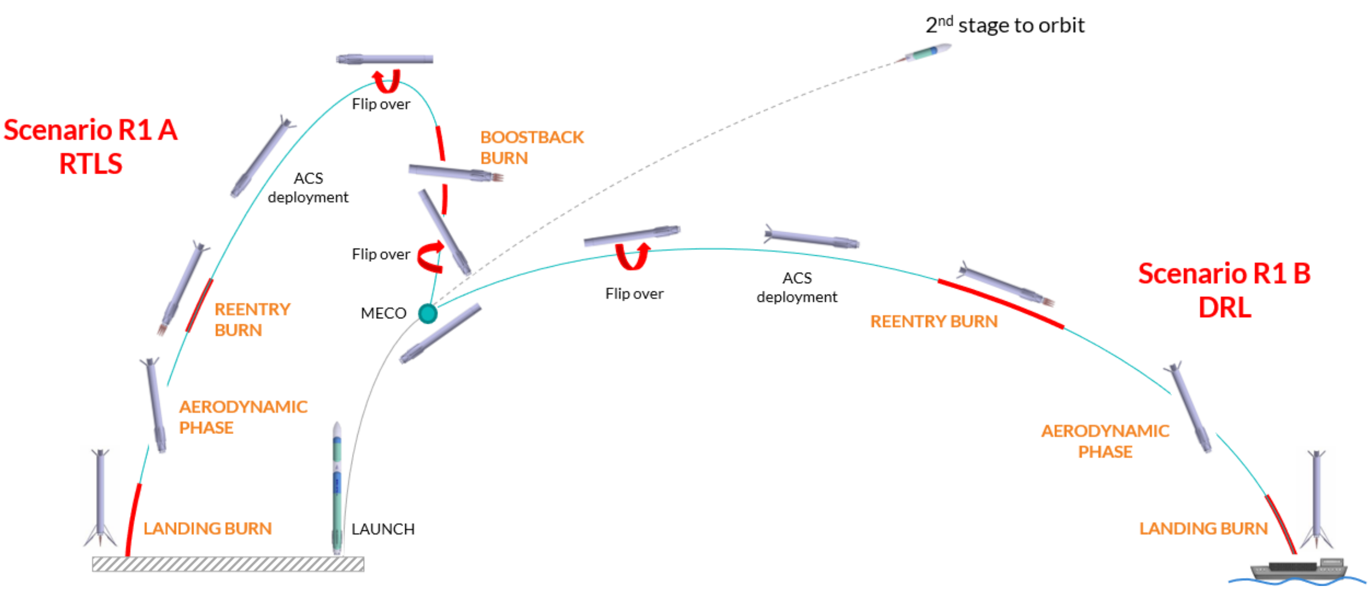

Figure 2 RETALT1 return mission concept

3. GNC DESIGN

3.1. Functional architecture

The GNC is split into the following sub-functions:

- *Navigation*: it provides position, velocity and attitude estimates during the return phase, making use of Inertial Navigation System (INS), or IMU, products hybridized with a GNSS. The use of (D)GNSS/Altimeter allows increasing the accuracy of the estimation close to landing.
- *Guidance*: it defines the re-entry, descent, and landing trajectories during the return phases. This serves to ensure the vehicle is able to perform a pinpoint landing, respecting the mission and flight path constraints.
- *Control*: it tracks the reference produced by the guidance and ensures a stable attitude, using the effective actuators for the phase. This includes the actuator management.

This architecture is illustrated in Figure 3, where the interactions between each sub-function, the Flight Manager, the sensors and actuators are also included. The GNC operational modes are defined by the mission phase in Table 1, together with the sensors and actuators applicable for each mode. The Guidance commands the attitude manoeuvres required in each phase of the flight, the modulation of the attitude during the re-entry burn and the aerodynamic phase to target the correct location at the start of the landing burn.

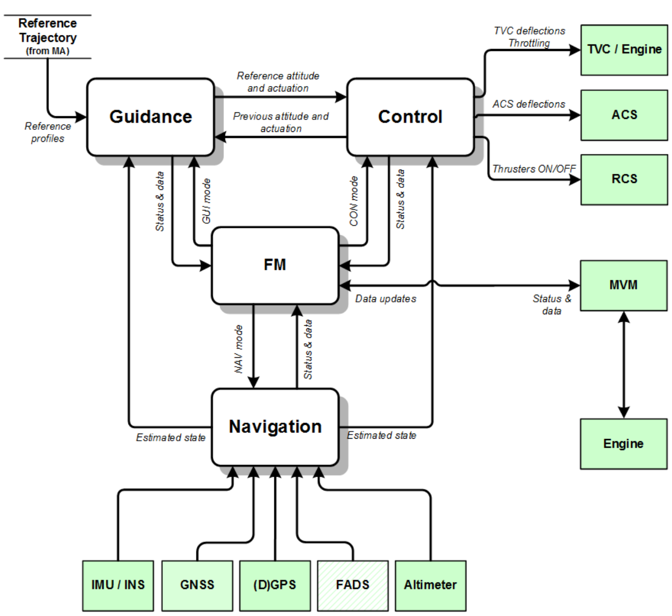

Figure 3 RETALT1 recovery GNC functional architecture

The Control takes care of executing these manoeuvres while rejecting perturbations, making use of Thrust Vectoring Control (TVC), Reaction Control System (RCS), and Aerodynamic Control Surfaces (ACS) based on their availability during the flight. The Navigation could also use (F)ADS, or altimeter, if needed, to further improve the estimation accuracy close to the landing site.

3.2. Guidance

The purpose of the guidance during the return mission is to steer the first stage to the desired landing site, either the launch site or a barge depending on the return scenario, and guarantee a pinpoint landing. The guidance strategy varies for each specific phase of the return mission, due to the different objectives and dynamics encountered for each of the phases, being the powered descent and landing guidance the key algorithm as it shall cope with the fast dynamics of the powered landing phase, where the aerodynamic contribution is still relevant, and shall be robust to the vehicle and environmental uncertainties.

The solution selected for the RETALT powered descend and landing guidance relies on the definition of an OCP that is optimized on-board. The OCP is defined with a dynamic model, an objective function, and a set of constraints, discretized, and then solved at a low frequency in real-time using available optimization solvers, as illustrated in Figure 4. Extensive research has been successfully conducted in the last years to study how this methodology can be applied to the powered descent guidance problem for Mars landing missions [5],[6] aiming at fuel optimal solutions in presence of non-negligible aerodynamic forces [7]. The adaptation of these techniques to the booster recovery problem has been studied [8] [9] and has been proposed for the CALLISTO experiment [10]. More notably, the guidance employed by SpaceX for the Falcon 9 landing also utilizes this type of strategy [2].

Table 1 RETALT1 recovery GNC modes

Phase	Guidance	Navigation	Control	Maneuvers
Boostback burn	Landing site targeting	Hybrid IMU/INS – (D)GNSS	Maneuvering, Pert. Rejection TVC / RCS	Quick Flip over Boostback burn
High altitude ballistic flight	-		Maneuvering, Pert. rejection RCS	Slow Flip over ACS deployment
Reentry burn	Trajectory corrections - powered		Maneuvering, Pert. rejection TVC / RCS	Reentry burn
Aerodynamic phase	Trajectory corrections - aerodynamics	Hybrid IMU/INS – (D)GNSS- FADS	Maneuvering, Pert. rejection ACS / RCS	Trim control and bank control
Landing burn	Pinpoint landing - powered	Hybrid IMU/INS – (D)GNSS- FADS - altimeter	Maneuvering, Pert. rejection TVC / ACS / RCS	Pitch control Landing burn

Optional

This type of online strategy is necessary especially for the landing phase due to its challenging nature, since a feasible trajectory must be computed from an initial condition which has accumulated considerable dispersions from previous phases, to a precise final position with an accuracy of a few meters. Moreover, several operational constraints exist that condition the feasibility of the generated reference trajectory, such as the available propellant, the thrust capabilities of the vehicle, namely throttling, and attitude constraints, including the maximum angle of attack and a near-vertical final orientation, which more traditional trajectory planning methods do not allow to implicitly satisfy.

The largest limitation of the selected strategy is the relatively high computational load necessary for solving the optimization problem, which must be sufficiently complex in order to capture the fast dynamics and constraints of the guidance problem. The dynamic modelling is the most critical step in the design of this algorithm: the model may be arbitrarily realistic and complex, which improves the fidelity of the guidance output, but also increases the computational effort required to obtain it. Therefore, the formulation of the optimal control problem is a trade-off between the fidelity and complexity of the problem, and the computational effort required to solve it [11].

The guidance solution implemented for RETALT [11] includes the modelling of non-linear aerodynamic forces, variable mass, and free manoeuvring time. It also allows for the implicit satisfaction of operational constraints such as: thrust throttle and attitude magnitude and rate, to consider limitations of the engine and TVC, terminal state, to ensure soft, vertical touchdown, glide slope and aerodynamic angles, to ensure the glidepath remains above a specified limit and the attitude copes with flying qualities [3]. These characteristics result in a non-convex optimisation problem, that is solved with successive convexification techniques that compared to alternative solutions allows exploiting benefits such as good convergence properties and low computation effort [7].

The guidance solution is developed focusing mainly on the powered descent and landing phase, but its applicability is tested also for the other phases of the return mission.

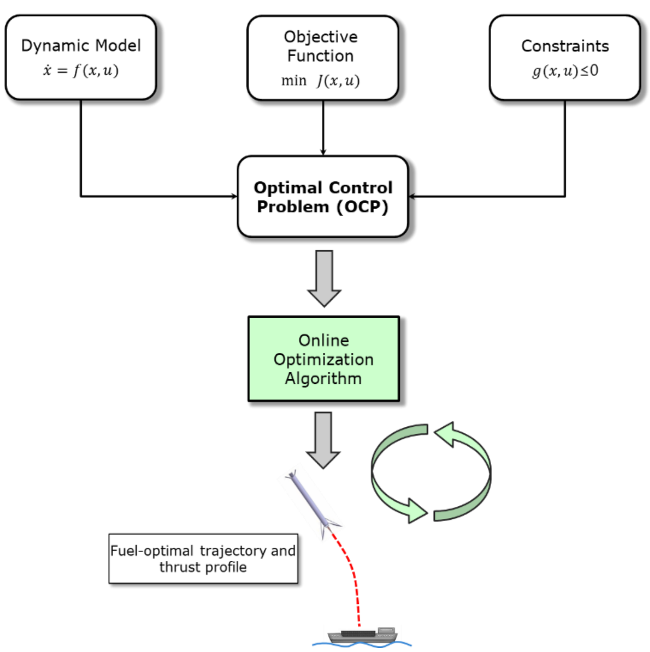

Figure 4 Powered descent and landing guidance strategy

3.2. Navigation

To allow the pinpoint landing of the RETALT1 first stage the navigation system shall be able to produce extremely precise estimations of the vehicle states, to give margins to the guidance and control contributions to the GNC error (e.g., position estimation accuracy at landing below 1m, velocity estimation accuracy below 0.2 m/s).

The navigation solution identified to cope with these demanding requirements is an INS/GNSS coupled system, in which the INS solution is hybridized with the observations provided by the GNSS receiver through an EKF-based filter (Considered Kalman Filter). The navigation algorithm implemented autonomously and internally manages the applicable process based on the availability of measurements from the different sensors. Figure 5 shows the estimation function architecture. This navigation solution has the advantage of simplicity and redundancy. In fact, this architecture can be used with any kind of INS and GNSS equipment and allows outage of GNSS measurements, as the two sensors work independently. Differential GNSS receivers could be used to complement or in alternative to the standard GNSS unit. Other available sensors (altimeter, FADS), could be integrated with an uncoupled architecture.

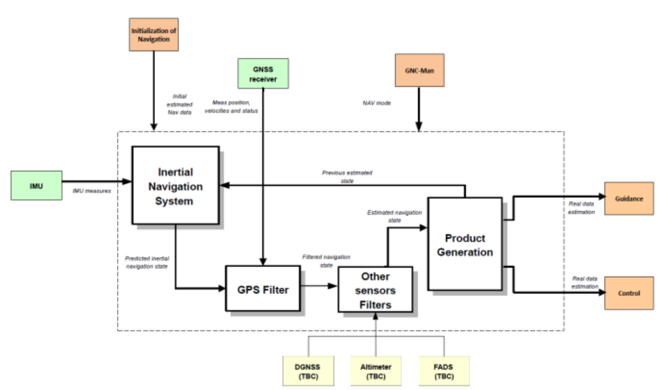

Figure 5 RETALT Navigation functional architecture

3.2. Control

The objective of the control function is to actuate the vehicle in order to maintain its attitude stable, while rejecting disturbances, and to track the reference attitude as commanded by the guidance, within a given accuracy, as specified by the control requirements. This must be done over the full set of flight conditions while respecting the actuator limitations and constraints.

The control for the recovery of RETALT decouples the control of the pitch and yaw channels exploiting vehicle axis-symmetry through TVC/ACS commands, and controls independently the roll rate control using RCS / ACS. Multiple MIMO controllers are designed for different points of the trajectory by solving an optimization problem aimed to ensure the closed-loop robustness to model uncertainty and perturbations, following a well structure design methodology which consists in the derivation, at first, of reliable models obtained by using the so-called Linear Fractional Transformation (LFT) framework, which is particularly suitable for robust control design. The LFT framework allows the representation of the system to control by means of the feedback connection of the nominal plant G(s) and a block diagonal uncertainty Δ(s) gathering all the uncertain parameters of the system. Then, the controller is synthetized using robust control design techniques. The controller synthesis problem (Figure 6) consists in finding the controller with transfer function K(s) that stabilizes the closed-loop system, while minimizing a given cost function. The structured H∞ control synthesis will be applied in order to obtain a controller which guarantees the robust performance of the closed-loop system in the presence of the uncertainties, while keeping a low order predefined controller structure. Finally, μ-analysis techniques are used to assess the robust stability of the system in presence of dynamical and parametric uncertainties.

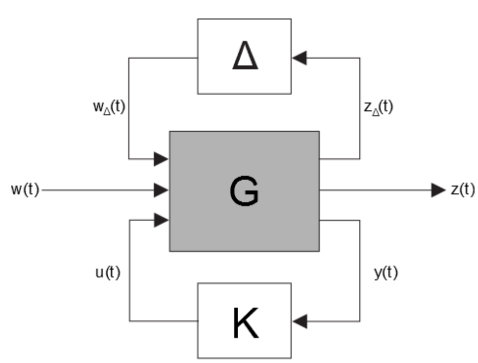

Figure 6 Control synthesis problem

4. GNC PERFORMANCE

4.1. Functional Engineering Simulator (FES)

A Functional Engineering Simulator (FES) has been used to support the GNC testing and evaluate the performance of the algorithms developed in RETALT. The RETALT-FES is a high-fidelity simulation environment based on SIMPLAT [12], that has been tailored to RETALT including detailed vehicle configurations and mission scenario models [3]. It allows performing simulations in 3 and 6 DoF, with G-N-C algorithms in the loop, and performance models of sensors and actuators, see Figure 7.

4.2. Control performance

For the controller a simple structure is chosen over a more complex full order structure. The tuning leverages on the structured multi-objective H∞ synthesis [13]. The performance of the controller are evaluated along the reference trajectory; indeed, given the high variability of the flight conditions for the mission considered, gain-scheduling is applied and the airspeed is used as scheduling variable. In addition, uncertainties in aerodynamics and MCI are considered for the assessment of the robustness properties of the controller. Before performing the synthesis, the control-oriented linear time-invariant models are compared with the FES (in open-loop) to ensure a good validity of the adopted modelling assumptions (see Figure 8), while the achieved closed-loop performance are summarized in Figure 9.

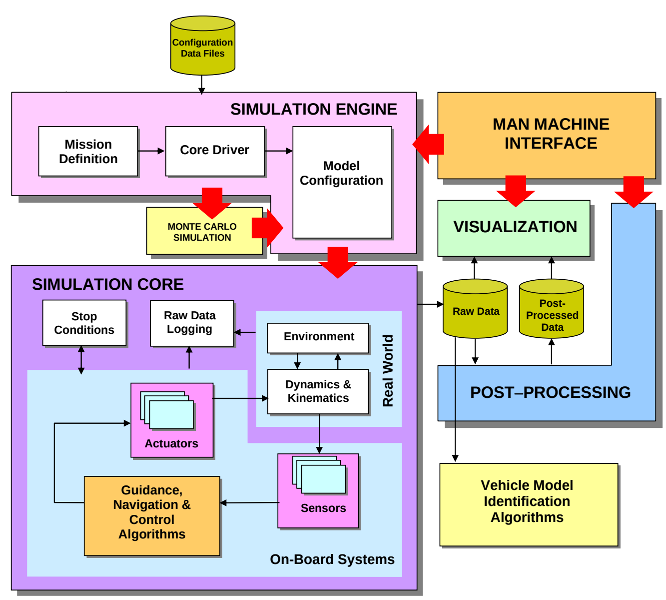

Figure 7 RETALT FES architecture

The robustness of the designed attitude controller with respect to the considered uncertainties is proved by the mu-analysis, whose results are reported in Figure 10; it can be seen that the upper bound of mu is below 1 for all the operating points, thus confirming robust stability for all the considered flight conditions.

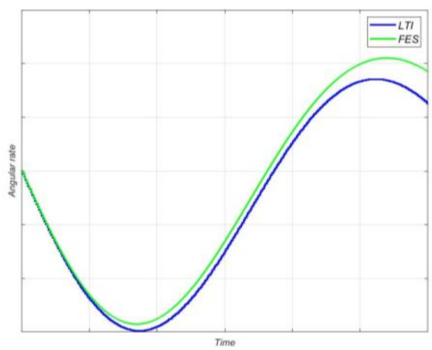

Figure 8 FES and LTI models comparison of open-loop response to a step of fin deflection at a specific operating point

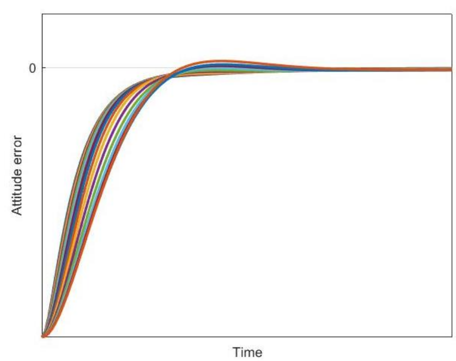

Figure 9 Pitch attitude controller time domain performance for different flight speeds; step response time history

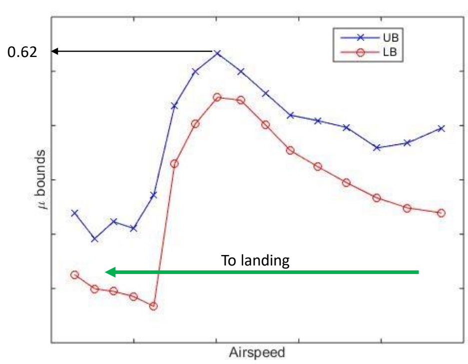

Figure 10 Structured singular value behavior along trajectory

4.3. Navigation performance

A trade-off of the navigation performance allowed the identification of a baseline sensors suite among state of art options: a class II IMU - LN-200E (Northrop Grumman) was used to provide reference performance –, and a differential GNSS (RTK), that acts as GNSS when outside the range of D-GNSS operativity.

End-2-end results obtained simulating from MECO until touchdown and considering uncertainties on sensors measurements, misalignments, initial conditions showed that the navigation concept implemented guarantees very good performance, in line with the requirements:

- Position errors < 0.5 m (3σ)
- Velocity errors < 0.2 m/s (3σ)
- Attitude errors < 0.5º (3σ)

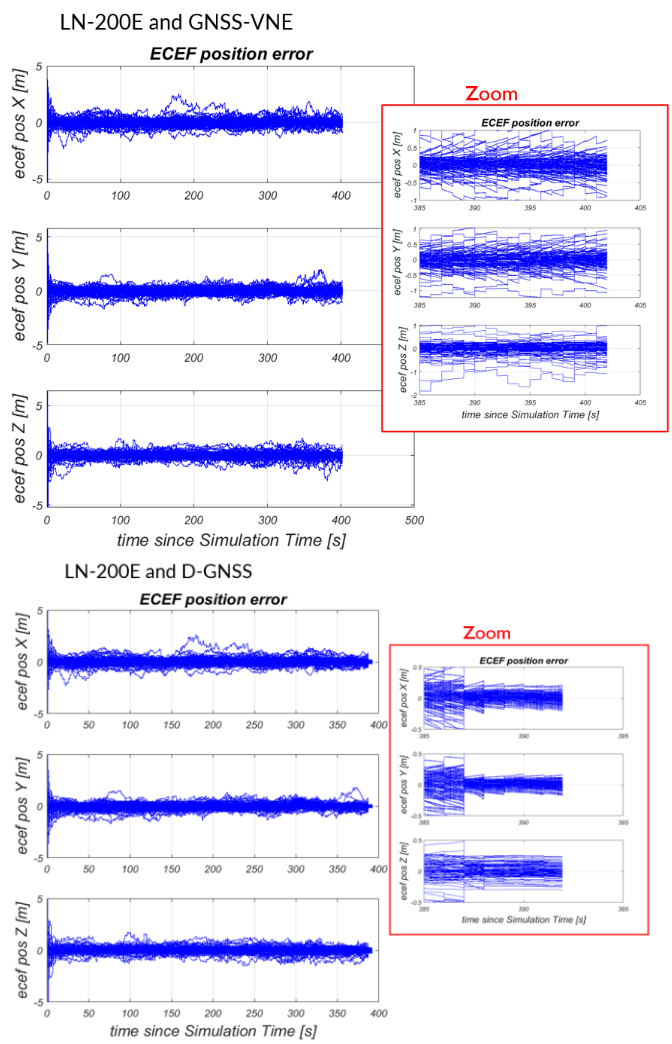

Figure 11 Position estimation accuracy, end-2-end return trajectory

In particular, the use of differential GNSS allows to improve the estimation of the position close to landing, reducing the estimation error below 0.5 m (see Figure 11).

The Navigation concept shows very good performance also in presence of winds, when an on-board wind table is used by the navigation. With a wind knowledge error assumed up to 15 m/s, the estimation performance are similar to the no wind case. The winds have a significant impact on the attitude throughout the flight, however the navigation performance are recovering the increased error during the propelled flight phase: roll angle estimation error is within the requirement, while pitch and yaw slightly exceed it. These results shows that the proposed navigation concept is able to provide the required estimation performance, and the use of additional sensors (e.g., (F)ADS) is not strictly necessary, even if their inclusion is not discarded a priori.

4.4. Guidance performance

The optimised guidance is able to solve the descent problem guaranteeing good performance in terms of convergence and accuracy of the solution. In the nominal case for the downrange landing scenario, for example, the algorithm converges in less than 15 iterations, with the cost function defined reaching the desired threshold, with the virtual controls used to help the convergence decreasing rapidly below negligible levels, see Figure 12.

The guidance is able to successfully recover uncertainties in initial conditions (in line with the trajectory control capability of the system [3]) environment, aerodynamics and MCI, with very good accuracy at touchdown, as 99.5% of the shots (200 in total) below 15 m of position deviation from the target (including algo the contribution of the Control to the GNC error), see Figure 13 and Figure 14. The velocity at touchdown is also kept under control, with more than 70% of the cases below 3 m/s in terms of horizontal velocity and 99% of the cases below 5m/s.

Vertical landing is achieved with the controller being able maintain the verticality of the vehicle as shown in Figure 15, with all the runs showing a final tilt angle less than 5 deg.

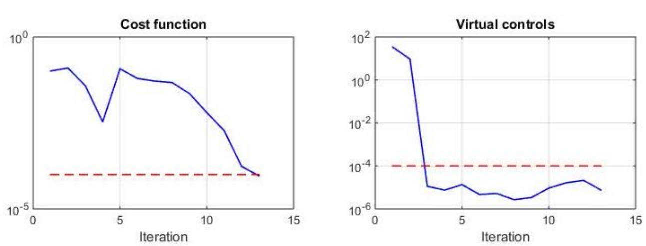

Figure 12 Convergence properties of the guidance solution, nominal case

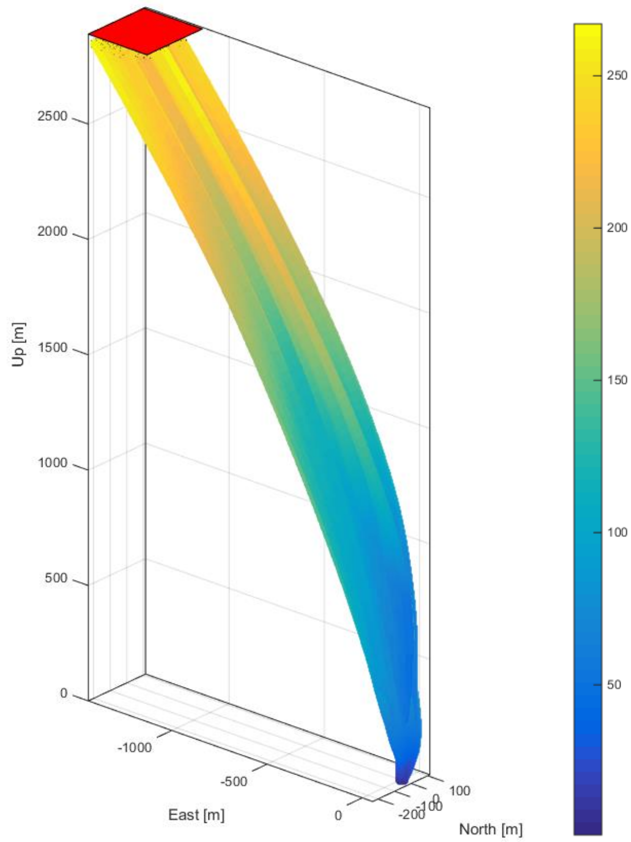

Figure 13 Trajectory path during the powered descent and landing phase

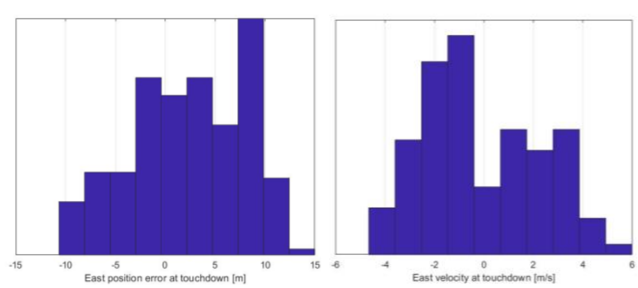

Figure 14 Statistics of position and velocity errors at touchdown

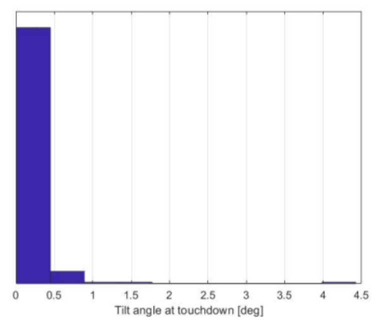

Figure 15 Tilt angle at touchdown

5. CONCLUSIONS

In the framework of RETALT a recovery GNC solution was defined to address the problem of steering the first stage of RETALT1 to the desired landing area, enabling therefore the recovery and thus the reusability of the booster. An end-2-end GNC architecture was defined, and critical algorithms were defined to assure a precise estimation of the vehicles state and the capability to perform pinpoint landing while recovering relevant uncertainties and with a fully controlled vehicle. The GNC solution relies on state-of-art sensors, and makes use of RCS, TVC, and ACS, depending on their availability during the return flight.

A high-fidelity functional engineering simulator framework was used to integrate the complex vehicle's models and the GNC algorithms, allowing the test of the proposed solution in a model-in-the-loop simulation environment.

The results of the simulation campaigns carried out in the context of RETALT showed good GNC functioning and promising performance. The main test campaigns focused on the powered descent and landing phase, that is the most critical part of the flight. For this phase, the proposed GNC solutions reached a TRL of 3. Further tuning and small improvements are necessary to be fully compliant with all the requirements, but the results obtained indicate that the solution proposed is valid.

Further development of the GNC shall focus on the consolidation of the end-2-end GNC solution for the complete return phase, including the management of the boost-back burn and the re-entry burn, for which preliminary tests were carried out but a fully integrated and coherent GNC solution is not yet fully consolidated. In particular, the focus should be the testing of the optimised guidance, as the hybrid navigation has been assessed for the complete return scenario, and the control synthesis also covered all phases of the return trajectory.

6. AKNOWLEDGMENTS

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