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# DESIGN OPTIMISATION AND PERFORMANCE ANALYSIS OF LAUNCH VEHICLES WITH ASTOS

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## Abstract

The design process of launch vehicles is a complex process with partly diverging objective functions and constraints which are often not defined by technical reasons. So much more it is important to map the technical aspects in an efficient design process. This paper starts with the design processes of the past 15 years and presents the newest developments in multidisciplinary optimisation (MDO) of launch vehicles and GNC sizing.
The most critical aspect of the launch vehicle design is the estimation of the structural mass. In the frame of an ESA technology development Astos Solutions has coupled together with MT Aerospace the ascent trajectory and vehicle optimisation with a structural optimisation on substructure level. This allows the estimation of the structural mass as function of stiffening concept, material, geometry and dimensioning load cases, which are directly depending on the optimised trajectory and attitude control.
In addition a preliminary design of propulsion systems is optimised followed by a simple performance analysis which is again coupled with the load cases. The design is finalized with an analysis of the controllability in combination with the aerodynamics.
The GNC system sizing allows a more detailed consideration of the controllability and of the GNC performance sizing thrust vector and attitude control systems. The consideration of flexible dynamics creates a link back to the structural optimisation which provides a finite element model for purpose of Eigen frequency analysis.
The advantages of the new design process are discussed followed by an outlook and conclusion.

## 1. OVERVIEW LAUNCHER DESIGN

The design of a launch vehicle requires the consideration of disciplines like trajectory optimisation, stage sizing, and system design, in particular propulsion system, structure, guidance, navigation and control (GNC) and aerodynamics. Other subsystems and aspects like ground services are important as well, but are not considered in this paper.

The easiest launcher design approach approximates the stage mass using the rocket equation formulated by Ziolkowski. It is based on structural indices or propellant mass fractions and multi-staging is possible too. With some effort losses might be considered, but trajectory related constraints are invisible. Often such an approach is combined with a design of the propulsion system and the structural design, but ignoring the trajectory and optimal control. Such an approach misses the link that the trajectory is partly defined by the propulsion system and is defining the load cases, which are relevant for the structural design.

Trajectory optimisation can be performed with a reduced set of parameters limiting the flight to vertical plane and using only limited freedom for the pitch angle control. The origin of such approaches can be found in the 90ties with limited CPU performance and less powerful NLP solvers. Only with a full optimal control optimisation all constraints of a trajectory design can be considered.

GNC sizing is often not considered in early design phases, which seems to make sense as the number of configurations to be considered is sometimes very large and extensive GNC simulations would be too costly. However, the robustness of a launcher design and sometimes its feasibility is often only visible after a GNC performance analysis.

The latest activities in Europe for the Future Launcher Preparatory Program (FLPP) and the New European Launch Service (NELS) have shown the need for design tools able to provide information, which was normally only an output of detailed design studies. The rationale behind is the huge development cost of a new launcher. As a consequence it was necessary to review the design process, to add further disciplines and to extend the optimisation by post-analysis task keeping the total computational time below few hours.

## 2. REQUIREMENTS

The resulting main requirements for launch vehicle design software can be summarized as follows:

- It shall compute the optimal control and the trajectory considering all relevant constraints and providing input for subsystem design.
- It shall size the stages of a launcher.
- It shall estimate the structural masses depending on the trajectory, material and structural design concepts.
- It shall provide a preliminary design of the propulsion system.
- It shall allow the preliminary sizing of the thrust vector control (TVC) system and the attitude control (AC) system.
- It shall provide a measure for the robustness and performance of the launch system, e.g. the injection accuracy.
- It shall consider safety aspects at the launch pad and during flight, compute impact locations and consider de-orbit requirements.

The most important aspects of trajectory design are [10]

- Free control after aerodynamic forces are small enough
- Pitch rate constraints
- Impact points of burned out stages
- Limitation of dynamic pressure, heat-flux, and acceleration
- Stage separation conditions
- Ground station visibility
- Ground safety constraints at launch pad and during flight
- Limitation of bending moment
- Target orbit

As the design process often requires the analysis of a huge number of configurations and a lot of interactions with other teams the following user requirements are mandatory

- Rapid configuration of launcher design scenarios
- Rapid evaluation of results
- Comparability of results
- Interface to external tools for data post-processing

## 3. MULTIDISCIPLINARY OPTIMISATION

### 3.1. Overview

Multidisciplinary vehicle design optimisation makes use of gradient-based methods like decomposition methods using single and multi-level methods, Random Search Methods (RSM) or sophisticated parametric models like Design of Experiments or Response Surface Methods. Various methods have been implemented in the past in several engineering fields. However, their industrial application in astronautics seems to lack in confidence. That might be driven by the difficulties to integrate MDO results in the classical engineering process of space systems. An optimal vehicle design cannot be defined just by one (global) optimal solution. Rather it requires the feasibility analysis of several vehicle subsystems, which cannot be considered all together in MDO processes especially when using RSM based methods.

For that reason Astos Solutions has developed since many years under ESA contract a multidisciplinary design approach that allows quick optimisation of launch vehicle designs. This development led to the latest version of the ASTOS software suite. ASTOS focuses on the optimal trajectory and GNC related aspects of a mission and includes all relevant subsystems and disciplines like GNC/AOCS, power, thermal, structure, aerodynamics, to provide a complete analysis of loads and budgets for all analysis and design processes.

For such a design process it is mandatory that the industrial and ESA's engineering process is properly reflected in the tool. Since any design solution needs to be verifiable and justifiable it is of less interest to obtain one most global optimal solution, rather than a multi-objective solution. In this kind of optimisation problems, many mission constraints have to be considered and a good system analysis is required to verify the feasibility of the final optimised concept.

### 3.2. Level of Detail

Important criteria for selection of the optimisation method and the models are how many different computations are required and that the various discipline models fit together in their level of detail. As normally the effort cannot be afforded that highly expensive numerical computations based on Computational Fluid Dynamics (CFD) or Finite Element (FE) methods, it is not required to make use of multi-level optimisation methods. As a consequence the best approach is to use an All-At-Once (AAO) optimisation based on gradient models with compliant discipline models, e.g. differentiable and continuous. The clear advantage is that convergence can be achieved and that the computation time will be well compliant with engineering tasks.

This approach is suitable for conceptual and preliminary design tasks. The implementation of discipline models themselves have to match in their level of fidelity and should not have a level of detail which requires extensive CPU-time.

MDO results depend on the implemented discipline models. In combination with trajectory optimisation such models are normally based on a small number of design parameters often using regression tables for the estimation of masses.

### 3.3. MDO with ASTOS

#### 3.3.1. Optimisation Method

The MDO functionality of ASTOS uses a single-level decomposition method, also called All-At-Once (AAO) method, based on the optimal control software CAMTOS with the sparse Non-Linear Programming (NLP) solver WORHP [7] considering a multitude of constraints and extending the optimisable parameter set by discipline models. The optimisation suits conceptual and preliminary design tasks. Multi-objective functions allow to consider diverging design aspects and to present them in a pareto-front. Knowing the cost drivers it is possible to optimise for cost efficient launch vehicle.

### 3.3.2. Propulsion System Design

The liquid and solid propulsion design model uses the chemical equilibrium software RPA [1] to compute the engine performance. Expander cycle, staged combustion, gas generator and pressure-fed systems are supported. Exhaust velocity and characteristic velocity depend directly on the optimisable design parameters throat area, expansion ratio, chamber pressure, and mixture ratio. Chamber sizing and optimal nozzle contour allows computing nozzle, reaction, friction, and divergence efficiency. The mass estimation could be performed with RPA but requires the sizing of turbo pump and other components, which is too time consuming for AAO optimisation. Hence a mass estimation regression [2] is used with comparable results.

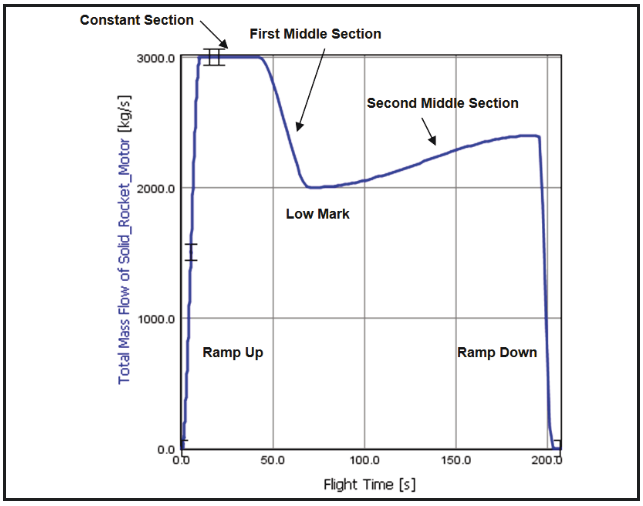


FIGURE 1. Scalable basic profile represented by polynomials with optimisable extreme values and durations.

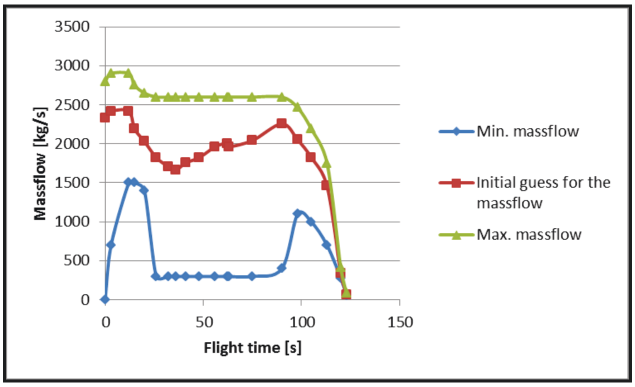


FIGURE 2. Bounded shape profile which is fully optimisable within user defined bounds.

Additional analysis of the flow separation in the nozzle and of the heat transfer can be performed considering convective or radiative cooling. The solid motor gran geometry can be modelled optimising the mass-flow profile using two different approaches. First, the scalable basic profile allows optimising the maxima, minima and duration of the burn phases following an existing profile (FIGURE 1). Second, the bounded shape approach allows optimising a profile within an upper and lower bounded mass-flow profile (FIGURE 2).

### 3.3.3. Structural Design

The structural design starts with the stage configuration, which is not optimisable as it is a basic engineering decision. It defines strap-on boosters and the use of stage under fairing. The number of boosters could be optimised. The tank configuration is again a fixed input choosing between separated, common bulkhead and enclosed tanks. The stage sizing is resulting from the optimisation process and triggered by empty tanks at stage separation. The structural mass is estimated by regression based on existing hardware or at least detailed design studies [2].

### 3.3.4. Aerothermodynamics Models

In addition thermal models for the estimation of the inner solid motor case insulation are implemented, as it provides a considerable mass contribution of up to 30% of the structural mass of a solid motor case.

Moreover an aerodynamic model based on analytic formulas is used which provides force, moment and pressure coefficients depending on Mach number and angle of attack. The moment coefficients are important for the load case computation and are required for the closed loop control simulation. The pressure coefficients are required for the computation of distributed aerodynamics.

### 3.3.5. Sensitivity

Extensive optimisations have been performed. Detailed analysis of the results has shown that the largest sensitivity has its origin in the structural mass estimation (14%), followed by the propulsion system performance (7%) and the aerodynamic drag (2%).

## 3.4. Structural Optimisation with ODIN

As a consequence of the strong impact of the structural design it was necessary to improve the structural mass estimation. The objective was to consider material properties and to obtain a link with the trajectory so that a change of the loads would impact the mass of the system.

Normally extensive computations with FE-methods are required to perform a structural design depending on the dimensioning load cases and considering material and stiffening concept.

With the structural optimisation tool ODIN [3] from MT Aerospace it is possible to perform such task as preliminary design task using analytical formulas. A random search method is used to identify the optimal design parameters for the stiffening concepts isotropic, orthogrid and sandwich for the substructures cylinder, bulkhead, y-ring, cone and strut cone (FIGURE 3). Running ODIN in a batch process it is possible to create large data tables depending on geometry, material, stiffening concept and dimensioning load cases for strength and buckling.

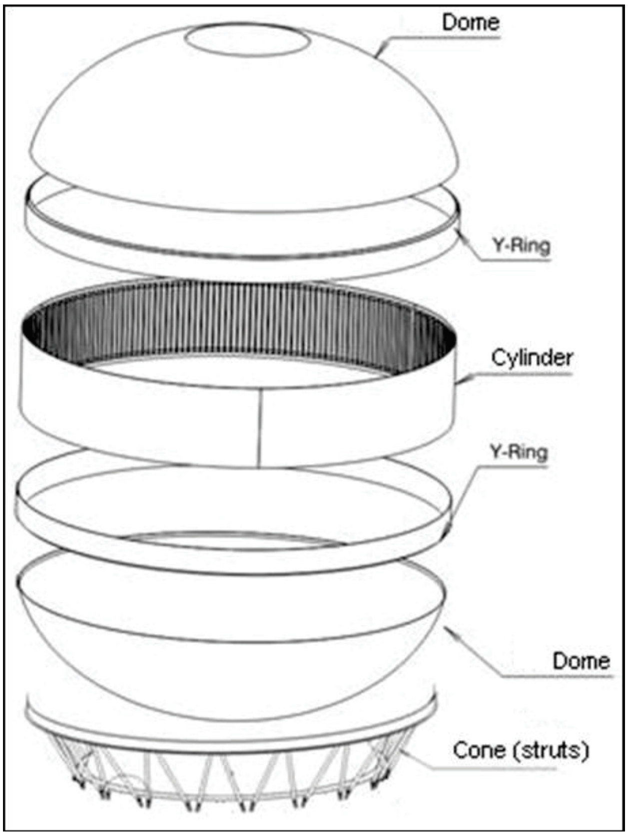


FIGURE 3. Substructures of ODIN

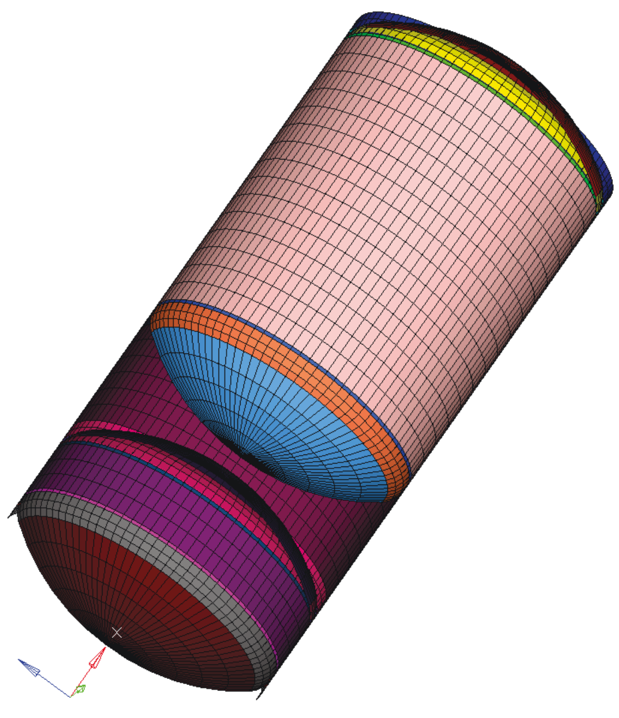


FIGURE 4. FEM export of ODIN

Those data tables are used inside ASTOS again for mass estimation regression. For each stage ASTOS defines a list of substructures composed of cylinders, cones, bulkheads, y-rings and strut cones for which the user has to specify material and stiffening concept. The mass is then calculated as function of geometry and dimensioning load case.

Finally ODIN provides a finite element export (FIGURE 4) using smeared wall thickness which is representative for frequency analysis.

## 3.5. Dimensioning Load Cases

The dimensioning load cases are relevant for the structural design. For simplification only one load case for strength and one for buckling for each substructure is determined. Each load case consists of flux and pressure.

The related fluxes *N* and pressures *p* are computed by a beam approximation which sums up all external forces like thrust and aerodynamic forces and mass forces over the beam. At each cutting plane of a substructure the membrane (m), axial (a), circular (circ), total (t) and equivalent fluxes (v) are computed as follows:

$$(1)\quad N_{m,x} = \frac{F_x}{2r\pi}$$

$$(2)\quad N_{a,x} = N_{m,x} \pm \frac{|M|}{r^2\pi}$$

$$(3)\quad N_{circ} = pr$$

$$(4)\quad N_{t,x} = N_{a,x} + 0.5N_{circ}$$

$$(5)\quad N_v^2 = N_{t,x}^2 + N_{circ}^2 - N_{circ}N_{t,x}$$

The dimensioning load cases are selected for each type of substructure at the following time point of the ascent trajectory as follows

- Cylinder, Cone, Y-Ring
  - Strength: maximum equivalent flux
  - Buckling: minimum total flux
- Strut Cone
  - Strength: maximum axial flux
  - Buckling: minimum axial flux
- Bulkhead
  - Strength: maximum pressure
  - Buckling: minimum pressure

In order to achieve realistic bending moments and in consequence meaningful load cases it is required to consider aerodynamic forces with an angle of attack due to wind gust [4] and resulting thrust vector deflections which can be computed using the control requirement [5]:

$$(6)\quad CR = \frac{T\sin\delta_E l_{COM-NPP} + N_F l_{COM-Fin}}{(C_{m_0} + C_{m_\alpha}\alpha + C_{m_{\delta,F}}\delta_F)qSl_{ref}} \geq 1.5$$

Beside flight loads also ground loads need to be considered, which are defined by shear wind, launch pad attachment point and tank filling procedures. The attachment points normally create unique forces on the launch pad, e.g. standing on the aft skirt of stage 1. The tank filling procedure creates different mass distributions and tank pressures.

## 3.6. Risk Assessment

Several risk factors are included during the design of the trajectory. These factors are translated into constraints that could affect a precise moment of the ascent or the full mission. During the vertical flight of the launcher, it is important to consider the launch-pad clearance; once the pitch-over manoeuvre starts the azimuth of the vehicle has to follow the limitations of the launch site. The next events to be considered during the risk assessment are the impact of empty stages that re-enter on the Earth surface.

ASTOS can evaluate the impact position and associated risk at several level of complexity [11]: from a simple analytic two-body orbit formulation, till the full integration of several debris considering aerodynamic drag, fragmentations, melting and explosion. In order to keep the computation time acceptable, the simple formulation is included in the optimisation, with the run of a dedicated analysis to ensure that the converged solution is following the international safety guidelines in terms of human risk. When possible the impact locations are placed in non inhabited areas (e.g. ocean); when this is not possible (e.g. Russia) strong limitations are applied on the trajectory in order to keep the impacts inside the designed areas. Also the dimension of the stages could be affected by these constraints: e.g. a smaller than optimal first stage could be the result of an impact area too near to the launch pad. The safety guidelines affect also the number and life-time of uncontrolled objects that are placed in orbit: a suitable mass of propellant should be allocated to ensure the deorbitation of the upper stage or the placement in an orbit that will naturally decay in less than 25 years.

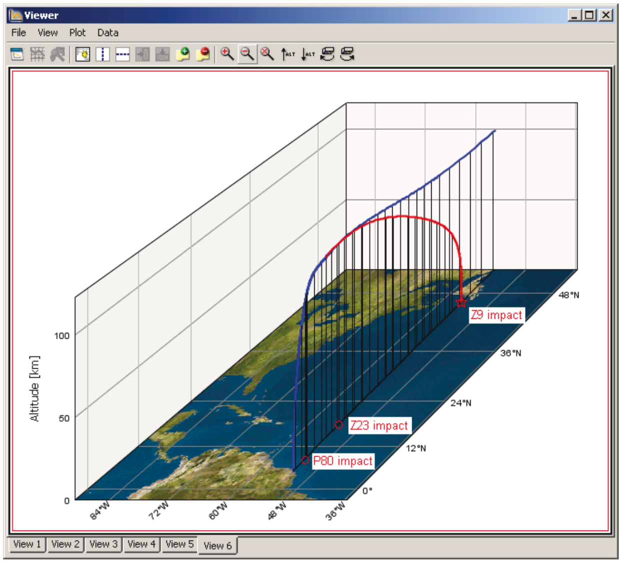


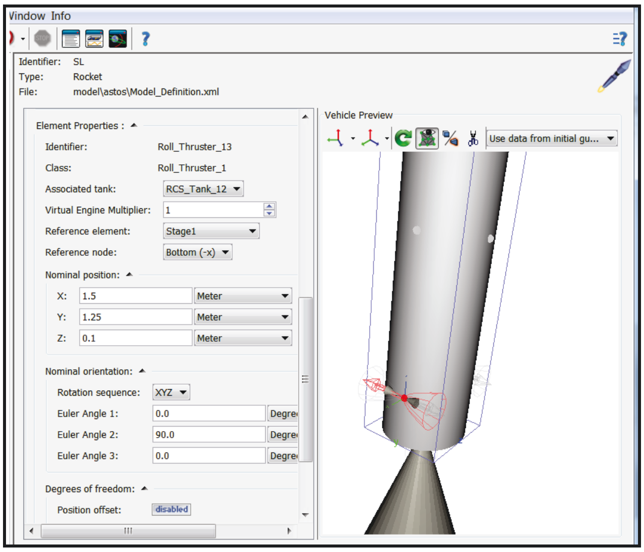
FIGURE 5. Impact locations of VEGA empty stages

Included in the risk assessment is the ground-station visibility aspect. This could have an important impact on the vehicle performance imposing a trajectory higher than the optimal in order to keep a constant link between the launcher and the ground-station net. This link is required to evaluate the correctness of the vehicle trajectory and eventually to transmit the termination command. Recent examples (Proton July 2013) have shown that this procedure is not followed by all the actual launchers, but it is mandatory for new launchers.

## 4. GNC DESIGN AND ANALYSIS

### 4.1. GNC Sizing

The major aspect of the GNC sizing is the determination of the maximum deflection angle of the thrust vector control (TVC) system and sizing of the attitude control (AC) system for the different flight phases. ASTOS supports these tasks by rapid configuration if the control system allocating the AC-thrusters and the TVC hinges graphically in a vehicle builder (FIGURE 6).



Identifier: SL
Type: Rocket
File: model\astos\Model_Definition.xml

Identifier: Roll_Thruster_13
Class: Roll_Thruster_1
Associated tank: RCS_Tank_12
Virtual Engine Multiplier: 1
Reference element: Stage1
Reference node: Bottom (-x)

Nominal position:
X: 1.5 Meter
Y: 1.25 Meter
Z: 0.1 Meter

Nominal orientation:
Rotation sequence: XYZ
Euler Angle 1: 0.0 Degre
Euler Angle 2: 90.0 Degre
Euler Angle 3: 0.0 Degre

Degrees of freedom:
Position offset: disabled

FIGURE 6. Part of the ASTOS Vehicle Builder showing allocation of control thrusters

The guidance and control simulations are performed in Simulink®, which calls an ASTOS s-function for the dynamics and environment computation. FIGURE 7 depicts the architecture of ASTOS-GNC with the environment and dynamics part purely in ASTOS or DCAP, the on-board algorithms in Simulink and the system representation in ASTOS or Simulink designed for a stepwise refinement in Simulink. While ASTOS provides the rigid body dynamics, DCAP is used to provide multi-body and flexible body dynamics,

The GNC algorithms, completely implemented in Simulink, consisting of navigation, guidance and control to ensure maximum flexibility and reusability of existing functionalities. The navigation makes use of pure IMU or coupled IMU/GPS navigation. The guidance uses open loop guidance for the atmospheric part interpolating the attitude angles as function of altitude or velocity and closed loop guidance for the exo-atmospheric flight. For the closed loop guidance several guidance laws (bi-linear-tangent law, linear sine law, optimal guidance, etc.) are available to investigate the impact on the target orbit.

The design of the rigid body controller uses a loop-shape design implemented in Matlab®/Simulink®. In a second step the flexible body dynamics are defined using the DCAP software. DCAP considers a free-free-beam in combination with spring damper elements between stages and at engine suspensions. Both, ASTOS and DCAP export all required data, e.g. mode shapes, for purpose of linearization to Matlab. The mode shape analysis considers locations of AC thrusters active TVC, navigation sensors and reference points for the distributed aerodynamic forces. Again Matlab/Simulink is used for the controller design implementing a body-bending filter to account for the flexible dynamics and propellant sloshing. PID and low-order state-space controller are used for the thrust vector control and a non-linear state-space feedback for the actuator control.

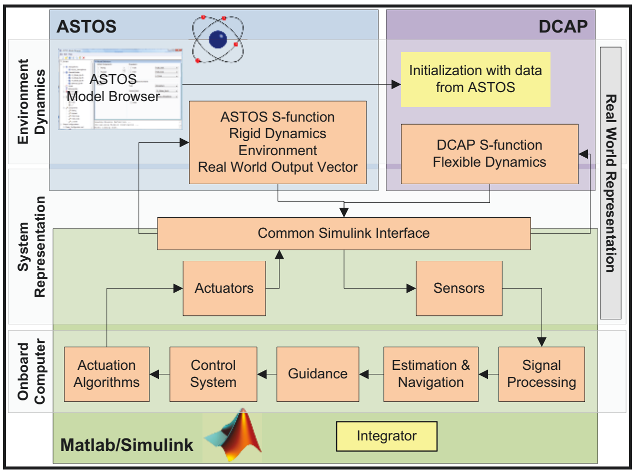


FIGURE 7. ASTOS-GNC architecture with ASTOS and DCAP s-function and on-board algorithms in Simulink

## 4.2. GNC Performance

### 4.2.1. Injection Accuracy

Most of the performance calculations are based on Monte Carlo simulations which make use of the ASTOS Batch Mode Inspector. It allows to set-up complex Monte Carlo runs modifying ASTOS and Simulink input parameters.

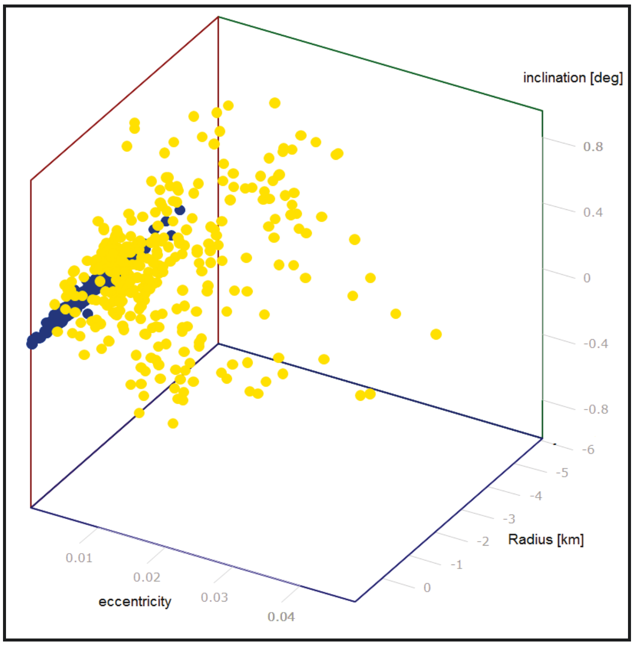


FIGURE 8. Monte Carlo 3D cloud, one sigma solutions in blue, others are yellow

The guidance Monte Carlo simulation results in the orbital injection accuracy (FIGURE 8) and provides information about the robustness of the launch system and reference trajectory. It shows the result of 1000 simulations, where the solutions inside 1-σ are blue dots and the others yellow dots. It could be noted that the blue dots presents a small variation in eccentricity and inclination. Unfortunately this good accuracy is not kept when considering all the solutions; therefore a higher performance reserve (e.g. propellant loading of upper stage) should be implemented.

### 4.2.2. Control System Performance

The performance analysis of the control system verifies that that the sizing and positioning of the AC thrusters in combination with available TVC systems and their maximum deflection angle allow to follow the guided trajectory in case of disturbances without larger additional losses. Depending on the stage configuration and need to reuse AC systems during the burn of different stages it might happen that the capability for pitch torques is too small, which has a big impact on the injection accuracy.

## 5. DESIGN EXAMPLE

### 5.1. Launch Vehicles

Two examples are used to present results (FIGURE 9):

- Small 3 stage launcher with a payload of 1500kg into LEO with solid propulsion in the first 2 stages.
- GTO launcher with two solid strap-on boosters and liquid propulsion in the core stages

### 5.2. Design Optimisation

The optimisation process considers typical trajectory constraints and vehicle design parameters as discussed above. It has been ensured that design parameters are not running against bounds, which are not technically driven.

The timely incidence of dimensioning load cases is varying during the optimisation process. The following list summarizes the distribution in the optimal design:

- The buckling load case of bulkheads takes place at maximum dynamic pressure as expected
- Both load cases of unpressurized shell structures (skirts, inter stages, etc) take place at maximum drag.
- The buckling load case of tank structures take place at low tank pressure on launch pad depending on the filling procedure.
- The strength load case of tank structures takes place at maximum acceleration. This occasion varies the most of all.
- The buckling load case of engine struts takes place at maximum acceleration of the stage.

Validation tests have shown good conformance with line loads of Ariane 5.

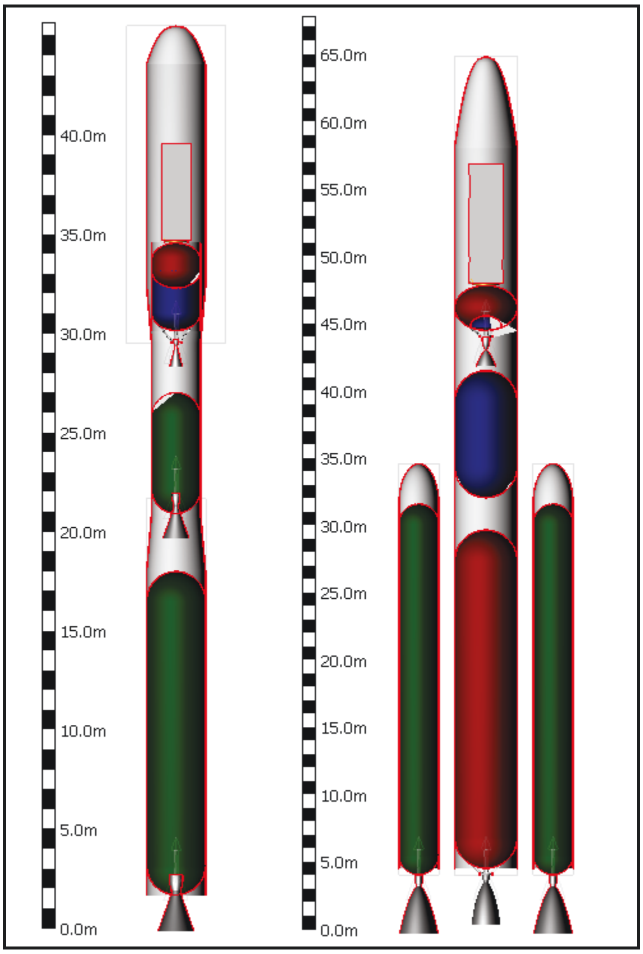


FIGURE 9. Graphical representation of test cases with coloured tank indicating propellant type.

The design optimisation of the two example cases results in structural indices ranging from 6% for Sandwich structures to 16% for steel structures. Considering aspects such as booster attachment and stage under fairing and other it can be stated that the regression as function of the dimensioning load case reflects very well existing designs.

### 5.3. GNC Sizing

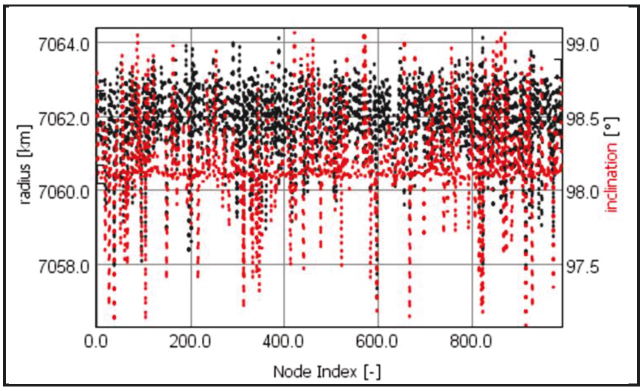


FIGURE 10. Final radius (black) and orbit inclination (red) for each run of the Monte Carlo simulations

The guidance Monte Carlo simulation provides the injection orbit in terms of 1-σ deviations from the nominal orbit parameters as known from launcher handbooks. The related distribution of final orbit radius and inclination is depicted in FIGURE 10.

## 6. CONCLUSION

This paper presented the latest development steps for preliminary design of launch vehicles considering trajectory optimisation, vehicle design optimisation and subsystem analysis. The most important innovation is the coupling of the subsystem design with the trajectory optimisation and the capability to perform a performance analysis with low effort.

The structural mass estimation takes place on substructure level and depends on the optimised dimensional load cases. The engine design considers efficiency factors depending on the trajectory.

The performance analysis performs guidance and control simulations allowing the sizing of the attitude control thrusters and of the thrust vector control system providing performance criteria such as injection accuracy.

The results can be directly used in detailed design tasks such as finite element exports or the preliminary GNC design.

ASTOS in combination with ODIN represent a highly flexible and powerful tool for launch vehicle design and with the planned extensions for multi-body simulation of actuator systems and flexible dynamics for modelling of structural dampers and sloshing effects it will cover an extremely large set of preliminary design tasks.

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