SysAOCS, how to digitalize the AOCS/GNC description using SysML

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EXTENDED ABSTRACT

Paper proposal applicable to the T-3 workshop objective.

Introduction

This paper introduces the ESA SysAOCS project currently ongoing at SENER Aeroespacial. It presents the main project objective, the planning, the work performed and the results obtained at the current stage. At the end of the paper, preliminary lessons learned and next steps are described.

SysAOCS Project

SysAOCS is an ESA project proposed by SENER Aeroespacial in the framework of the Open Space Innovation Platform (OSIP). The objective of the project is to investigate the use of SysML to digitalize the AOCS/GNC description. The expected benefit of a digital AOCS/GNC design would be to increase the design description accessibility, provide flexibility for modification, improve the integration with the system engineering activities and the models used at system level, foster the reusability across projects, and finally contribute to the digital continuity of the AOCS/GNC subsystem evolution in the frame of the mission. The final outputs of the SysAOCS project are expected to include SysML guidelines for designing AOCS/GNC with suggested relations amongst the different SysML model elements, diagrams and views. SENER will also generate SysML templates and validate these by modelling the AOCS/GNC of real ESA missions. The programmatic of the SysAOCS activity and the corresponding tasks are shown in Figure 1.

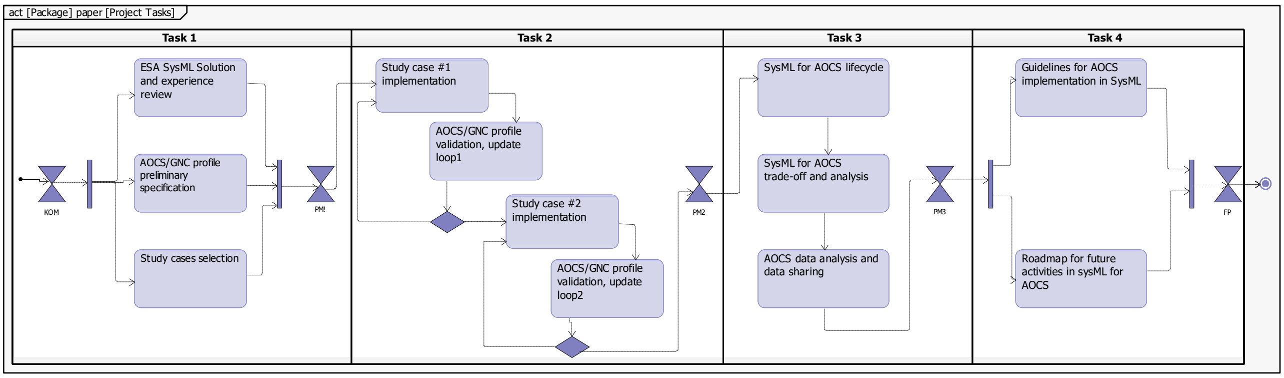

Figure 1:SysAOCS Project tasks

The project started in February 2022 and is organized into 4 tasks running for a total duration of 1 year. During the KOM it was decided to use IBM Rhapsody as modelling tool due to modelling skills in SENER and license availability. The first task was completed at the end of March 2022. It was devoted to the investigation of previous related activities and the selection of two study cases. Among the different SysML methodologies, the SysML ESA Solution was selected and used to build a dedicated AOCS/GNC profile. Space Rider GNC [6] and Euclid AOCS [7] were picked as reference study case due to documentation available for SENER, the maturity level of the AOCS/GNC as of functional, operational and physical architectures, and diversity of the missions, the former being a re-entry mission and the latter a science one. Task 2 is under execution at the time of writing. It is focused on the AOCS implementation in SysML using data from the selected use cases for the validation of the profile. As such this validation exercise is very useful to discover gaps while modelling and to adapt the SysML profile to cover them. In the next section, preliminary implementation of Space Rider GNC and tailored ESA SysML Solution is introduced. SENER team is putting special care on the model descriptiveness and, in particular, on the readability of the diagrams from the perspective of AOCS GNC engineers. Feedback from ESA experts will be gathered from a dedicated workshop foreseen before the end of the summer. Task 3 will start once the static description of an AOCS system is in place. The team will adapt the SysML solution and investigate how to progressively increase the details of the AOCS components along the mission lifecycle (e.g., from phase A to phase F). In particular, the static representation of the AOCS will be completed with views and templates for analysis and trade-off activities. The problematics of AOCS/GNC data analysis and data sharing will also be studied as part of this task. Finally, task 4 will be devoted to compiling the guidelines for the AOCS implementation in SysML in a standardisation document and preparing a roadmap of future activities.

ESA SysML Solution Analysis and Implementation in Rhapsody

Many MBSE description methodologies or architectural frameworks are currently used in the industry, including ARCADIA[1] by TAS, MOFLT[2] by ADS, UAF[3] by OMG, Harmony[4] by IBM, and the ESA SysML Solution[5] by ESA. A trade-off among these methodologies was performed as part of the OSIP proposition and the ESA SysML Solution was selected for the SysAOCS project. The ESA SysML Solution, referred as *Solution* from here on, organizes models in viewpoints or "layers" that can capture both the software and hardware aspects of an AOCS/GNC subsystem. It is a combination of language and methodology that describes the "System of Interest" (SoI), defined by ISO/IEC/IEEE 15288:2015, from a black-box perspective and a white-box perspective. The black-box perspective provides the description of the complete mission and SoI with no interest in its internal workings and includes the "Mission Specification" and "SoI Specification" layers. The white-box perspective covers the functional and physical design of the SoI with emphasis on its internal structure and interfaces and is represented by the "Functional Design" and "Physical Design" layers, respectively.

To address the Mission Specification, SoI Specification, Functional Design, and Physical Design layers, the *Solution* defines new elements named "space system", "SoI", "function" and "product", replacing the SysML basic "block" element. In the *Solution*, the SoI is clearly separated from any other system involved in the mission. These "external systems" replace the SysML "actors". External systems are stakeholders that interact with the space system and the SoI, remaining outside the scope of the latter. The *Solution* also includes the "Transversal" layer, containing the elements used throughout all the layers, and the "Requirement" layer, capturing textual requirements and specification documents. The Mission Specification, SoI Specification, Functional Design and Physical Design layers are highly interconnected by the SysML "allocation" relation and new relations defined in the *Solution* (Figure 2). As methodology, the *Solution* suggests the creation of dedicated diagrams for each of the six layers, detailing the diagram's purpose, its main elements and required relationships that should be modelled. Special emphasis is put on the context diagrams used for the Mission and SoI Specification layers.

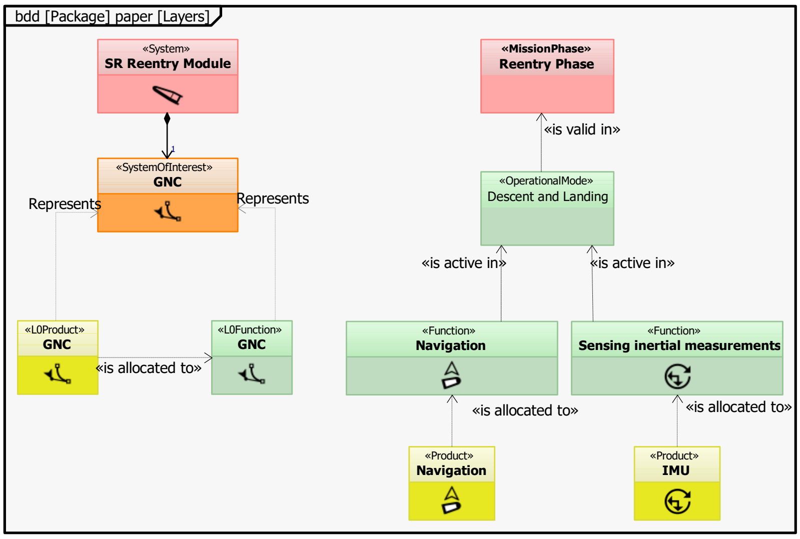

Figure 2: MBSE layers and relationships among them: Mission Specification (pink), SoI Specification (orange), Functional Design (green), and Physical Design (yellow)

At the start of this activity, the *Solution* was available in Cameo and SENER attempted to automatically export it to Rhapsody, but it was not successful due to the different profiling features of each tool. Therefore, the *Solution* was implemented in Rhapsody manually respecting the documentation and mapping to SysMLv1. Rhapsody menus and toolboxes were customized to include the new concepts and the *Solution* color code was adopted. A minor tailoring of the *Solution* was performed to solve the constraints introduced by the tool, mainly regarding behavioral elements. In particular, Cameo allows generating "statechart" diagrams as a standalone element whereas in Rhapsody the statechart shall be included inside a block. As a result, the "mission lifecycle" statechart used in the *Solution* to show the mission phases has been generated in Rhapsody within the top-level element of the mission, the space system. Moreover, Rhapsody automatically generates an "activity diagram" for each "activity" and therefore mapping the "mission activity" element used in the *Solution* to the SysML activity is not supported. It has been mapped to "action block" in order to be able to use it as a white-box element in the Mission Specification layer diagrams. Finally, the majority of attributes defined in Cameo are not supported in Rhapsody and they have been added as tags. It is worth mentioning IBM Rhapsody had been selected as modelling tool due to modelling skills in SENER and license availability.

Space Rider GNC Study Case

The *Solution* is currently being validated by implementing the Space Rider GNC reference scenario. Using real GNC data it is possible to address the problematics of a complex subsystem that combines hardware and software and adapt the diagrams and the methodology. In this exercise, SENER already performed a tailoring of the *Solution* including an International System value type library, failure management for FDIR description, tags to extend the proposed element attributes and a new concept for the Mission Specification layer named "system". The concept refers to any element or system of the space system segments containing the SoI at lower-levels, in accordance with ECSS-S-ST-00-01C.

The **Mission Specification layer** is used as context to describe the Space Rider mission and to introduce the AOCS/GNC SoI. Space Rider (SR) is a reusable European space transportation system enabling routine "access to" and "return from" space. SR mission includes Ground and Operation Segment, Space Segment and Launch Segment. The Space Segment is composed of the Re-entry Module (an upgraded version of IXV with a cargo bay that is responsible for the re-entry phases) and the AVUM Orbital Module (a modified version of the VEGA-C upper stage in charge of the orbital phases). The SoI of the SysAOCS project is the GNC of the Re-entry Module, depicted in orange in the Mission Context diagram (Figure 3). The Space Segment and SR Re-entry Module have been defined as system because of the "directed composition" relation with the SoI as they will have a greater impact on its design. "Interaction" relations with external systems are defined in the Mission Context diagram and detailed interfaces are modelled in the Functional Design and Physical Design layers.

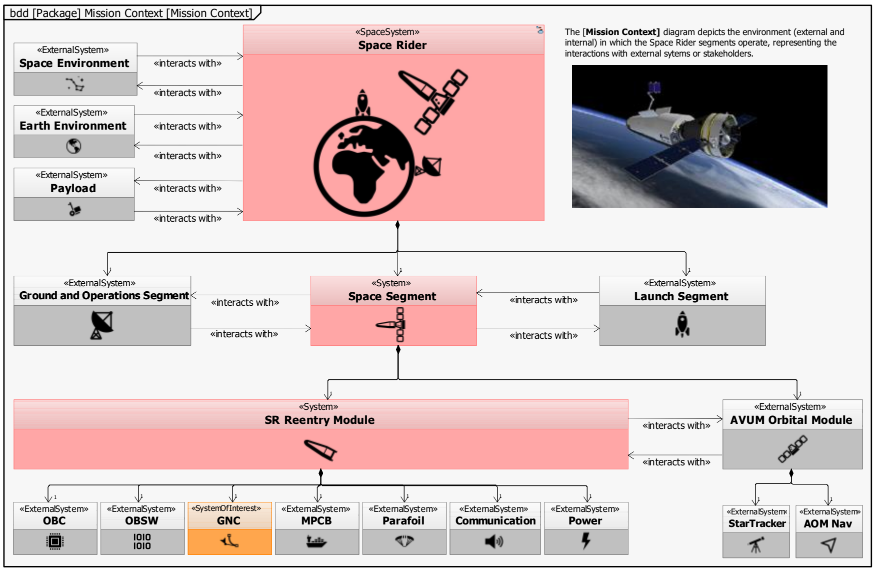

Figure 3: Space Rider Context diagram

The **Functional Design layer** aims to describe the behavior of the SoI by defining a top-level function that represents it from a functional point of view (named "L0 function") and its decomposition into lower-level functions. The SR GNC operational modes are defined and represented in statecharts. The sequence of functions

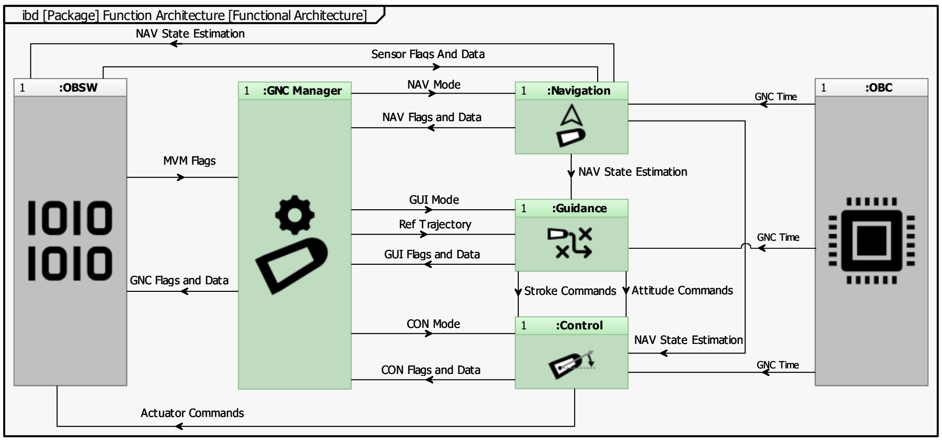

Figure 4: RM GNC Functional Architecture diagram

including all the event occurrences are addressed using a “functional scenario” sequence or activity diagram. All GNC functions are “active in” on one or more operational modes identified for the AOCS/GNC, which will be “valid in” the mission phases corresponding to the re-entry. GNC software functions internal and external interfaces are included in this Functional Design layer with the Functional Architecture diagram depicted in Figure 4. The interfaces are represented by the “exchange items” flowing to or from the functions, depicted as arrows on the connectors. Even if in this example the exchange items are data, they can also be matter or energy being transferred between functions or products.

The **Physical Design layer** represents the GNC from a physical point of view starting from an “L0 product”, which is decomposed into the sub-products. This physical decomposition is represented in a Product Tree diagram in Figure 5 and allocation between the products and the functions they implement is established and displayed using matrix views. Other methodologies use “component” rather than “product” for the Physical Design, however, SENER considers that the product concept defined by ECSS-S-ST-00-01C is better suited for the hardware and software elements of the AOCS/GNC subsystem. An internal block diagram at top level has been created to model interfaces between the main GNC products and the OBSW external system.

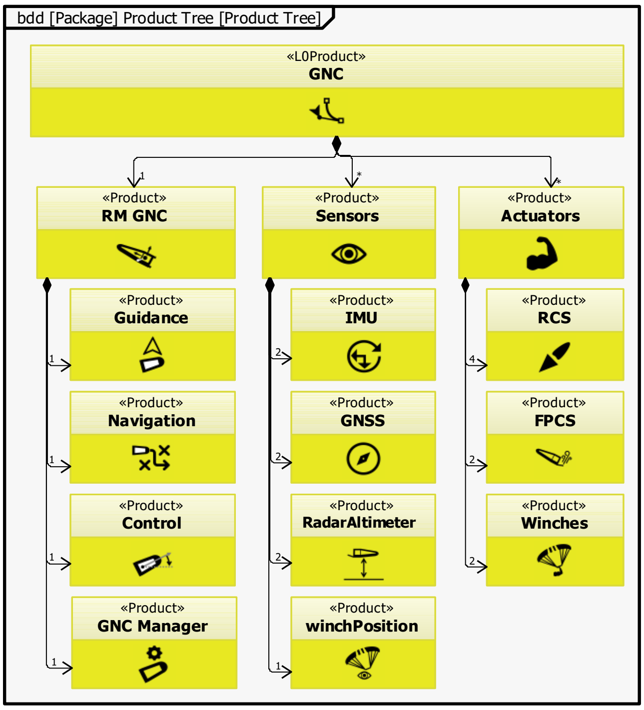

Figure 5: AOCS/GNC Product Tree

The **Transversal layer** compiles all elements used throughout the other layers, meaning external systems interacting with the space system or SoI, exchange items flowing to or from functions and products and the failure analysis for Fault Detection, Isolation and Recovery (FDIR) design. This FDIR description is depicted in a Failure Analysis diagram, where the failures that could make functions not available, classified by severity level, have been identified and linked to the corresponding function. Along the failure, new elements are employed: recovery actions taken depending on the FDIR level, the effect of their occurrence, mitigations to prevent the failure from happening and detection means.

The model organization established for the SysAOCS project supports navigability with deeply nested diagrams to easily access system information at lower levels. SENER proposes to create two main packages, one for the DDF (or any other AOCS document) and the other as a common database. The first package will contain hyperlinks to diagrams, tables and matrix views needed to justify the information required from the ECSS standard, whereas the common database will contain all the mission information. This model organization limits the duplication and enables the reuse of elements in different AOCS documents.

Euclid AOCS Study Case

A second validation activity of the AOCS/GNC profile was performed by modelling the Euclid AOCS study case. Early in the process it was identified the need to include the spacecraft modes for a feasible AOCS description. The *Solution* offers operational modes modelling for elements from SoI onwards, therefore spacecraft modes are exclusively contemplated when the SoI is the Space System. SENER defined a new element named “mission mode” based on the existing operational mode.

Euclid is an ESA second class mission dedicated to investigating the dark matter and dark universe. The Space Segment is composed of the Payload Module, which integrates the telescope and required instruments, and the Service Module, comprising all the subsystems necessary for the mission. The SoI in the Euclid study case is the AOCS (depicted in orange in Figure 6). Implementing this study case arose the problematic of having a scattered System of Interest, not supported by the *Solution*, since the Fine Guidance Sensor necessary for the control of the spacecraft and therefore part of the AOCS, is mounted into the Payload Module, as seen in Figure 6. SENER employed external system to represent the structural belongingness and product for the real description of the sensor.

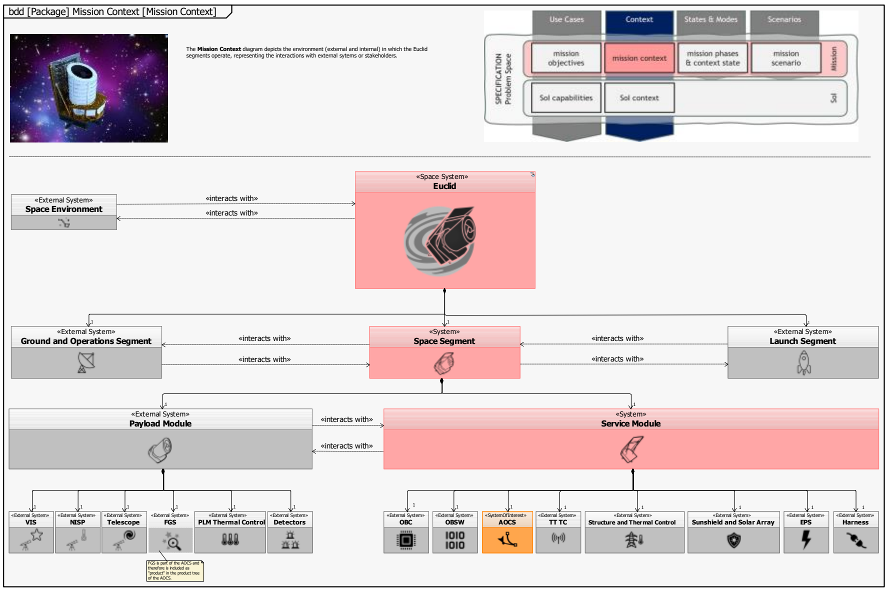

Figure 6 Euclid Mission Context diagram

The main difference with respect to the SR study case is the modelling of the AOCS/GNC decomposition into products. The product tree in SR GNC is organized by navigation, guidance and control functions and subfunctions, whilst the Euclid AOCS is structured by a mode architecture. This organization influences the implementation of mode cycle diagrams and interface diagrams. Therefore dividing the AOCS/GNC profile into two profiles was deemed necessary to better fit the differences in structure between an AOCS and a GNC.

Conclusions and Outcomes

Despite the early stage of the project, the main outcome of the activity is the discovery of the very good maturity level of the ESA SysML Solution and its full suitability to describe the AOCS/GNC subsystem. Little rework was needed to migrate the Solution from Cameo to Rhapsody and to adapt it to AOCS/GNC subsystem. The AOCS/GNC models have been reviewed by system engineers and AOCS/GNC engineers in SENER who gave very good feedback in terms of clarity, readability and completeness. In the next phase of the project, it is expected that SysAOCS will be reviewed by ESA experts and further adapted to cover the full AOCS/GNC lifecycle. Currently, there is a huge interest in SENER for extending this pilot initiative to other projects in space and defense areas. In the future, links with MATLAB/Simulink will also be investigated in order to ensure a proper digital continuity from the simulation environment to the description world. Proper model standardisation and publication may foster the generation model library for a more straightforward integration and reuse of AOCS/GNC subsystems.

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