Concept and Performance Simulation with ASTOS

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ABSTRACT

Advanced space missions, like orbital servicing missions, comprise a high degree of dependencies considering subsystems and analysis procedures conceptual, preliminary and detailed design phases. Those dependencies are normally not very well represented by today's analysis tools as used for standard space missions with well defined and separated design processes. However, advanced space missions require a high degree of confidence in early mission phases to keep the overall costs low. An efficient approach to achieve such confidence is a highly flexible simulation environment, which allows coupled analysis of mission, GNC and system aspects at the same time already in Phase A of a project.

The presented ASTOS software combines trajectory optimization, vehicle design optimisation, mission analysis, GNC design and analysis, and system analysis as well as realistic visualization of the scenario with OpenGL, including detailed computation of environmental disturbances utilizing the geometrical knowledge within OpenGL.

This paper presents how ASTOS suits to the concept of System Concept, Mission Performance and Functional Engineering Simulators. Moreover it presents how it connects those aspects by coupled simulations and how in addition also Hardware-in-the-Loop (HIL) aspects are addressed.

INTRODUCTION

The ECSS Technical Memorandum "System Modelling and Simulation" [1] describes in detail the need for Virtual Spacecraft Design to increase the confidence in early project phases and as a consequence the impact on the cost reduction of the whole project. Moreover it defines the various simulators used during the space system lifecycle. This paper focuses only on the Phase 0 to C with the main tasks feasibility and performance analysis, requirements specification, design verification, system and mission performance verification and partly functional subsystem verification and validation. The relevant simulators are

- System Concept Simulator (SCS)
- Mission Performance Simulator (MPS), also called End-to-End Simulator (E2E)
- Functional Engineering Simulator (FES)

The characteristic of those simulators are summarized and compared in Table 1. SCS is mainly used in Phase A using input from Phase 0. But also its use in Phase 0 is possible as far as the configuration effort and CPU-time is low. MPS and FES are applied from Phase A to Phase C/D providing input to various other simulators as explained in [1]. Table 2 summarizes the relevant engineering activities during the space system lifecycle as it is relevant for the utilization of the ASTOS software. In the following it is shown, how ASTOS suits to this system.

	SCS	MPS	FES
Objective	• Rapid evaluation of system design concepts validated against high-level mission requirements	• Establishment and verification of the overall performance of the baseline mission from the user point of view	• Verification of critical elements of a baseline system design (such as AOCS/GNC algorithms) • Preparation of the basis for building the real-time simulators that are exploited in the subsequent design/test phases
Analysis Requirements	• Verification of the system functional design • Design trade-off decisions • Concept visualisation	• Trade-Off analysis on concept level • System performance analysis • Sensitivity analysis	• Extensive analysis capability like perturbation analysis, covariance analysis, MonteCarlo analysis, worst-case analysis
Specific Modelling Requirements	• Low fidelity model with interfaces on state and parameter level	• Physical environment models under study • Adequate payload/instrument models • Equipment models with application algorithms	• Functional model which is representative of the behaviour of the real modelled elements
Specific Aspects	• No formal validation required • High level of reusability	• Reuse of subsystem models of SCS with additional payload models to be reused in Phase E, • Verification of payload model as far as possible	• Real-time capable • Verification: unit level tests in open loop • Validation: closed loop tests • Reuse of parts of SCS is possible
Products	• Mission Concept • Mission Requirements	• Performance of the Mission Product(s) • E2E mission performance budgets • Synthetic mission data	• Consolidated system requirements (SRR) • Verification that the preliminary (PDR)/detailed (CDR) design meets the system requirements

Table 1: Comparison of SCS, MPS and FES [1]

Engineering and Operations activities	**Phase 0**	**Phase A**	**Phase B**	**Phase C**
Feasibility and Performance Analysis/Trade-Offs	Concurrent Design Activities			
Requirements Specification	Concurrent Design Activities	System & Mission Analysis		
Design Verification		System Interfaces and End-to-End Design Trade-off		
System and Mission performance verification		System Interfaces and End-to-End Design Trade-off		
Functional (Subsystem) V&V			Interfaces and End-to-End	

Table 2: Engineering activities during the space system lifecycle Phase 0 to Phase C [1]

ASTOS - AEROSPACE TRAJECTORY OPTIMIZATION SOFTWARE

The ASTOS software is an industrial grade COTS optimization, mission and system analysis software. It combines a highly flexible scenario definition based on a graphical user interface and an extensive object oriented model library with tools for trajectory and vehicle design optimization using large scale direct optimization and random search techniques, short and long time propagation based on numerical and semi-analytical methods, and interfaces to various tools like Simulink for detailed GNC/AOCS design and analysis. ASTOS is suited to model and analyse endo- and exo-atmospheric, orbital and interplanetary missions like launch, (re-)entry, observation, satellite communication, rendezvous, formation flying, constellations, aero-assisted missions.

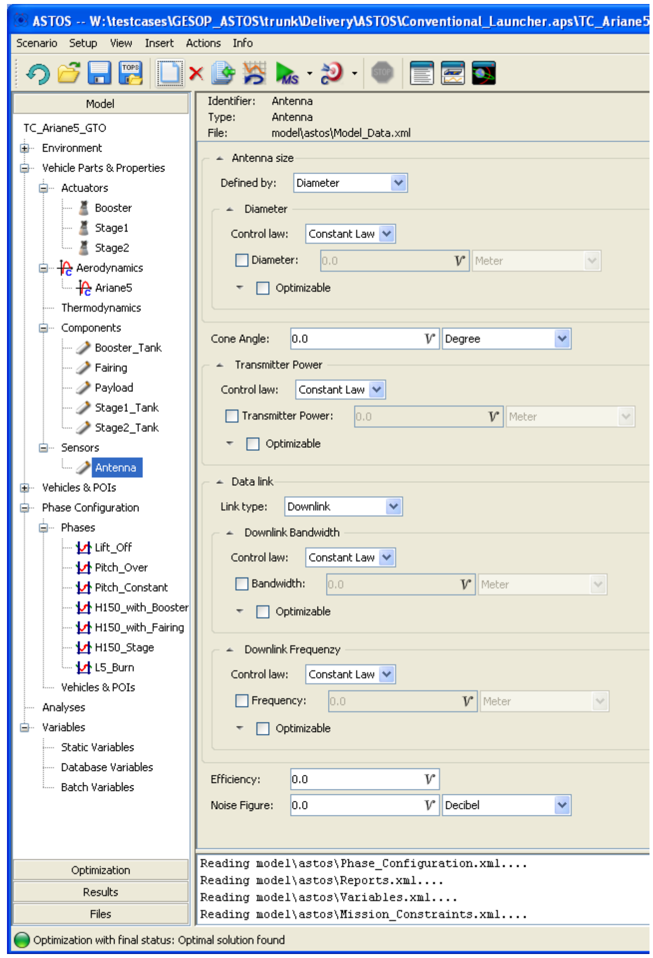

Figure 1: Sensor configuration

Originally established as optimization software, ASTOS has been extended to a powerful mission analysis software providing a virtual spacecraft designer (Fig. 3) including sensor specification (Fig. 1) and analysis and a GNC design and analysis software interfacing with Simulink. The ASTOS-GNC version provides the capability to specify the space scenario in the well-known ASTOS user environment and provides the dynamics and environment simulation as Sfunction to Simulink (Fig. 4), where the sensor and actuator equipment can be modelled in detail and where all onboard algorithms can be implemented for later export to real-time platforms. Moreover a ground station and simulation station completes the functionality. A Simulink library with equipment models and algorithms reduces the configuration time at least for a first analysis step. Finally, a 3D visualization and animation can be performed with the VESTA software (Virtual Environment for Space and Terrestrial Applications, Fig. 2).

Figure 2: VESTA Screenshots

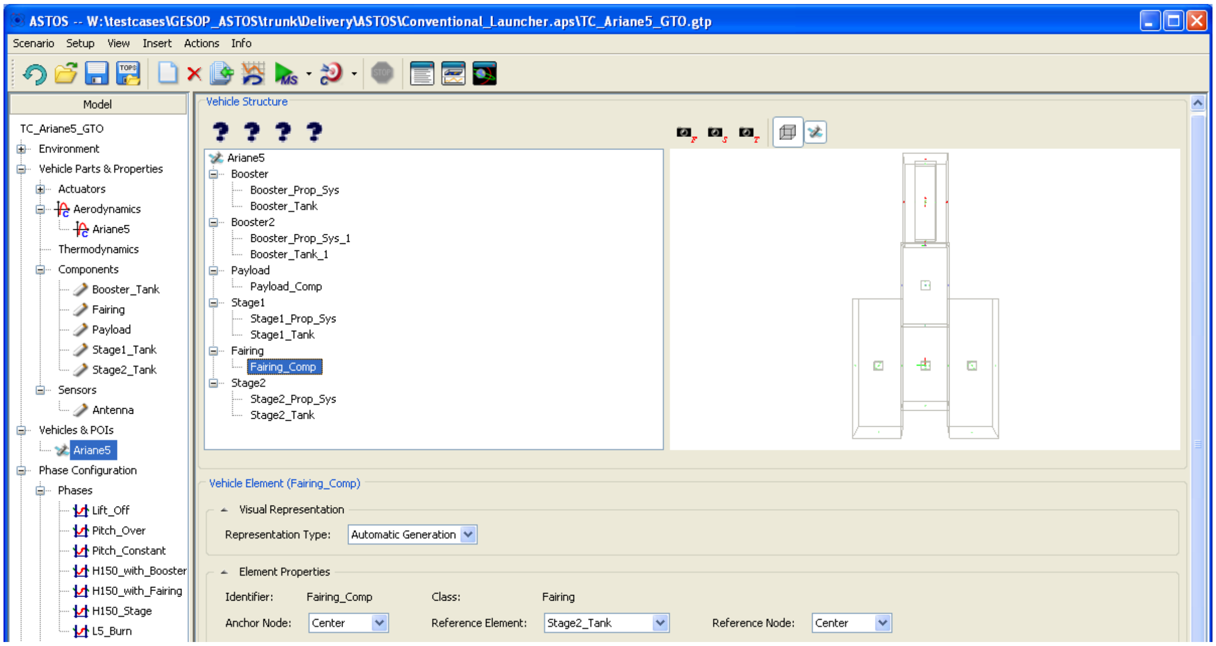

Figure 3: Vehicle configuration management with virtual vehicle configuration

ASTOS focuses on the 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 during for all analysis processes.

The realistic visualization is done by VESTA, which provides highly realistic visualizations in combination with visual helpers for mission analysis (Fig. 2). Moreover VESTA is real-time capable and presents the space scenario parallel to a functional engineering simulation. It computes the differential forces and moments due to solar pressure and air drag and partial shadowing in high accuracy and real-time and feeds back this information to the GNC simulation (Fig. 4). Moreover VESTA mimics the scenario as realistic as possible, which allows verifying the performance of visual sensors. Such sensors are essential for any rendezvous or planetary and lunar landing manoeuvres and are normally difficult to test for complete space scenarios. Finally, an interface for a manipulator arm completes the list of features. The combination of Simulink with the COTS software ASTOS and the open source software VESTA provides an extremely flexible and powerful solution to investigate critical flight phases of advanced mission scenarios.

ASTOS is used at the ESA CDF and provides interfaces to IDM for fast configuration setups. Through its fully data driven approach it is highly suited for collaborative working environments and rapid prototyping tasks. ASTOS is the basis for the Launcher GNC Simulation Sizing Tool and it has been applied as Space Robotics Simulator to the German

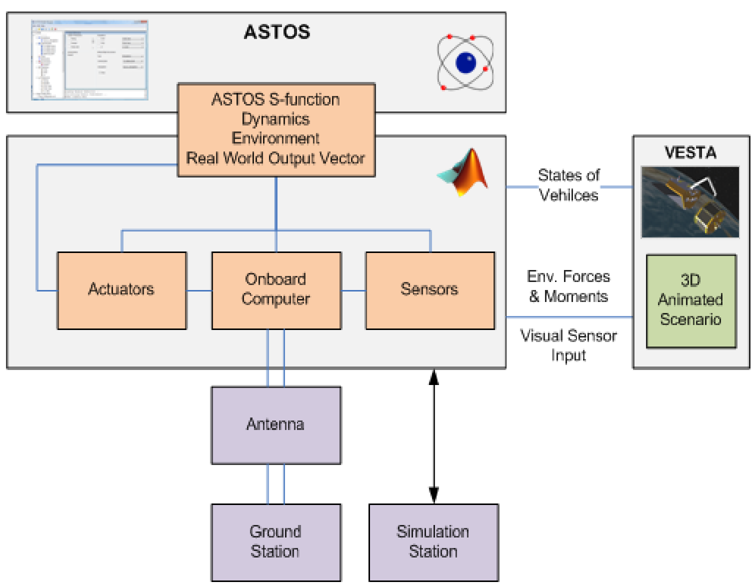

Figure 4: ASTOS-GNC architecture

Orbital Servicing Mission (DEOS), where it has proven its added value for future space projects. Especially for close approach manoeuvres, like berthing manoeuvres, the coupled analysis is able to give full confidence in proposed strategies or to expose its weak points.

Virtual mission design is derived from the trajectory analysis including related simulations and subsystems. Such are primarily trajectory design and analysis, mission analysis, vehicle design, GNC and related subsystems and disciplines like propulsion, aerodynamics, structure, power, thermal, communication, and data handling. Such subsystems are considered in a relevant maturity to answer questions concerning the feasibility of a concept or mission analysing loads and budgets.

SOFTWARE REQUIREMENTS

Table 3 presents the most relevant requirements of SCS, MPS, and FES as presented in [1] and compares them with the capabilities of ASTOS.

Categories	Requirements according to [1]	ASTOS Capabilities
Functional	• Monitoring and control functions, like start/pause/resume/stop, data saving, or Failure injection • Automatically configurable by the stored spacecraft model • Consistency checking • Visualize the output data • Compare and export data • Run in batch mode	• ASTOS is fully data driven by xml input files. Input data is checked on consistency during initialization. • Input and output data can be visualized in various ways. Comparison of data is supported • A Batch Mode Inspector allows complex automation tasks
Scripting Language	• Access models • Monitor/control simulator	• The data driven models can be accessed externally via xml files • For complex new models DLL interfaces are provided • Matlab can be used for scripting in the GNC environment
Operational	• Controllable from Man Machine Interface and command line • Provide a scenario definition report	• ASTOS provides a high elaborated GUI and a command line interface. • Various automatic reports are supported
Design	• Declaration of system of units • Definition of reference frame • Content of Scenario	• ASTOS allows input and output in any unit and uses internally SI-units. • Standardized reference frames and user defined coordinate frames are provided. • ASTOS supports most scenarios in a single tool and defines reusability in a new way.
Verification and Validation	• Validation against other simulators, reference data, real data	• ASTOS has been verified against many 3rd party tools, its own past versions and by many users worldwide.
SCS specific	• Rapid configuration of the virtual system model. • Quick and easy modification of the system parameters to support design trade-off activities. • Compare output data of key system parameters against the mission baseline to validate the system concept design. • Define simulated operational activities and events for different phases of a scenario time-line.	• ASTOS offers an extremely rapid configuration process • The state parameter model is extended by an optimization interface for optimal multidisciplinary design. • A stepwise refinement allows to focus on the needs of the specific project phase, but allows also more extensive analysis in early design phases • Coupled mission, system and GNC analysis
MPS specific	• Produce synthetic mission data (engineering data) • Include modelling of instruments/payloads, ground user processing, orbit and attitude, physical environment under study	• In case of GNC related payloads ASTOS is able to mimic an MPS including flexible dynamics • Scientific payload models will be linked in future • Environmental models according ECSS-E-ST-10-04C

Categories	Requirements according to [1]	ASTOS Capabilities
FES specific	• Developed on the basis of an identification of the functions and subsystems of the general system. • Perform open and close loop simulations. • Provide sensitivity analysis on a set of variables identified at system design level.	• Modelling of rigid any flexible body dynamics using n interface to DCAP [5] • GNC open and closed loop simulation with Simulink and ASTOS s-function • ASTOS driven sensitivity analysis with Batch Mode Inspector

Table 3: Simulator requirements vs. ASTOS capabilities

VERIFICATION AND VALIDATION PROCESSES

ASTOS supports the validation process with the following integrated functionalities

- Requirements Specification and Verification
  ASTOS allows the specification of requirements according to [2] with details like justification and constraint and provides an automatic reporting of the verification results based on the simulation process. The requirements can be maintained during the lifecycle.
- Performance Verification
  The requirements management allows the specification of performance requirements concerning fidelity, accuracy, and stability. Adequate calculation rules need to be defined based on the constraints class of ASTOS.
- Design Trade-Offs at System Level and Design Verification
  Rapid change of the configuration in combination with multidisciplinary optimization techniques allows efficient analysis and design verification ending up in robust and optimal system concepts. The system level need to cope with the fidelity of the models provided within ASTOS.
- Visual Validation
  Plotting features and 3D visualization with VESTA improve awareness of the mission and spacecraft concept.
- Assessment of Engineering Margins
  Engineering margins can be assessed based on sensitivity and worst-case analysis using the ASTOS optimization functions
- Model Specification
  During the lifecycle the models and the mission can be defined in different levels of fidelity and can be maintained during the life cycle.
- System and Mission Performance Verification
  Considering ASTOS supported subsystems and a GNC related payload (in contrast to a scientific payload) ASTOS provides all required environment and dynamic models, external model interfaces and an interface to Simulink to perform required tests. Interfaces for scientific payloads are planned for upcoming versions.
- Functional Subsystem Verification and Validation
  Functional engineering tests can be performed primarily on the GNC/AOCS subsystem considering relationships to other subsystems and disciplines as far as required.

- Functional Validation Testbench
  The ASTOS environment and dynamics simulation and the camera simulator will be available on a real-time capable computer system providing reusability also for Processor/Hardware-in-the Loop environments.

APPLICATION CASES

Preliminary Design Using Multidisciplinary Optimisation and Mission Analysis

ASTOS is utilized at ESA/CDF for preliminary design of launch and entry vehicles using multidisciplinary optimization. Considered subsystems and disciplines are trajectory, structure, propulsion, aerothermodynamics, thermal protection, power, and AOCS/GNC [4]. The same approach can be applied to parameterised components and equipment of any spacecraft as ASTOS models provides an optimization interface. Depending on the level of complexity of the mission and system concept more sophisticated models can be selected from the ASTOS model database and a more detailed mission sequence can be defined by the user. The flexible frame and vector definition allow the analysis and verification of user defined design aspects. By fixing the design parameters and extending the models by some further details depending on the mission requirements ASTOS can be immediately used as SCS. The user is able to verify the high-level mission requirements against the simulated mission concept and to obtain automatic reports. The latest application case of ASTOS for mission analysis and concept verification was ESA’s Cosmic Vision study QUEST Phase A.

Mission Performance of the Space Robotics Mission DEOS

ASTOS-GNC is derived from the Space Robotics Simulator (SRSIM) which’s development was co-funded by a grant of DLR/BMWi. SRSIM can be understood as MPS for the German In-Orbit Servicing Mission (DEOS) suitable for Phase A/B1. The payload in this mission is the capture capability of an incorporative satellite and not an instrument product. However various visual sensors are modelled for purpose of relative navigation.

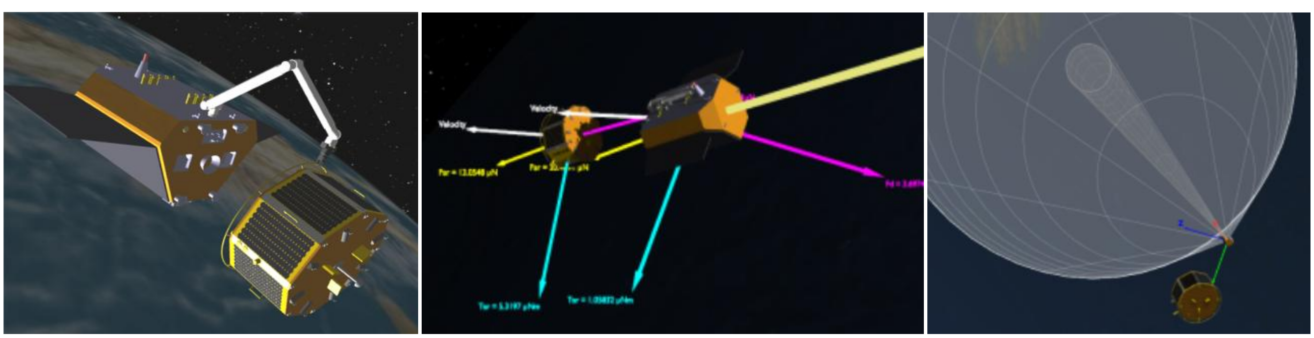

Figure 5: DEOS scenario with differential forces (middle) and relative navigation sensors (right)

SRSIM provides all the relevant equipment models in Simulink. As differential forces are of importance, VESTA computes and feeds back forces and moments due to air drag and solar radiation pressure into the dynamic system. The simulator runs under real-time or faster. The robotic arm is modelled by a model representing the overall performance. SRSIM provides a coupled mission and GNC simulation which allows the parallel computation of mission performance and of the GNC budgets [3].

Subsystem Performance Using the Launcher GNC Simulation Sizing Tools (LGSST)

In the frame of an ESA contract ASTOS-GNC is extended to ESA's Launcher GNS Simulator. Instead of defining a rendezvous scenario as in SRSIM a launcher is configured in ASTOS. The ASTOS library, which is initialized during runtime, provides the rigid body dynamics and environment to Simulink. On Simulink side the navigation, guidance and control algorithms are implemented. A controller design tool is provided under Matlab. Flexible body dynamics are provided by DCAP [5] which is driven by ASTOS. The onboard algorithms can be exported to a real-time testbed using Simulink functions. An extensive set of analysis functions is provided to compute the GNC performance and budgets leading to a fully functional FES. Parallel to LGSST the environment and dynamics simulation with ASTOS is extended for real-time environments using specific hardware components.

CONCLUSION

This paper has shown that ASTOS fulfils most important criteria required by SCS, MPS and FES when applied during Phase 0 to Phase C. ASTOS realizes the term reusability in a unique way as it provides most of the required methods, models, and algorithms. All of them can be reused without additional verification effort. The integrated working environment allows rapid configuration and maintenance during the lifecycle of the space system. Beside that ASTOS allows the coupled mission, system and GNC analysis. That allows consideration of aspects in an analysis which are normally not possible in standard simulators and it allows performing verification and validation with the same tool in different project phases. Finally, such coupled utilization of ASTOS will improve the confidence in complex space missions in early design phases and hence to reduce project costs.

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