Lessons learned from the use of SysML in Space Systems at SENER Aeroespacial

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EXTENDED ABSTRACT

The practical application of the SysML language in engineering processes of stablished organizations is a relevant feedback to steer the evolution and consolidation of the associated methods and tools. SENER started using SysML for Space Systems in 2014. The first project to use SysML was the ESA Proba-3 formation flying demonstration mission. SysML methodology was used for the system design of the ground segment and operations. Since then the number of SENER projects adopting this technique has grown, bringing to a cross fertilization and to the internal standardization of the SysML modeling approach (Figure 1). This paper deals with the evolution of the SysML use in SENER describing for representative projects, covering from full flight systems and subsystems to equipment, the reasons to implement this standard, the benefit achieved and the main lessons learned from its adoption.

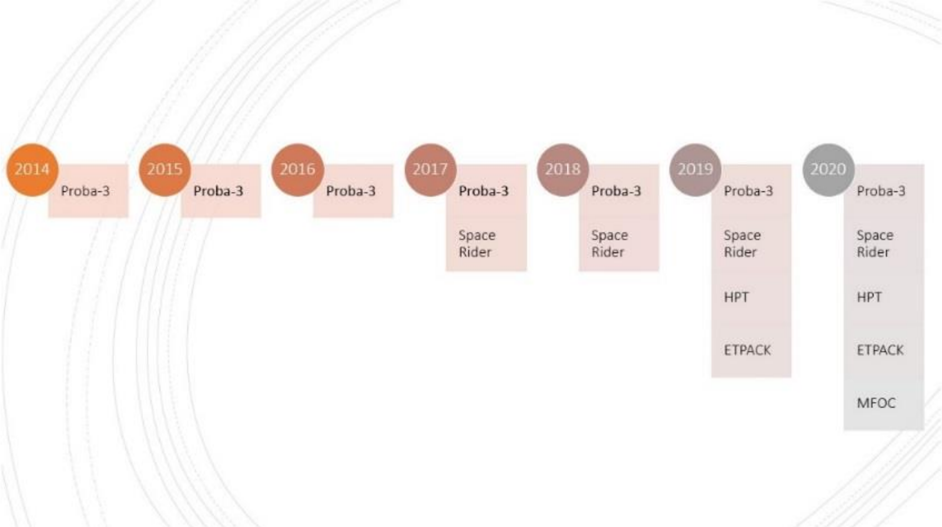


Figure 1: SENER SysML adoption timeline

Proba-3 is a complex ESA formation flying demonstration mission. In 2014, at the beginning of phase C, SENER as prime contractor was in charge to define the ground segment and operations approach. The challenge was to adapt the Redu ground station and the Proba1&2 operations environment to the demanding and highly autonomous Proba-3 formation flying operations. A Mission Operation Concept Document (MOCD) was required in a very short time frame since these activities were not included in the previous phase for budgetary reasons. Thanks to SysML diagram sharing and agile design methodology, ground segment use cases were prepared in a very reduced time. Flight autonomy versus Ground autonomy versus manual operation discussion was possible by the use of SysML activity diagrams. Final consensus was reached in due time resulting in a solid MOCD that is still currently used. This case of success showed the critical importance of using unambiguous semantics understandable by system engineers, software engineers and operations engineers [1]. SysML was also used at component level in Proba-3 for defining unit requirements from the use cases. At system level SysML was used to model the complex mode architecture including spacecraft modes, Formation Flying modes and the GNC modes at spacecraft level. This logical model allowed to simulate and verify the logic correctness and the mode transitions. SysML was also used to compile and maintain Proba-3 power budget. This budget was particularly complex due to the large number of units and operating modes. Additionally, the SysML simulation feature was used for the independent design verification of the Failure Identification and Recovery (FDIR) system (Figure 2). The main lesson learned from Proba-3 is that SysML models are of great help in the system design. SysML should be adopted in the initial phase of the project and the model evolved during its development [2].

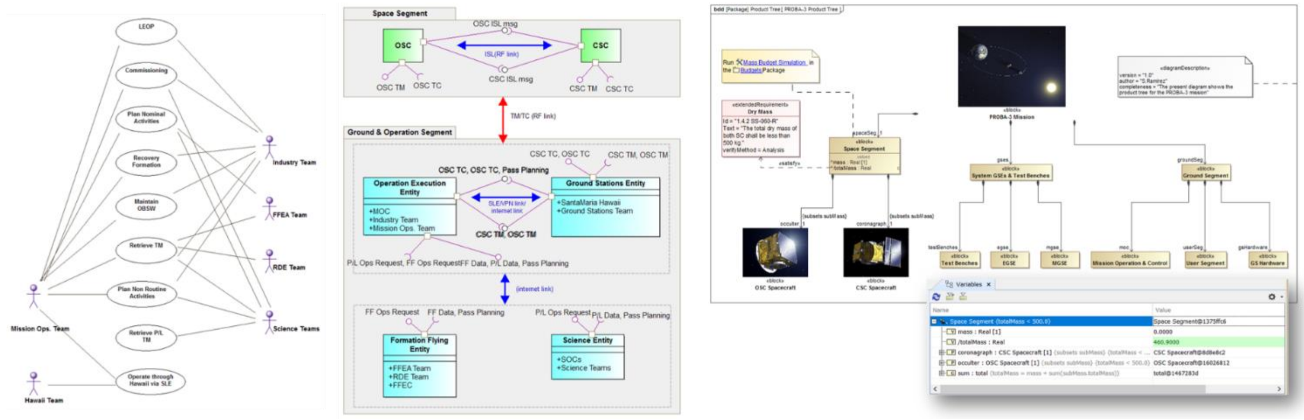


Figure 2: Proba-3 MOCD (left) & System Budgets (right)

Space Rider is the space program managed by ESA for the development of a reusable robotic spacecraft. In 2017, during phase A/B1, Space Rider was under Thales Alenia Space and CIRA co-primeship and SENER was responsible for the GNC including the requirements definition. Adopting SysML methodology, SENER defined GNC use cases starting from the mission requirement. For each use case a dedicated activity diagram led to identify the critical requirements. In a second step, the GNC system was designed ad-hoc to satisfy the requirements [3]. Moreover, the high degree of autonomy, scenarios and phases for the GNC of Space Rider called for a systematic approach to move from the high level mission requirements to the allocation of functions at component level, which motivated the adoption of SysML at GNC subsystem level. In 2018 Space Rider mission and system was substantially updated. The modified VEGA AVUM was selected as external orbital module and SENER, that designed an integrated GNC system suitable for the orbit and re-entry phase should adapt the GNC exclusively for the Re-Entry Module. Thanks to the SysML digital design, the change was absorbed with limited impact. SysML orbital GNC modules were removed and GNC re-entry module were reused and improved in order to obtain the detailed operations definition. Despite the complex consortium organization and the split of the GNC development responsibility by phase, using SysML, SENER managed to provide and maintain a consistent implementation of the Re-Entry GNC functions interfaces (Figure 3). The clear interface design was of paramount importance to identify additional requirements and analysis to be performed [4]. Again, SysML handled the system complexity and demonstrated high flexibility to adapt the design.

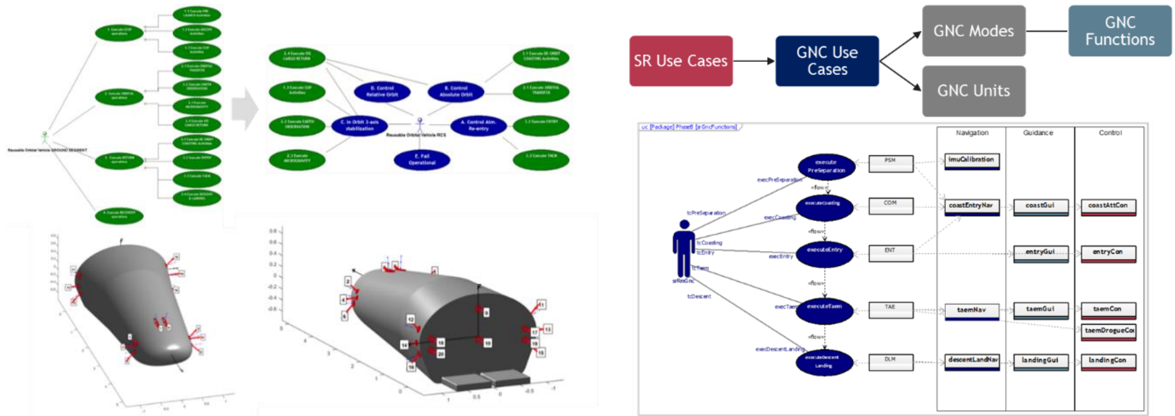


Figure 3: Space Rider GNC requirement definition (left) and GNC function architecture (right)

The **Helicon Plasma Thruster** (HPT) is a radio frequency-powered plasma propulsion technology that can perform well while eliminating many issues that have affected Electric Propulsion Systems (EPSs) to date. SENER started the development of the HPT in 2013 in collaboration with the University Carlos III of Madrid, based on internal funding and ESA's GSTP support programmes. Since then, several prototypes have been built to increase the technology TRL. In 2020, SENER is leading a consortium to evolve the HPT system to TRL 6 in the frame of an EU-funded project called HIPATIA. In order to optimize the project efficiency and to speed up the design loop review, in 2019 SENER started to implement and maintain the complete system design of the HPT (Figure 4). In this model based oriented project, all the project reviews are performed directly on model's views reducing to the barely minimum the technical documentation. At the same time external reviewer have continuous full access to the detailed design [5].

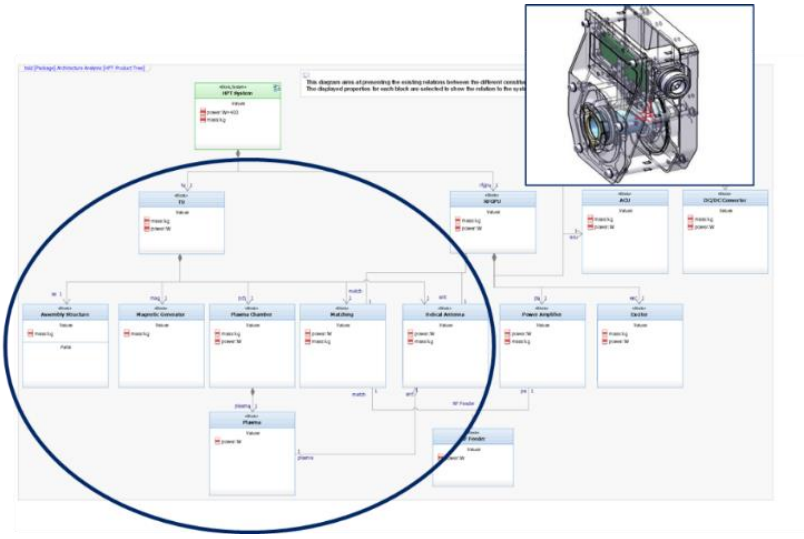


Figure 4: HPT SysML model

E.T.PACK is an EU funded project aimed to design a deorbit kit device based on electrodynamic tether and develop a prototype up to TRL4 by 2022. The project will follow the successful HPT SysML implementation scheme taking full advantages of the lessons learned and building on it (Figure 5). In this project SysML design will mimic the prototype to build a digital twin. The objective is to reduce to the minimum the cost of the technology development that will hopefully end in a demonstration flight in 2025 [6].

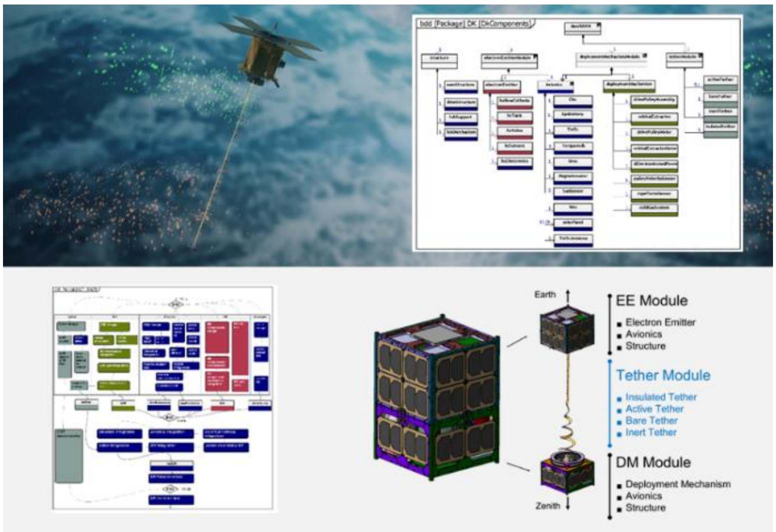
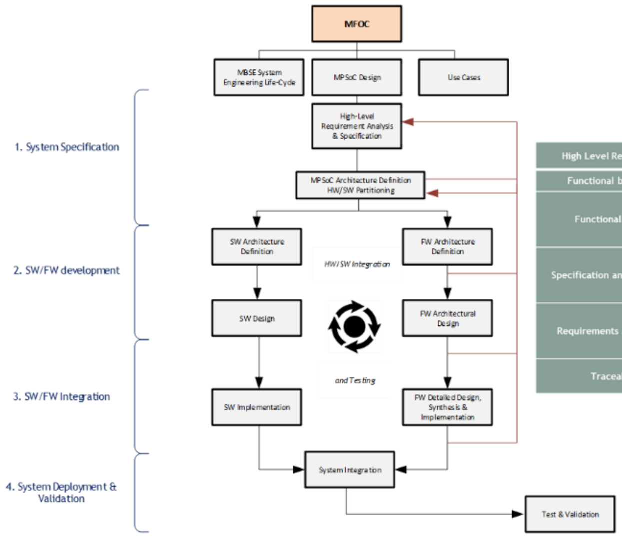


Figure 5: ETPACK system design with SysML

The **Madrid Flight on Chip** (MFOC) is a project funded by Comunidad de Madrid and the European Union to develop an execution platform based on MultiProcessor System on Chip (MPSoC) for future new space applications and satellites [7]. MFOC started in 2018 and includes work packages dedicated to the advanced use of MBSE and in particular to SysML, integrated in a complete engineering design environment. Within this activity, SENER is with The Reuse Company to maximize the exploitation of the SysML tool and its connectivity to other system design tools. Currently, this project is actively supporting SysML standardization activity in SENER.

Within MFOC, SysML formal modeling has been adopted at the System Specification phase of a hardware-software co-design and co-verification approach. This approach has been implemented to better exploit trade-offs between firmware and software partitioning and to design architectures conforming functional and stringent performance requirements with a shorter design cycle (Figure 6).



High Level Requirements	Methods	Techniques and Notations
Functional breakdown	System Context	SysML internal block diagram (IBD)
Functional Analysis	System Behavior	UML/SysML activity diagrams UML/SysML State machines diagrams ModelicaML
Specification and Verification	System Behavior Simulations	Simulink Cameo Simulation Toolkit for SysML OpenGeode for SDL
Requirements Management	Standard text-based requirements Requirements Modelling	DOORS Reqtify SysML Requirements Diagram
Traceability	Verification Matrix	DOORS Reqtify

Figure 6: MFOC project aiming at integrating SysML with the complete electronic development environment

In the frame of the ESA Open Space Innovation Platform (OSIP), SENER proposed an idea for designing **ESA AOCS/GNC with SysML**. If selected, the activity goal would be to digitalize the AOCS/GNC design process. With SysML the final user would be capable to easily follow and operate the subsystem by the originated diagrams avoiding the need of very detailed documentation and hard-to-follow texts. The final outputs would be a set of guidelines for a SysML based AOCS/GNC Design, the definition of the relations amongst the different model elements, diagrams and views, the generation of templates and a roadmap for the reuse of AOCS/GNC data [8].

As conclusions, SysML is considered a mature methodology in SENER and is widely used for internal developments, proposals, ESA and EC projects. SENER is also teaching SysML for Space at the University Carlos III of Madrid. SysML allows mastering the complexity with a reduced number of graphical elements and associated documentation. The standardized SENER working procedure guides the engineer in the early task of requirement definition up to the level of definition of the component detailed design. The increase in the engineer's productivity results has demonstrated to lead to higher project efficiency with consequent saving of money. SysML is well accepted by customers and brings to considerable optimization of the work. The key for methodology acceptance is that different projects have adopted SysML at different levels according to their needs and expectations, concurrence with the rest of stakeholders, communication and training as well as a definition of the scope within already stablished engineering processes

References

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[7] Open Space Innovation Platform. (https://ideas.esa.int/)