Modelling of Real Time Units in the Verification and Validation Process of Satellite Systems

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Abstract: *Verification and Validation (V&V) methodologies are essential to ensure the correct operations of control algorithms of the embedded software during a satellite mission. This paper addresses a critical aspect of aerospace systems development, namely the process of testing the flight software during the V&V campaign for functional qualification on ground.*

Having as reference the European Attitude Determination and Control System (E-ADCS) for nano satellites and small satellites up to 80 kg, the study investigates the integration of two main testing stages, Model-in-the-Loop (MIL) and Processor-in-the-Loop (PIL) within a performance validation framework.

The PIL phase is described by the exchange of telemetry (TM) and telecommand (TC) messages between the onboard computer (OBC) and a computer acting as a simulated ground station. This phase enables the validation of the flight software that is loaded and runs on the OBC.

The MIL phase is implemented using a Speedgoat machine, which supports the real-time execution of Simulink-based models of sensors and actuators, running our custom-made Attitude and Orbit Control Systems (AOCS) algorithms. Communication with the models is achieved by writing commands inputs through MATLAB-based test scripts and reading outputs via dedicated interface adapters that enable the interaction between the PC and Speedgoat machine.

The integration phase is described by the relation between PC, OBC and Speedgoat (End-to-End testing) where the validation takes place for both the embedded software and AOCS algorithms with the sensors and actuators in the loop.

This framework contributes to improving the robustness of the E-ADCS product by enabling early detection of integration issues and comprehensive system-level validation. At this stage, it provides significantly greater visibility and debugging capability compared to later testing environments (e.g. flat-sat) that involve physical units only.

The work in this paper is part of an ESA Incubed co-financed project led by Indra Space, with Skylabs as a consortium partner for providing the OBC.

Key Words: *Real Time Systems, Matlab, Simulink, Speedgoat, Model-in-the-Loop, Processor-in-the-loop*

1. INTRODUCTION

Verification and Validation (V&V) activities are essential in the development of aerospace embedded systems, ensuring that flight software and control algorithms perform correctly under mission conditions. Since satellite systems cannot be easily tested or debugged in orbit, extensive ground-based validation is required to increase reliability and reduce integration risks.

This paper addresses the V&V process applied to the European Attitude Determination and Control System (E-ADCS) for nanosatellites and small satellites up to 80 kg. The proposed approach combines Model-in-the-Loop (MIL) and Processor-in-the-Loop (PIL) testing within a unified validation framework. MIL enables early-stage testing of AOCS algorithms using real-time simulation models of sensors and actuators, while PIL introduces the onboard computer (OBC), allowing execution of flight software with realistic telemetry and telecommand exchanges.

An end-to-end integration phase further combines MIL and PIL elements to validate system-level interactions between software, hardware interfaces, and communication links. This multi-level approach improves observability and enables early detection of integration issues compared to later-stage hardware testing environments.

The work is carried out within an ESA InCubed co-financed project led by Indra Space, with Skylabs contributing as the onboard computer provider.

2. REAL TIME VS SIMULATED UNITS

Real-time systems play a crucial role in every verification and validation scenario, particularly in aerospace applications where timing constraints and system reliability are critical. In this section, the E-ADCS project and the real-time system employed within it is detailed.

The sensors used within the E-ADCS project include magnetometer, sun sensor, star tracker, and gyroscope. Each of these components contributes to accurate attitude determination by providing different types of measurements.

- Magnetometer measures the Earth’s magnetic field, and it is primarily used during the detumbling phase, when the satellite must reduce its initial rotational motion after deployment.
- Star tracker is a high-precision sensor used for determining the satellite’s position and orientation by observing star patterns.
- Sun sensor detects the direction of the Sun, providing coarse attitude information that is especially useful during safe-mode operations.
- Gyroscope measures angular velocity, contributing to the estimation of the satellite’s orientation and rotational dynamics.

In addition to sensors, the E-ADCS subsystem includes actuators that enable active control of the satellite’s attitude. The main actuators are reaction wheels and magnetorquers.

- Reaction wheels are used to generate control torques through the conservation of angular momentum, allowing precise adjustments of the satellite’s orientation.
- Magnetorquers, on the other hand, interact with the Earth’s magnetic field to generate torque, and are commonly used for attitude control and momentum dumping.

The role of Verification and Validation of this Subsystem consists in modelling each sensor and actuator and running them in Real Time to simulate the real behavior of the satellite against the mission requirements.

3. VALIDATION AND VERIFICATION SCENARIOS

Three main types of testing scenarios are defined within the system architecture:

I. PC to Speedgoat

This scenario involves a server (PC) that simulates a ground station communicating with the Speedgoat platform via different interfaces.

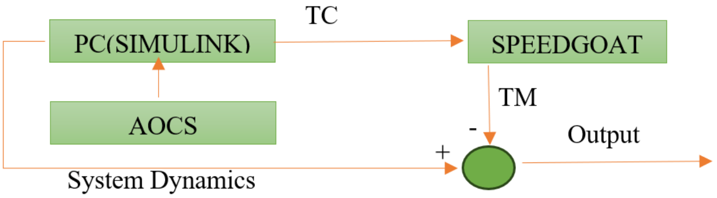

Fig. 1 PC to SPEEDGOAT

II. OBC to Speedgoat

This scenario focuses on the communication between OBC and the Speedgoat platform for the testing and validation of the, communication protocols.

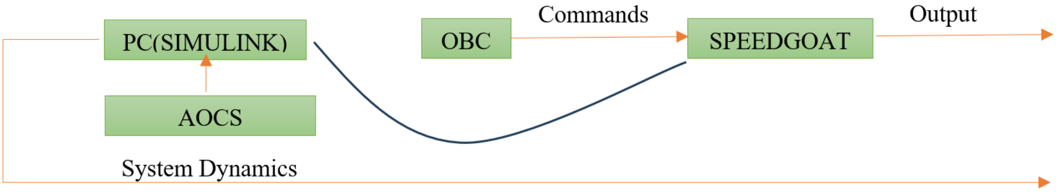

Fig. 2 OBC to SPEEDGOAT

III. End to End (Closed-Loop)

It consists of a closed-loop configuration involving a host PC, OBC, and Speedgoat platform. This configuration is referred to as an end-to-end scenario, as it enables comprehensive system-level testing within the integration of all the simulated sensors and actuators.

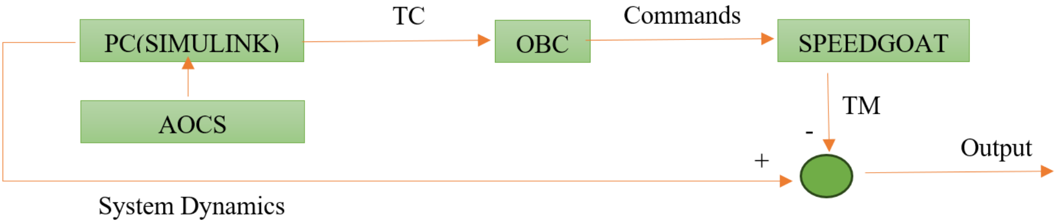

Fig. 3 End to End

4. DVF (DEVELOPMENT AND VERIFICATION FACILITY) LABORATORY

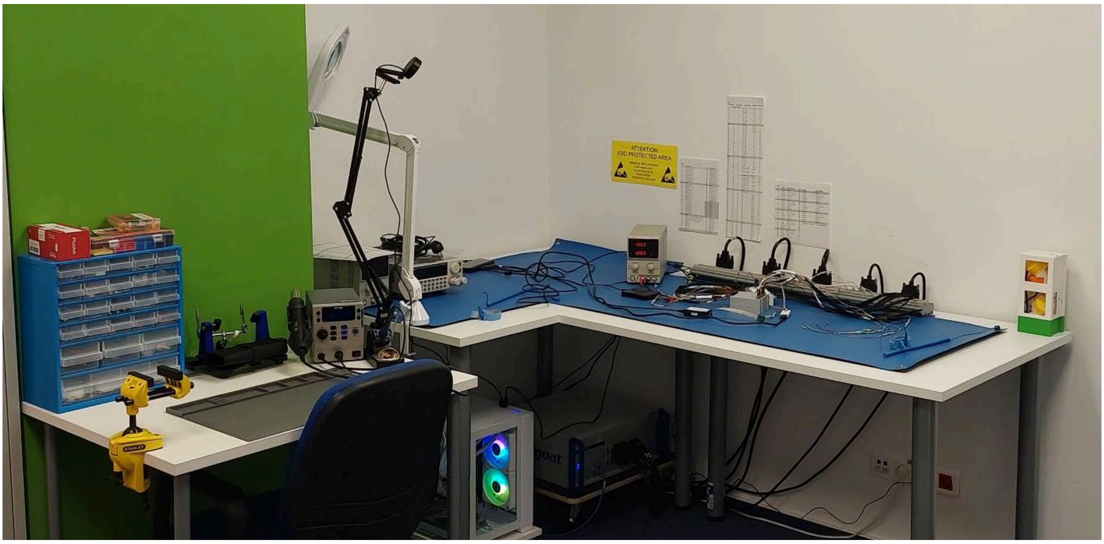

Fig. 4 DVF Laboratory

In order to implement these scenarios, a well-defined laboratory setup is required. The laboratory environment includes a set of key components that enable testing and validation activities, serving as the primary platform for integration, validation and testing of the satellite subsystem. It is equipped with power supply units, programmable electronic load, communication adapters, high-speed logic analyzer, and precision multimeter. In addition, the laboratory provides capabilities for harness manufacturing, such as soldering and rework station, wiring materials, crimping tools, and different mechanical and electrical components.

Electrostatic discharge (ESD) protection measures are implemented throughout the workspace, antistatic mats, wrist straps, and proper handling procedures to ensure the safety and reliability of sensitive electronic components.

In addition, the laboratory is equipped with a custom air quality monitoring system capable of measuring key environmental parameters, including temperature, humidity, and oxygen and carbon dioxide levels. A standalone air conditioning system ensures proper control of both air temperature and humidity.

A dedicated PC serves as the central interface for communication with both the OBC and the Speedgoat machine, enabling efficient system control, real-time monitoring, and testing. A critical component of the setup is the Speedgoat machine, which is used to execute simulated models in real time. It provides the necessary computational performance and deterministic timing required for real-time applications. Additionally, the Speedgoat platforms are equipped with predefined or customizable input/output modules, providing multiple I/O channels that support various communication protocols such as I2C, RS-485, RS-422, and RS-232. The platform also supports additional expansion cards, enabling increased flexibility for the simulation of various components. The system also offers expandability through, providing enhanced flexibility to accommodate the simulation and integration of a wide range of hardware components.

The OBC represents the central processing unit of the satellite subsystem, offering the capability to command actuators and acquire data from sensors, thus playing a key role in both control and data handling. The communication between all these elements is achieved through multiple interfaces, depending on the specific requirements of each scenario and protocol under test.

5. REAL TIME SYSTEM

The real-time system is modeled through the implementation of sensor command registers in C code. The unit's behavior is validated via a series of tests, in which commands are provided as inputs and corresponding responses are received. These responses are compared against expected values, with the goal of ensuring that the resulting error is zero or within acceptable limits. This implementation is referred to as the Electrical Wrapper of the unit, as it encapsulates the low-level electrical and communication behavior required for proper interaction with the system.

In addition, a set of several scripts are developed to manage input and output operations, along with a dedicated script for error injection.

Finally, all components are integrated by mapping each script to a corresponding block within a Simulink diagram, resulting in a modular and structured simulation environment.

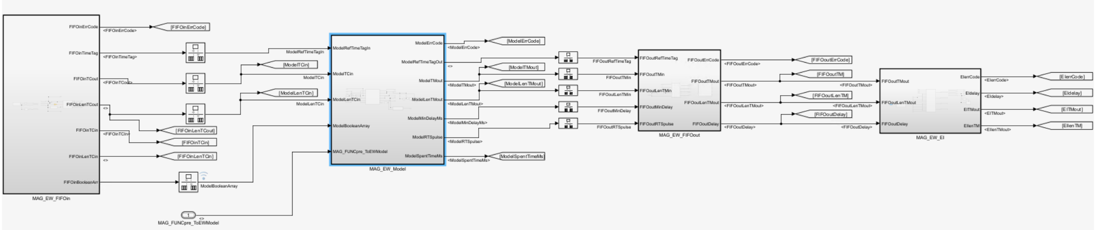

Fig. 5 Magnetometer EW (Electrical Wrapper)

The input and output handlers are implemented as two blocks within the Speedgoat module, as illustrated in the figure below. These blocks enable bidirectional communication, allowing data to be read from and written to the Speedgoat system.

In the magnetometer use case, communication is carried out using the I2C protocol, which ensures reliable data exchange between the sensor interface and the processing unit.

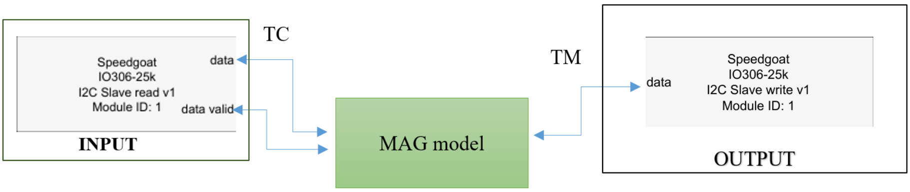

Fig. 6 Magnetometer Open-Loop Test

In addition to the aforementioned blocks, the system includes a dedicated block within the Simulink environment that provides data for a given scenario. For the magnetometer use case, this block provides magnetic field measurements along with additional relevant sensor data.

The model operates at a sampling rate of 5 ms, consistent with the overall system timing architecture. To ensure proper synchronization with components operating at a 1 ms sampling rate, a rate transition block is employed. This mechanism guarantees correct data exchange between subsystems operating at different temporal resolutions.

6. RESULTS

The validation criteria in most Verification and Validation (V&V) scenarios are defined by a simple rule: the input data transmitted to the system under test must match the corresponding output data within a one-bit tolerance. This strict requirement ensures data integrity and deterministic system behavior.

In the Speedgoat-to-PC configuration, commands are transmitted from MATLAB running on the host PC to the Speedgoat platform. For example, a command may request magnetic field measurements. In parallel, the simulation model computes the full system dynamics of the system through the AOCS (Attitude and Orbit Control System) block, which provides the reference sensor data.

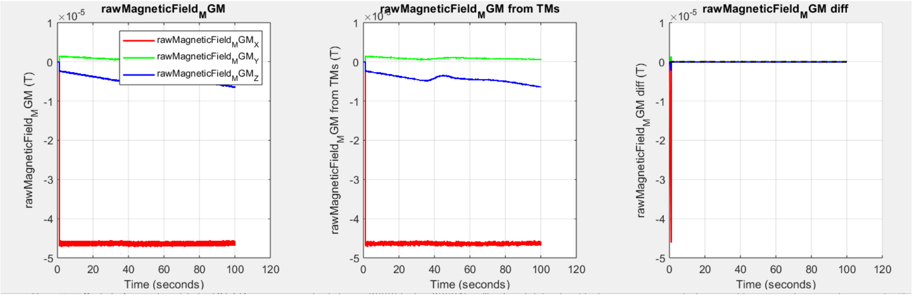

Fig. 7 MAG results

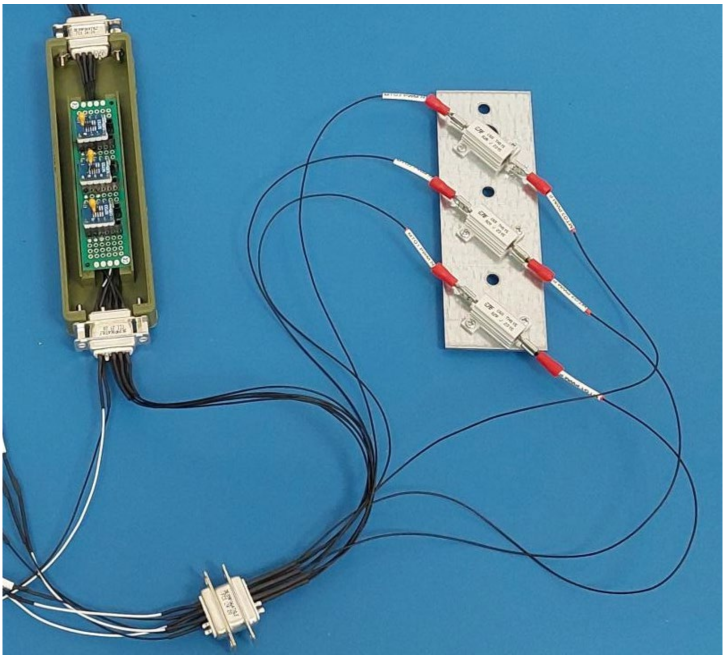

Fig. 8 MTQ - resistor load

Magnetic Torquers (MTQs) are represented in this setup using fixed-value resistor loads to emulate their electrical and thermal behavior under controlled conditions. This approach allows repeatable testing without requiring the actual active magnetic actuators. The resistor loads are mounted on a metal chassis, which serves as a passive heat sink to ensure efficient thermal dissipation during operation. This configuration helps maintain stable temperature conditions, preventing localized overheating and enabling more accurate characterization of the system's electrical response under simulated MTQ operating conditions.

The plots below present the results obtained for one of the actuators. These results illustrate the actuator's behavior under the tested scenarios and provide insight into its response within the overall system.

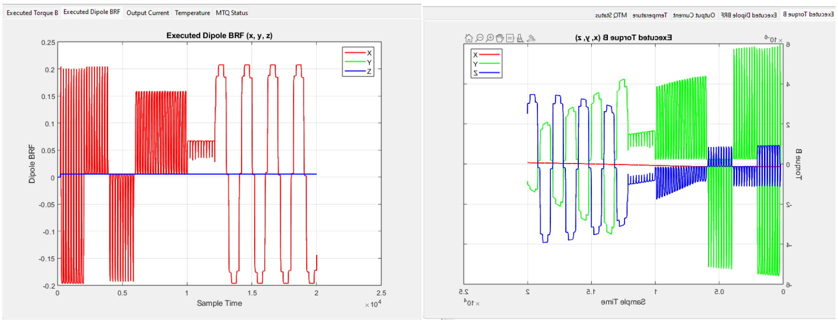

Fig. 9 MTQ results

7. CONCLUSIONS

This paper presents a real-time Verification and Validation (V&V) framework for the E-ADCS satellite subsystem, implemented within a Hardware-in-the-Loop (HIL) environment. The proposed architecture integrates a PC acting as a ground station, an On-Board Computer (OBC), and a Speedgoat real-time platform used for model execution and system simulation.

The developed setup enables the evaluation of multiple testing scenarios, including PC-to-Speedgoat, OBC-to-Speedgoat, and full end-to-end closed-loop configurations. The E-ADCS functionality was implemented through sensor and actuator interfaces, including magnetometer, sun sensor, star tracker, gyroscope, reaction wheels, and magnetorquers, using a combination of C-based electrical wrappers, sensor Interface Control Documents (ICDs), and Simulink-based models.

A validation strategy based on strict comparison between telecommand and telemetry data was applied, using a one-bit tolerance criterion. The results confirmed consistency between real-time execution and reference model outputs, demonstrating correct behavior of the communication chain and control logic implementation.

Overall, the proposed framework provides a reliable and scalable approach for real-time satellite subsystem verification, ensuring alignment between simulated models and embedded implementation, and supporting system-level validation for space applications.

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