Project: **EVVADE**

De-Risk New AOCS V&V Technologies for Industrial Efficiency

Contract No.: 4000140610/22/NL/GLC/cb

Title: **Executive Summary Report**

Doc. No.: EVVADE-ADS-ESR-i1
Issue: 1.0
Date: 06/11/2023

	Name	Function	Date	Signature
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SUMMARY

The Executive Summary Report shall concisely summarise the findings of the Contract. It shall be suitable for non-experts in the field and should also be appropriate for publication.

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CHANGE RECORD

Issue	Date	Pages/Section	Changes
1.0	06/11/2023	All	First complete version

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1 Executive Summary

The de-risk study “De-Risk New AOCS V&V Technologies for Industrial Efficiency” aims at reducing/closing the gap between the V&V technology available at research institutes and some commercial suppliers and the V&V technology established in industry to the benefit of both.

Background & Motivation

- There is a steady increase of cost pressure in industry despite a steady increase of satellite system complexity. This bears the risk of cost explosion in future missions if not counteracted early enough. The study proposed here is an essential step to counteract this risky trend by increasing the industrial efficiency.
- Verification & Validation (V&V) activities constitute approximately 30-60% of the overall Attitude and Orbit Control System (AOCS) cost. This large proportion justifies “V&V” as being the focus of this study.
- There is an increasing gap between the leading-edge V&V technologies developed at research institutes and the V&V performed by large space industry. So this study aims at bridging the gap between research institutions and industry to the benefit of both.
- New V&V technologies not only bear the potential of an increased industrial efficiency, but they have also proven to be a mission enabler (LISA Pathfinder).

End goals

- Generic V&V toolset and process for upcoming B2/C/D missions

  ⇒ Generic product & process
- Enabling future system complexity avoiding cost explosions

  ⇒ Risk reduction
- V&V process cost reduction by approximately 60-80%

  ⇒ Cost reduction
- Enabling high reliability for new-space-type Small-SATs

  ⇒ Enabler

A first iteration to achieves these goals were done within the de-risk study. The approach and results are summarised in this section. The four major activities were:

- AOCS V&V Cost Drivers
- V&V Methods, Tools and Processes
- Simplified Mission Benchmark
- Follow-on Phases and Consortium

1.1 AOCS V&V Cost Drivers

An overview of the AOCS development costs from four recent mission (MetOp-SG, Biomass, JUICE, NGSAR) are summarised. The costs are broken down into activities (design, tuning, analysis, performance evaluation from simulation campaigns) and modes (normal mode, acquisition and safe mode, orbit control mode). For each mission, cost drivers are identified by creating pie charts shown in Figure 1.

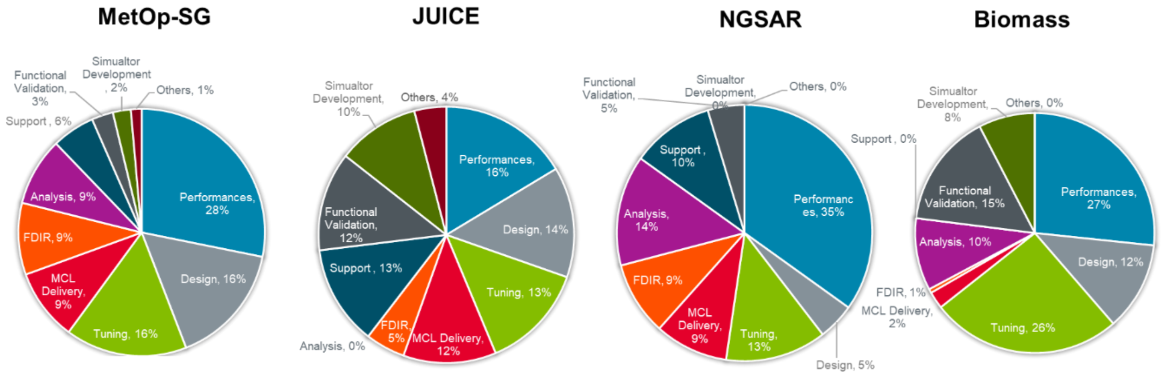

Figure 1: Cost driver identification for four missions divided into various.

Despite the wide range of missions (from Earth observation to planetary exploration), the overall costs show a similar trend as summarized in Table 1. The performance campaign is the largest contributor with ~20%-30% of the total costs. Design and tuning together account for ~20% - 40%, hence there is the potential to reduce the overall costs in this area as well. Also, activities not related to V&V such as MCL deliveries, FDIR, support, etc., are additional drivers in the order of ~30%-40%.

Performance campaigns can be costly, but are essential to capture nonlinear phenomena, which cannot easily be identified beforehand. A worst-case analysis approach would help to identify critical scenarios quickly without many simulations. This would help to discover issues early on, so that less iterations are necessary during tuning and sometimes design. Therefore, the goal of the new V&V technologies for industrial efficiency shall be to better understand the system's behaviour early on through innovative V&V techniques, so that costly iterations and Monte Carlo simulations can be reduced.

Table 1: Comparison of Overall Costs per Mission.

Mission	Performance	Design	Tuning	Analysis
MetOp-SG	28%	16%	16%	9%
JUICE	16%	14%	13%	
NGSAR	35%	5%	13%	14%
Biomass	27%	12%	26%	10%

1.2 V&V Methods, Tools and Processes

The main objective was to identify the "innovation gap" between academia and industry in terms of available technologies for:

- Plant modelling
- Robust stability analysis
- Monte Carlo simulations
- Robust Performance analysis

A parallel review was performed both at Airbus to summarise the current industrial practise and at TUD to identify the state-of-the-art in academia and literature. After the separate review, two workshops were conducted between Airbus and TU Dresden. This resulted in a breakdown of the four categories into work flow diagrams and available tools. An example for the flow diagram of the plant modelling is given Figure 2. In this example, three technologies from industry and academia were identified as potential candidates. After applying the technologies to a benchmark scenario, each technology is compared and evaluated.

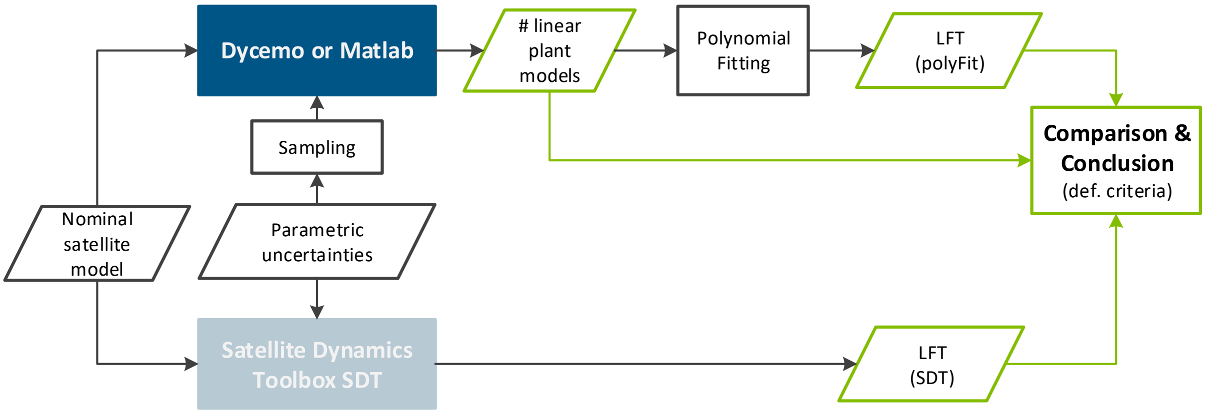

Figure 2: Process for analysing plan modelling approaches

1.3 Simplified Mission Benchmark

To evaluate all the V&V technologies, a simplified mission benchmark has been defined. It is based on the CDR-level of MetOp-SG, Sat-B. The spacecraft is modelled as a multibody system according to Figure 3 consisting of 1) the central body (rigid), tank (rigid or pendulum depending on mode), solar array (flexible appendage) and two scatterometer antennas (flexible appendage). The solar array can be rotated using the solar array drive mechanism (SADM) indicated by the SADM angle.

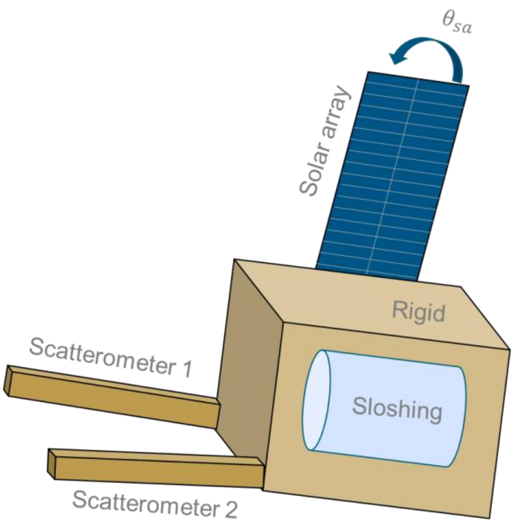

Figure 3: MetOp-SG SAT-B simplified multibody model.

The simplified benchmark is restricted to the normal mode (NOM), orbit control mode (OCM) during a dV manoeuvre, and the acquisition and safe mode (ASM). Taken together, these modes represent various complexities for the first iteration V&V analysis as highlighted in Figure 4.

The term “simplified” only refers to the NOM and OCM. In these modes, the plant and controller are taken from the B2/C/D benchmark of MetOp-SG (no simplification). The simplified parts are neglected dynamics in the sensors and actuators and verifying the correct parametrisation of the input shaping filters for the noise and disturbances of the system. Additionally, the analysis is conducted in continuous time compared to discrete multi-rate systems in B2/C/D missions. The ASM does not have any simplification and uses the high-fidelity MetOp-SG simulator directly from the B2/C/D project phase.

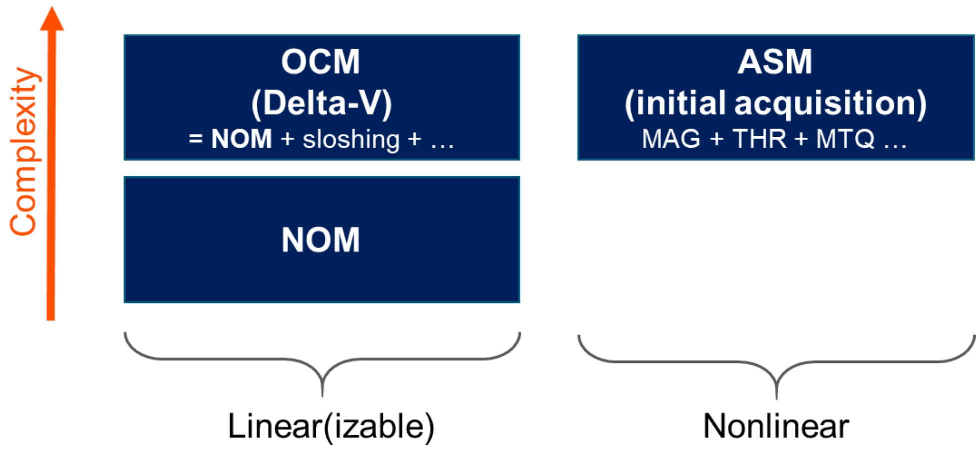

Figure 4: Overview of modes and associated complexity for the first iteration

The uncertainties for the Normal Mode (NOM) and the Orbit Control Mode (OCM) are given in Table 2. The first twenty uncertainties belong to the NOM and the OCM has the additional two last uncertainties. In the simplified mission benchmark, the only uncertainty distributions for probabilistic metrics are the normal (Gaussian) distribution and the uniform distribution.

Table 2: Uncertainties for the MetOp-SG simplified mission benchmark model.

Uncertainty	Range
Central body mass	10%
Central body MoI	20%
Fuel mass	23%
Solar array mass	10%
Solar array MoI	20%
Solar array cantilever frequency (six frequencies)	10%
SADM angle	$[0,2\pi]$
Scatterometer 1 mass	10%
Scatterometer 1 MoI	20%
Scatterometer 1 cantilever frequency	10%
Scatterometer 2 mass	10%
Scatterometer 2 MoI	20%
Scatterometer 2 cantilever frequency	10%
Tank pressure	44%
Modulation ratio	20%

The identified V&V technologies are applied to the simplified benchmark. Two main approaches are tested on the simplified benchmark. The first one is to sample the uncertainty space and the second one uses the Linear Fractional Transform (LFT) to model the uncertainties in a continuous space. The former approach is closer to current industrial standards, whereas the latter approach is often used in academia. For both approaches suitable technologies and tools were found that could capture the dynamical effects of the simplified benchmark (plant modelling), analyse the robust stability and performance.

The results lead to the evaluation of each tool in terms of generic metrics (e.g. tool user friendliness) and category specific metrics (e.g. scalability with respect to uncertainties). Gaps with respect to CDR-level benchmarks are identified for each technology.

1.4 Follow-on Phases and Consortium

From the de-risk study results the following technical fields-of-work of the V&V technology providers in the follow-on study were derived.

Case 1: for analysing the linear(ised) control loop

1. Modelling of the uncertain control plant (satellite dynamics) in LFT form using DyCSyT's SDTlib tool
2. Sensitivity, probabilistic worst case and robustness analysis (stability, performance) of uncertain hybrid multi-rate control loops
    a. Using LFT-based model: ONERA tools GSST, SMART, STOWAT
    b. Using sampled LFT-based model: TU Dresden tool STAMP

    Remark: the approaches a. and b. provide overlapping capabilities. This is done on purpose in order to mitigate the risk in the follow-on study in case of too strong limitations of one approach. But also for cross-check, validation of results, comparison (pros, cons, limitations) to select the tools to be integrated in the V&V process.

Case 2: for analysing the nonlinear control loop

- Worst case identification, robustness and sensitivity by coupling the high-fidelity B2/C/D simulator with the optimisation framework OPTI set-up by Airbus

Remark: the cases 1 and 2 can provide overlapping capabilities especially with respect to performance. This is done on purpose in order to mitigate the risk in the follow-on study if one case has too strong limitations. But also for cross-check, validation of results, comparison (pros, cons, limitations) to select the tools to be integrated in the V&V process.

To assess these methods and tools in a real-world industrial environment, the V&V technology users Airbus Defence and Space (DE, FR, UK) and Astrofein (DE) will define one CDR-level mission benchmark per entity of real missions where these methods and tools will be applied.

The follow-on consortium and the individual major fields-of-work are shown in Figure 5. Airbus Defence and Space GmbH will serve as study prime with Airbus Defence and Space SAS, Airbus Defence and Space Ltd., Astrofein, ONERA, TU Dresden and DyCSyT all at the same level. This is explicitly mentioned to ensure that no misunderstanding is derived from Figure 5.

Additionally, the Work Breakdown Structure (WBS) and the Work Package Description (WPD), time schedule, work logic, and share of total cost were derived.

Figure 5: Consortium of follow-on study.