ASTOS: A TOOL FOR MISSION AND SYSTEMS CONCEPT ANALYSIS AND DESIGN

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INTRODUCTION

Originally ASTOS is known as a trajectory and vehicle design optimization software. Recently it has been extended to mission analysis, system concept analysis and GNC sizing and simulation and it has been coupled with the multi-body simulation and flexible body dynamics software DCAP. ASTOS focuses on the mission performance which is depending on the spacecraft dynamics and interaction with the environment. Most analysis tasks are somehow related to the trajectory of the spacecraft.

DESIGN WORKFLOW

The ASTOS workflow normally starts with the trajectory design using orbit propagation, impulsive manoeuvres or optimal control (see Fig. 1). Based on that a first mission analysis can be performed analysing delta-V budget, ground station visibility including selection of station networks, visibility of other satellites e.g. for relay communication or navigation, sensor field of view of navigation and payload sensors, maximum transferable data volume. Up to now ideal attitude is considered.

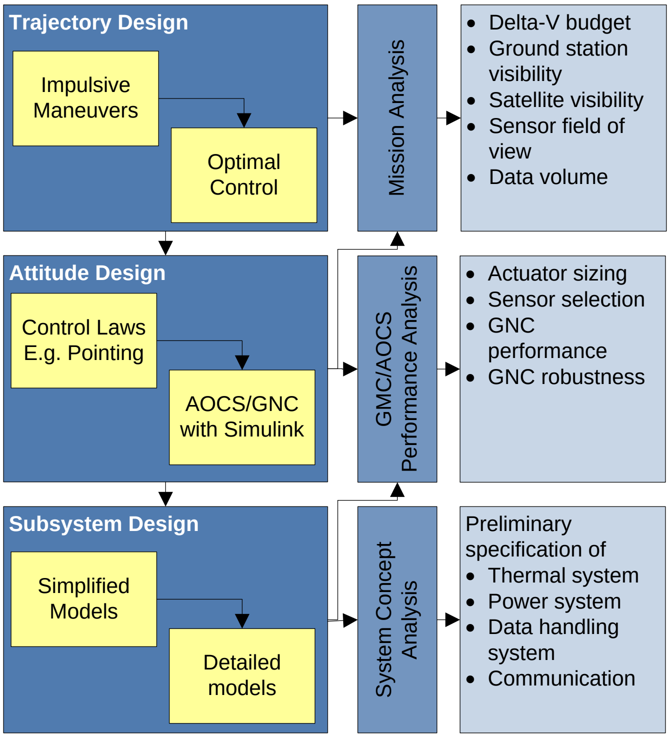

Fig. 1: ASTOS workflow from trajectory to attitude and subsystem design with analysis tasks and results.

The next step works on the design of the attitude during the mission. It can be understood as step-wise improvement of the mission analysis looking into the pointing of sensors and antennas not ignoring the spacecraft attitude. But depending on the type mission the AOCS and GNC design might contribute highly to the feasibility of the mission, e.g. launcher ascent, re-entry and rendezvous and docking. In such cases it is possible to perform the whole GNC design for attitude bit also for the pointing of sensors inside Simulink®.
Finally, the subsystem models are refined exchanging simple parameter definitions by more complex algorithms.

ATTITUDE AND ORBIT CONTROL

After a preliminary design of the AOCS using pointing laws and impulsive orbit manoeuvres a detailed design task in a typical controller design environment is required. Therefore an interface between Simulink® and ASTOS is provided.
As depicted in Fig. 2 ASTOS provides the dynamics and environment simulation. The scenario configuration used for preliminary design and mission analysis stays mainly unchanged. The main task requires the specification of actuators and sensors used for AOCS.

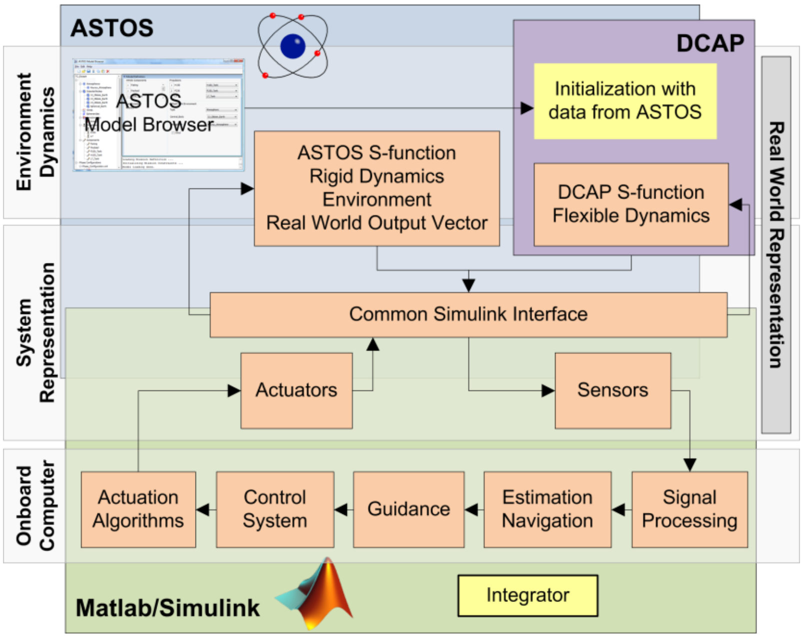

Fig. 2: Simulink interface between ASTOS and Simulink with real world, system and on-board computer representation.

Property	**3-dof propagation**	**6-dof control simulation**
Translational state	state derivative	state derivative
Rotational state	control law, e.g. pointing law, profile	state derivative
Thruster throttle, on/off	control law	controller input
Reaction wheel, other actuators	not considered, limited requirements verification	controller input
Hinge angles	rigid or control law	controller input
Sensors	field of view	Simulink algorithms
Centre of mass	origin of body fixed frame, gravity-gradient possible with DCAP	origin of body fixed frame, gravity-gradient possible with DCAP
Inertia	not considered	mandatory

Table 1: Changing definition of ASTOS properties during 3-dof propagation and 6-dof control simulation. A control law can define a constant value, linear law, complex pointing laws, interpolated profiles, an optimisable control etc.

Again ASTOS provides the capability to start with very simple equipment models an, which might be specified mainly in ASTOS, and to refine them step by step moving the system model definition to Simulink. Table 1 lists several

ASTOS properties and their different interpretations for the two main processes of 3-dof propagation and 6-dof control simulation. The most important changes are the additional state derivatives in combination with additional Inertia information and the possibility to define control variables as controller input exported to Simulink.
The simplest actuator models in ASTOS just provide the capability to pulse thrusters or to control the thrust level or to turn a hinge. The sensor information provided by ASTOS is always the simulated state or sensor field of view. In a second step more detailed models can be defined in Simulink.
A coupling with the DCAP software allows the modelling of multi-body and flexible body dynamics directly inside ASTOS and to consider related effects in the dynamics simulation. This extends the simulation to gravity gradient computations, complex multi-body scenarios, such as robotic arm movements including contact simulations or solar panel deployments, and flexibility effects such as oscillating structures and propellant sloshing.
ASTOS and DCAP are linked to Simulink through a common Simulink interface which provides the controller inputs and 6-dof state derivative, both used by the Simulink integrator.
It is in the responsibility of the user to implement signal processing, state estimation, navigation and guidance algorithms, control algorithms and actuation algorithms in Simulink.
For purpose of controller design ASTOS and DCAP exports information about inertia, distributed aerodynamics, and mode shapes. Alternatively a complete linearized model can be exported.
If you like to perform mission and system analysis on top of a trajectory resulting from GNC simulation, e.g. complex rendezvous approach, without having access to the GNC simulator or not interested in the GNC part, you can import the state history and perform you analysis at each time point provided without propagating the state history again.
For advanced camera or LIDAR based navigation an interface to the 3D-animation software VESTA is provided. With VESTA it is possible to perform signal processing of sensor information for purpose of navigation. For real time applications a real-time capable sensor emulator can be linked.
ASTOS allows specifying parameters as controller input, which are not relevant for the spacecraft attitude. For example: hinge angles of manipulator arms used for antenna deployment or robotic arms, actuators for solar panel deployment, pointing mechanism of antennas and sensors.

Performance Analysis for Launch Vehicles

ESA's Launcher GNC Simulation and Sizing Tool (LGSST) is based on ASTOS-GNC. It allows configuring a launcher scenario for open-loop guidance and closed-loop control simulation. The control simulation might be performed with rigid body dynamics or with flexible body dynamics considering propellant sloshing. Monte Carlo simulations and worst case analysis are supported to analyse the launcher robustness. One of the results is the injection accuracy in orbit.

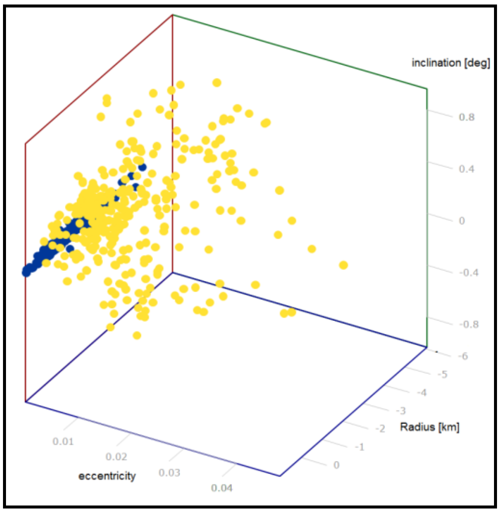

Fig. 3: Monte Carlo 3D cloud, one sigma solutions in blue, others are yellow

SUBSYSTEM DESIGN

During the maintenance of the models increasing their fidelity and being prepared for the requirements of the next phase, the dependencies of the subsystems are growing. The most important ones with impact on the mission performance are power, thermal data handling subsystem.

Sensors

Under ‘sensors’ a variety of different models have been implemented, which provide from very basic to very specific functionalities.
A basic sensor model provides, without knowing any detail about the sensor itself (e.g. type, specifics, geometry, etc.), some fundamental functionality, which is available also in more detailed models as the visibility computation. The pointing law of each sensor can be individually selected amongst the following models:

- constant law (fixed orientation);
- linear or profile law (orientation changing in time linearly or following a user defined profile);
- target pointing (the sensor tries to follow a predefined target, whenever possible).

Together with the pointing law, the field of view of the sensor can be specified in order to define not only where the sensor is looking at, but also how far from the pointing direction it can observe. A list of targets can be then provided in order to evaluate the visibility condition to each of them, checking also if any celestial body is obstructing the view.
While the abovementioned functionalities are available to all the sensor types, some sensor allows some more specific and detailed computation. It is the case of cameras, which allow taking snapshots of the central body during the simulation, or of transmitters and receivers, which, in pairs, allow the user to assess the link quality to be used for communication (see the chapter about Link Budget) or positioning (see Navigation).

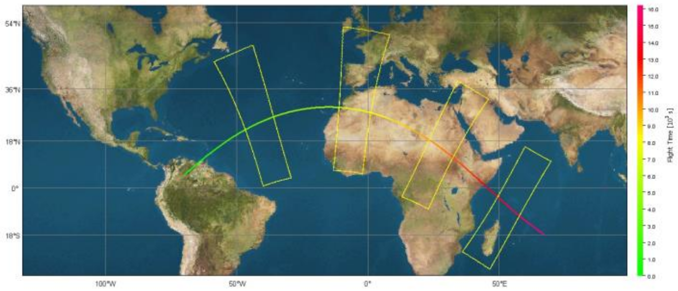

Fig. 4: ASTOS map plot showing snapshots taken at each hour along a MEO.

Link Budget

A link budget is the accounting of all gains and losses of transferring an electromagnetic signal from a source, transmitter, to a target, receiver. The main objective of a link budget is to compute the received power at the receiver, which tells the quality of the signal after the propagation. Several figures of merit can be computed in order to evaluate the performance, as for instance the Signal-to-Noise ratio, the Carrier-to-Noise ratio or the Bit Error Rate.

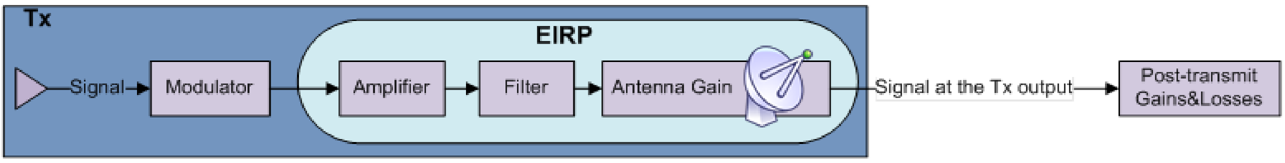

Fig. 5: Diagram of the transmitter components.

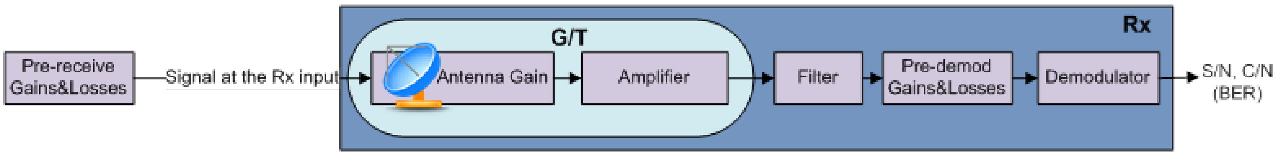

Fig. 6: Diagram of the receiver components.

While the visibility computation allows the user to understand when a certain target is in view and to modify the trajectory in order to improve the visibility, the link budget allows the user to know whether a link between two antennas can be established and how to improve the antenna design in order to maximize the signal strength.
For this purpose an important role is played by the antenna model, which characterizes the geometry and the gain of the antenna. Also in this case, a simple model is available, which does not require knowing the antenna design, as well as detailed models as isotropic, dipole, parabolic, horn, axial helix and ‘user-defined’, that is completely customizable.
The signal itself can be defined at various levels of detail: different frequencies, bandwidths, polarizations and modulations can be selected. Depending on the inputs provided by the user, the link budget analysis can be more or less detailed. The same is with the signal propagation. Different sources of atmospheric signal absorptions and noise can be

considered. The free-space path loss is always computed, while the atmospheric losses are user defined. ITU-R recommendations have been implemented in order to be able to consider at least rain, clouds, fog and gaseous absorptions [3].

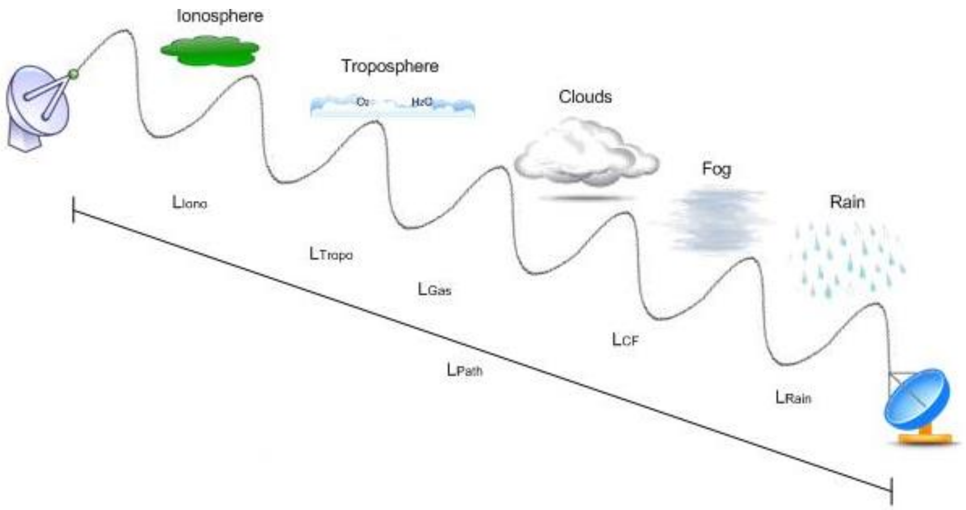

Fig. 7: Signal propagation diagram.

Navigation

A typical application of the link budget analysis is positioning via Global Navigation Satellite Systems (GNSS), which is a system of satellites providing autonomous geo-spatial positioning with global coverage, without the need of the ground section, usually expensive and time-consuming. It allows receivers to determine their location (longitude, latitude, and altitude) within a few meters using time signals transmitted along a line-of-sight from satellites.
The ASTOS navigation feature allows determining the accuracy that could be reached if a satellite was navigated only by means of GNSS receivers. The two main problems of using such technique on a spacecraft are coverage and accuracy. Since GNSS were designed to be used on Earth, they guarantee coverage on the Earth surface, but not in space. Depending on the specific trajectory, on the receiver configurations and on the GNSS signals used, the coverage, and indeed the accuracy, might be not good enough to navigate the spacecraft. This feature allows the user to estimate the coverage and accuracy along the orbit.

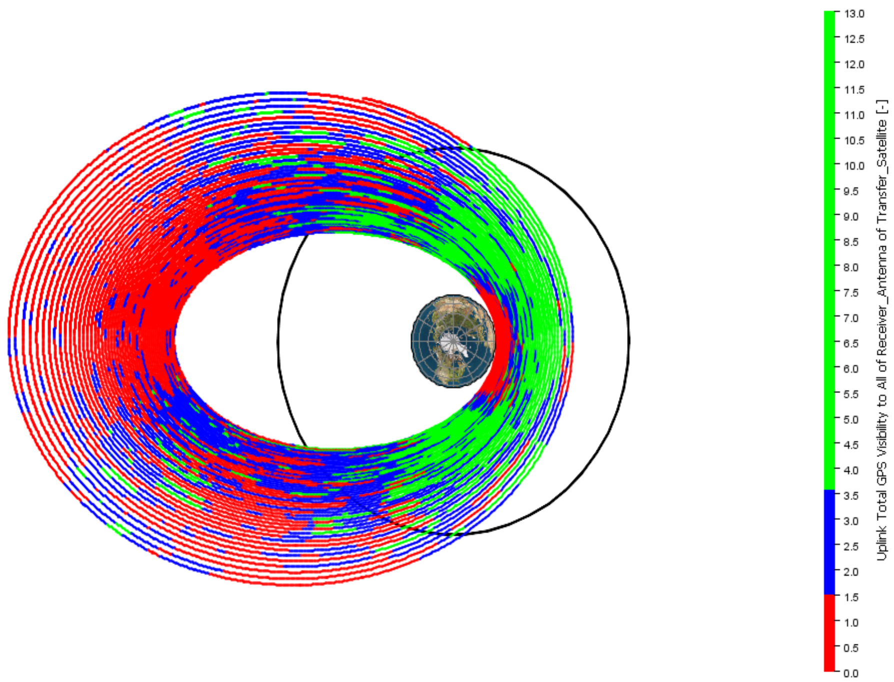

Fig. 8: ASTOS plot showing number of visible GPS satellites along the first part of a GTO transfer orbit.

The navigation analysis evaluates the link between the selected receivers and all the GNSS satellites specified by the user, keeping the same flexibility as explained in the previous chapter. The only difference is that the navigation analysis makes use of a predefined set of signals, which represent the real GNSS signals: GPS, GLONASS and Galileo. The user can just select which signals he is interested in.

The key role is played by the GNSS receiver. The reception and handling of the incoming signal are common to all the receivers; on the other hand, the computation of the position is performed only by GNSS receivers.
Also in this case ASTOS provides a basic GNSS receiver model, which allows computing the number of visible GNSS satellites (as showed in the next figure), the number of satellites, which can be tracked, the time outage and the DOP values, which measure the quality of the GNSS constellation geometry. If the user is interested in a more detailed analysis, he can specify the characteristics of both the tracking phases of the receiver: the carrier phase tracking (performed by PLL or FLL) and the code phase tracking (performed by DLL) [4]. If these inputs are provided by the user, ASTOS can compute also an estimate of the accuracy (the so called user equivalent range error) that can be achieved by the receiver while estimating its own position.

Thermal Control System

The thermal model shall provide information about the extreme temperature during a mission for different spacecraft parts and it shall allow the preliminary design of radiators and absorbers. The coupling with the trajectory and the attitude of the spacecraft shall be reflected. Therefore a thermal node model is applied as depicted in Fig. 9.
Each element of the vehicle model (components, sensors, actuators, etc.) has user-configured thermal characteristics. It can produce heat and has a certain heat capacity. The user-defined connections between these elements are parameterized by their absolute thermal resistance R_{th}. Each element of the vehicle model is treated as a lumped thermal mass, i.e. it becomes a single node of the thermal model. At each node a state for the temperature is defined and integrated over time. Such a model can be set up straight forward considering different operational equipment modes like switched-off, stand-by, switched-on.
Outer surfaces are modelled based on primitive shapes or CAD mesh data. In latter case the user has to define surface groups that are united into a single thermal node, i.e. a unique temperature, emissivity and heat capacity is associated to them. Each surface group or primitive shape becomes a node in the thermal model and has to be connected to elements of the vehicle. The reduction of the surface elements is mandatory to maintain the performance of the optimization and simulations high and also to reduce the effort the user has to invest in order to connect thermal nodes.
The thermal model provides the time history of the temperatures and heat fluxes of each node.
Models for radiators and heaters are provided that can be integrated in a design optimization process, i.e. they can be optimally sized with respect to the mission profile.

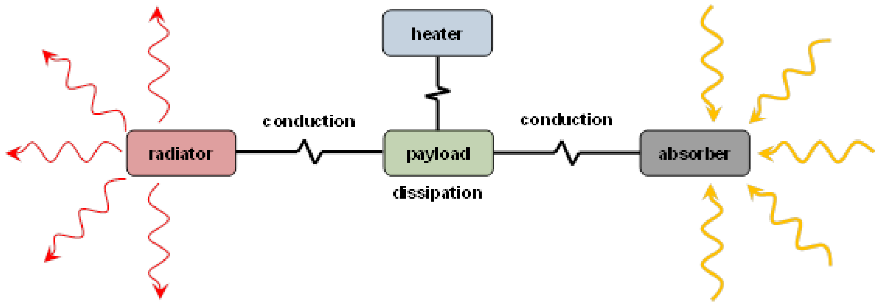

Fig. 9: Thermal node model

Data Communication System

The data communication system reproduces the data cycle from creation by sensors over storage devices to the ground contact and signal depending transmission to ground (Fig. 10).
The major objective is to consider the mission time dependent data rate of sensors and to analyse the schedule of the data transfer to ground considering buffering on spacecraft with storage devices and signal losses during transfer.
Moreover it is possible to analyse operational modes of sensors, especially if not all sensors on board can work at the same time for power or data rate constraints.

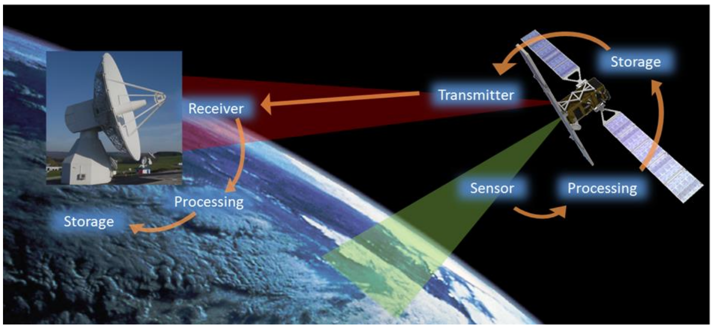

Fig. 10: Data flow modelled by ASTOS.

Similar to the thermal model, all elements of the vehicle like sensors but also thrusters (housekeeping, e.g. temperature information) can be defined as data sources. Further special vehicle element models are made available for data storage and data reduction. These elements can be connected by the user to establish a data network. This network covers also transmissions to ground stations whereas the link is model as described in the paragraph Link Budget above.
The model provides the data rates produced or consumed by each element of the vehicle, the current filling level of each storage element and the delay between data generation and final reception. Multiple and separate data networks can be defined in this way, e.g. to distinguish payload and housekeeping data.

Power System

The power system connects most of the subsystems and performs the important step of closing the loop of dependencies. As already described for the thermal and data communication model, again a node representation is used to model the power system, i.e. each vehicle element has parameters to define its power consumption, which is either constant or can be defined as state-dependent (e.g. sensor mode).
Special vehicle element models for batteries, solar generators and RTGs are made available to the user such that a complete power network can be defined. Aging and thermal dependencies can be independent variable of battery capacities and generator power. The power provided by the solar generator further depends on the calculated solar irradiation that considers the vehicle attitude and position as well as eclipses caused by celestial bodies.
The power model allows the sizing of the solar panels and batteries and is required for specification of e.g. operational modes of sensors or management of eclipse phases.

DESIGN OPTIMIZATION

ASTOS provides the capability to define optimisable parameters and controls in any subsystem model. In combination with constraints and objective functions a gradient based optimisation or a random search method can be applied. In both cases it has to be considered that an optimization tasks fits to the complexity of the scenario, the suitability of gradient-methods or random search methods, and the computational effort.
Typical examples for subsystem optimization are

- Sizing of radiators to fit thermal constraints
- Design of antennas to fit data volume or ground coverage constraints
- Sizing and positioning of AOCS thruster for station keeping

Launch Vehicle Design Optimisation

Recently, the design optimization of launch vehicles has been improved a lot with ESA funding. ASTOS has been extended based on the concurrent design optimization approach [5] focusing on the most sensitive aspects such as structural mass estimation and engine performance. The resulting software [6] estimates the structural mass on subcomponent level (Fig. 11) as function of geometry, material, stiffening concept, and dimension loadcases using ODIN [7] for computation of mass estimation regression tables for each substructure. This approach reduces the design error from app. 20% below 5%.

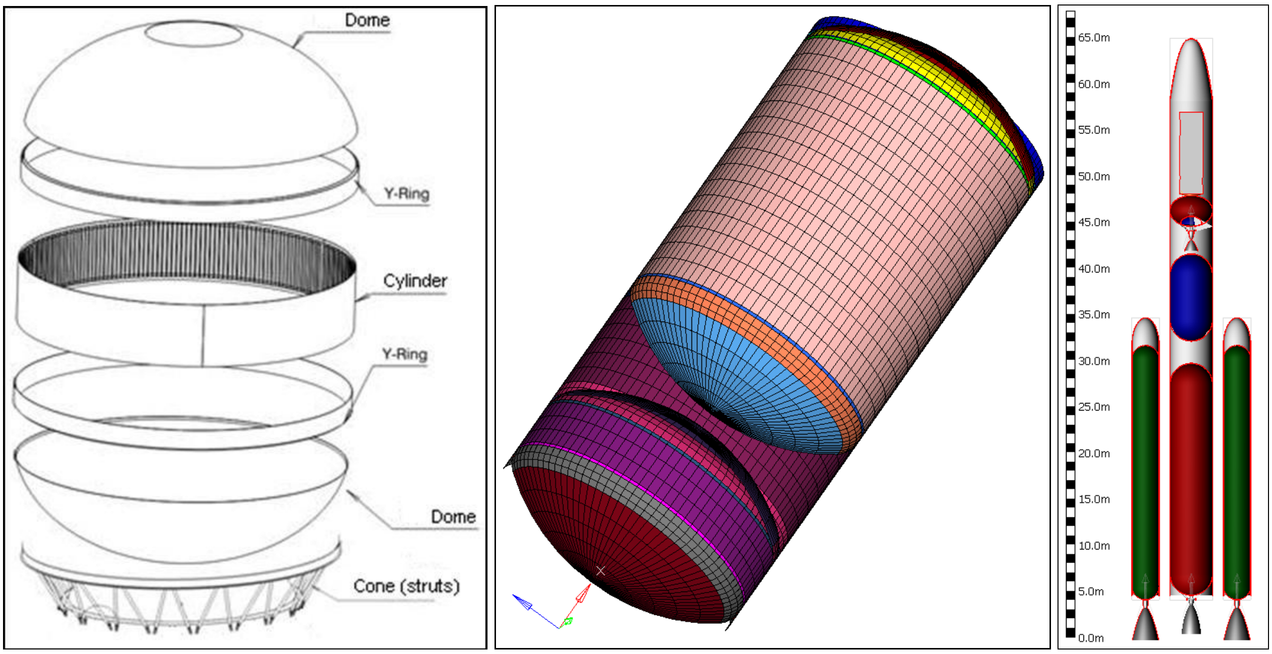

Fig. 11: ODIN subcomponents (left), automatic finite element export (mid), ASTOS cutaway view (right).

ODIN provides a finite element export (Fig. 11) with smeared wall thickness, which can be used for frequency analysis in the previously mentioned controller design with flexible dynamics. The loadcase determination is performed by ASTOS for each substructure and considers flight and ground load cases [6].

The propulsion system module has been extended by more detailed computations of the geometry and efficiency factors and provides post analysis of flow separation and thermal analysis. Preliminary cycle analysis tasks are possible using the RPA software [8].

REQUIREMNTS SPECIFICATION AND VERIFICATION

All design and analysis tasks for trajectory, attitude and subsystems need to be executed several times. While the number of design loops shall be as small as possible for cost and time reasons, a large number of verification runs is required and it should not be limited for cost reasons. Hence it is necessary to support recurrent simulation runs and their evaluation as efficient as possible.

ASTOS provides the possibility to compare specification values against the results of simulations and to report them automatically. Also post-processing in external tools is supported. This way a nearby automatic processing of verification runs is possible.

CONCLUSIONS

In many design processes trajectory planning is linked with mission analysis and with system concept analysis. The workflow in terms of configuration management and configuration maintenance should be straight forward. For that purpose the new system analysis features of ASTOS offers to the user the capability to define subsystem models according to his needs and to maintain them during the project lifetime.

ASTOS focuses on the most important design and analysis tasks such as trajectory, GNC/AOCS, link budget, navigation, power, thermal and data handling and offers them in a software environment for rapid configuration and rapid evaluation.

The new features of ASTOS clearly demonstrate that ASTOS has evolved from a trajectory analysis tool to a mission and system concept analysis tool. It supports all tasks starting already before Phase 0 up to Phase B and for some applications up to Phase F.

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