Standardization training program
E-60 discipline: Control

Control Engineering Handbook
ECSS-E-HB-60A

European Space Agency

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The ECSS E60 branch

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ECSS Standards | *ECSS Handbooks* | *ESA Handbooks*

E-60: Control

Level 2
- ***E-60 Control Engineering***
  - E-HB-60A Control Engineering Handbook

Dynamics and Control
- E-ST-60-10C Control performance
  - E-HB-60-10A Control Performance Guidelines

Sensors and Actuators
- E-ST-60-20C Star Sensors Terminology & Performance Specification
  - E-ST-60-21C Gyro Terminology & Performance Specification

Special Applications
- E-ST-60-30C Satellite AOCS Requirements
  - ESSB-E-HB-E-003 ESA Pointing Error Engineering
    - ESA-E-HB-E-XX ESA Pointing Error Mapping (not started)

Introduction

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- This handbook has been adapted from the first document elaborated by the very first Working Group of the E60 branch
  - The initial document was originally published as the Control Engineering Standard ECSS-E-60A in September 2004
  - ECSS Task Force 2 did not recognize it as a standard since it was addressing the control engineering process rather than requirements and decided to replace it with a handbook
- This Control Engineering Handbook was published in Dec 2010
  - This high level document is quite generic since it addresses all systems involving any kind of control (including e.g. thermal control, but not "ground control")
  - It focuses on the specific issues involved in control engineering and is intended to be used as a structured set of systematic engineering provisions
  - Specialised requirements for attitude control and associated equipment will be found in lower level documents such as the Satellite AOCS Requirements Standard or Star Tracker Standard

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Quick insight

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- Chapter 2 contains the normative references
  - High level ECSS documents: Glossary of Terms, Space Engineering Requirements and Process, Space Project Management
- Chapter 3 provides definitions of control-related terms
  - e.g. actuator, autonomy, control, controllability, estimated state, estimator, guidance, robustness, sensor, simulation model, stability, state, etc.
- Chapter 4 describes the space system control engineering process
  - main engineering activities defined and characterized by the following:
  - inputs, tasks to be performed, outputs (including documents), milestones and relationship to the project phases
- Chapter 5 contains recommendations for the engineering activities
  - a checklist of recommendations for tasks to be performed and the associated expected outputs

Introduction
General Control Structure

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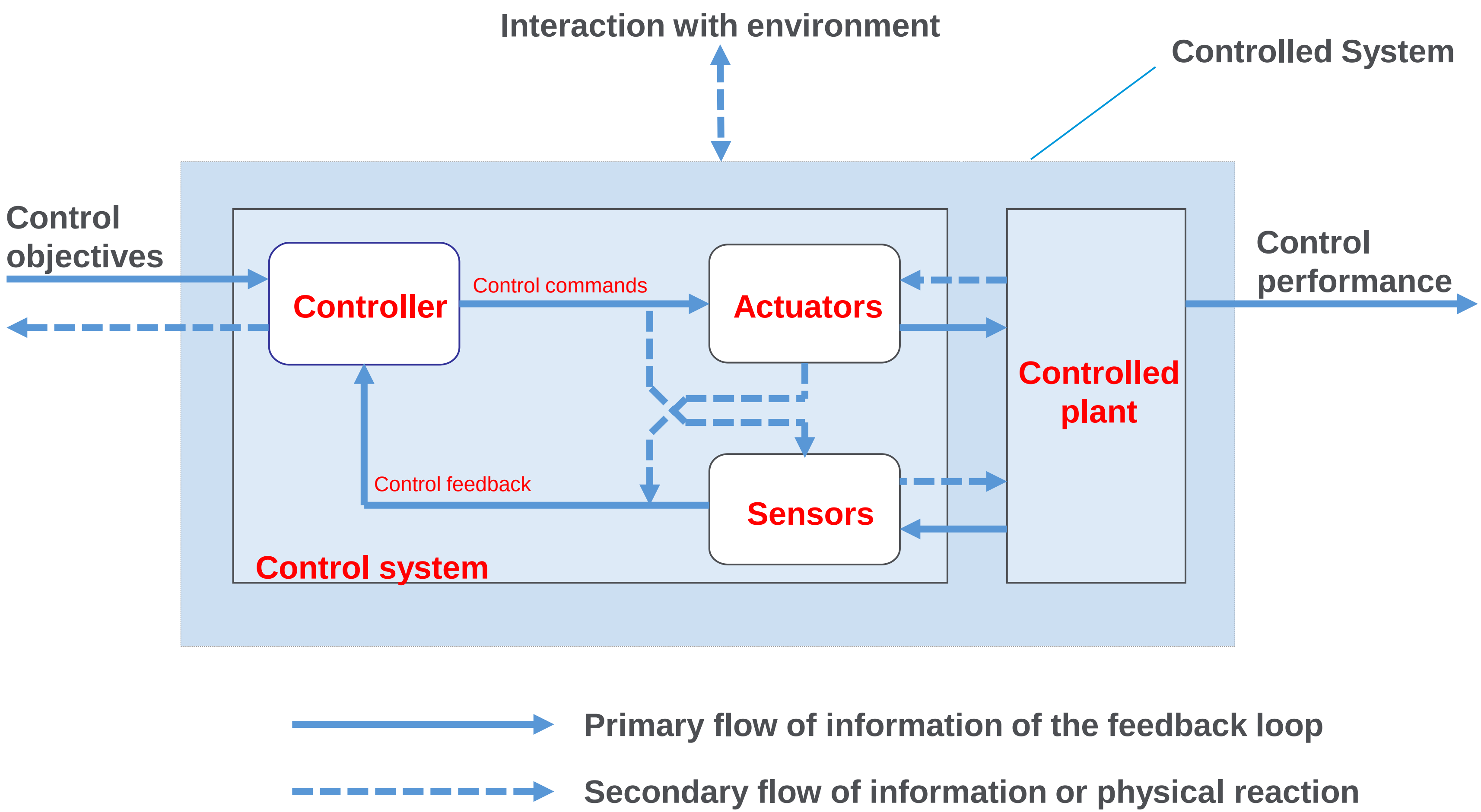

4.1.2 Control Engineering Activities

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- From the general control structure introduced previously, control engineering includes, as a minimum:
  - analysis of the mission objectives in order to define the control objectives;
  - requirements analysis and specification
  - analysis and modelling of the controlled plant and its interaction with the environment;
  - analysis, modelling and specification of sensors and actuators (configuration and characteristics) w.r.t. the control requirements;
  - design and configuration of the controller;
  - verification of the control performance;
  - control system related ground operations.

- Consequently control engineering
  - is multidisciplinary
    - cannot be performed without significant insight into at least mechanics, dynamics, the space environment and its effects, digital and analogue electronics, control theory, computer systems and networks, software engineering, and operations;
  - has a strong system aspect
    - significant level of interaction with the system engineering process specified in ECSS-E-ST-10.

4.2 Definition of the Control Engineering Process

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- As part of the system engineering process defined in ECSS-E-ST-10, it can similarly be decomposed into the same engineering activities:
  - Integration and Control
    - integration of the various control related disciplines throughout all project phases towards the total definition and realization of the controlled system (management, planning, database, interface control, risk control, change and non conformance control,…)
  - Requirements Engineering
    - proper interpretation of the mission and system requirements, coherent and appropriate derivation of control requirements, definition of lower component or equipment level requirements and continuous supervision of their status and traceability
  - Design and Configuration
    - derivation of a physical control architecture and the controller design capable of meeting the control requirements (supported by proper analyses and trade-offs)
    - derivation of all the control budgets with appropriate budget methodology and margin policy
  - Analysis
    - performed at all levels and in all domains for the purpose of resolving control related functional and performance requirements, evaluating control design alternatives, consolidating and verifying control performances and complementing tests
  - Verification and Validation
    - demonstrates, through a dedicated process, that the controlled system meets its control objectives and requirements

4.2 Interaction between Control Engineering activities

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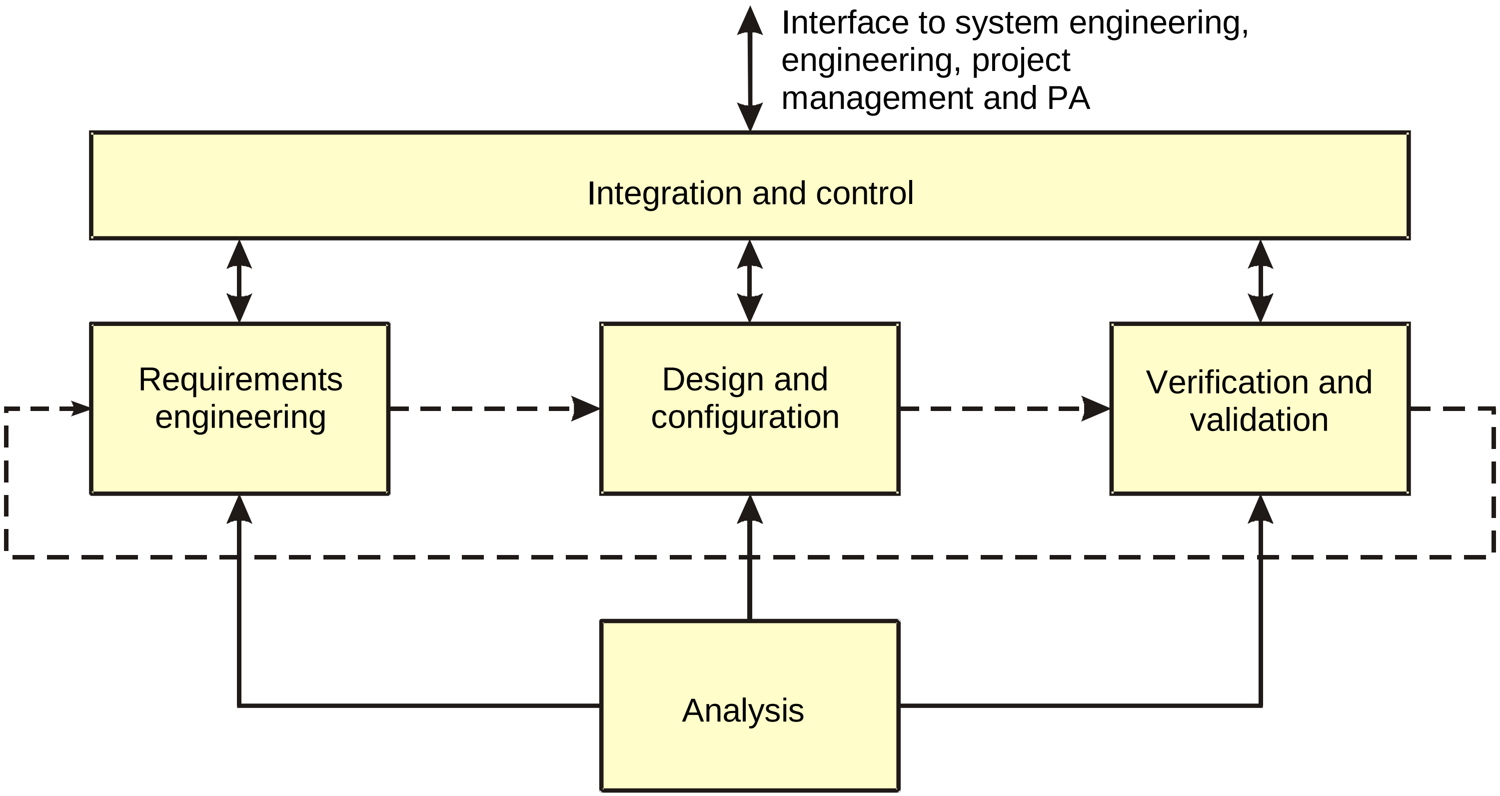
- At various phases of the system development, the control engineering activities are conducted in parallel to support one another in the proper development of the control system and of its components.



- Iterative between system engineering and lower assembly or equipment level engineering
- Progressive from preliminary design to verification and inflight validation.

4.3 Control Engineering Tasks
Integration and Control

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Integration and control	Main deliverables
- Organization and planning of control engineering activities - Contribution to system engineering database - Management of interfaces, with other o disciplines, e.g. mechanical engineering and software engineering o activities, e.g. procurement and quality assurance - Contribution to human factors engineering when humans in the loop - Definition of budget and margin philosophy for control - Assessment of control technology and cost effectiveness - Risk management - Engineering support to control components procurement - Support to change management involving control - Control engineering capability assessment and resource management	**Phase 0 / A**: inputs to - System Engineering Plan - cost and schedule estimates - Technology Plan **Phase B**: inputs to - System Engineering Plan - cost and schedule estimates **Phase C / D**: inputs to - system database - operations handbook - cost estimates for Phase E/F **Phase E / F**: updates to - disposal plan

4.3 Control Engineering Tasks
Requirements Engineering

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Requirements engineering	Main deliverables
- Generation of control requirements from system and mission requirements - Contribution to system requirements to meet control requirements - Allocation of control requirements to subassemblies or equipment o sensors, actuators and controller H/W - Definition of control S/W requirements - Definition of control interface requirements between control components - Definition of control operations requirements - Definition of control verification requirements	**Phase 0 / A**: inputs to - Project Requirements Documentation **Phase B**: inputs to - System and S/S technical specifications - lower level technical specifications - Interface Control Documents **Phase C / D**: updated inputs to - System and S/S technical specifications - lower level technical specifications - Interface Control Documents **Phase E / F**: inputs to - new control related operational requirements

4.3 Control Engineering Tasks Design and Configuration

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Design and configuration	Main deliverables
- Definition of functional control architecture o including functional interfaces - Definition of operational control architecture o including modes - Definition of physical control architecture o including H/W, S/W and human operation - Design of control concepts and algorithms - Control design tradeoffs - Generation of control budgets - Contribution to selection and procurement of control components - Contribution to system configuration management	**Phase 0/A**: - Preliminary control system design and analysis report **Phase B**: - Control system design report (incl. design justification) (DDF, DJF) - Preliminary control algorithms specification - Preliminary control system budgets **Phase C/D**: - Final control system design report (DDF, DJF) - Final control algorithms specification - Final control system budgets **Phase E/F**: - Controller design updates

4.3 Control Engineering Tasks
Analysis

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<table>
<tr><th>Analysis</th><th>Main deliverables</th></tr>
<tr><td rowspan="4">
- Selection of adequate analysis tools and methodologies
- Requirements evaluation and budgets breakdown
- Disturbances evaluation
- Numerical trade studies
  o to support the definition of the control architecture with respect to requirements
  o considering programme imposed constraints such as cost, schedule and risk
- Numerical analysis to support the control design
- Performance verification analysis
  o including simulation
- Numerical analysis to support inflight evaluation
</td><td>Phase 0 / A:
- Control system analyses</td></tr>
<tr><td>Phase B:
- Controlled system analysis report (including simulation models description)</td></tr>
<tr><td>Phase C / D:
- Controlled system analysis report
- Strategies for the inflight calibration and performance analysis</td></tr>
<tr><td>Phase E / F:
- Inputs to controlled system operational performance report
- Inputs to payload data evaluation</td></tr>
</table>

4.3 Control Engineering Tasks
Verification and validation

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Verification and validation	Main deliverables
- Definition of control verification and validation strategy o including specification of requirements for test environments - Preliminary verification of performance o by analysis or prototyping - Final functional and performance verification o by analysis - Final verification and validation of controlled system o H/W, S/W and human operation o by hardwareintheloop tests - Inflight validation of controlled system behaviour	**Phase 0 / A**: inputs to - development and verification planning
	Phase B: - Controlled system verification plan - Preliminary controlled system verification report
	Phase C / D: - Controlled system verification report - Inputs to inflight verification plan
	Phase E / F: inputs to - inflight acceptance report - periodic mission reports

5.1 Control Engineering Process Recommendations Integration and Control

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→ INTEGRATION AND CONTROL

- Contribution to system engineering data base and documentation
  - Control engineering provides inputs to the system engineering database concerning controller data, and control related sensor and actuator parameters (e.g. flight dynamics database).
  - Control engineering provides a consistent set of control related documentation for the complete development process which is in line with the general system documentation.

- **Budget and margin philosophy for control**
  - **For control related budgets with several contributors, summation rules are defined and used consistently throughout the design process. A margin policy is established and applied. Budget methodology and margin philosophy can evolve during the development according to the level of maturity of the control system.**

- Support to change management involving control
  - Control engineering:
  - supports the management of nonconformances related to control.
  - handles changes related to controller design and implementation.
  - reviews changes in control related disciplines.

5.2 Control Engineering Process Recommendations Requirements Engineering

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→ GENERATION OF CONTROL REQUIREMENTS

- **Control requirements**
  - derived from the directly applicable system requirements
    - taking into account constraints imposed by other system requirements
    - e.g. electrical power, mechanical configuration, thermal conditions and operations
  - **allocated to lower level requirements for the control components**
    - controller, sensors and actuators
    - iterative allocation process, supported by analyses and tests
- **Control requirements engineering**
  - maintains traceability and justification of the control requirements
    - in line with the system requirements engineering process
  - considers system FDIR requirements and failure management definitions
  - supports system requirements engineering
    - to identify and eventually resolve conflicts between requirements, requirements ambiguities and conflicts between requirements and environmental factors or design constraints
- **Control engineering**
  - defines and justifies any control requirement generating a specific system constraint
    - through an appropriate document (e.g. DJF)
    - e.g. minimum allowable thruster tilt for plume effect limitation, sensors/actuators implementation w.r.t. FOV, alignment, mechanical stiffness, eigen-frequencies

Refer to E60-20, 21, 30

5.3 Control Engineering Process Recommendations Analysis Methods and Tools

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Control engineering activity	Analysis tasks	Usual methods and tools
Requirements engineering	- requirement analysis - requirements feasibility assessment - disturbance quantification - error source identification and relevant numerical figures allocation to budgets	- analytical relationships and models - spreadsheet analysis tools - control CAE tools - control, environment, sensors, actuators and plant models
Design	- numerical trade studies in support of control architecture definition - numerical analysis to support control design - disturbance effects detailed analysis - stability - robustness - sensitivity to additional or parametric disturbances - performance against applicable requirements - control budget numerical figures consolidation	- analytical relationships and models - spreadsheet analysis tools - 3D CAD system model - control CAE tools - closed-loop simulation (including detailed control, environment, sensors, actuators and plant models) - simulation data analysis tools (e.g. statistical methods) - time-frequency domain methods - linear and non-linear methods
Verification	- performance analysis - test data analysis resulting from H/W-, S/W- and human-in-the-loop tests - inflight data analysis - support to payload data evaluation	- closed-loop simulation (including detailed control, environment, sensors, actuators and plant models) - test data evaluation tools (e.g. statistical methods) - telemetry data processing tools - control CAE tools

5.4 Control Engineering Process Recommendations Design and Configuration

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→ OPERATIONAL DESIGN

- The logical organization of the functions leads to a logical or operational architecture made up of a set of control modes and transitions between these modes
- Control engineering defines the operational control architecture, which consists of a set of control modes and transitions between modes covering all specified (nominal and non-nominal) conditions of operations of the control system
- The composition of functions and allocations to a control mode is based on existing and common knowledge (experience) of optimum use of sensors, actuators, controllers and operational items
- The operational control architecture is usually presented in the form of diagrams showing control modes, transitions and data flows

Refer to E60-30

5.5 Control Engineering Process Recommendations Verification and Validation

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→ FUNCTIONAL AND PERFORMANCE VERIFICATION

- **Verification by analysis**
  - The performance of the controlled system is demonstrated by closed-loop analysis based on the use of system representative simulation models. The verification covers all configurations of control modes, sensors and actuators, including backup configurations
    - Worst cases conditions are generally used w.r.t system dynamical and geometrical configurations, including FDIR aspects and the associated possibly degraded configurations
  - When relevant or possible, verification by analysis is supported by H/W testing
    - A typical example is to correlate a sensor mathematical model, including its parameters, with H/W tests results

- **Verification with flight H/W and S/W**
  - The control verification process includes, when relevant, functional validation in closed-loop tests with flight S/W and flight H/W models or flight representative models.
    - The real sensors are stimulated by the EGSE
    - The stimuli can be electrical (test connector) or physical (detector level)

BACK UP SLIDES

Summary of GNC/AOCS Functional Chain Verification Logic

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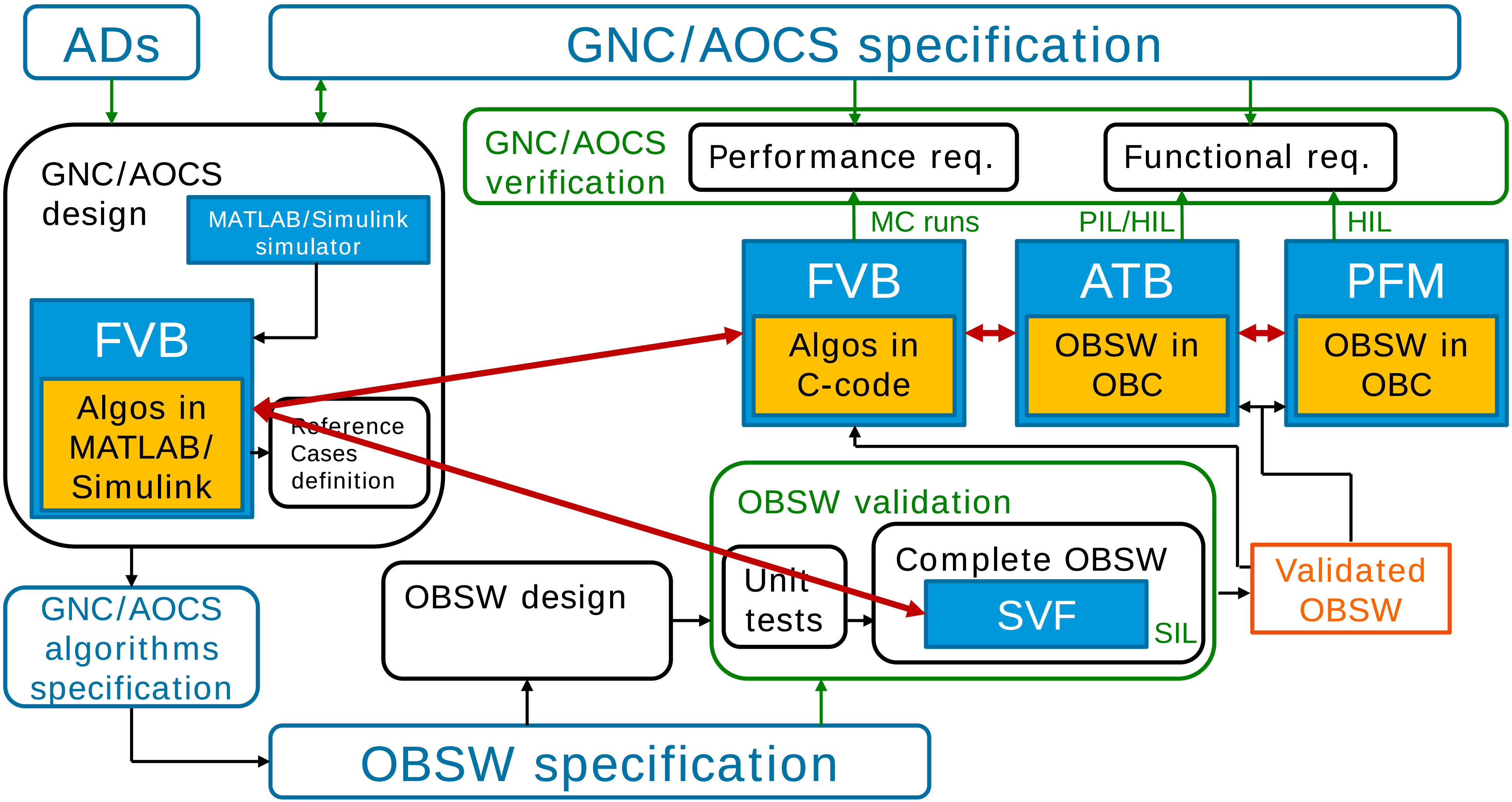

Avionics Functional Verification

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- Due to the tight interconnection between GNC and AOCS subsystems and OBSW, a joint verification process is needed (at avionics level)
- Avionics verification includes:
  - GNC/AOCS Performance Verification campaign, to validate the GNC/AOCS requirements, to check the tuning the GNC/AOCS parameters, and verify closed-loop performance on the FVB
  - OBSW Verification campaign, which entails SW module-level testing, HW/SW models verification and calibration, and finally OBSW integration and final verification on the SVF
  - Functional Chain Verification campaign, which includes real HW and has system-level oriented objectives. It is performed on the SVF, on the ATB, and on PFM
  - AIT campaign, which includes verification of system interfaces and is performed on PFM

AOCS interfaces

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AOCS design

Communications and data
- Antenna pointing reqt
- control, safe mode design, data to down/uplink

Thermal
- PF and PL Thermal const.
- Modes design, control tuning, FDIR, safe mode design

Ground operations
- Post-processing reqt
- Availability
- Autonomy level, control and estimation design

Power
- SA pointing
- Control design, safe mode design

System / Mission
- Mission reqt (pointing, agility, availability, coverage, …)
- Microvibration or optical constraints …
- Mode design, estimation and control tuning, FDIR, …

SW and HW
- CPU and delay budget
- Format, bus …
- Control tuning
- Algorithm complexity limit

Structures and configuration
- mass, inertia, surfaces
- blinding, multipath, …
- perturbation level
- sensor/actuation errors

Mission analysis
- Launcher separation conditions
- Orbit
- Acquisition mode tuning
- Perturbation level
- Maintenance mode design

And also cost, propulsion…