RETALT: Development of an Optimal GNC Solution for Recovery of an Orbital Launch Vehicle

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ABSTRACT

This paper presents the Guidance, Navigation and Control solution currently in development by DEIMOS Space for RETALT (Retro Propulsion Assisted Landing Technologies), an EU Horizon 2020 project for studying launch system re-usability technology. The general high-level GNC architecture is presented, with a more in-depth discussion on the navigation and landing phase guidance solutions. The navigation solution is based on a Considered Kalman Filter and a sensor suite that includes an INS/GNSS coupled system as baseline. Navigation simulation results are presented, which demonstrate very good performance. The guidance strategy is based on direct optimal control methods via on-board optimization, which is the only available solution able to satisfy the demanding requirements for a booster recovery mission as such. Within this methodology two approaches are identified, namely single convex optimization and successive convexification, for which a trade-off is performed. The former has been preliminarily selected for the RETALT landing guidance due to its lower computational complexity but still high fidelity. High-fidelity simulation results, however, demonstrate that the fidelity achievable with this approach is not sufficient to satisfy the mission requirements, and therefore a more complex solution based on successive convexification is required.

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 EU and ESA have made increasing efforts to achieve the goal of making launcher reusability the state-of-the-art in Europe. One such effort is RETALT (Retro Propulsion Assisted Landing Technologies) [2], a Horizon 2020 project with six partners in four European countries, with the goal of investigating launch system re-usability technology for two classes of launch vehicles with retro-propulsive recovery (Figure 1): RETALT1, a two-stage to orbit (TSTO) launcher, similar to SpaceX's Falcon 9; RETALT2, single-stage to orbit (SSTO), similar to the DC-

X. For the former, only first stage recovery is performed. The project aims to increase the Technology Readiness Level (TRL) of the recovery technologies up to 5 for structures and mechanisms, and up to TRL 3 for GNC.

1.1 Mission Scenarios

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 boostback 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 and dispersions, and an active aerodynamic descent phase enabled by the use of control surfaces. Finally, the first stage recovery mission ends with an engine-powered descent, which slows the vehicle down to a pinpoint and soft vertical landing.

One of the great technical challenges in this endeavour lies in the recovery Guidance, Navigation and Control (GNC) system, of which DEIMOS Space is in charge for RETALT. In particular, the design of the powered landing phase GNC offers a difficult challenge, since it must allow the system to perform a precision landing in a fast-dynamic environment, with limited fuel margins, and with significant unknown dispersions accumulated during prior phases.

Figure 1. RETALT1 and RETALT2 concepts

After the definition of the functional architecture and the modes for the end-2-end GNC solution (from MECO to landing), the preliminary design of the GNC solution focused on the end-2-end Navigation that shall ensure a precise estimation of the vehicle state compatible with the pinpoint landing accuracy required, and the Guidance for the powered landing phase.

The design solutions obtained at preliminary are the focus of the present paper. Section 2 presents the overall GNC architecture considered for RETALT, while Sections 3 and 4 present in detail the Navigation and powered landing Guidance solutions identified. Section 5 reports the preliminary results obtained and, finally, Section 6 discusses the main conclusions and the way forward.

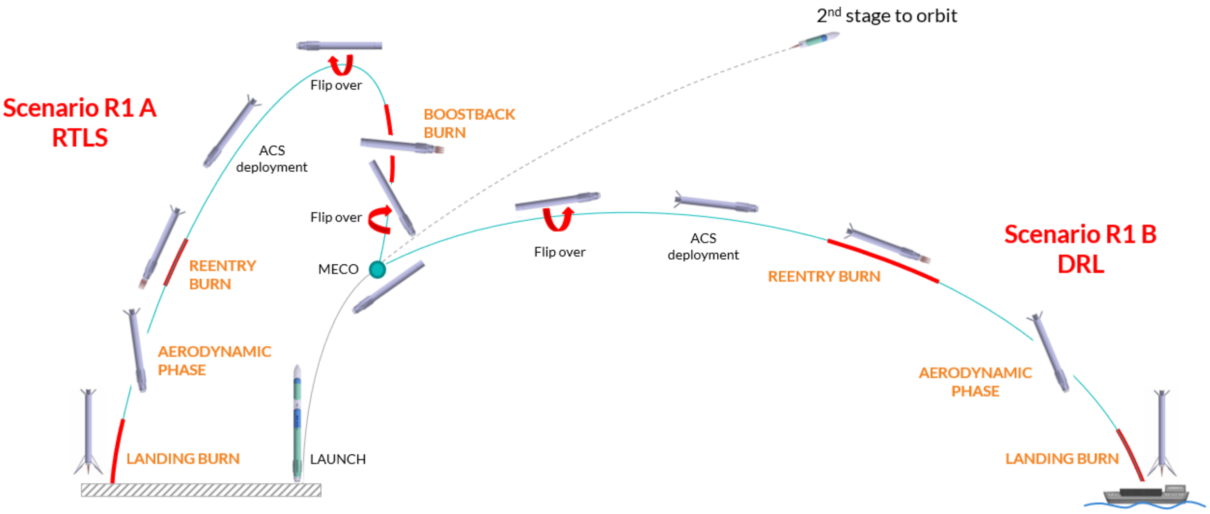


Figure 2. RETALT1 return mission concept

2 GNC Architecture

The GNC is split into the following sub-functions:

- Navigation: This consists of a navigation position, velocity and attitude estimate solution, served primarily by Inertial Navigation System (INS), or IMU, products, and hybridized with a GNSS. The use of (D)GNSS, altimeter and (F)ADS is also under evaluation.
- Guidance: This consists of a guidance algorithm whose aim is to define 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: The control tracks the guidance trajectory and ensures a stable attitude, using the effective actuators for the phase. This includes the actuator management.

This architecture is illustrated in Figure 3, which includes the relations between each sub-function, the Flight Manager, the sensors and actuators. The GNC operational modes are defined by the mission phase in Table 1, together with the sensors and actuators applicable for each mode.

Table 1. GNC modes for the return mission of RETALT1

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

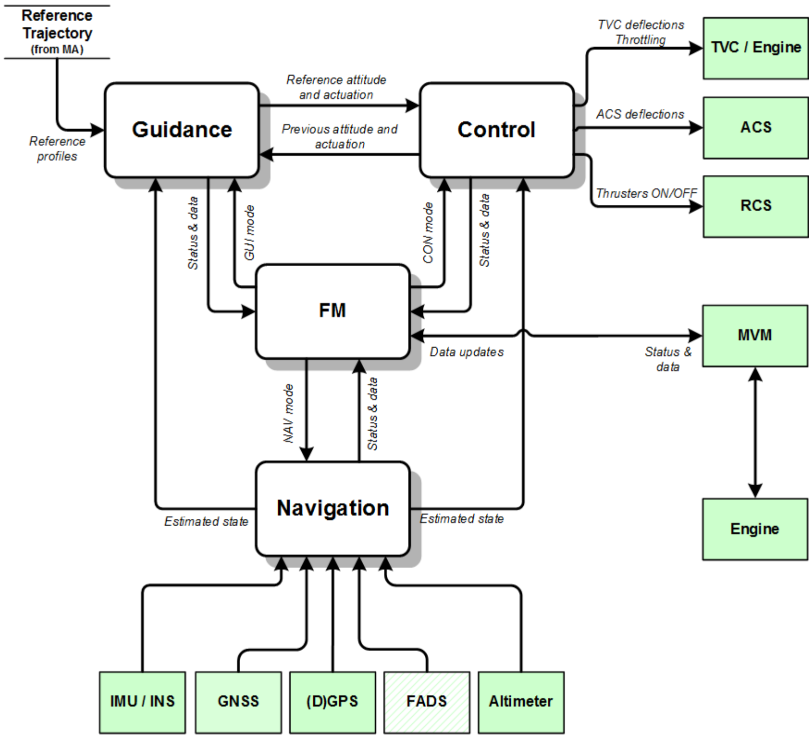


Figure 3. RETALT1 recovery GNC functional architecture

The Guidance commands the attitude maneuvers 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. The Control takes care of executing these maneuvers 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 may also use (F)ADS, altimeter and differential GNSS, if necessary, to further improve the estimation accuracy close to the landing site.

3 Navigation

Given the very demanding requirements for the RETALT mission, the Navigation solution implemented 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 autonomously and internally manages the applicable process based on the availability of measurements from the different sensors. Figure 4 shows the estimation function architecture. The other available sensors (DGNSS, altimeter, FADS), could be integrated with an uncoupled architecture (or even replacing the GNSS unit in the case D-GNSS), providing corrections to the INS/GNSS hybrid estimations, if necessary. Based on the preliminary end-2-end performance obtained (see Section 5.1), a baseline sensors suite was identified among state of art options for the RETALT1:

- The LN-200E (Northrop Grumman) IMU
- G3Star Space GNSS Receiver under development by Deimos [3]
- A differential GNSS (RTK)

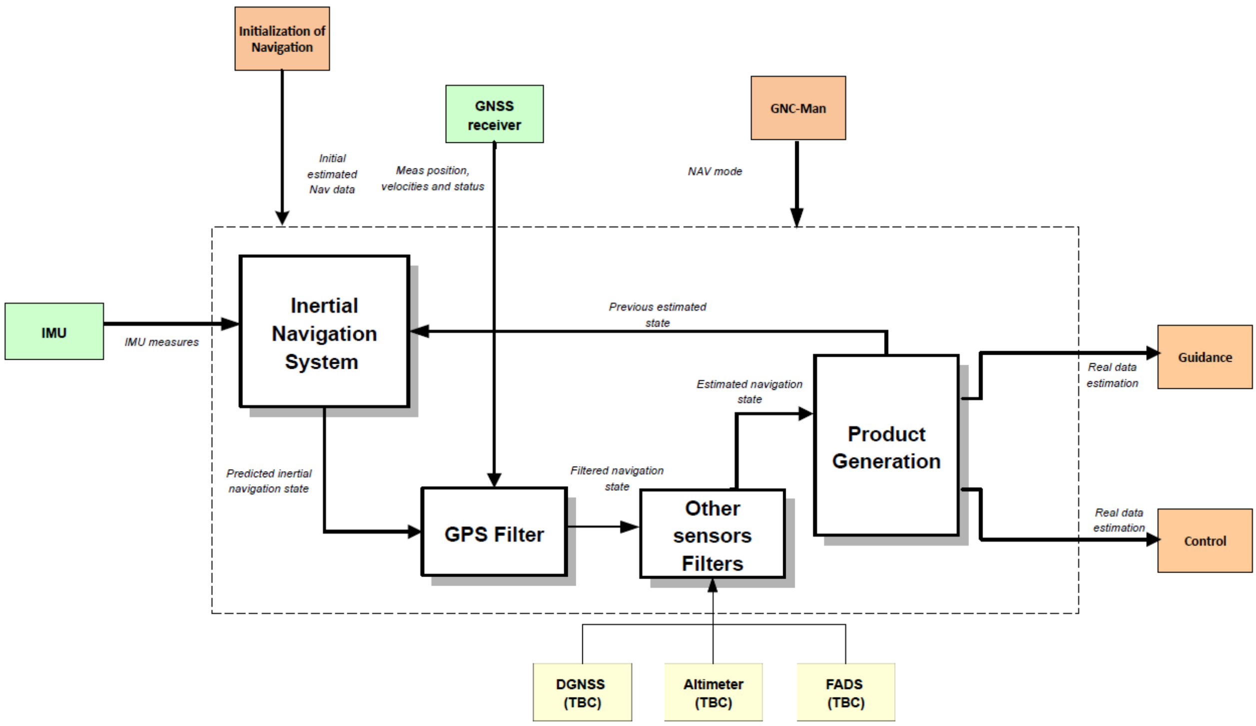


Figure 4. RETALT Navigation functional architecture

4 Landing Guidance

The purpose of the Guidance sub-function is to generate a reference trajectory and attitude for the Control sub-function to track. It typically runs in open-loop, or in closed-loop but at a low frequency in order to decouple it from the closed-loop behaviour of the Control. Furthermore, the guidance strategy varies for each specific phase, due to the different objectives and dynamics encountered for each of them.

The landing Guidance in particular requires sophisticated state-of-the-art algorithms based on the on-board optimization [4]-[11]. The strategy is to formulate an optimal control problem (OCP), which is defined with a dynamic model, an objective function, and a set of constraints. The problem is then discretised and solved directly in real-time at a low frequency with a numerical optimization solver, as illustrated in Figure 5. 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 constraints.

Extensive research has been successfully conducted in the literature in applying this methodology to the powered descent guidance by Açikmeşe *et al.*, *e.g.* [4],[5] and other works, which also yielded real flight experiments [6]. Other important contributions include those by Sagliano *et al.* [7], Lee and Mesbahi [8], Simplício and Marcos [9]. More notably, the guidance employed by SpaceX for the Falcon 9 landing also utilizes this type of strategy [10]. Despite the present work focusing on the landing phase, this strategy may also be extended to other recovery mission phases, namely the re-entry burn and the aerodynamic phase.

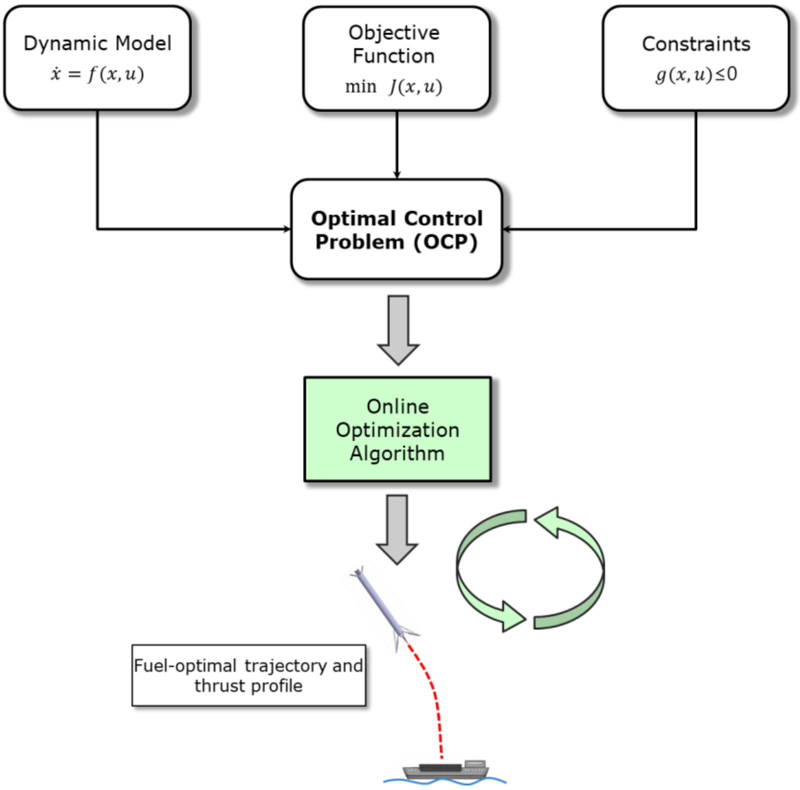


Figure 5. Landing guidance strategy

This type of online strategy is necessary 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 throttling rate, 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 resulting trajectory is then tracked by a low-level and high-frequency attitude controller in the Control sub-function, utilizing the available actuators. Furthermore, the guidance is also complemented with an outer control-loop that closes the loop between optimizations, as discussed later in Section 4.5.

The dynamics at this phase are considerably fast, imposing a computational limitation on the guidance. This is the main downside of the present strategy, given the relatively high computational load necessary for solving the optimization problem, which must be sufficiently complex in order to capture the dynamics and constraints of the guidance problem.

4.1 Optimal Control Formulation

The most critical step in the design of this guidance algorithm is the dynamic modelling. 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. The most important modelling decisions identified are the following:

- Degrees of freedom (DoF)
  - 3-DoF: translational dynamics only, thrust vector defines the attitude.
  - 6-DoF: attitude dynamics also modelled.
- Aerodynamics
  - No aerodynamics: no drag or lift forces.
  - Aerodynamic model: drag and/or lift forces are modelled.
- Vehicle mass
  - Fixed: propellant consumption not modelled.
  - Variable: propellant consumption is modelled.
- Final/ignition time
  - Fixed: final and ignition times are fixed *a priori*.
  - Free: final and/or ignition times are part of the optimization.

The choice of the model affects the complexity of the problem. While a simple 3-DoF model may be linear, introducing attitude dynamics makes the problem highly-nonlinear and non-convex. Furthermore, the modelling of drag forces introduces a quadratic non-linearity, which may be possible to linearise with sufficient accuracy, and modelling lift forces introduces even more significant non-convexities. On the other hand, while modelling the change of vehicle mass introduces a non-convexity in the dynamic model and thrust magnitude constraints, a lossless convexification technique is available [4] which makes the problem linear without loss of generality or optimality. Finally, problems with free final-time and free initial-time also make the problem non-convex and therefore are harder to optimize than fixed-time problems.

The design of the guidance also includes the choice of the OCP constraints, which can be used to avoid the state and control variables to violate certain system and performance requirements, of which some have been mentioned in the previous section. Naturally, the inclusion of complex constraints may also introduce non-convexities. Finally, the objective function is typically chosen such that the problem yields a fuel-optimal solution, by either minimizing the integral of the thrust magnitude or maximizing the final mass.

The selection of the guidance optimization formulation is a trade-off between the computational complexity and robustness of solving the OCP in real-time, and the fidelity of the resulting trajectory and control profile. Depending on the design of the formulation, two main approaches within this framework are identified and discussed next, differing mainly on the dynamic modelling, and consequently also on the method of optimization. We will consider both approaches and present the trade-off performed for RETALT in Section 4.4.

4.2 Single Convex Optimization

The first and simplest approach relies on employing a simple linear model of the vehicle dynamics (e.g. 3-DoF, no/linearised aerodynamics, fixed final-time, etc) and linear or second-order state and control constraints. This approach yields a convex OCP, therefore allowing it to be solved with convex programming techniques, namely second-order cone programming (SOCP) [4]. This is desirable for a real-time application, since there are robust convex programming algorithms with convergence guarantees in polynomial time readily available [11].

In order to compensate for the low-fidelity dynamic model utilized in the guidance, which results in a trajectory that is increasingly infeasible to track with time, the problem is re-solved periodically with an updated state estimate, thus closing the guidance loop, similar to a model predictive control (MPC) approach. On the other hand, as previously mentioned, there is a limitation on the guidance re-solve rate, which must be significantly lower than the Control frequency in order to decouple the frequency response of the two sub-functions, which otherwise may interfere in the Control closed-loop performance and stability.

4.3 Successive Convexification

On the other hand, more complex nonlinear dynamic models (e.g. 6-DoF dynamics, aerodynamics, free final-time, etc) and constraints may be employed, which result in a solution with a higher-fidelity reference trajectory and control profile, but also in a non-convex optimization problem. Solving this requires non-linear programming (NLP) algorithms, which are undesirable to use in real-time, since there is typically no guarantee of convergence to a local minimum. However, state-of-the-art NLP algorithms for optimal control problems have been developed in the literature and are better suited than generic algorithms.

One example specifically developed for the powered descent and landing problem is Successive Convexification [5], which relies on sequential SOCP optimizations that iteratively converge to a solution of the original nonlinear OCP. Therefore, the time complexity of this algorithm is naturally higher than performing a single convex optimization, and depends on the degree of non-convexity of the dynamic model and constraints. Furthermore, in practice the algorithm is often prone to failing to converge, often due to numerical instability, and due to the convergence behaviour being extremely sensitive to the algorithm parameters. Therefore, these characteristics may prohibit the use of the Successive Convexification algorithm for on-board guidance.

On the other hand, given the potential higher fidelity of the trajectory and control profile generated with this approach, there will be less demand for re-solving the guidance at a high rate, and it may even enable the guidance to run in open-loop, *i.e.*, optimizing only once at the beginning of the landing burn.

4.4 Trade-Off and Selection

To select an optimization formulation, a trade-off is performed. For this, the results of different optimizations considering several modelling options are compared. The parameters and initial conditions considered are those for the RETALT1 DRL nominal scenario [2]. Table 2 contains the computational performance for the following optimizations. While the computational times are not representative of a final real flight implementation, they are still useful for giving intuition on the real-time feasibility of each of the formulations.

Table 2. Landing guidance optimization results.

Aerodynamics	Mass model	Final time	Optimization type	Number of SOCPs	Computation time [s]
No	Fixed	Fixed	Convex programming	1	< 10 ms
No	Variable	Fixed	Convex programming	1	< 10 ms
Linearised drag	Variable	Fixed	Convex programming	1	< 40 ms
Nonlinear drag	Variable	Fixed	Successive convexification	6	< 2 s
Nonlinear drag	Variable	Free	Successive convexification	10	< 3 s

As can be seen from Table 2, with the inclusion of variable mass and linearised drag models, the computational load remains relatively low, and potentially feasible for on-board implementation. On the other hand, with the inclusion of more complex formulations requiring a successive convexification, such as nonlinear drag and free final-time solution, the computational times increase dramatically.

To evaluate the benefit in accuracy of using a nonlinear drag formulation versus the linearised drag one, the difference between the two optimization results is plotted in Figure 6. As can be seen, the difference is relatively low, and can expectedly be compensated for by closing the guidance loop. Note, however, that the nonlinear drag model considered here is still not fully realistic, since it assumes a 180 deg angle of attack and therefore does not model lift forces or the change of the drag coefficient due to this parameter.

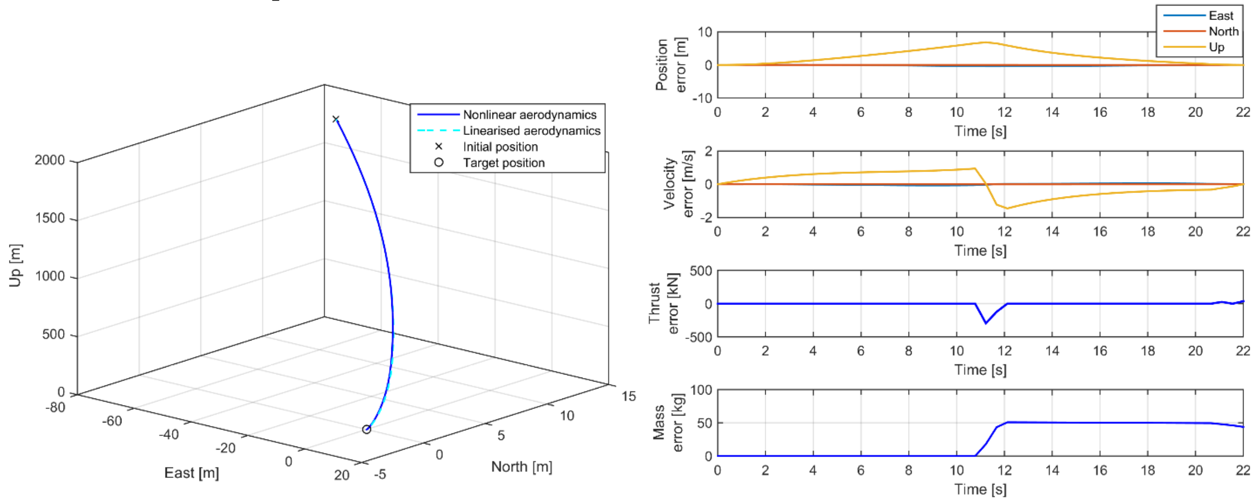


Figure 6. Comparison between guidance with nonlinear and linearised drag model.

Finally, to evaluate the sensitivity of the problem, namely the required propellant, w.r.t. the landing burn duration, Figure 7 is presented, containing the optimal propellant consumption computed by the guidance as a function of that time. Although the propellant is quite sensitive to the final time, this variation is well within the propellant margins for RETALT1. Therefore, the final-time formulation is deemed to not be necessary for the RETALT1 guidance formulation.

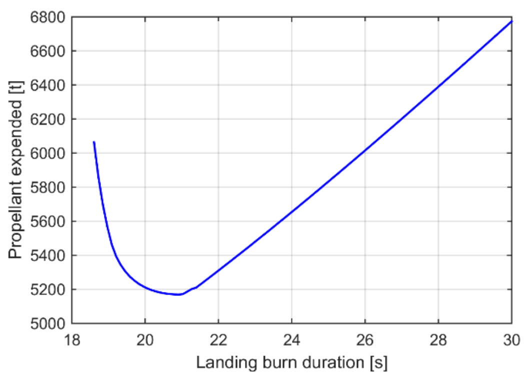


Figure 7. Propellant consumption expected by guidance as a function of the landing burn duration.

Given the relatively low increase in fidelity gained by employing a nonlinear drag model versus linearised drag when compared to the significant increase in computational complexity, and given that the free-final time formulation is not necessary, the guidance solution based on convex programming was selected at this time, namely the formulation with fixed final-time, variable mass, and linearised drag model.

4.5 Trajectory Tracker

As mentioned previously, the trajectory tracker is a controller that precedes the Control sub-function and thus minimizes the trajectory dispersions accumulated between optimizations by running at a higher frequency than the main guidance algorithm. The reference thrust profile from the main guidance algorithm is used as a feed-forward control, around which the tracker computes a small thrust deviation such that the real position and/or velocity is controlled to the reference. This sub-function does not substitute the main attitude Control feed-back loop, and is interpreted as being part of the Guidance since it does not directly compute actuator commands. For the results discussed in Section 5.2, a simple trajectory tracker implemented with an LQR controller has been implemented.

5 Preliminary GNC performance

This section presents the preliminary simulation results of the proposed GNC solutions tested in the RETALT Functional Engineering Simulator (FES), a high-fidelity simulation environment based on SIMPLAT [12] and developed in RETALT to support the GNC testing.

5.1 End-2-end Navigation Results

The Navigation performance were evaluated in the FES for the reference trajectories of RETALT1 from MECO to touchdown [2]. To assess the robustness of the Navigation performance, and to select the proper sensors suite, several IMU performance models were considered (Northrop Grumman's LN-200E, Airbus' Astrix 1090 NEO, and Thales' TopAxyz).

In general, the results in nominal (no failure) conditions, show that the Navigation concept proposed is promising (see Figure 8 and Figure 9), and shows very good performance:

- Position errors < 2 m
- Velocity errors < 0.2 m/s
- Attitude errors < 0.7 deg

The Navigation performances obtained are quite similar despite the sensors and the trajectory. This can be explained knowing the specific nature of the Navigation filter, which takes into account the expected accuracy levels of each sensor, to compute the Covariance matrix that is used to update the estimated state. This makes the Navigation solution quite robust and easy to tune, once the expected accuracy (usually detailed in the datasheets) of the selected sensor is known.

If, formally, compliance with requirements is not achieved (e.g the requirement assumed is 0.5/1 m in altitude/horizontal position error respectively at landing), the Navigation is likely to fulfil the requirements if complemented with proper additional sensors. Hence, a further step, to reach the desired accuracy level, will be to add one (or several) additional sensors, such as DGNSS, Altimeter and/or FADS, in an uncoupled architecture, to improve the performance and reach the desired precision due for landing.

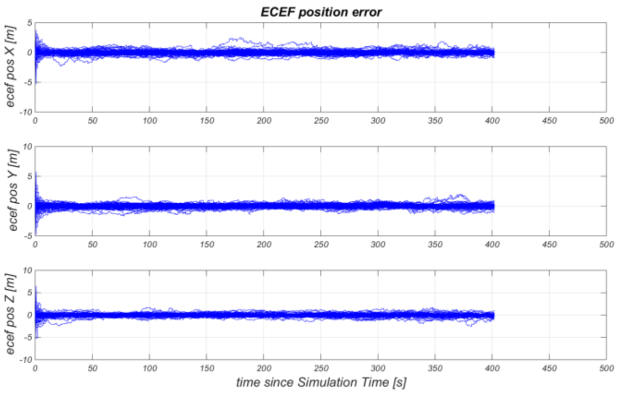


Figure 8. Position estimation error as function of time from MECO, LN-200E

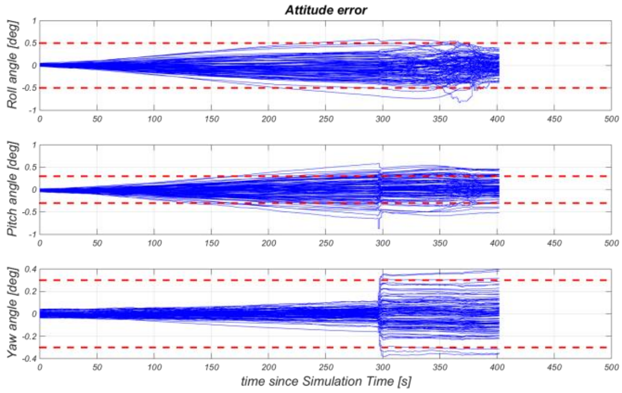


Figure 9. Attitude estimation error as function of time from MECO, LN-200E.

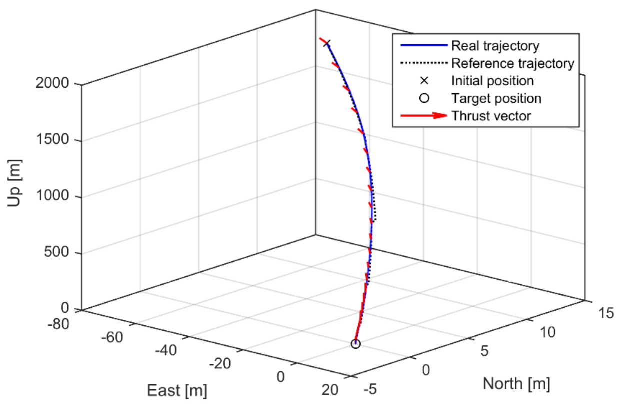
5.2 Landing Simulation Results

Preliminary tests of the powered Guidance solution are carried out utilizing the guidance strategy selected in Section 4 and assuming perfect Navigation in order to separately evaluate the Guidance performance. Furthermore, to also separately test the Guidance from Control, the following simulations have 3-DoF (no attitude dynamics), and the thrust vector commanded by the guidance is directly and instantly translated to the attitude of the vehicle, and therefore the TVC is not utilized. Nevertheless, the trajectory tracker is still present.

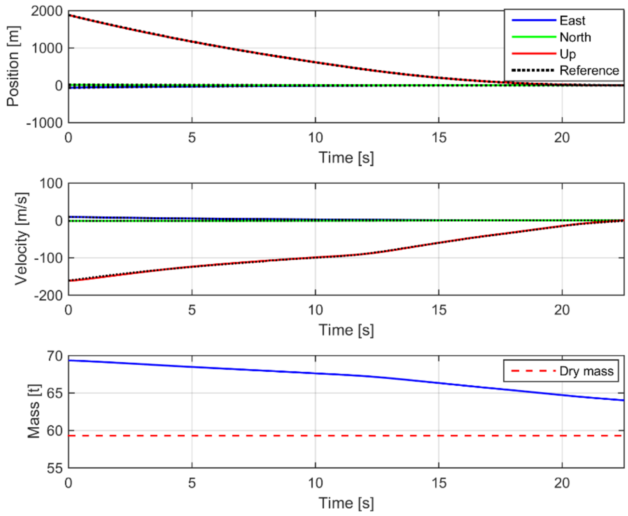
The guidance optimization is re-computed at a fixed frequency of 0.25 Hz, and the trajectory tracker operates at 10 Hz. The landing burn ignition instant is fixed, triggered at approximately 1.9 km of altitude. Although the final landing time is fixed *a priori* and optimized offline, upon each guidance re-computation it is updated based on the expected and real change in the state.

5.2.1 Nominal conditions

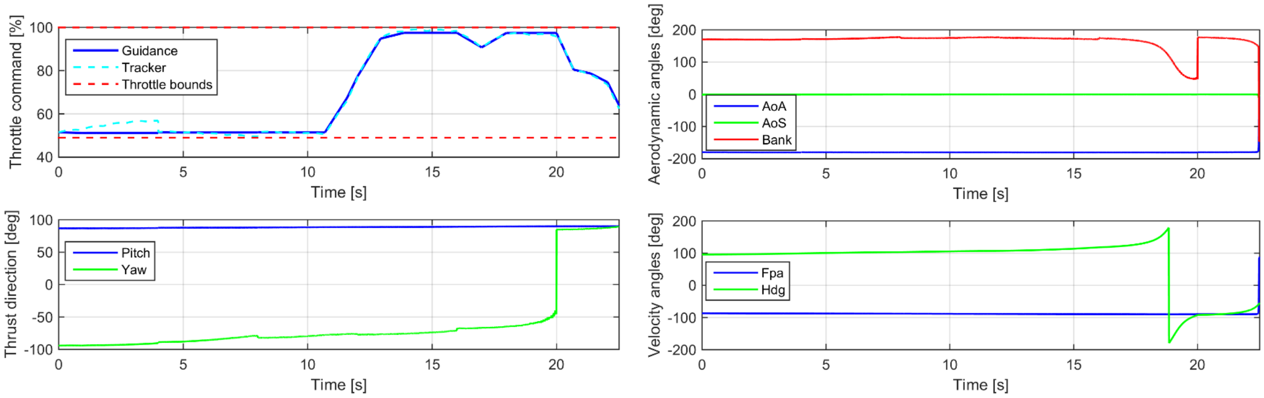
A first Guidance test simulation is performed in nominal conditions, *i.e.*, in the absence of any perturbations, presented in Figure 10. Performance metrics are presented in Table 3.



a) Trajectory



b) State variables



c) Thrust command d) Aerodynamic and velocity angles

Figure 10. Landing guidance simulation in nominal conditions

Table 3. Results of landing guidance simulation in nominal conditions.

Landing burn duration	Propellant expended	Touchdown velocity	Horizontal error	Final pitch angle
22.51 s	5.304 t	0.1255 m/s	0.004921 m	89.93 deg

In nominal conditions, the guidance is able to land the vehicle and safely satisfy all the performance requirements, namely the propellant requirements, and the touchdown position velocity and attitude requirements. Similarly, Figure 10d) shows that the angle of attack is always close to 180 degrees and within the requirements. The effect of the trajectory tracker can be seen in the throttle plot in Figure 10c), where it commands a value around the reference thrust profile in order to follow the reference state.

5.2.2 Dispersed initial conditions

Next, a Monte Carlo campaign is performed, dispersing the initial conditions to the range expected by the mission analysis. The results of the campaign are presented in Figure 11 and Table 4.

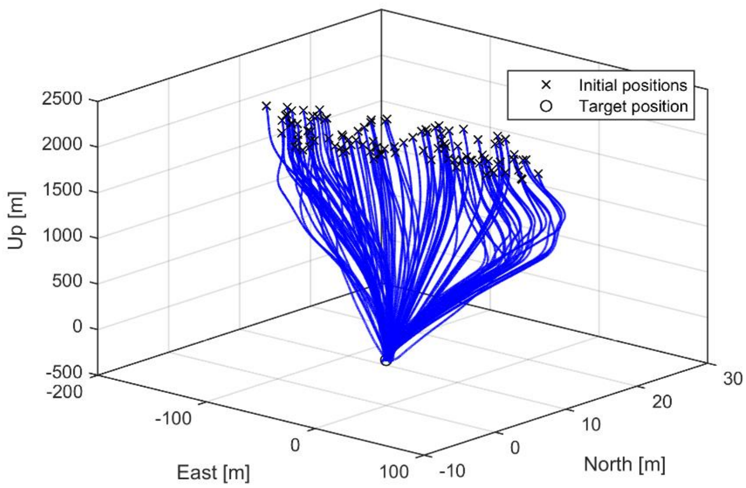


Figure 11. Landing guidance Monte Carlo simulation with initial condition dispersions.

Table 4. Results of landing guidance Monte Carlo simulation campaign with initial condition dispersions.

	Landing burn duration [s]	Propellant expended [t]	Touchdown velocity [m/s]	Horizontal error [m]	Final pitch angle [deg]
Mean	24.00	5.303	0.3475	0.6301	89.61
Minimum	20.80	5.098	0.1134	0.0160	85.40
Maximum	26.99	5.526	2.416	3.985	89.99

Once again, all landing performance requirements were satisfied for all shots of the Monte Carlo campaign. However, due the higher amplitude of the horizontal diversion manoeuvre in some cases, the angle of attack sometimes exceeds the performance requirements (not presented here), since the selected guidance solution based on convex optimization does not allow for constraining this parameter, since it would be a non-convex constraint.

5.2.3 Dispersed aerodynamics and atmosphere

Two more Monte Carlo campaigns are performed in this section, dispersing the simulator atmospheric and aerodynamic models. In the first, only the atmospheric and aerodynamic drag models are dispersed. The results are presented in Figure 12 and Table 5.

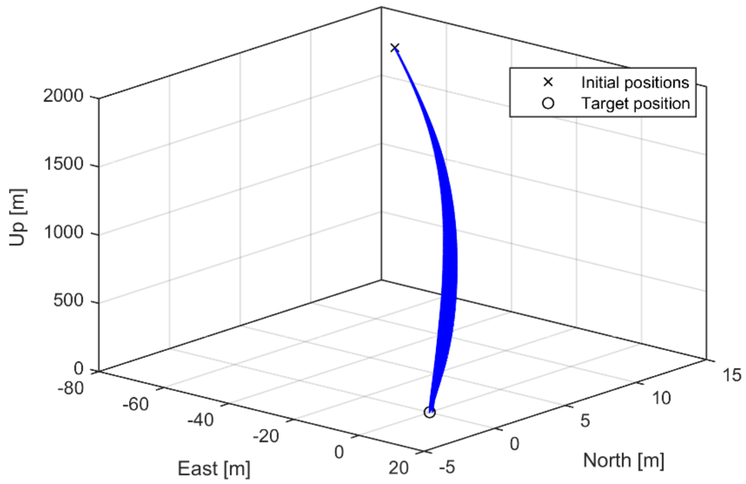


Figure 12. Landing guidance Monte Carlo simulation with atmospheric and aerodynamic (drag) dispersions.

Table 5. Results of landing guidance Monte Carlo simulation campaign with atmospheric and aerodynamic (drag) dispersions.

	Landing burn duration [s]	Propellant expended [t]	Touchdown velocity [m/s]	Horizontal error [m]	Final pitch angle [deg]
Mean	22.40	5.283	0.1220	0.05408	89.93
Minimum	20.75	5.087	0.1004	0.001688	89.64
Maximum	23.26	5.504	0.1833	0.3248	89.99

Once again, with atmospheric and drag model dispersions, the guidance is fully able to compensate the uncertainty and satisfy all performance requirements.

In the second campaign, the aerodynamic lift model is also dispersed. The results are presented in Figure 13 and Table 6.

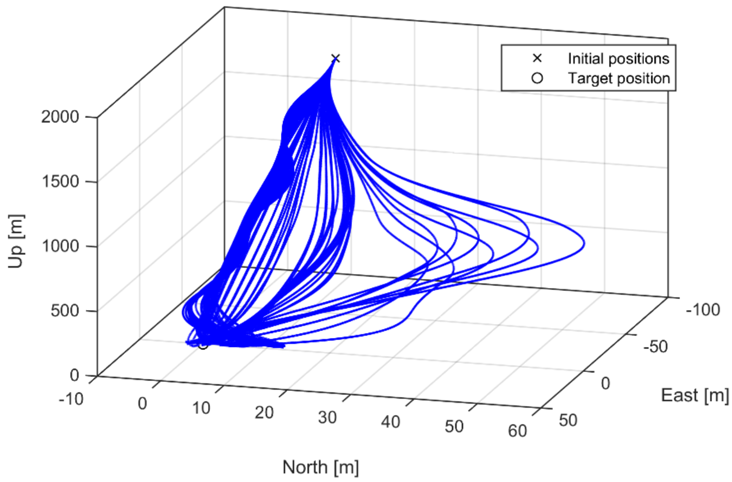


Figure 13. Landing guidance Monte Carlo simulation with atmospheric and aerodynamic (drag and lift) dispersions.

Table 6. Results of landing guidance Monte Carlo simulation campaign with atmospheric and aerodynamic (drag and lift) dispersions.

	Landing burn duration [s]	**Propellant expended [t]**	**Touchdown velocity [m/s]**	**Horizontal error [m]**	**Final pitch angle [deg]**
Mean	21.95	5.165	3.594	1.926	88.15
Minimum	19.44	4.354	0.1097	0.004921	76.22
Maximum	23.82	5.471	26.98	13.09	90.00

It can be seen that with the addition of lift model dispersions, the guidance performance is highly depreciated and does not satisfy the touchdown requirements in some extreme cases, and neither the angle of attack requirements. This is due to the lift dispersions veering the vehicle to off-nominal conditions where the lift forces increasingly act on the vehicle. Therefore, since the guidance does not model these lift forces, the real trajectory deviates significantly from the reference one. One way to improve this performance is by including the lift forces in the guidance model, which requires a change of approach to using a Successive Convexification algorithm.

6 Conclusions and way forward

This paper has presented the current status in the development of the RETALT [2] recovery GNC, including the general high-level GNC architecture. The Navigation solution is based on a Considered Kalman Filter and a sensor suite that includes a INS/GNSS coupled system as baseline, for which simulation results were presented, which have demonstrated very good performance.
The landing guidance was also addressed, which is based on state-of-the-art optimization algorithms. Two main approaches were identified and addressed, namely single convex optimization, and successive convexification. Given the computational limitations identified for the latter versus the low benefit expected with respect to the former, the design principle for RETALT was to select the simplest option, single convex optimization, until the need for greater fidelity was encountered. The performance of this guidance was demonstrated in a high-fidelity simulation environment, where the guidance performed adequately in nominal conditions, satisfying all performance requirements. In some off-nominal cases, however, the limitation of the aerodynamic guidance model, namely the lack of lift modelling, resulted in the violation of the performance requirements. Future work will focus on overcoming this problem, by adopting a successive

convexification solution that allows for including a lift model, which was not addressed in this work, and on making that solution feasible to run in real-time.
While the Control sub-function has not been addressed in this work, an optimum control solution based on H-infinity is under development.

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