Workshop on Simulation for European Space Programmes (SESP)

Model Based Design Environment for Launcher Upper Stage GNC Development

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24 March 2015

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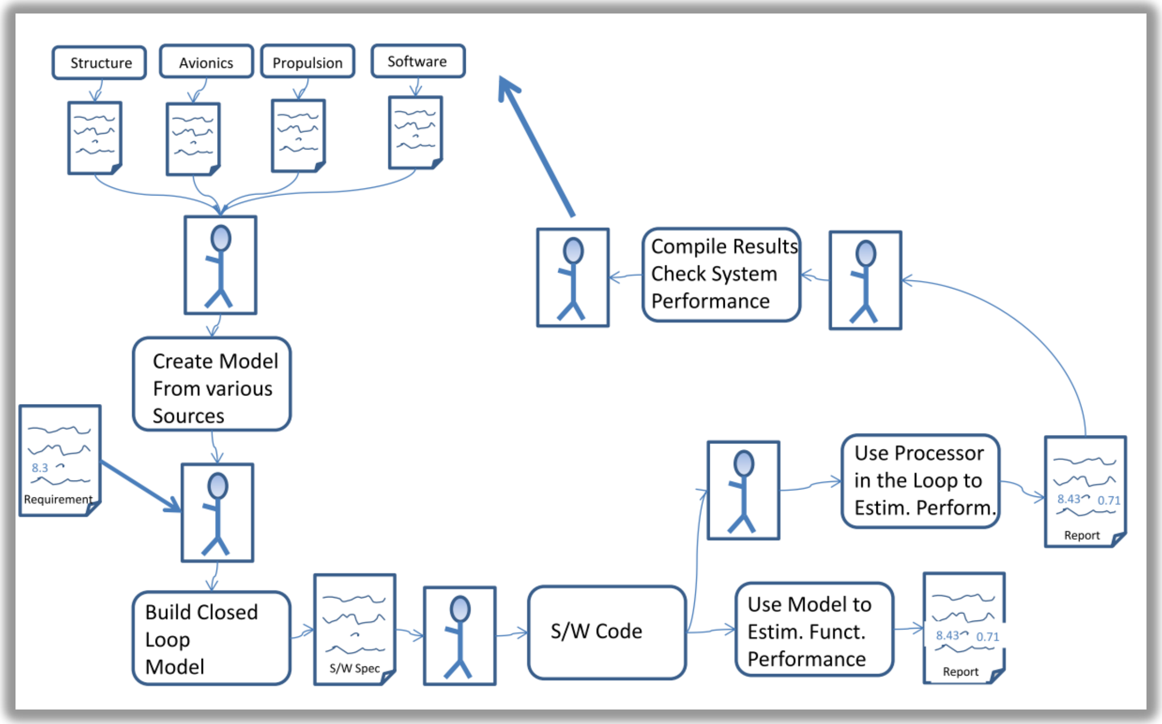
Goal of the Framework: Unifying the Overall Development Process by Building on a Multi-Disciplinary Design Approach

Gains:

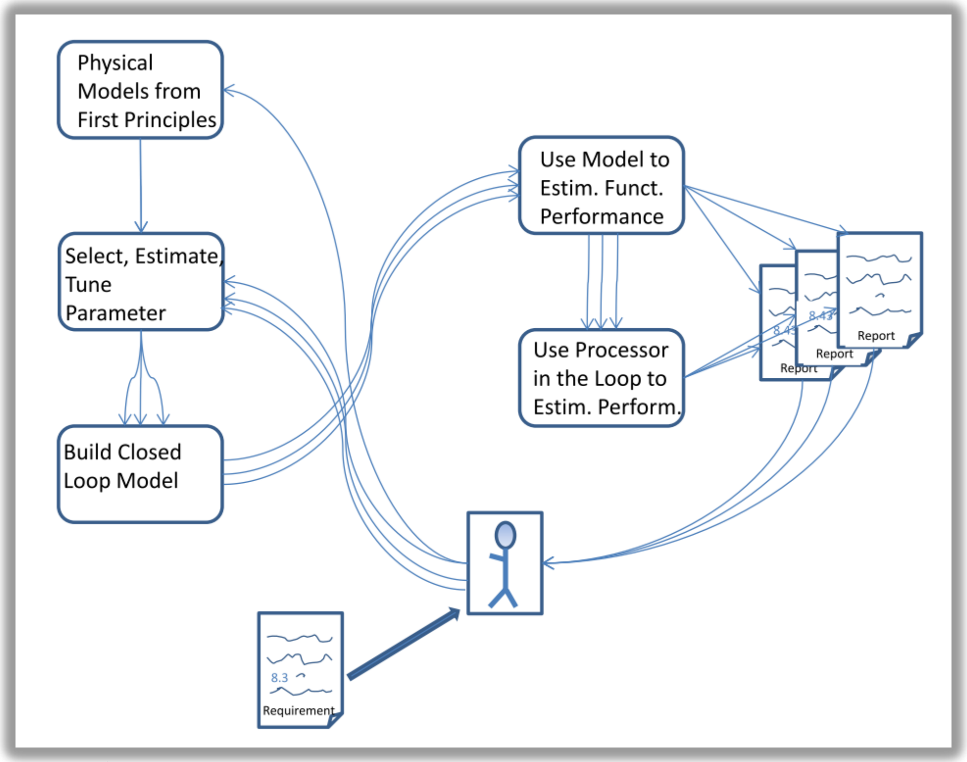
- Allows advanced Control Concepts grounded in Multi-physics Models extending the Functionalities
- Increases Productivity by Automation of Design Process and Multi-disciplinary Setting
- Allows faster Iteration Cycles responding to evolving System Requirements

Upper Stage Attitude Control Development Framework (USACDF) developed within the Future Launcher Preparatory Program (FLPP) initiated by ESA Launcher Directorate (2013-2014)

Towards a seamless, unified Design Methodology



Current Development Process



USACDF: Step towards Model Based Design Method

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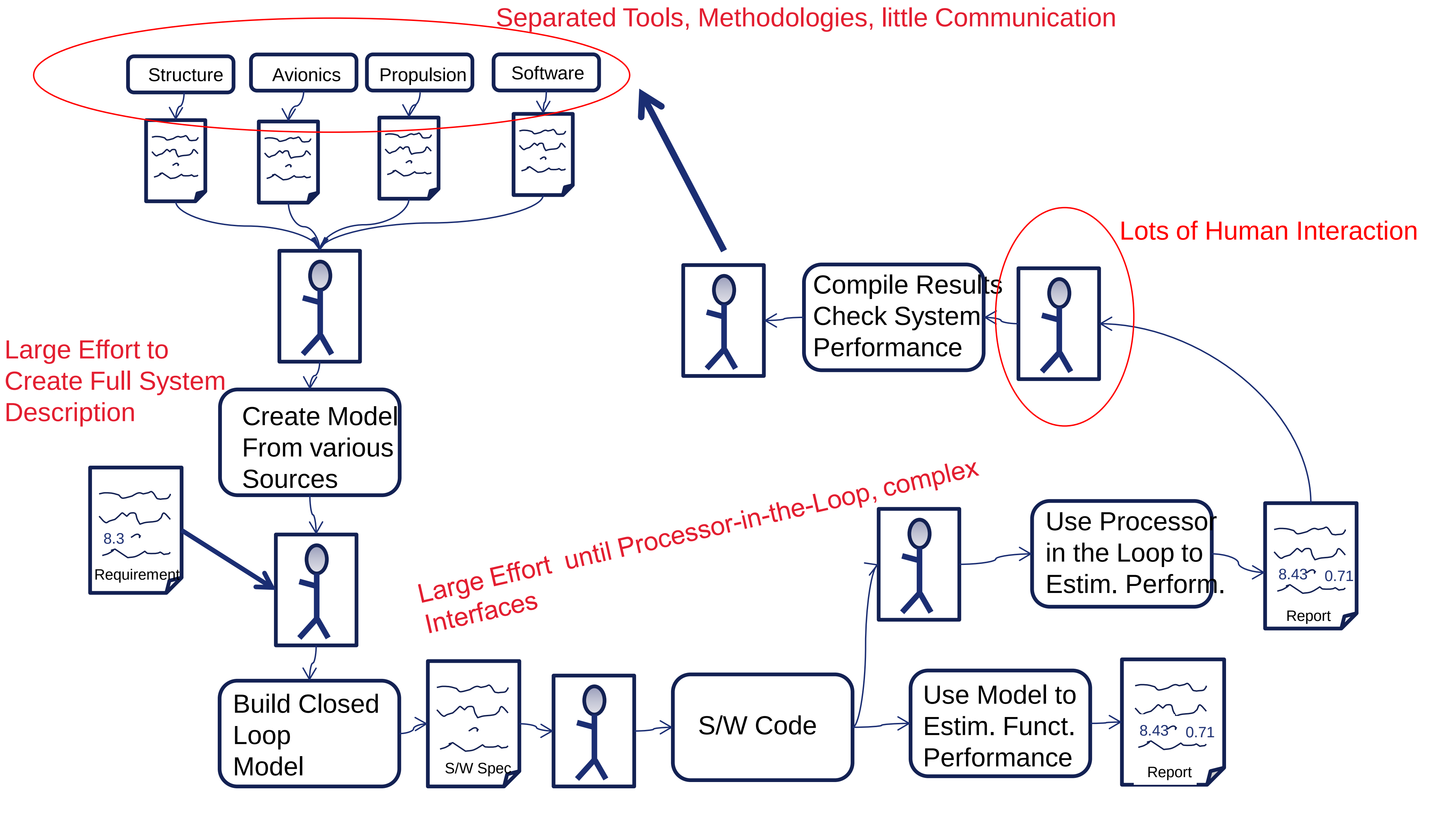
Current Status: Complex Interfaces, Lots of Manual Interaction



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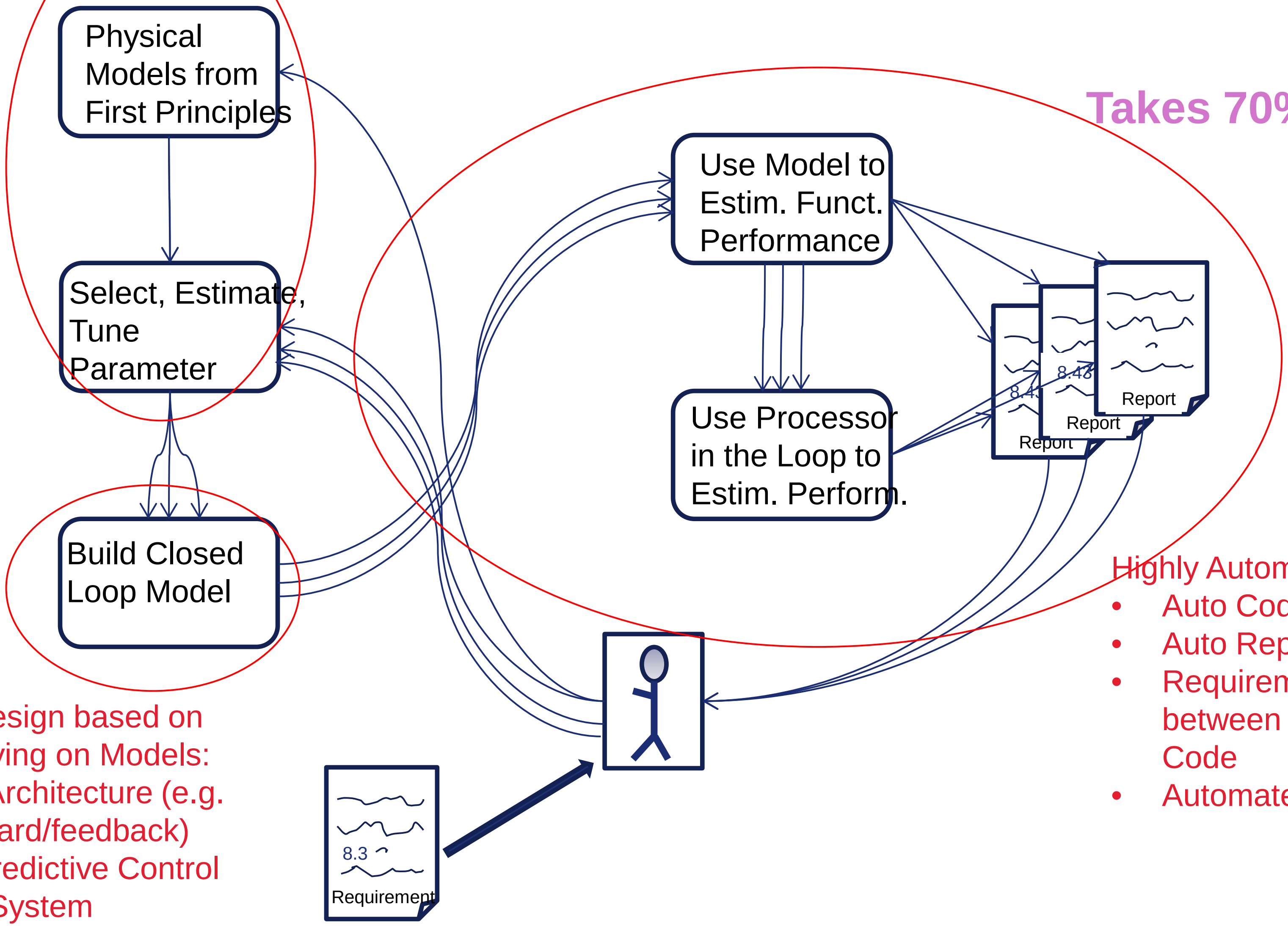
Goal: Unified Toolchain, Multi-Disciplinary Approach, High Automation

Physical Principal -> Test -> System Identification -> Model Adaptation in unified, multi-disciplinary Environment

Takes 70% of time



Highly Automated:

- Auto Code
- Auto Reporting
- Requirements Linking between Specification and Code
- Automated Testprocedures

Algorithm Design based on Methods relying on Models:

- Control Architecture (e.g. feedforward/feedback)
- Model Predictive Control
- In-flight System Identification
- etc

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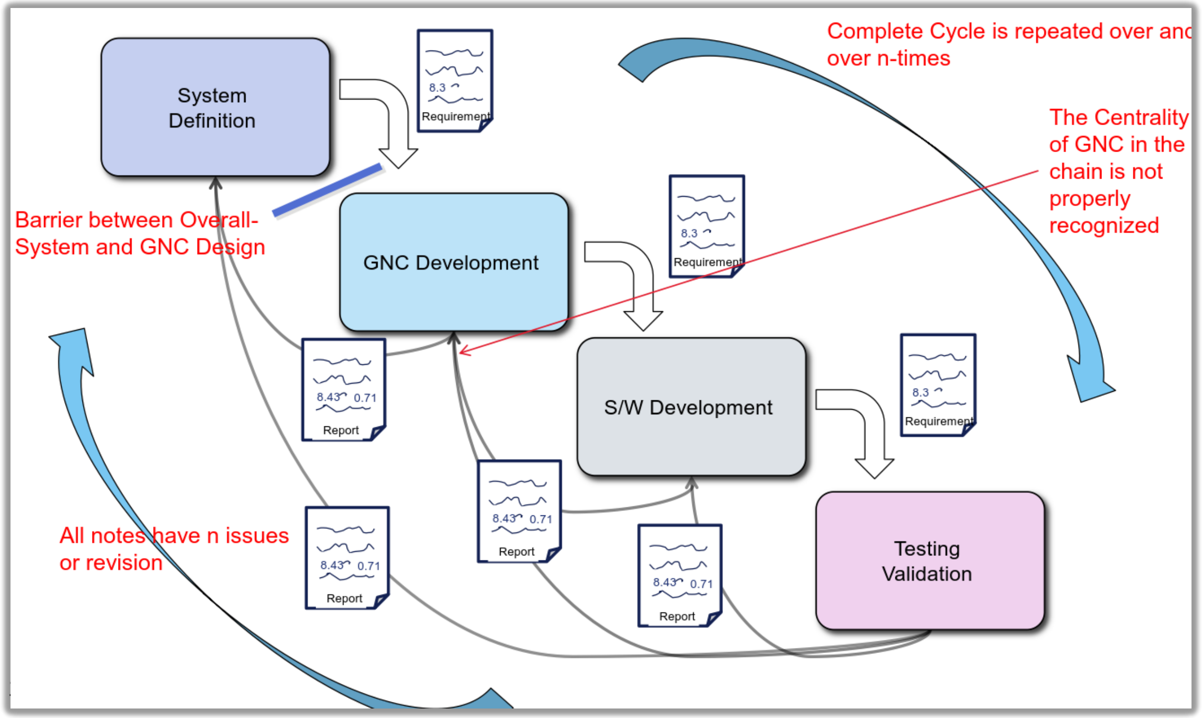
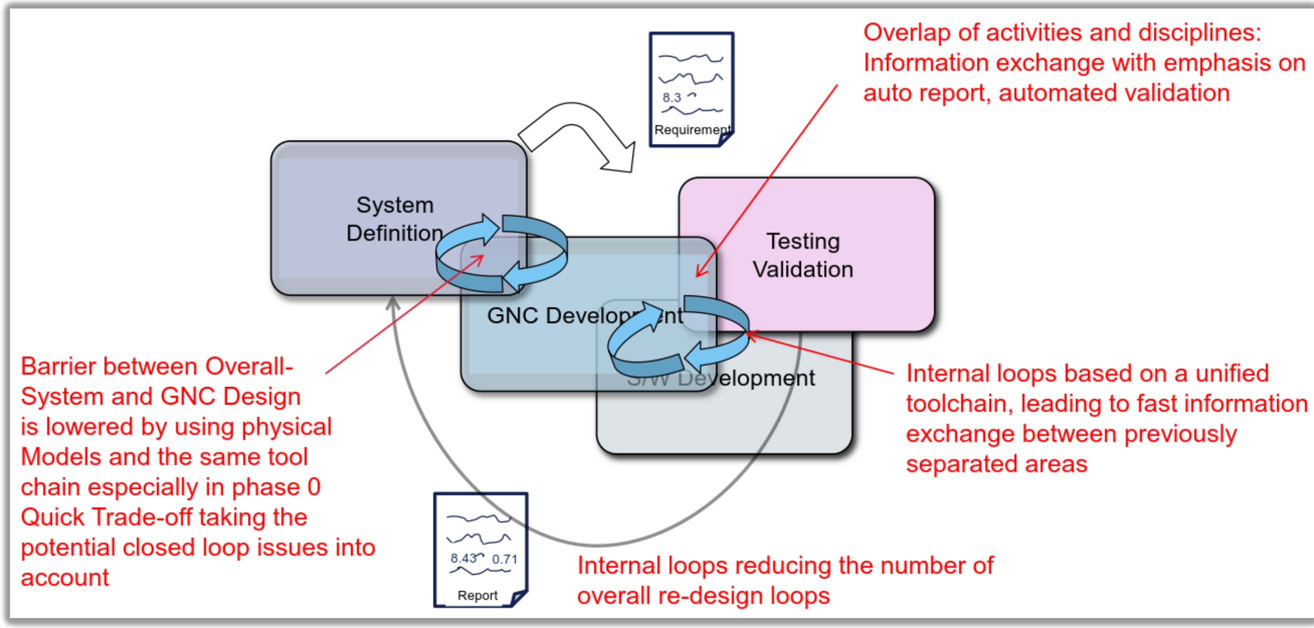
Breaking the Barriers between System Definition and GNC





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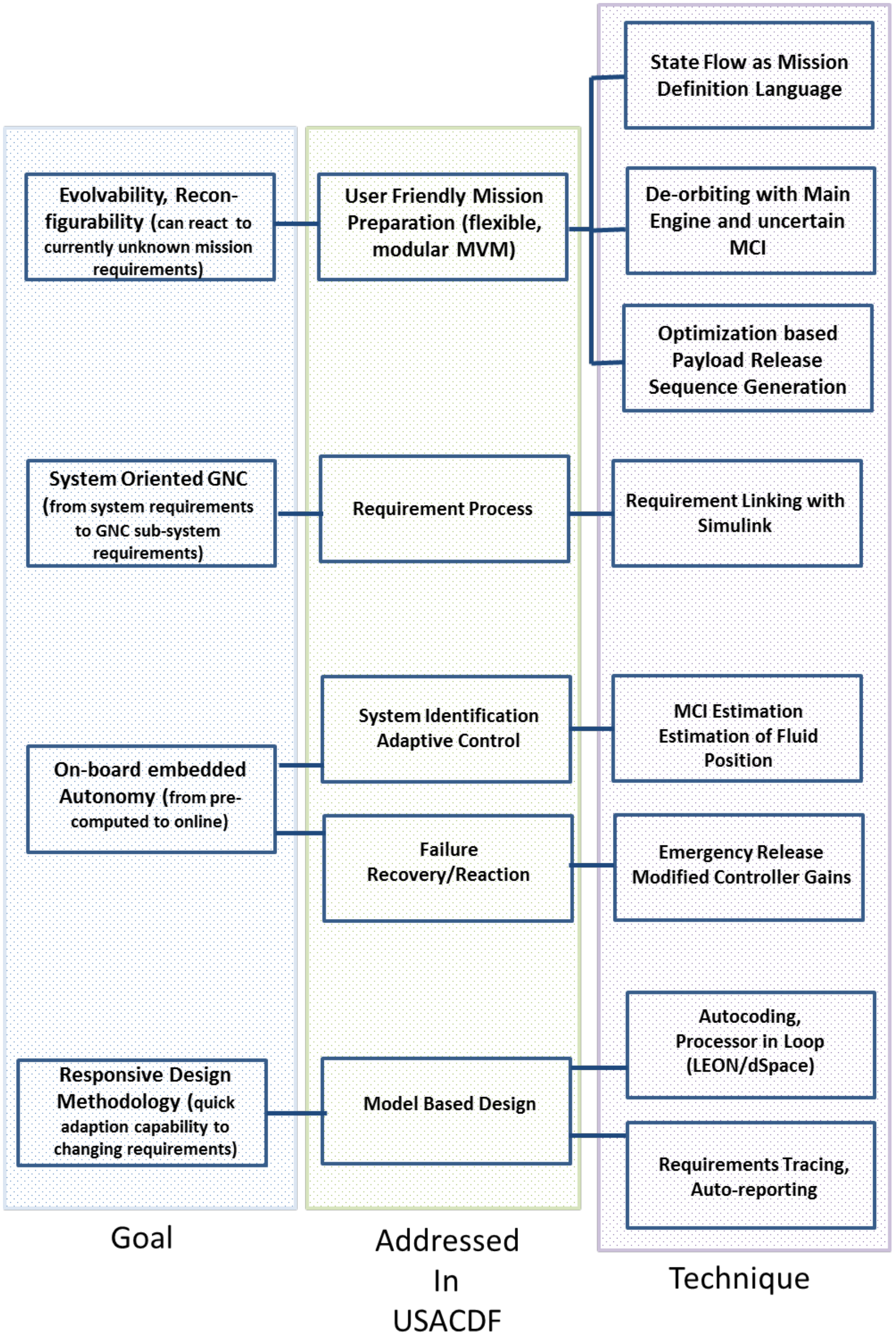
Goals on **System Engineering Level** addressed in the Framework



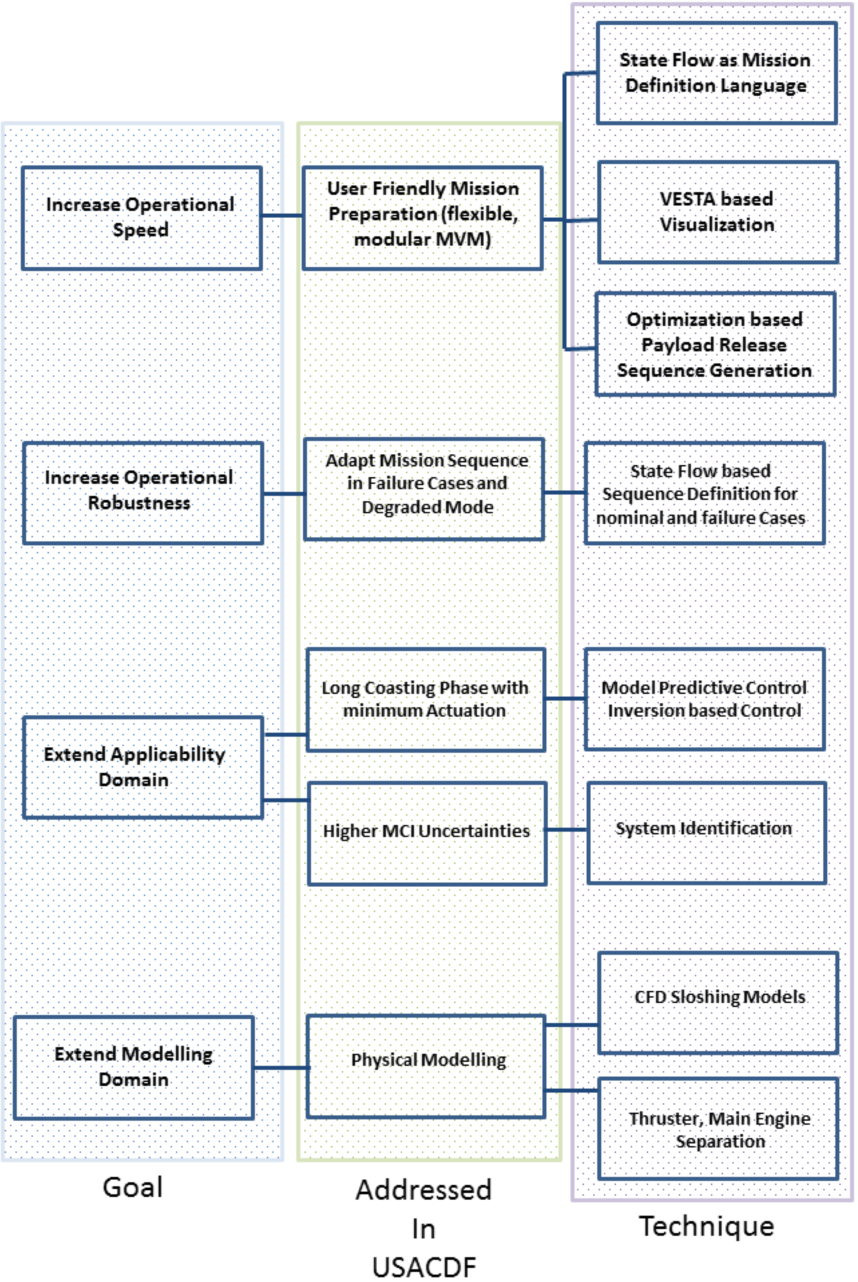
Overall Goal for New Launcher:

- Responsive Design Methodology
- On-Board Autonomy
- System Oriented GNC Design

Elements serving the Goal:

- New Design Methodology:
  Model Based Design
  Improve Requirements Process

Goals on **GNC Subsystem Level** addressed in in the Framework



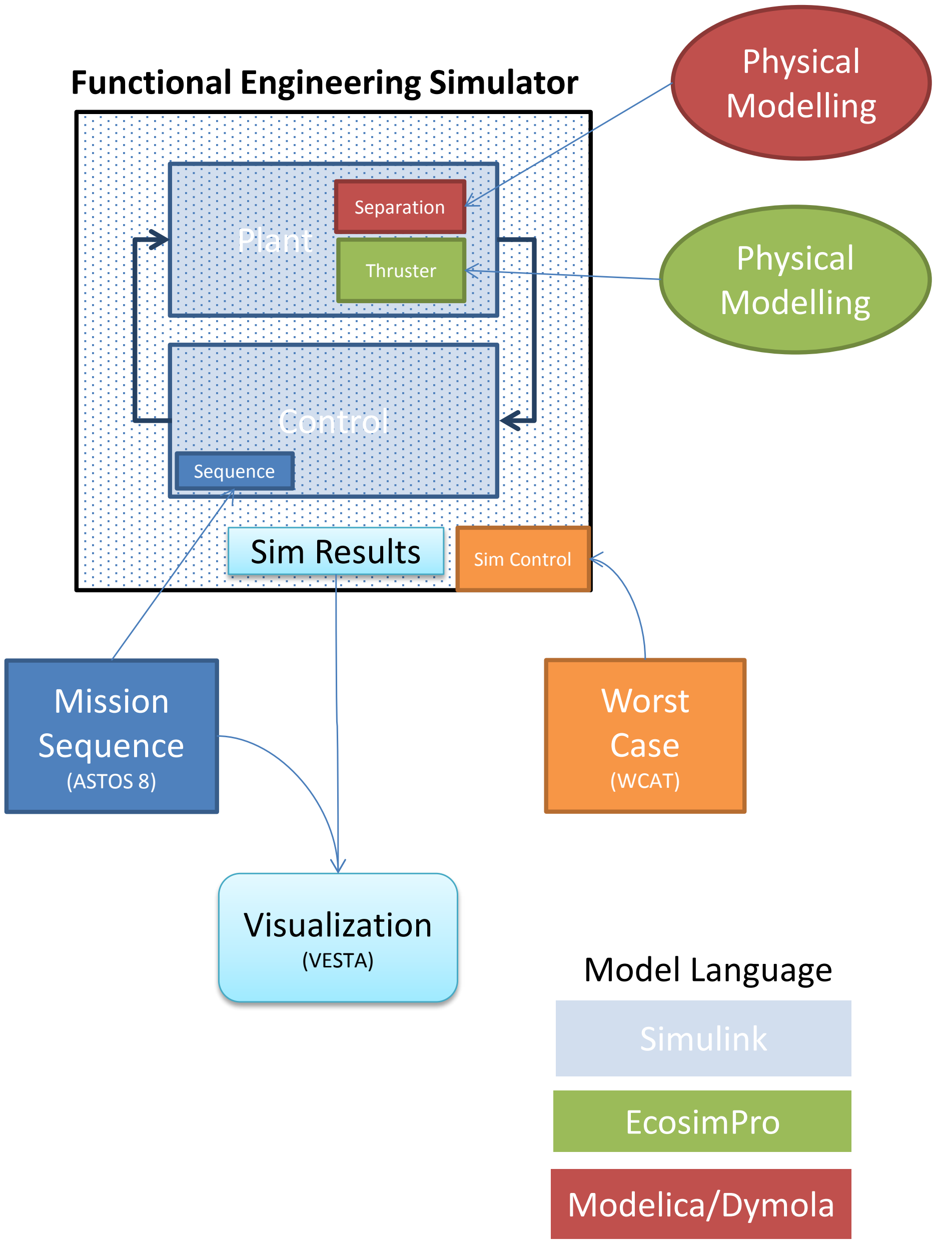
Overall Goal for GNC:

- Operational Robustness
- Large Application Domain
- Better Modelling

Elements serving the Goal:

- Physical Modelling
- On-line Adaptation to Failure or Degradation
- Adaptive Control

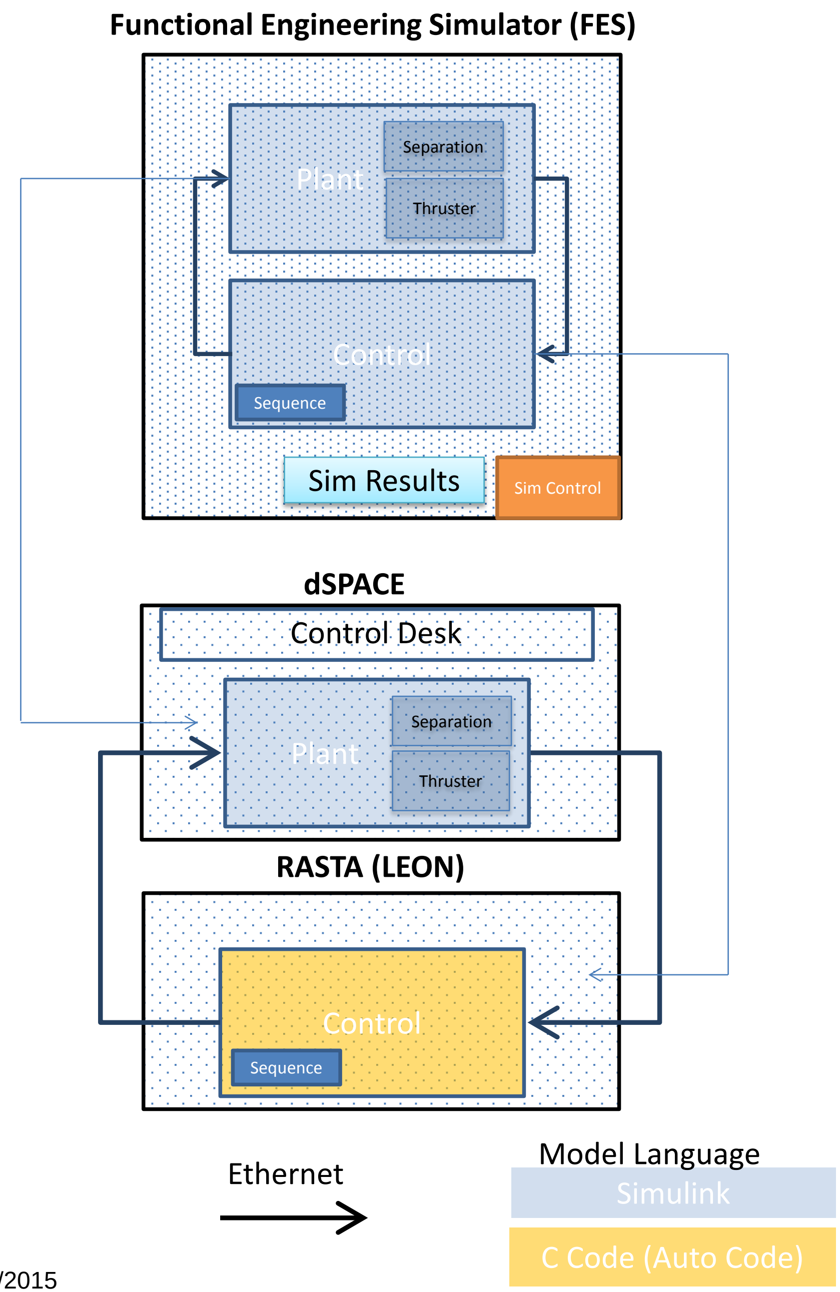
Elements, Modelling Approach and Languages of the Framework



- Three Modeling Languages
  - Simulink
  - EcosimPro
  - Modelica

- Simulator
- Off-line Tools
  - Worst Case Analysis
  - Mission Sequence Generation

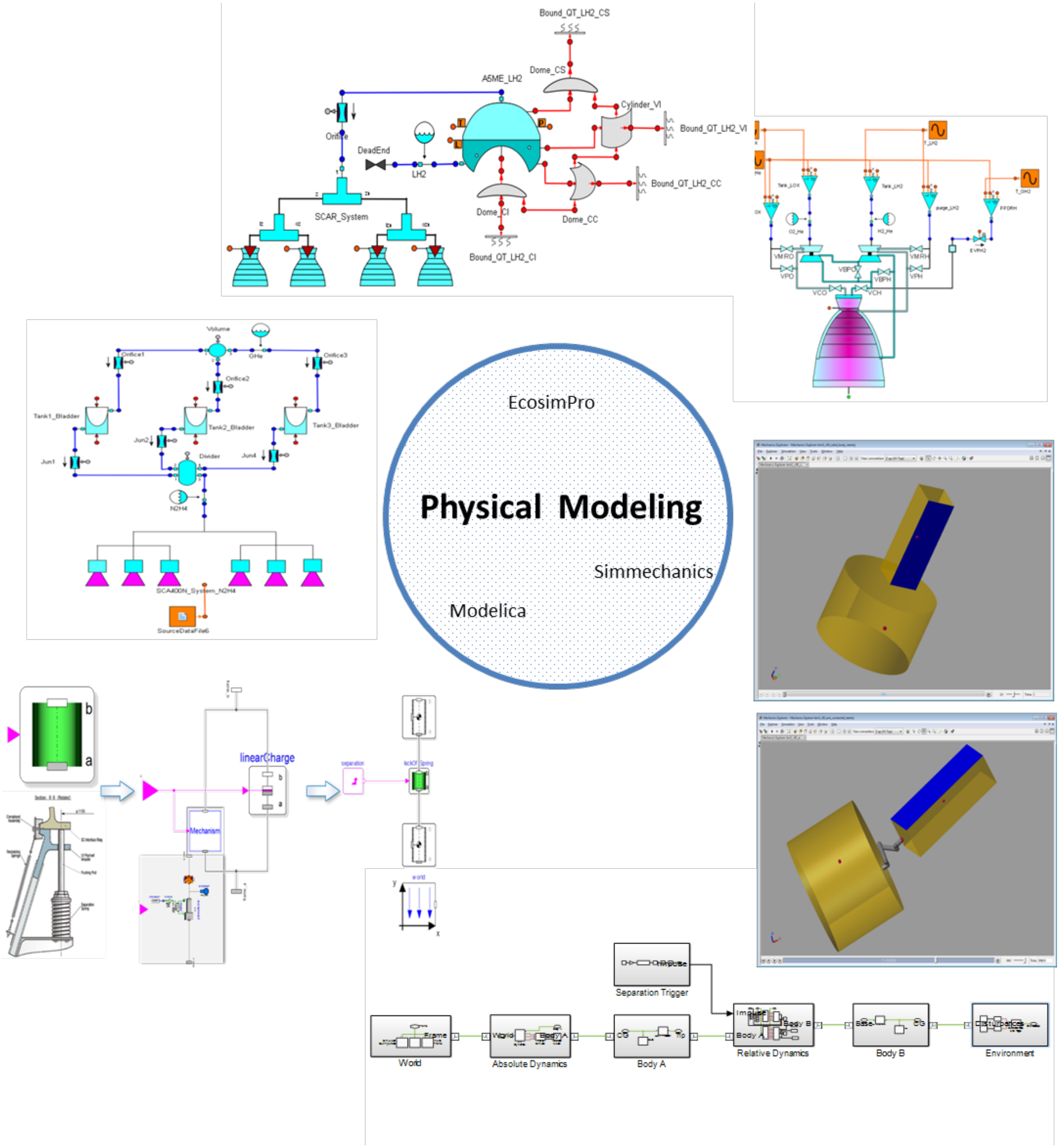
From Functional Simulator (FES) to Processor-in-the-Loop (PIL)



- Functional Simulator based on PC
  - Simulink

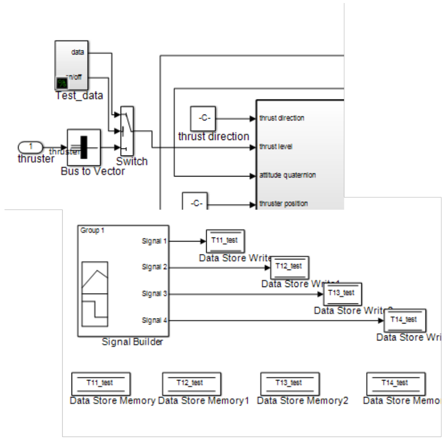
- Separation of Plant and Dynamics
  - Embedded Coder from Mathworks
  - TASTE for Configuring the Application Software

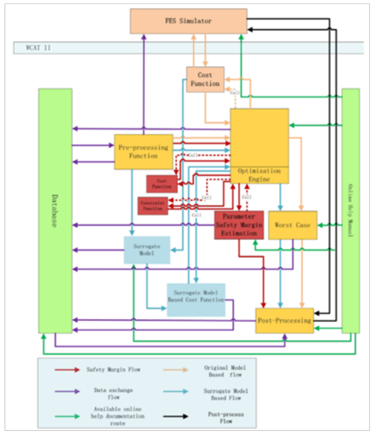
Physical Modelling for selected Subsystems

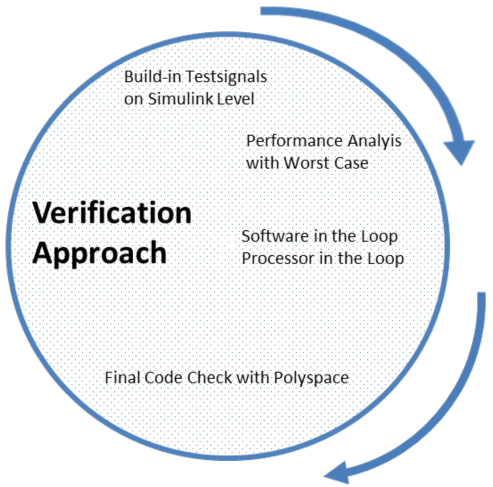


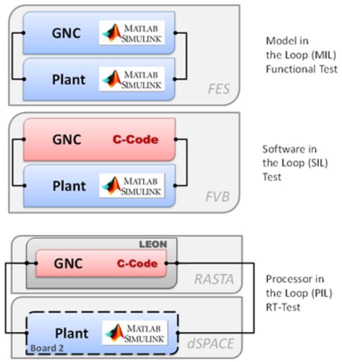
- Use of Models already generated in other Context:
  - Ecosim Pro in Propulsion Modelling
- Models specifically developed for USACDF:
  - Modelica for Separation Mechanism
  - SimMechanics for Mated System
- Hybrid Approach: Simulink and Physical Models incorporated via C code

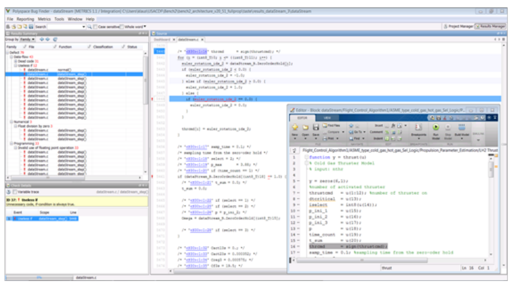
Unified Verification Approach











- Simultaneously Programming the Test Signals and Checks while Building the Application Software

- Improved Statistical Evaluation using Worst Case and Cross Entropy thereby augmenting the Monte Carlo Technique

- Automated Code Checking via Polyspace

Automatic Linking between Requirement Document and S/W

5. System Level: Stage Requirements

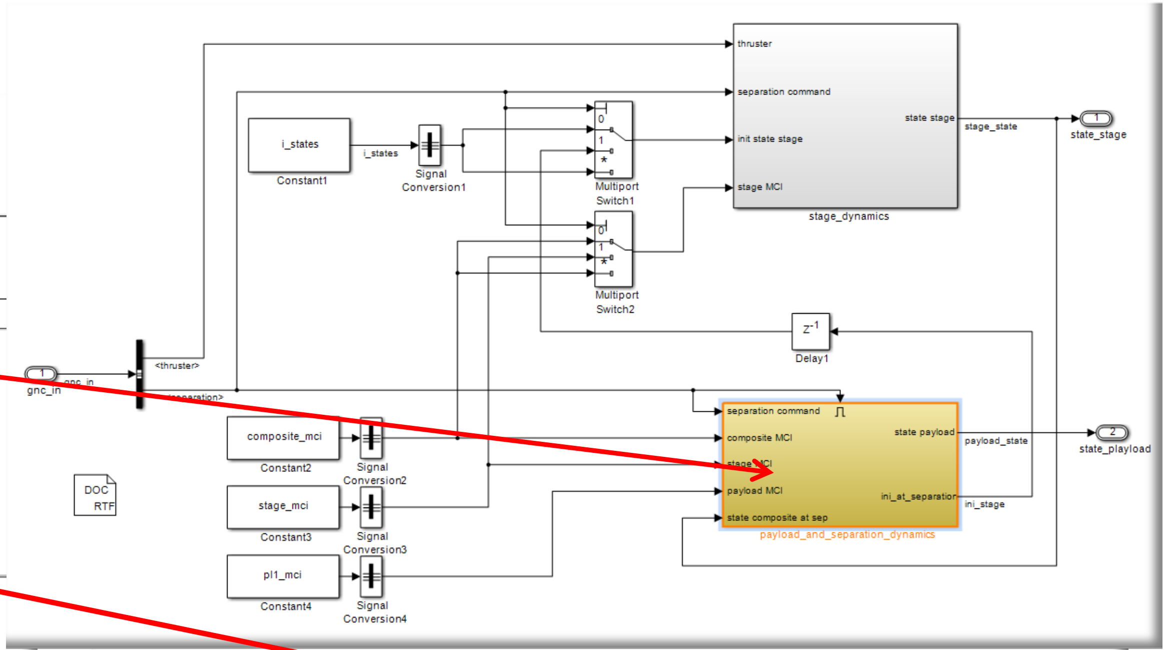
5.1 Mission Requirement

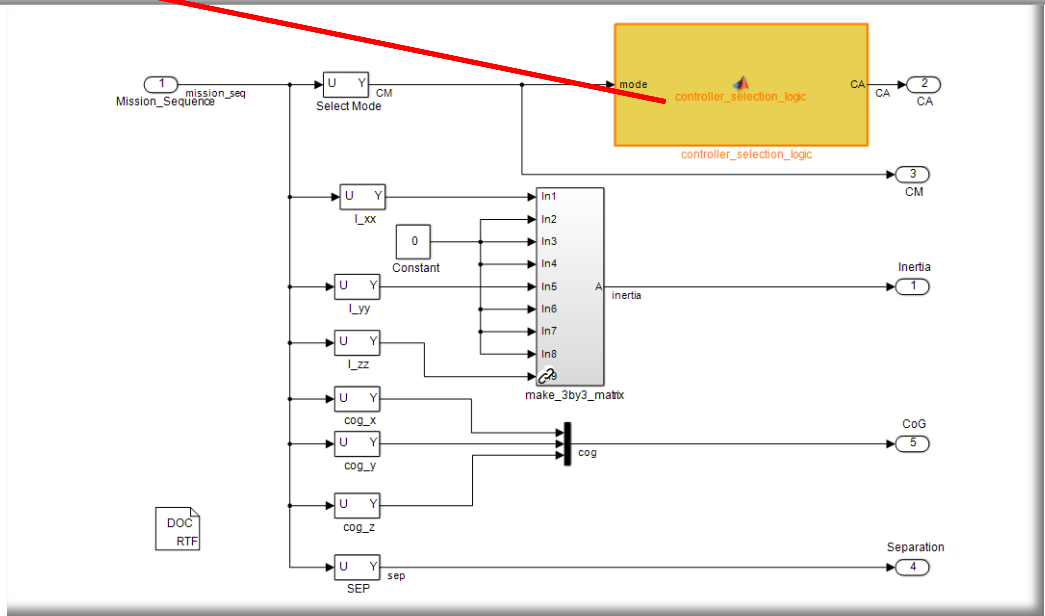
MReq. 1-1	The nominal mission is a single payload GTO release	
MReq. 2-1	The nominal mission GTO shall have the following segments: • Rate damping and attitude orientation after main engine shut down • Spin-up, nutation damping and angular momentum de-pointing control with payload release • Three axis stabilized payload release • Dv-Distancing Maneuver	

5.2 Configuration-, Operation- Performance-Requirements

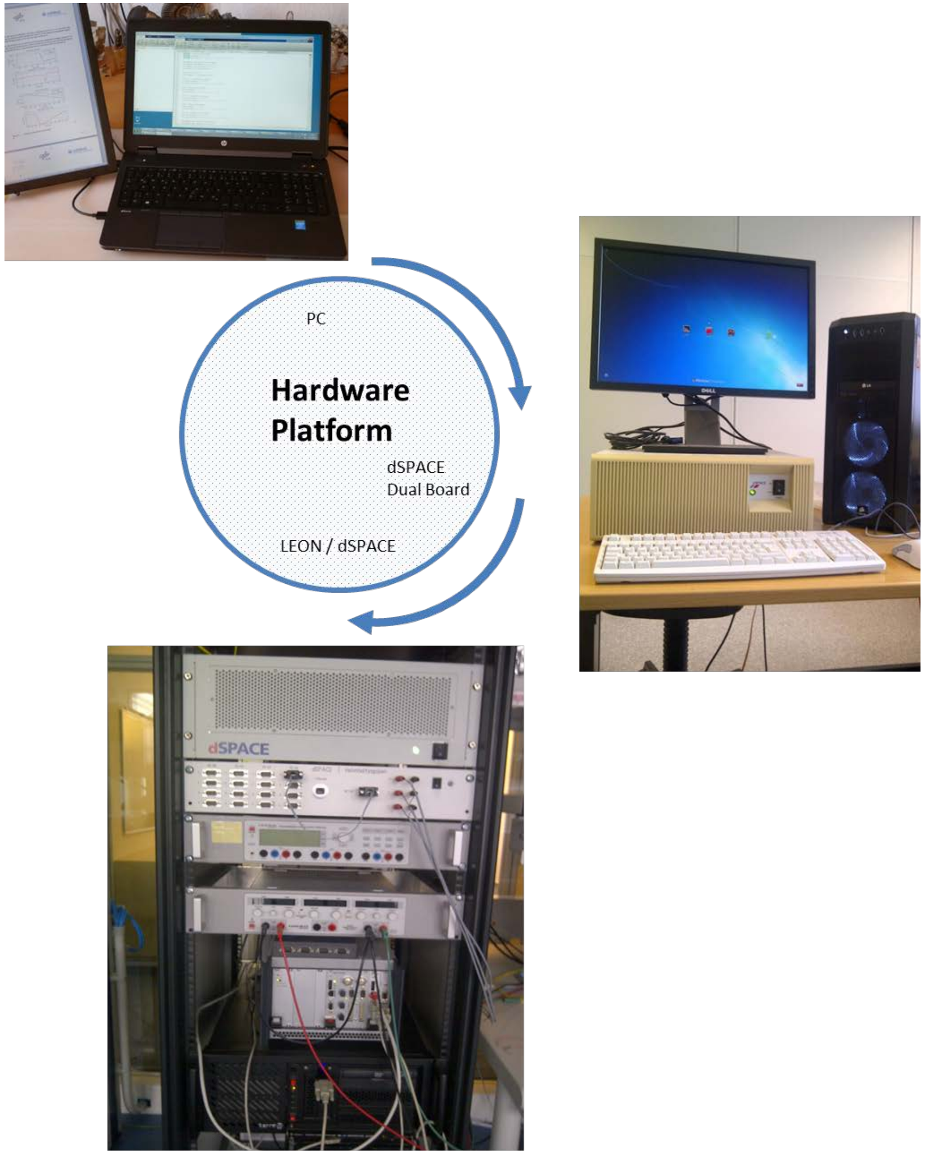
The next requirements define the range of MCI, which has to be covered. A selection of the test cases are given in set of mission files .

CReq. 1-1	The CoG of the composite, i.e. stage plus payload or stage without payload, can be from 0.2m to 2.0m from the separation plane	
CReq. 1-2	The static unbalance of the composite, i.e. the distance between CoG and body roll x axis, can be • <0.015m for spinning payloads releases • <0.030m for three axis stabilized payload releases	



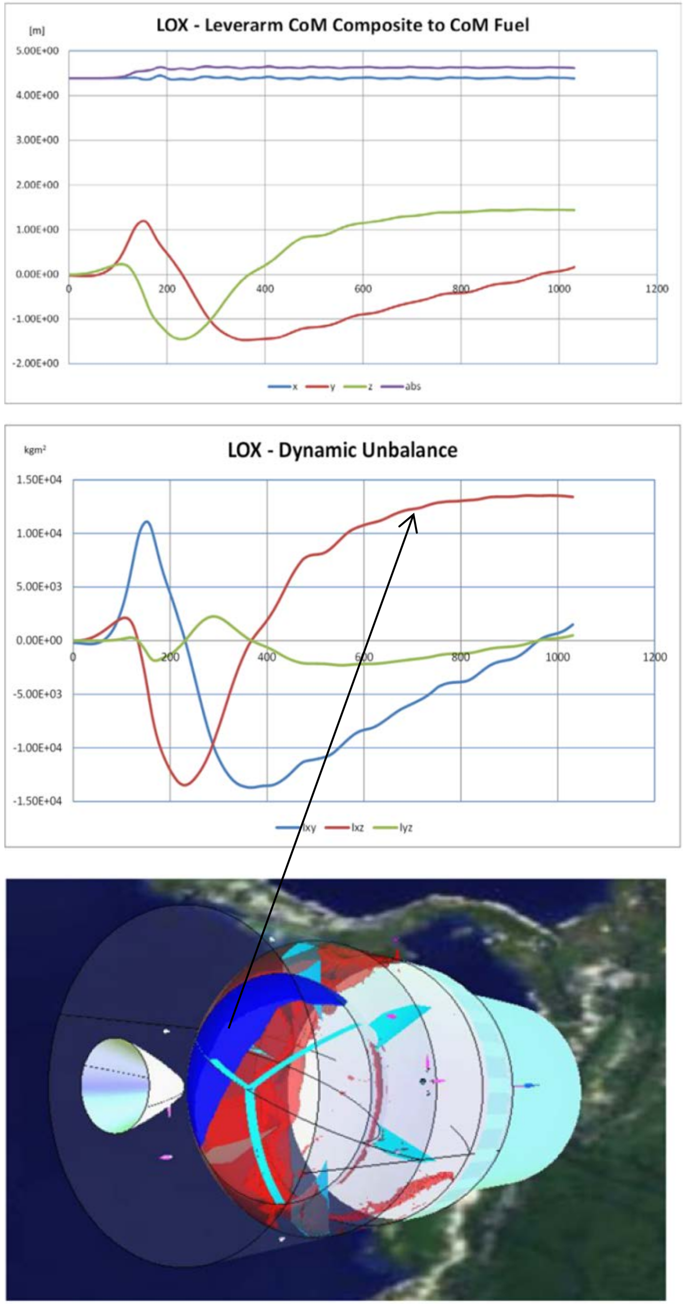


Seamless Move from Algorithm Design to Software Testing

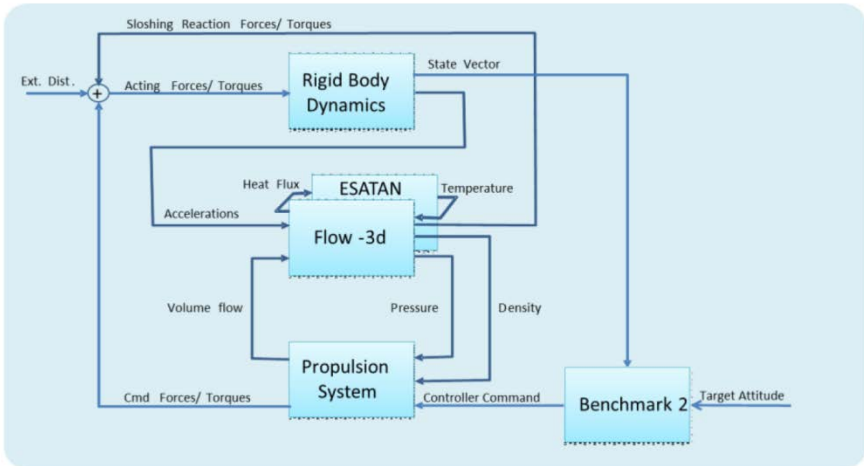


- Algorithm Development of Functional Simulator on PC
- Moving to Dual Board dSPACE and checking auto coded Software
- Running on Flight representative Hardware

Control Objectives addressed in the Framework as Benchmark Problems for Validating the Design Suite: **Sloshing with CFD in the Loop**



- New Sloshing Problem, occurring in Spinning Stages, has been addressed:
  - Simulation in Open and Closed Loop
  - Determination of the MCI Evolution
  - Analytic Model



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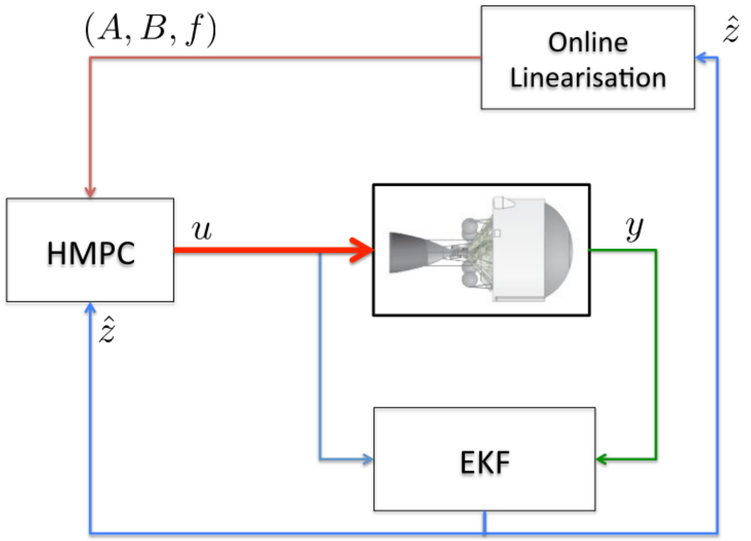
Control Objectives addressed in the Framework: **Model Predictive Control, System Identification and Adaptive Control**



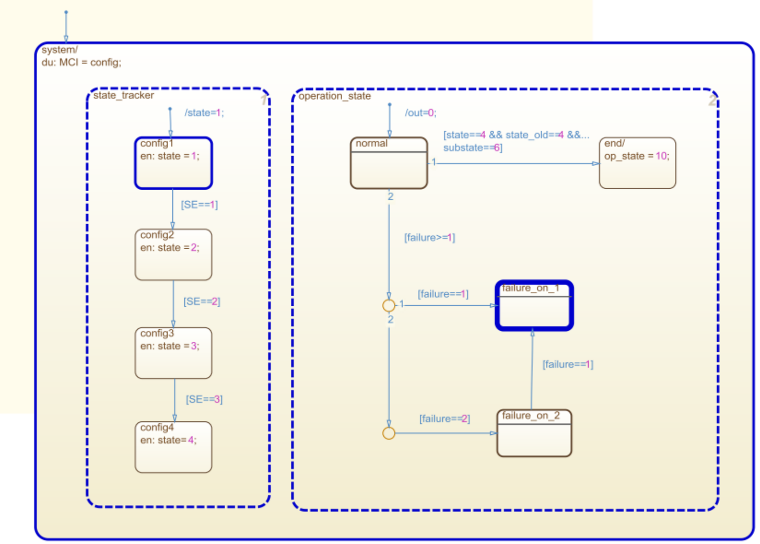
$$\mathcal{U} = [-u_{\max}, u_{\min}] \cup \{0\} \cup [u_{\min}, u_{\max}]$$

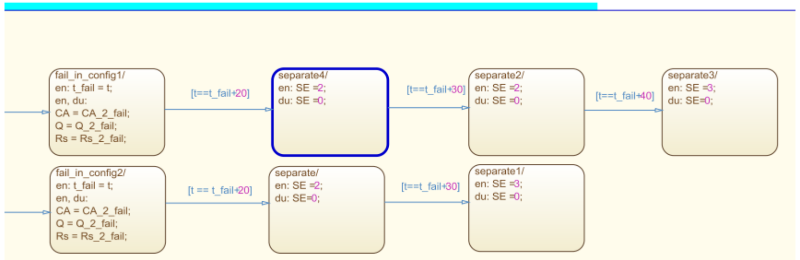
$$-u_{\max} \leq u_k \leq u_{\max},$$

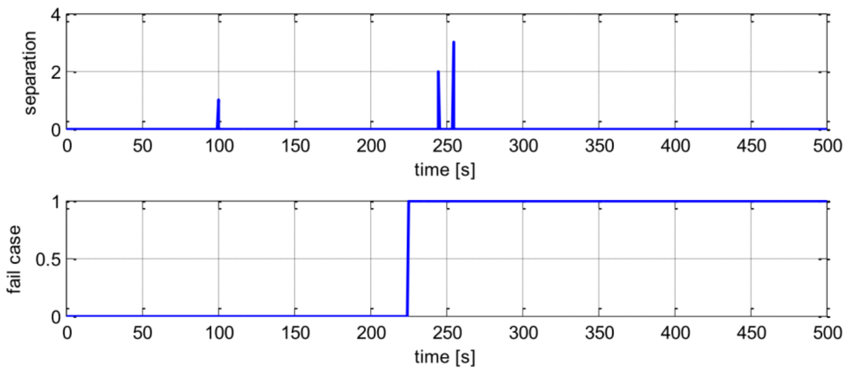
$$\begin{aligned} &\mathbb{P}(x_0, \gamma_0, A, B, f): \\ &\min_{\pi_N} \quad V_N(\pi_N, \gamma_0) \\ \text{s.t.} \quad &x(0) = x_0, \ \gamma(0) = \gamma_0, \\ &\text{Constraints (99)} - \text{(105), for } k \in \mathbb{N}_{[0, N_u]}, \\ &z_{k+1} = Az_k + B\eta_k + f, \ \text{ for } k \in \mathbb{N}_{[N_u, N-1]}, \\ &-u_{max} \leq \eta_k \leq u_{max}, \ \text{ for } k \in \mathbb{N}_{[N_u, N-1]} \end{aligned}$$

- Extended Kalman Filter for Plant Identification
- System Identification for Position of the Propellant Bulge
- Hybrid Model for MIB Phenomenon
- Model Predictive Control establishing a lower Limit for best achievable Results in Terms in Number of Actuation

Mission&Vehicle Management addressed in the Framework: **State Machine Concept for Defining the Mission Sequence**







- Mathworks’ StateFlow used for Defining the GNC related MVM
- In-Flight Adaptation of the Mission Sequence in Response to Failure of Degradation:
  - Emergency Release of Payloads
  - Controller Modification in Response to Subsystem Degradation in order to cope with reduced Margins

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USACDF Approach in Line with State-of-the Art Development

Best practices for developing DO-178 compliant software using Model-Based Design

Raymond G. Estrada, Jr.[1] and Gen Sasaki[2]
The MathWorks, Torrance, CA, 90502

Eric Dillaber.[3]
The MathWorks, Natick, MA, 01760

Model-Based Design with automatic code generation is an established approach for developing embedded control systems and is now commonly used on applications that must satisfy the commercial aviation software standard DO-178B. Model-Based Design enables engineers to create advanced embedded software systems using an executable model as the basis for design, simulation, and software verification and validation. The complexity of m… so… in… ob… ex…

AIAA Modeling and Simulation Technologies Conference
13 - 16 August 2012, Minneapolis, Minnesota
AIAA 2012-4627

MODEL-BASED DESIGN STRATEGIES FOR REAL-TIME HARDWARE-IN-THE-LOOP ROCKET SYSTEM SIMULATIONS

Scott A. Kowalchuk*
Sandia National Laboratories, Albuquerque, NM

AIAA Guidance, Navigation, and Control Conference
13 - 16 August 2012, Minneapolis, Minnesota
AIAA 2012-5036

ORION GN&C MODEL BASED DEVELOPMENT: EXPERIENCE AND LESSONS LEARNED

Mark C. Jackson[1]
Charles Stark Draper Laboratory, Houston, Tx, 77062

and

Joel R. Henry[2]
NASA Johnson Space Center, Houston, TX, 77058

The Orion Guidance Navigation and Control (GN&C) team is charged with developing GN&C algorithms for the Exploration Flight Test One (EFT-1) vehicle. The GN&C team is a joint team consisting primarily of Prime Contractor (Lockheed Martin) and NASA

A PLAN FOR ADVANCED GUIDANCE AND CONTROL TECHNOLOGY FOR 2ND GENERATION REUSABLE LAUNCH VEHICLES

John M. Hanson
Aerospace Engineer, NASA Marshall Space Flight Center, Huntsville, AL

Conclusion

Project Orion

- **Orion paid some upfront costs for transitioning to an MBD process:**
  - A steep learning curve for engineers not familiar with MBD tools
  - Initially slow and complex development tools and processes
  - Configuration management issues
- **These issues were mitigated by many of the lessons learned, improved Mathworks products and custom tools that are described in the paper**
- **Some of the benefits that GN&C is now observing include:**
  - Detailed requirements review was replaced by review of MBD artifacts which had proven functionality
  - Automated test framework and report generation has simplified testing and production of test artifacts
  - Automated standards checking tools (e.g. Model Advisor) and graphical artifacts have facilitated the inspection process
  - No schedule time was needed for hand coding GN&C algorithms (40,000+ SLOC were autocoded by CDR)

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Conclusions

- A multi-disciplinary, System oriented Approach towards the GNC Development of Upper Stage Control has been successfully adopted :
  - Physical Modelling of selected Subsystems provided better Modelling (including Failure Simulation)
  - Application of modern Control Concepts – System Identification, Model Predictive Control, Adaptive Control to illustrate the Gains on Functional Level
  - Fast and seamless Move from Algorithm Design to Processor-in-the-Loop
  - TRLevel 6 demonstrated for the Toolchain of Model based, Multi-disciplinary Design Approach including Autocoding
- **Move Forward**: USACDF 2 – Hardware in the Loop / Demonstrator extending the Model Based Design Approach to the complete Cycle including Hardware in the Loop