Fostering Aerospace Collaboration: COOPERANTS' Initiative towards Continuous Integration of Component Models

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ABSTRACT

This paper introduces the pioneering efforts of the COOPERANTS initiative, aimed at fostering collaboration among industry, SMEs, and research institutions in the aerospace domain. Addressing critical hurdles in digital collaboration, COOPERANTS establishes a unified data ecosystem adhering to Gaia-X standards. Within the domain of Advanced Smart Services, the specific task, ”Component Models for Continuous Integration and Verification,” seeks to overhaul the digital exchange landscape between aerospace component manufacturers and system integrators.

The absence of robust solutions enabling a seamless digital exchange for aerospace system development and integration has spurred COOPERANTS into action. While the European Space Agency (ESA) has initiated preliminary steps with Electronic Data Sheets (EDS) for components, a definitive standard remains elusive. COOPERANTS endeavors to fill this void by devising data structures and models, forming ”Digital Twins,” facilitating continuous exchange and integration of components across the development lifecycle.

The core objective of this endeavor is to establish a systematic framework for generating and exchanging functional ”Digital Twins” in data structure format. These twins enable the creation and configuration of equipment models crucial for onboard software development and validation. These software models, pivotal for numerical simulations spanning various developmental stages (MiL, SiL, HiL), contribute significantly to the holistic integration of the overarching system.

The paper delineates the project's aims, underscoring the creation of a systematic groundwork for generating and exchanging functional ”Digital Twins.” These models provide vital insights into component behavior, accuracy, and potential error scenarios throughout the developmental continuum, markedly enhancing efficiency while mitigating project costs and risks. A pilot project with a component manufacturer showcases the successful integration of component models into the developmental cycle, validating the project's feasibility.

The proposed solution entails defining requirements, establishing interfaces and data structures for model and model-data exchange, and implementing a generic interface for exchanging

individual model components. The process culminates in the execution of a pilot project, followed by an assessment of outcomes to refine interfaces, data structures, processes, and tools. This paper offers a comprehensive overview of COOPERANTS' innovative stride and preliminary achievements, heralding a new era of collaborative and digitally integrated aerospace development.

Keywords: Digitalization; Digital Twin; Electronic Data Sheet; SMP2

1 Introduction

1.1 Motivation

Designing and developing an Attitude and Orbit Control System (AOCS) in past involved a more manual, (electronic) paper-based, and linear process, which was time-consuming and prone to errors. The absence of digital tools means reliance on physical and electronical documents, face-to-face meetings, and traditional communication methods (e.g., phone calls, emails). Here's a more detailed look at what the main gaps have been or still are.

Focusing on Phase A of the AOCS design and development process, which includes preliminary simulations used for component selection and feasibility studies, there are several drawbacks related to the absence of standardized electronic sensor and actuator datasheets. These drawbacks primarily stem from challenges in accessing, sharing, and interpreting component specifications necessary for accurate simulation and decision-making. This could be for example attributed to:

1) Inconsistent Data Formats: Without standardized electronic datasheets, component specifications for sensors and actuators may come in various formats, leading to inconsistencies in how data is interpreted and utilized in simulations. Engineers might spend significant time converting or manually entering data into a usable format, increasing the risk of errors.
2) Limited Accessibility: If sensor and actuator data are not centrally stored and easily accessible, engineers may face delays in obtaining the necessary specifications for preliminary simulations. This can slow down the feasibility studies and component selection process, as obtaining up-to-date and complete data from manufacturers can be time-consuming without a standardized digital repository.
3) Data Integrity and Version Control: With datasheets and specifications shared via email or physical documents, there's a risk of using outdated or incorrect information in simulations. The lack of a centralized, version-controlled database makes it difficult to ensure that all team members are using the most current data, leading to potential discrepancies in simulation results.
4) Efficiency in Simulation Iterations: Preliminary simulations often require iterations with varied component specifications to explore different design scenarios. The manual handling of sensor and actuator data can make these iterations cumbersome and time-intensive, limiting the ability to quickly evaluate different design options and make informed decisions.

In summary, the challenges posed by the lack of standardized electronic sensor and actuator datasheets in Phase A underscore the importance of digitalization and standardization in modern spacecraft design and development. Addressing these drawbacks through more unified data management and sharing practices can significantly enhance the efficiency, accuracy, and collaborative potential of the AOCS development process.

In the later phases of AOCS development, where detailed models of sensors and actuators are crucial for proving performance and verifying system functionality, the absence of standardized models and datasets introduces several gaps and challenges. We want to highlight the following:

1) Incompatibility Across Simulation Platforms: Current practices often lead to compatibility problems between sensor and actuator models and the various simulation platforms used across dif-

ferent phases of development. Adapting models to work across different environments can be resource-intensive and prone to errors.

2) Increased Development Burden: The need to individually develop or adapt models for each sensor and actuator, based on disparate datasheets and specifications, places a significant burden on development teams. This process is inefficient and increases the likelihood of introducing errors into the system.
3) Difficulty in Model Validation: Validating the accuracy of sensor and actuator models is a complex and uncertain process. Engineers must rely on limited data or perform extensive testing to ensure models are reflective of real-world performance, which may still leave substantial uncertainties.
4) Challenges in System-Level Integration and Testing: The integration of sensor and actuator models at the system level requires the definition and maintenance of interfaces. Differences in model interfaces and performance metrics can lead to integration challenges, making it difficult to assess and optimize overall system performance.

In the existing framework without digitalization using standardized models and datasets, the AOCS development process is marked by inefficiencies and challenges that impact the timely, cost-effective, and successful completion of space missions. The reliance on custom, project-specific solutions for each sensor and actuator model exacerbates these issues, highlighting the need for a more digital and standardized approach to AOCS development.

The current situation described above is known and several activities have been started and implemented to tackle these issues. The following digitalization approaches can enhance the development process of AOCS development. These approaches leverage modern technologies and methodologies to streamline design, testing, integration, and operation. Here are some noteworthy digitalization strategies:

- Model-Based Systems Engineering (MBSE): MBSE uses digital models as the primary means of information exchange throughout the engineering process. For AOCS development, MBSE can facilitate the integration of different subsystem models, enabling a more cohesive design process and easier iteration between design phases.
- Digital Twin Technology: Creating a digital twin of the AOCS allows for real-time monitoring and simulation of the system throughout its lifecycle. This approach can predict performance under various conditions, identify potential issues before they arise in the physical system, and support decision-making during mission operations. This is approach is not new and already applied to many missions. However, it lacks a continuity from the very early mission design to mission operations.
- Cloud-Based Collaboration Platforms: Cloud-based platforms can centralize data and models, enabling remote teams to collaborate more effectively. These platforms can support version control, real-time updates, and access control, ensuring that team members are always working with the latest information.
- Continuous Integration and Deployment (CI/CD) for Software Development: Implementing CI/CD pipelines for the software components of AOCS allows for the continuous integration of code changes into a shared repository. This facilitates automated testing and deployment, leading to more efficient development cycles and higher software quality. This is nowadays a common approach. It lacks an interoperability between and compatibility between LSIs.

By leveraging these digitalization strategies, AOCS development can become more efficient, flexible, and robust, leading to better-performing systems that can be developed and iterated upon more quickly and at a lower cost. The project COOPERANTS (Collaborative Processes and Services for Aeronautics and Space) is aiming at developing infrastructure and services to enable these strategies.

1.2 What is COOPERANTS?

COOPERANTS (Collaborative Processes and Services for Aeronautics and Space) [1] is a lighthouse project designed to accelerate the digitization of the aerospace industry by developing efficient, decentralized working methods and processes throughout the lifecycle of space and air vehicles. It aims to enhance the competitiveness of the industry within Germany and the European Union by fostering collaboration across national consortiums, integrating innovative technologies, and creating a secure digital ecosystem in alignment with the Gaia-X initiative. This project facilitates a collaborative environment where data is shared securely and efficiently, ensuring control and sovereignty over data while driving forward the European data economy and digital sovereignty.

1.3 What is Gaia-X?

Gaia-X [2, 3] is a European initiative aimed at creating a federated, open, and secure data infrastructure that upholds European values of data sovereignty, transparency, and interoperability. It seeks to establish a trustworthy and efficient digital ecosystem where businesses, governments, and individuals can store, share, and manage data across various cloud services and platforms while retaining full control over their data. Gaia-X envisions enabling a digital single market within Europe, fostering innovation, data sharing, and the development of new services across industries by setting standards and frameworks for data usage and cloud interoperability. This initiative brings together stakeholders from the public and private sectors to collaborate on building a decentralized infrastructure that supports the digital economy's needs while ensuring compliance with EU regulations and standards.

1.4 AOCS Component Models for Continuous Development, Integration and Verification

Regarding the AOCS development the specific answer to the digitalization of the development process is provided in the work package "Component Models for Continuous Integration and Verification". It has the goal to develop and establish a framework for the development, integration, and verification of sensor and actuator models within the Attitude and Orbit Control System (AOCS) design and development process, thereby addressing the current inefficiencies and risks associated with past and current practices. It shall contribute to the following key aspects:

- Enhance Model Compatibility: Develop and adopt standardized model formats and interfaces for sensors and actuators that ensure seamless compatibility across various simulation platforms and tools. This will facilitate smoother integration processes and reduce the burden of model adaptation.
- Streamline Development Processes: Implement a centralized market place of standardized, validated models and datasets for sensors and actuators. This repository will serve as a shared resource, significantly reducing the time and effort required to develop or adapt individual models for each component.
- Simplify Model Validation: Establish benchmark datasets and validation protocols based on standardized models. This will enable more straightforward and reliable validation of sensor and actuator models, ensuring their accuracy and real-world performance alignment.
- Foster Effective Collaboration: Create a shared platform or framework that allows for the easy exchange and collaborative refinement of standardized models among teams and organizations. This platform will support collective efforts in optimizing design and troubleshooting, enhancing the collaborative potential within and across projects.
- Enable Efficient Design Exploration: Utilize the standardized models and datasets to facilitate rapid and comprehensive exploration of design alternatives. This will allow teams to efficiently evaluate different sensor and actuator configurations, leading to optimal design decisions based on robust simulations.

- Ensure Systematic Verification and Compliance: Leverage standardized models to streamline the verification process, ensuring that all AOCS components and the system as a whole meet regulatory and mission-specific requirements with a higher degree of confidence and efficiency.
- Promote Knowledge Sharing and Reusability: Encourage the development of a knowledge base around standardized models and datasets that can be reused and built upon in future projects, minimizing redundant efforts and fostering innovation.

The goal within COOPERANTS is to serve as a pathfinder to overcome the fragmentation and inefficiencies in the current AOCS development landscape by implementing a new approach to sensor and actuator modeling. This will not only improve the design, integration, and verification phases but also enhance collaboration, compliance, and innovation within the aerospace industry.

For that purpose, we will contribute to the following points in the work package:

- Define the marketplace for equipment, models, and datasets.
- Develop procedures and tools to convert and share models between platforms.
- Integrate models into system simulations for verification.
- Provide simulation models and simulations as a service.

2 Embedding the AOCS Development Workflow in a Digital Environment

In order to facilitate the creation and ongoing exchange of digital data throughout the development and verification phases of space missions it is important to understand the development work flow which allows to derive the requirements for information, models, and functions. This digital data, comprising both raw data and models, is crucial for the systematic development and validation of the AOCS onboard software. The models simulate the performance, accuracy, and potential error scenarios of components, serving as essential tools throughout the entire development cycle for both development and verification by the system integrator (MiL, SiL, HiL). The goal is for these models to consistently inform the system integrator of component properties from design through to delivery, integrating the component development lifecycle into the system's continuous integration process. Figure 1 provides a graphical overview how the development process can be improved by embedding it into Gaia-X.

Analysis of key interactions among suppliers, the Lead System Integrator (LSI), and mission customers throughout the project lifecycle has highlighted a need for two distinct data exchange zones. First, a market place area for equipment as well as their models, and secondly, a protected project area for sharing data during the development, implementation, integration, and verification phases.

The market place is mainly used at project inception when the LSI Systems Engineer must conduct a thorough market analysis to identify available equipment. This process enables the selection of components, the determination of budget allocations, and the potential configuration of a spacecraft. Typically, this analysis involves extensive research, engagement with multiple suppliers, and review of their product catalogues. Additionally, customers frequently conduct reviews and audits of project progress.

Following the signing of contracts, suppliers can transmit sensitive data to the LSI in a protected project area, maintaining data sovereignty. In the context of numerical simulations, the simulation team can employ the equipment data to develop or adjust simulation models. These models are then disseminated across various areas, enabling participants to execute the numerical simulations. Concurrently, the LSI can utilize this sensitive data and share outcomes with customers such as ESA.

In this setup, GAIA-X connects various participants through dedicated workspaces: the marketplace and the protected project area.

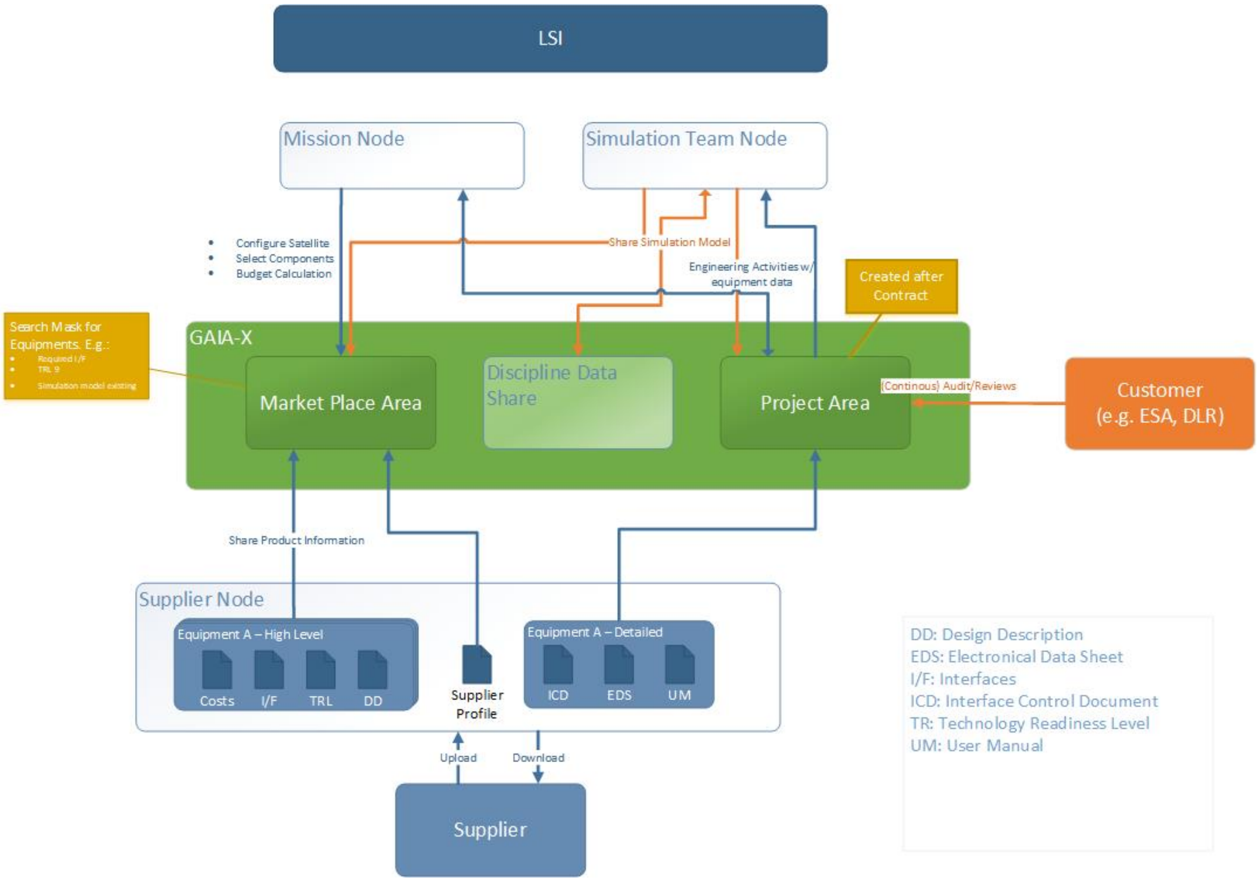


Fig. 1 Conception of embedding the development workflow and data spaces into Gaia-X

2.1 Marketplace

The marketplace is to be established as a public platform specifically designed for the initial phases of a project. It is aimed at facilitating the exploration and selection of equipment and suppliers, crucial for the foundational stages of project development.

2.1.1 Purpose of the Marketplace

The marketplace primarily functions to enable the Lead System Integrator (LSI) to survey available equipment and suppliers effectively. It serves as a central repository where suppliers can list their products, complete with comprehensive details such as interfaces, Technology Readiness Levels (TRL), costs, and design descriptions. This setup allows the LSI to access a wide array of potential resources necessary for the project. In this dynamic environment, the LSI leverages the marketplace to filter and select equipment that meets specific project requirements. This process often involves evaluating equipment based on particular attributes like TRL or compatibility with existing systems, ensuring that selections align precisely with project needs.

2.1.2 Features and Functionalities

The marketplace offers high-level data from suppliers in a machine-readable format, significantly simplifying the task of filtering and comparing different equipment options. This capability is instrumental in supporting the LSI to make informed, efficient decisions. Suppliers in the marketplace provide detailed profiles that encapsulate general information about their capabilities, historical performance, and reliability. These profiles are crucial for the LSI in assessing the suitability of potential partners for the project.

2.1.3 Implementation and Use

During the early project phases, the LSI Systems Engineer utilizes the marketplace to conduct a thorough market analysis. This analysis is pivotal in identifying the best components that meet the project's requirements, including considerations for budget impacts and potential satellite configurations. The marketplace enhances decision-making processes by providing a comprehensive view of the available technological landscape. It equips the LSI with the knowledge of what technologies are available and identifies which suppliers can meet the stringent requirements of the project.

2.1.4 Strategic Importance

By centralizing supplier information and equipment data, the marketplace significantly streamlines the procurement process. This centralization reduces the time and effort required to identify and engage with potential suppliers, making the procurement process more efficient. Having access to a broad range of equipment and supplier data early in the project lifecycle greatly enhances project planning. This access allows for more accurate forecasting and budgeting, which are critical for the successful planning and execution of complex projects such as space missions.

2.2 Protected Project Area

The protected project area serves as a secure environment within the project infrastructure, specifically designed for handling sensitive data exchanges between the project's key stakeholders, including suppliers, the Lead System Integrator (LSI), and customers. This area is pivotal for managing proprietary and confidential information throughout the lifecycle of space mission projects.

2.2.1 Purpose and Functionality

The primary purpose of the protected project area is to ensure data security and confidentiality. It acts as a safeguarded space where sensitive information related to the project can be exchanged and stored without the risk of unauthorized access or data breaches. This secure environment is crucial for maintaining the integrity and sovereignty of data, which is particularly important in industries where data sensitivity is high, such as aerospace and defense. Access to the protected project area is strictly regulated through robust access controls and authentication mechanisms. Only authorized personnel are granted access based on their role and involvement in the project, ensuring that each stakeholder can only access data relevant to their specific tasks. This controlled access facilitates secure collaboration between different parties, allowing them to share, discuss, and work on sensitive project details within a protected framework.

2.2.2 Implementation and Use

Within the protected project area, stakeholders can securely communicate and collaborate on various aspects of the project. This includes the sharing of design documents, simulation data, simulation models, simulators, test results, and other critical information that requires a high level of protection. The area is equipped with tools that support secure file sharing, real-time communication, and collaborative problem-solving, all within a secure digital environment. The protected project area is designed to comply with strict data protection regulations and standards, ensuring that all data handling processes meet legal and ethical requirements. This is essential for projects that involve multiple international stakeholders, where compliance with diverse regulatory frameworks is necessary. The area helps in managing data in a way that respects data sovereignty, with mechanisms in place to control where and how data is stored and accessed.

2.2.3 *Strategic Importance*

The establishment of a protected project area enhances the overall security and trustworthiness of the project. By demonstrating a commitment to data security and regulatory compliance, project leaders can strengthen relationships with stakeholders and build a reputation for reliability and integrity. This is crucial for attracting and retaining partners and customers in sectors where security is a paramount concern. In the scenario of high-stakes development, such as that in aerospace, the protected project area enables the detailed and secure analysis of data and development models. Engineers and scientists can work with sensitive data to refine designs, improve systems, and validate technologies without the risk of compromising intellectual property or strategic information.

3 Analysis and Requirements Breakdown on Services and Tools

Since this work is embedded within the COOPERANTS project underlying and general services and tools are subject of other work packages. Therefore the focus of the analysis is to identify the specifically needed services and tools for the AOCS development and verification process. This section outlines the process of translating the high-level requirements into practical, achievable tasks. The purpose is to ensure clarity and prevent any overlap with other ongoing work packages.

3.1 Analysis of Requirements and Their Implementation

The concept of workspaces overlaps within COOPERANTS with work packages addressing generic needs of digital collaboration e.g. the work package ”Data Spaces”. In terms of data handling, the foundational element is the management of data formats and their integration with existing databases, which is covered in work package ”Collaborative Engineering”. The marketplace is envisioned to add significant value during early project phases of AOCS development. This is similar to other engineering disciplines and development processes. Therefore the development of the market place is handled in the generic work package ”Collaborative Engineering”, which involves creating a platform for sharing this information. Similarly, the establishment of a dedicated project area offers substantial benefits for collaborative work within a cloud-based infrastructure; however, its implementation may extend beyond the scope of this work package.

3.2 Conclusion and Future Directions

Given the current constraints, the concept of workspaces will be adopted. Instead, the focus will shift towards General Data Requirements and the utilization of readily available information. Key tasks of this work are centered around the digital exchange of equipment information to support model-based development of simulation models and the sharing of these models via GAIA-X. This approach emphasizes the marketplace's role in facilitating access to simulation models for external customers. To successfully implement this, a standardized data format and tools for verifying and uploading usable simulation models are necessary. Additionally, simulations representing digital versions of real equipment should link directly to their corresponding hardware units. Executing simulations in the cloud involves accessing and loading models from various cloud nodes into a unified simulation environment, and running these environments on a cloud node while allowing peripheral access from edge devices.

In conclusion, this work focuses on the following three main aspects:

1) Exchange of Equipment Information: Addressing the technical and logistical aspects of sharing equipment data across platforms.
2) Exchange of Equipment Model/Artifact Library: Establishing a comprehensive library of equipment models that can be accessed and utilized across different stages of the project.

3) Remote Execution of Simulation Environment: Facilitating the execution of simulations remotely, which encompasses loading and running simulation models effectively in a cloud-based framework.

In the following section the design and implementation of the three elements is provided in more detail.

4 Design & Implementation

In COOPERANTS functions, processes and databases are integrated as ”Smart Services”. They refer to advanced, digital solutions that facilitate collaborative and decentralized working methods across the aerospace industry’s entire lifecycle. These services are designed to enhance efficiency and security, and they are particularly focused on the following areas:

- Collaborative Program Management and Engineering
- Intelligent Assistants and Dashboard Systems
- Simulation and Verification
- Data Management and Integration

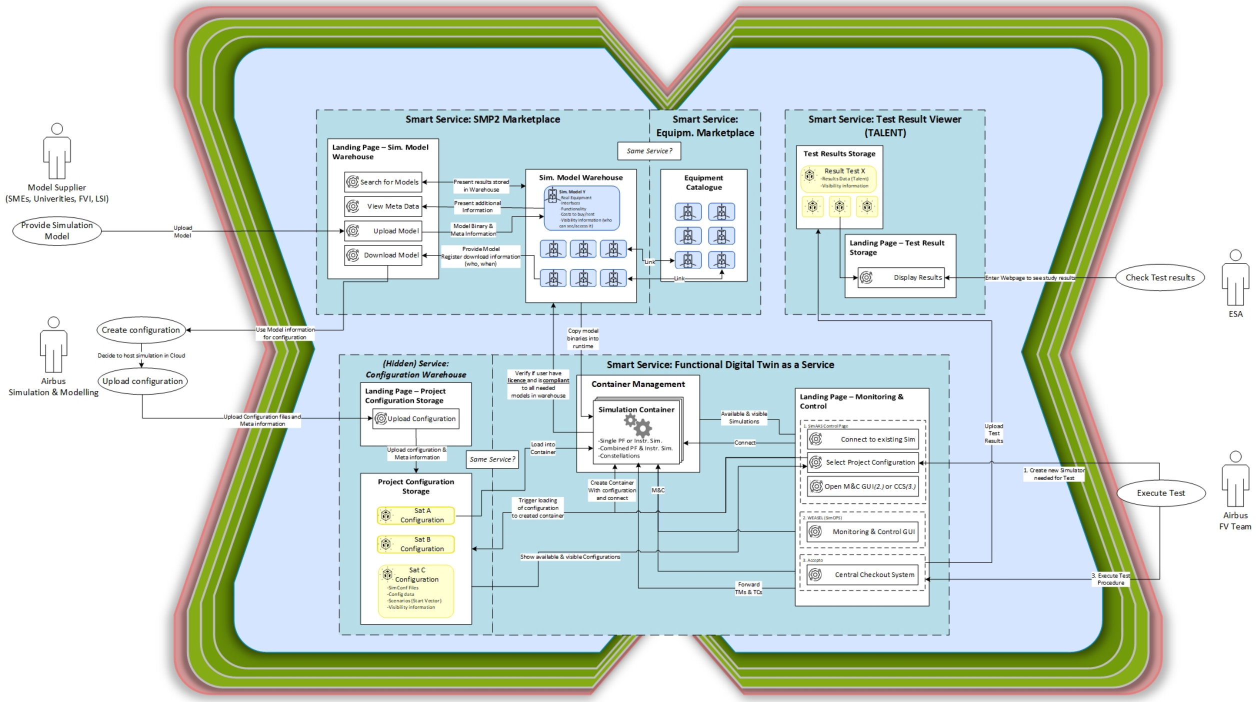


Fig. 2 Smart Services of the AOCS development and verification process and their interaction within the Gaia-X environment

Figure 2 depicts how the three main aspects (cf. Sect. 3.2) will be integrated into Gaia-X and how they will interact as part of the AOCS development and verification process. In the following subsections these elements will be described in more detail.

4.1 Exchange of Equipment Information

4.1.1 Design

For establishing and operating a marketplace for equipment information and models Tab. 1 outlines the specific requirements This marketplace is designed to facilitate the digital exchange of critical equipment data among stakeholders within the aerospace and defense industries. The aim is to enhance interoperability, streamline design and manufacturing processes, and ensure compliance with industry standards through a centralized platform. Each requirement listed below addresses essential aspects of data standardization, governance, and accessibility. The infrastructure and tooling provided through cloud technologies support the efficient management and dissemination of this information, thereby fostering a more connected and transparent supply chain environment.

Table 1 Requirements for the Marketplace

No.	Requirements on Infrastructure and Tooling
1	The Exchange of Data Sheets for the Equipment Information shall be based on a standardized format/template (e.g., EDS [4]).
2	The cloud platform shall provide a web-based artifact library to allow to upload, store, search, and download the data sheets for equipment information as a single file/artifact.
3	A data governance process shall be established detailing the process, responsibilities, and ownership of the data.
4	The Artifact Library for the EDS Equipment Information shall provide additional Meta Data for: Equipment Type, Product Designation and Version, Supplier/Manufacturer, A dedicated Version Number and Release Date for the EDS Files.
5	The data sheets for the Equipment Properties shall at least contain the information on: Connectors & Channel Allocation, Power consumption & Power Dissipation, Operational temperatures (Maximum/Minimum).
6	The EDS for the Equipment Properties shall at least contain the following information (if applicable for the equipment): Command Messages And Format, Command Message Data & Aggregate Parameter, Command Calibration Format & Data, Acquisition Messages And Format, Acquisition Message Data & Aggregate Parameter, Acquisition Calibration Format & Data.
7	The cloud platform shall provide the possibility to exchange information on the Functional Behavior of the Equipment HW. Note: As a first iteration it will be sufficient to provide this data in the form of Design Descriptions, User Manual and ICD Documents.
8	The cloud platform shall provide the possibility to exchange information required to model the operational modes of the equipment based on a finite state machine. This shall cover at least: Operational Modes, Mode Transitions and Trigger, Timing Information/Transition Delays.

4.1.2 Implementation and Results

The marketplace development is managed by a dedicated team within COOPERANTS, enabling not only the sharing of data but also providing access to algorithms and software as a service (SaaS) concepts. The current focus of this activity is on providing and locating these datasets and services. Consequently, at present, the data cannot be clustered for specific equipment, nor is version control available. Nevertheless, the foundation has been established so that, in the future, missing functionalities can be added to enable a fully functional equipment warehouse.

4.2 Exchange of Equipment Model/Artifact Library

4.2.1 Design

The purpose of the equipment model library is to facilitate a standardized, accessible, and efficient method for managing and exchanging equipment models that can significantly enhance collaborative efforts and streamline processes from design through verification and beyond. The requirements in Tab. 2

aim to support not only the creation and maintenance of this model library but also ensure its integration with existing project management and development tools. By doing so, it provides an infrastructure that enhances the reusability of models, ensures adherence to industry standards, and supports the diverse needs of project stakeholders. The table organizes these requirements in terms of the data or items to be exchanged, the supporting cloud infrastructure and tooling, and exchanged information.

Table 2 Requirements for the Exchange of Equipment Models

No.	Requirements on Infrastructure and Tooling
1	The cloud platform shall provide a web-based artifact library to allow to upload, store, search and download the Equipment Model or Model Components as a single artifact.
2	The exchange of the Simulation Model shall be based on a standardized architecture, including at least the SMP2 Standard as basis for the simulation activities in an ESA context.
3	For Released Model a minimum Quality Rules / Standards / Process shall be defined and applied.
4	The Model Data Package shall be composed of a standard set of documentation including: Design Documentation, Interface Description, Test & Validation Spec and Report, User Manual.
5	The Model Data Package shall include the Binaries pre-built for the target platform (OS).
6	The Model Data Package shall include the Source Code of the Model to be able to maintain, modify, and recompile the binaries in the local environment.
7	The Model Data Package shall include a default set of configuration parameters.
8	A data governance process shall be established detailing the process, responsibilities, and ownership of the data.
9	The Artifact Library for the Equipment Models shall provide additional Meta Data for: Equipment Type, Product Designation and Version, Supplier/Manufacturer, A dedicated Version Number and Release Date for the EDS Files, Target Operating System, Applicable Modelling Standard.
10	The Artifact Library for the Equipment Models shall provide a concept for limited user access and licensing.
11	It shall be possible to link the model library to a local continuous build system.
12	The Artifact Library shall provide the possibility to exchange standalone model components to be integrated into the local model development. Components might be built as SMP2 Model, Matlab Model, C/C++ Library with standardized interface functions (e.g., init, update).

4.2.2 Implementation and Results

The primary objective is to enable the digital exchange and integration of simulation models for Attitude and Orbit Control System (AOCS) components of satellites, focusing on using standards for the exchange of models and libraries. In this context, existing formats and standards were analyzed.

SMP2 (Simulation Model Portability version 2) is a standard that specifically focuses on the portability of simulation models, with tools and methodologies that might be used in both European and international contexts. It provides a specific methodology for the portability of simulation models, allowing them to be used across various simulation platforms. It is not confined to the space sector and can be applied in different industries that require robust simulation capabilities. With the release of the ECSS-E-ST-40-07 ”Simulation modelling platform” [5, 6] SMP2 was incorporated into the ECSS (European Cooperation for Space Standardization) standards. While the ECSS-E-ST-40-07 extends SMP2 it maintains a backwards compatibility allowing the reuse of existing SMP2 models and libraries.

The Simulation Model Portability Version 2 (SMP2) standard was chosen for the exchange of models. One reason is that it is widely used by LSIs and ESA for verification and ground reference models [7–9]. It also ensures compatibility with existing models and infrastructure. Another reason is that a transformation tool from Matlab/Simulink exists. With Matlab/Simulink as the main modeling and simulation tools for GNC engineering, this allows porting existing simulation models on Matlab/Simulink into C/C++ software based models follwing the SMP2 standard. This tool, MOSAIC [10, 11], developed by the National Aerospace Laboratory (NLR) of the Netherlands, was procured and implemented on behalf of ESA.

To develop and demonstrate the functionality and the workflow, a pilot SMP2 model of an AOCS equipment was generated via the modeling in Matlab/Simulink. For that purpose the SMP2 model for the AMR Magnetometer of ZARM Technik AG was chosen. The process involved several key steps:

1) **Modeling in Matlab/Simulink:** Detailed modeling of the magnetometer in Matlab/Simulink was undertaken to capture essential functionalities and interfaces necessary for accurate simulations.
2) **Conversion to SMP2 using MOSAIC Tool:** The MOSAIC tool was utilized to convert the Matlab/Simulink model to an SMP2-compliant format, ensuring compatibility and functional integrity.
3) **Integration into SMP2 Simulation Environment:** The converted model was integrated into the SMP2 simulation environment to verify its operation and interaction with other system components.

To verify the accuracy and reliability of the converted models, extensive testing and validation activities were carried out. Benchmark data were generated from the original Matlab/Simulink model to serve as a basis for comparison. Furthermore, the outputs and behaviors of the SMP2 model were thoroughly compared against the original Matlab/Simulink model. This comprehensive comparison and analysis ensured that the essential dynamics and functionalities were preserved during the conversion process.

The model's transition to SMP2 was successful, with the SMP2 model closely matching the original in terms of output and functionality. However, challenges were encountered, particularly with the conversion tool's limitations in handling complex structures and achieving full compatibility with SMP2 requirements.

The successful export of the Matlab/Simulink model to SMP2 marks a significant step in facilitating the exchange of equipment models within the aerospace sector. This capability is expected to enhance collaborative efforts and streamline development and validation processes for onboard software and system integration, reflecting the importance of developing interoperable and standards-compliant modeling tools in aerospace.

4.3 Remote Execution of Simulation Environment

4.3.1 Design

For enabling remote execution of simulation environments within a cloud-based system Tab. 3 summarizes the key infrastructure requirements. These requirements are designed to ensure seamless integration, management, and operation of simulation models and tools through a web-based platform. Each requirement focuses on enhancing the flexibility, accessibility, and efficiency of simulation processes by utilizing modern cloud technologies and containerization. This approach aims to support collaborative simulations, dynamic resource allocation, and secure user interactions, thereby facilitating robust simulation workflows that are critical in research and development settings.

Table 3 Requirements for the Execution of Simulations

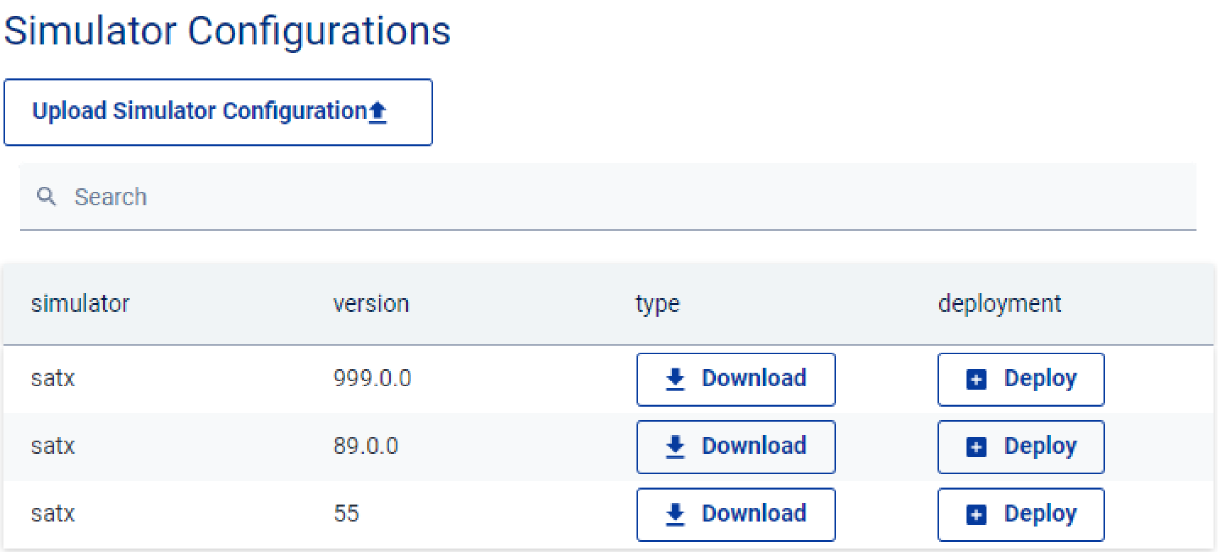
No.	Requirements on Infrastructure and Tooling (Cloud)
1	It shall be possible to select a simulation based on data provided by a database via a web-based front-end. Alternatively, it shall be possible to upload a simulator into the Cloud node directly.
2	After selection of the simulation, a container shall be set up hosting the simulation. Interfaces shall be provided by this container to allow interacting with the simulation.
3	The user shall be able to run tests on the simulator by having either access to a repository or uploading them.
4	It shall be possible to load the binaries of simulation models from different cloud nodes. This facilitates collaborative working by using simulation models from suppliers.
5	The landing page of the service shall allow the user either to connect to an already running simulation or to launch a new one. The option to connect to an already existing simulation shall allow one user to have a break or that several users can work simultaneously on one simulation.
6	A user shall only see and connect to running simulations, which are accessible with his user/entity profile.
7	A user shall only see and start launchable simulations, which are accessible with his user/entity profile.
8	One simulation shall be running in a container.
9	The launchable simulations shall be defined by a configuration artifact, which a user can load and store inside the service. The artifact shall contain XML-Files defining the used models and how they are configured, and can include binaries or data files necessary for the proper execution and simulation.
10	When uploading the configuration, it shall be checked if all models are available either inside the artifact or in a model storage/warehouse.
11	After a simulation is selected/launched, a new docker container shall be started. Several containers are possible and intended for the possibility of constellation simulations.
12	To allow more flexibility regarding the hosted simulations, either the simulation models shall be copied to the container dynamically after launch or as an alternative, the upload of a simulation configuration will create a new docker image.
13	It shall be possible to connect a Checkout system with a simulation running inside the container allowing the execution of tests.
14	Test results shall be stored separately and can be made accessible to other users/entities.

4.3.2 Implementation and Results

The implementation was carried out on the OVHcloud platform, chosen as the cloud environment for COOPERANTS. The current solution, based on OpenStack, adheres to most software as a service (SaaS) concepts. Users enter a landing page, as shown in Fig. 3, where they can upload and download XML-based simulator configurations, facilitating deployment within the cloud environment.

The deployment process involves creating a container and populating it with the necessary libraries and simulation models from dedicated storage. Users can then interact with the simulation via a Graphical User Interface (GUI), which communicates with the simulation container using a RESTful API.

As part of the COOPERANTS project, the service will be extended to include user management with GAIA-X verification, enabling users to either hide or share simulation instances with other users



simulator	version	type	deployment
satx	999.0.0	Download	Deploy
satx	89.0.0	Download	Deploy
satx	55	Download	Deploy

Fig. 3 Landing page of the Simulation as a Service

or companies. Additionally, a checkout system will be added to allow the execution of test scripts for operational usage of the service.

Finally, there is an aim to load SMP2 models from the marketplace (see Sect. 4.2) into this SaaS, utilizing the GAIA-X infrastructure to establish contracts between the model providers and the users.

5 Conclusion & Outlook

As the work in COOPERANTS advances, the project continues to break new ground in the digital exchange of equipment models. This work specifically addresses the development and implementation of a systematic framework for generating, exchanging, and validating ”Digital Twins” of aerospace components. These models are crucial for the continuous integration and verification processes that enhance the digital collaboration ecosystem within the aerospace sector.

To date, the achievements within this work package have demonstrated progress in establishing a unified and interoperable platform that supports the seamless exchange of equipment data. The pilot projects carried out have validated the practicality and feasibility of the digital twins.

Looking forward, the work is set to delve deeper into refining these digital twins and expanding their functionalities. On short term a completion and refinement of the building blocks is foreseen. The next phase will focus on deploying these prototypes for enhancing model accuracy, expanding the range of components covered, and increasing the fidelity of simulations.

In conclusion, the journey of COOPERANTS and of this work is far from complete, with further enhancements and achievements on the horizon. Stakeholders and participants can look forward to new developments that will not only address the current challenges but also pave the way for next-generation aerospace solutions that leverage digital technologies to their fullest potential.

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References

[1] Birgit Suhr, Michael Benkel, Uwe Brauer, Udo Corleis, Hauke Ernst, Daniel Esser, Luis Fischer, Andreas Graf, Hannes Hüffer, Tra-Mi Ho, Michael Maurus, Jan Novacek, Nicole Reuter, Andre Seidel, Federik Strehlow, Uwe Teicher, Alexander Viehl, and Marco Witzmann. Digital Collaborative Services and Tools for the Aeronautics and Space Sector. In *IAC 2022*, September 2022. `https://elib.dlr.de/197064/`.

[2] Gaia-X Framework. `https://docs.gaia-x.eu/framework/`.

[3] Gaia-X Architecture Document - 22.10 Release. `https://docs.gaia-x.eu/technical-committee/architecture-document/22.10/`.

[4] Electronic Data Sheets: a common language for space. `https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Electronic_Data_Sheets_a_common_language_for_space`.

[5] ECSS-E-ST-40-07C – Simulation modelling platform, Mar 2020. `https://ecss.nl/standard/ecss-e-st-40-07c-simulation-modelling-platform-2-march-2020/`.

[6] Peter Fritzen, Alberto Ingenito, Robert Blommestijn, Vemund Reggestad, and Anthony Walsh. Evolution of the SMP2 Standard into ECSS SMP. In *Workshop on Simulation for European Space Programmes (SESP)*, 2017.

[7] Joaquim Barreto, Leandro Hoffmann, and Ana Ambrosio. *Using SMP2 Standard in Operational and Analytical Simulators*. DOI: 10.2514/6.2010-2267.

[8] Ludmila Nozhenkova, Olga Isaeva, and Evgeniy Gruzenko. Architecture of the Simulation Modeling Infrastructure Based on the Simulation Model Portability Standard. In *Proceedings of the 2017 International Conference on Applied Mathematics, Modelling and Statistics Application (AMMSA 2017)*, pages 125–128. Atlantis Press, 2017/05. ISBN: 978-94-6252-355-5. DOI: 10.2991/ammsa-17.2017.27, `https://doi.org/10.2991/ammsa-17.2017.27`.

[9] Hong Wei Zhou, Hong Tao Hou, Wang Xun Zhang, Qun Li, and Qiang Chang. A Model Integration Framework Based Portability for GNSS Simulation. In *Materials Science and Engineering Technology*, volume 936 of *Advanced Materials Research*, pages 2302–2306. Trans Tech Publications Ltd, 7 2014. DOI: 10.4028/www.scientific.net/AMR.936.2302.

[10] Wim Lammen, Jeroen Moelands, and Quirien Wijnands. New developments in automated model transfer with MOSAIC from the user perspective. In *Workshop on Simulation for European Space Programmes (SESP)*, 2010.

[11] MOSAIC - Automated model transfer from Simulink to the real-time simulation tool EuroSim and ESA's Simulation Model Compatibility (SMP2) standard. `https://www.mathworks.com/products/connections/product_detail/mosaic.html`.