ACTIVE DIGITAL TWINS @ ESA'S CONTROL LAB ENABLERS FOR COMPLEX SPACECRAFT CONTROLS SOLUTIONS

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Senior GNC Systems Advisor

GNC & AOCS Pointing Division

ESA ESTEC Noordwijk

ESTEC: WHO ARE WE?

ESTEC

- Largest ESA site, 600 Engineers
- Technical & Scientific heart of the Agency
- Incubator of the European Space Effort
  - ESA Projects are born, developed and exploited.
  - ESA's R&D Technology programmes
- 35 Laboratories
  - Europe's biggest vacuum chamber,
  - Sun Simulator,
  - Ultra Loud Sound System,
  - most powerful Hydraulic Shaker
- ESTEC develops Tech-Demo Missions,
- ESA runs a budget of 14.5 BEuro over 3 years

ESTEC - GNC, AOCS and Pointing Systems Division

esa

→ Samir Bennani
→ Senior Advisor

Bénédicte Girouart
Head of the AOCS & Pointing Systems Division

Bénédicte Girouart
Head AOCS & Pointing Systems Section

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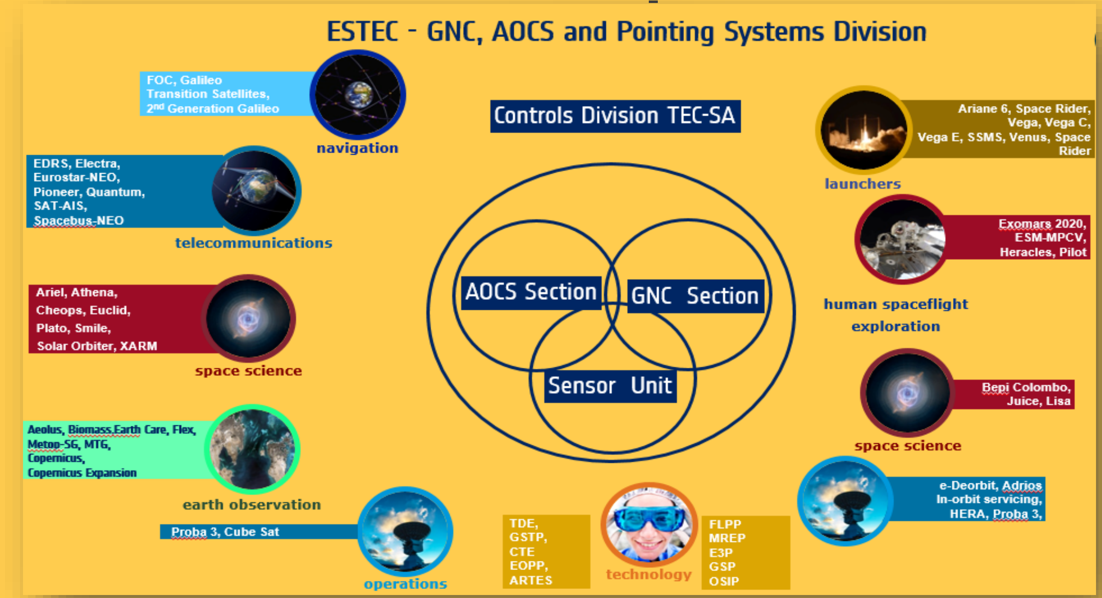


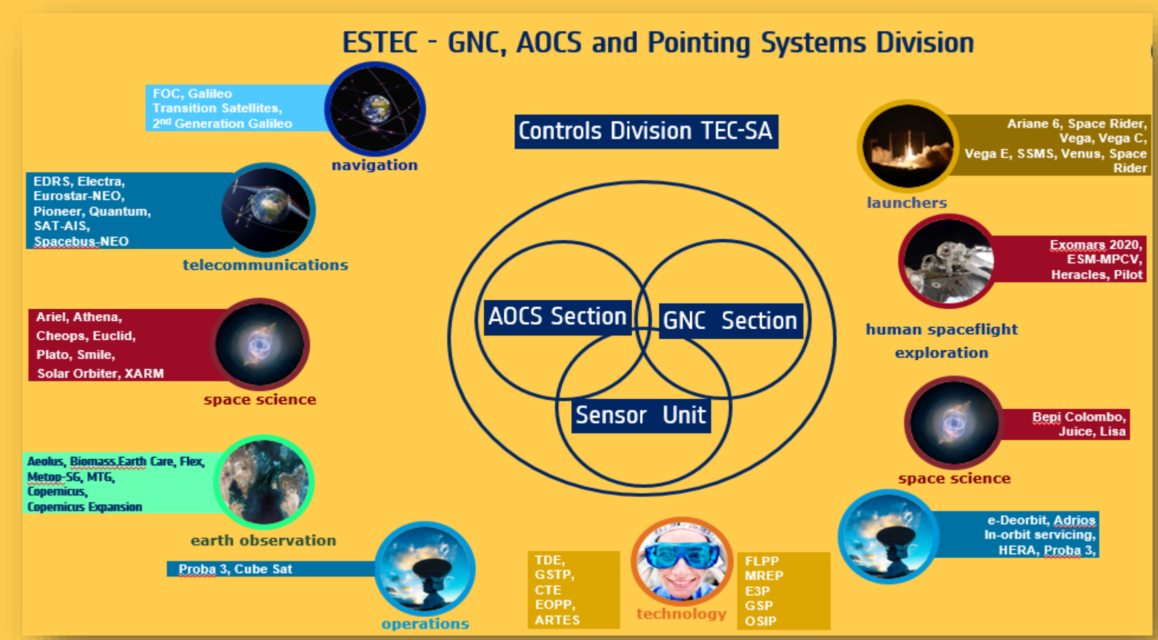
Massimo Casasco
Head of the
Guidance Navigation & Control Section

-

Steeve Kovaltschek
Head of the AOCS Sensor Unit

ESTEC - GNC, AOCS and Pointing Systems Division

- Control team is about 40
- We serve all ESA directorates with technical support
- We operate a robotic, sensor, & mechatronic Lab
- We perform advanced R&D
- We develop technology demonstration mission (Proba, CubeSats, Adrios, Hera ..and many others..)



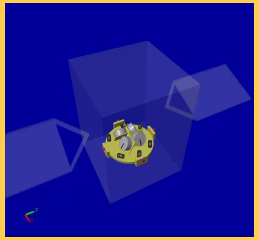
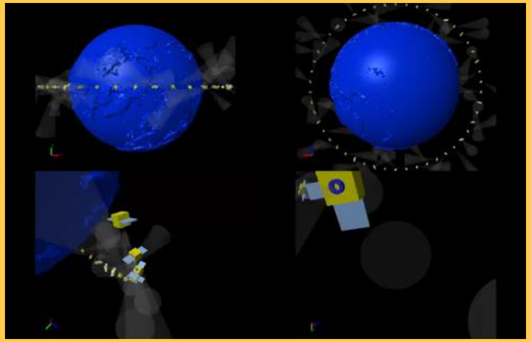
VEGA: GNC for Launchers

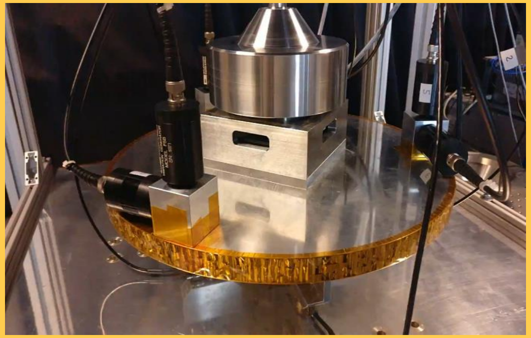
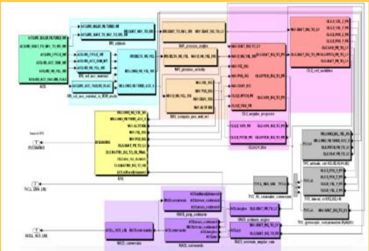
ADRIOS: GNC for Active Debris Removal

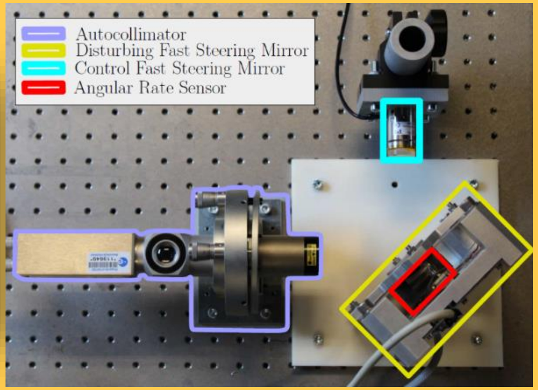
HERA: GNC for a Planetary Interceptor

CONTROLS: WHAT ARE WE DOING?

- → **Design Requirements:** System to Subsystem Specifications
- → **Design Architectures**: System sizing, sensors, actuators, computers, multi-disciplinary design
- → **Physical Modeling & Simulation:** Multi-Physics Modeling, Digital Twins, System Identification from Measurements and Data
- → **G-N-C Design:** Model Based Design, Optimisation, Advanced Algorithms, AI & Machine Learning, Theory of Dynamical Systems, Stability, Sensor Fusion, etc…
- → **G-N-C Implementation:** Laboratory, Hardware Demonstrators, Verification & Validation, Worst Case Analysis & Testing
- → **Commissioning:** In Flight Calibration and tuning,
- → **Operations:** Post Flight Analysis, Diagnostics, Assessments
- → Upgrading

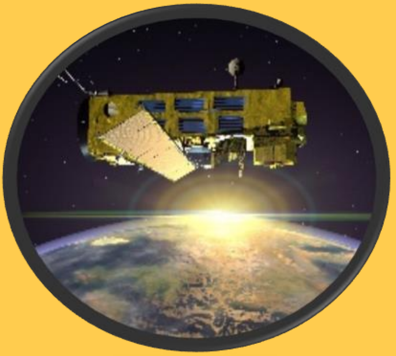





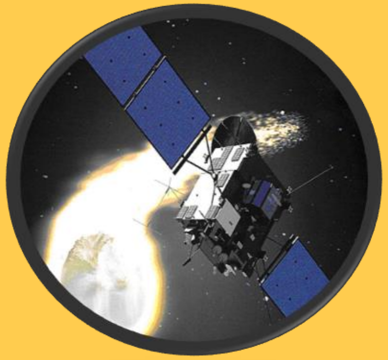
MISSIONS

ESA Missions using $H\infty$ Control design

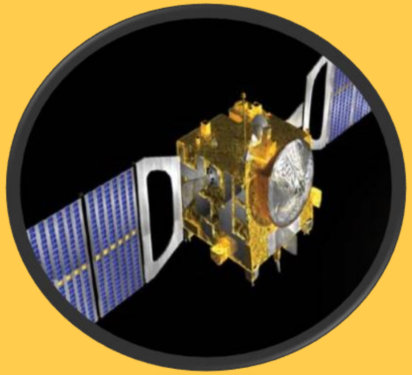


GOMOS
Sensor (2020)

Mars Express
(2003)



Rosetta
(2004 -2014)



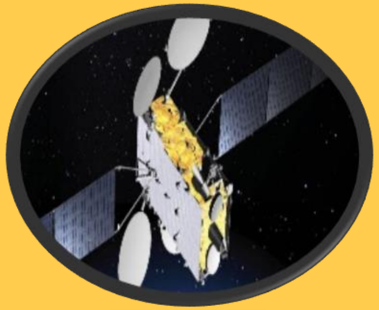
Venus Express
(2006)

SatCOM
(2014)

BepiColombo
(2016)

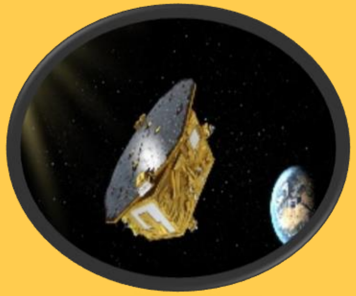
Ariane V
(1996 -Today)
more than 100 Flights

TAS SpaceBus 4000
(2003 - 2010)
more than 15 Satellites



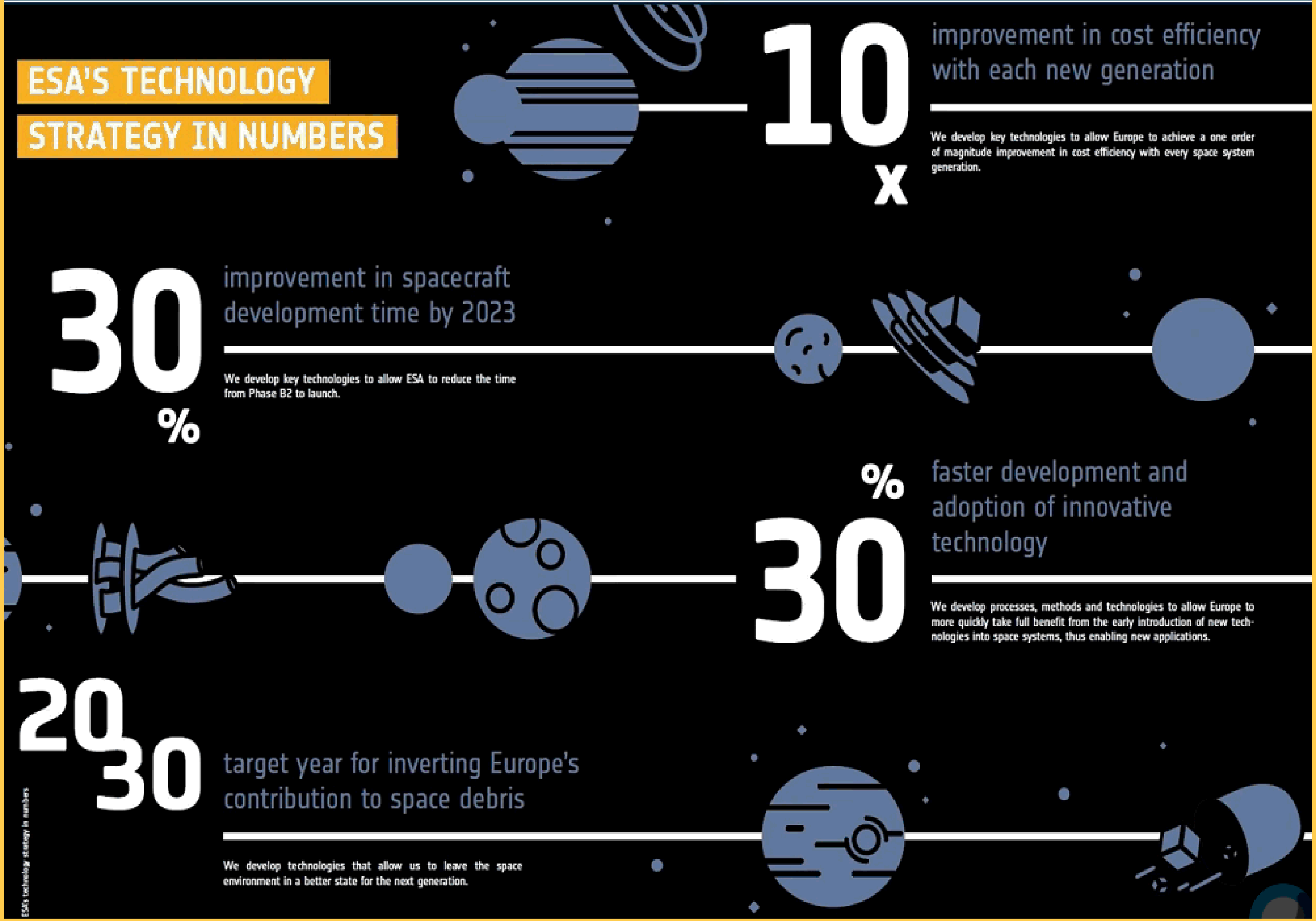
ATV Automated Transfer Vehicle
(2008 - 2015)
5 flights

LISA Pathfinder
(2015)



Solar Orbiter
(2020)

ESA NEEDS & KEY TAKEAWAYS

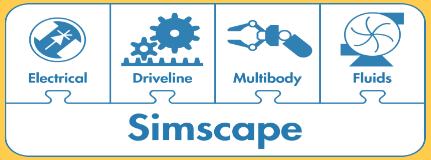


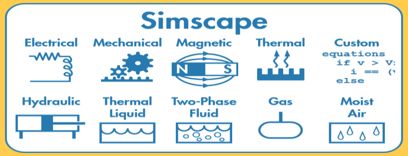
ESA NEEDS & KEY TAKEAWAYS

- **Digital Twins (DT) are crucial for active controls of innovative concepts**
  - DT integrate physics & allow flexible E2E design&testing
  - DT reveal complex multi-physics inter-dynamic couplings & system wide design drivers
  - DT enable uncertainty management (Robust Modelling Analysis and Control Tools)
- **Digital Twins within the MathWorks Toolchain**
  - From Concept Design to HW Implementation in matter of weeks
  - Estimated time & cost saving factor about 10
  - Demonstrated performance improvement factor 100
  - Realised innovative generic technology

Enabler for Innovation and technology acceleration

→ Main tools used: Simulink, Simscape, Robust Control Toolbox, System Identification Toolbox





OUTLINE

1. **Problem Statement**
2. **Solutions**
3. **Tools Used**
4. **Results**
5. **Benefits**
6. **TakeAway/Conclusion**

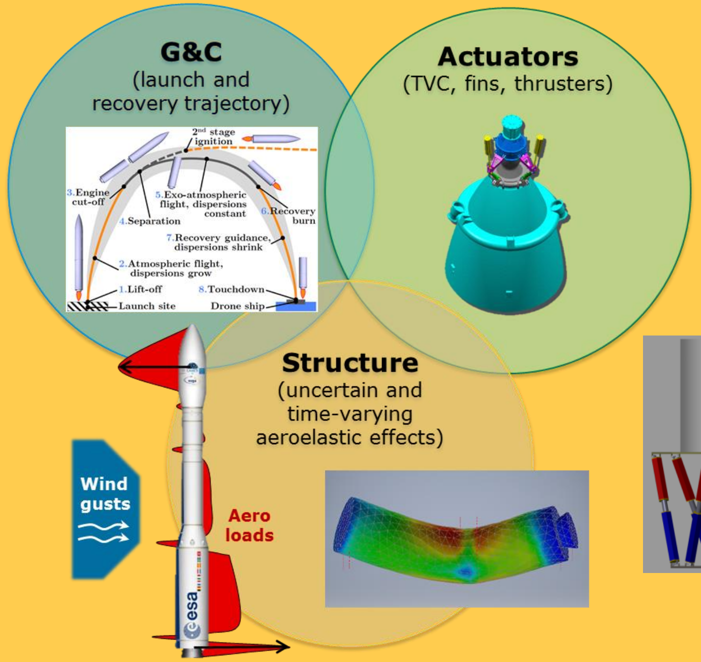
"A Digital Twin is a set of **virtual information constructs that mimics the structure, context, and behavior of an individual/unique physical asset**, is **dynamically updated** with data from its physical asset, is **dynamically updated** with data from its physical twin **throughout its lifecycle**, and **informs decisions that realize value**"

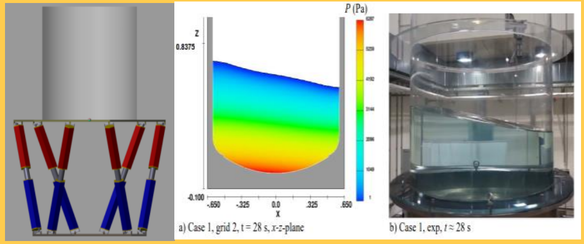
AIAA Digital Twin Subcommittee, SciTech 2020

PROBLEM STATEMENT: WHY SIMSCAPE?

Observation:

- **Traditional Design Process has limitations**
  - does not allow design adaptation late in the design without having serious impacts
  - cost/schedule impact of changes increase with system maturity
- **We deal with Complex Dynamical Systems**
  - Local component dynamical models may have simple behaviors
  - when connected into a system interactions propagate into the entire system and these need to be understood – managed….
- **The behavior of complex integrated-interconnected nonlinear system is not the just sum of its components….. Especially in the face of uncertainties**



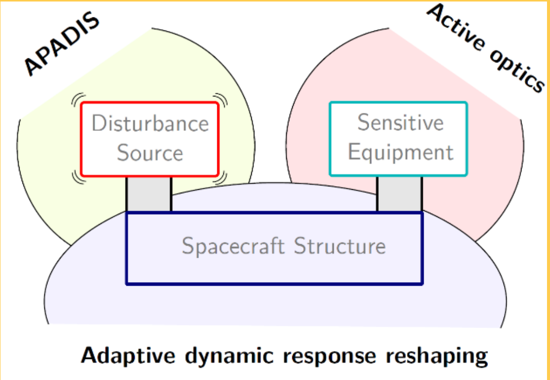


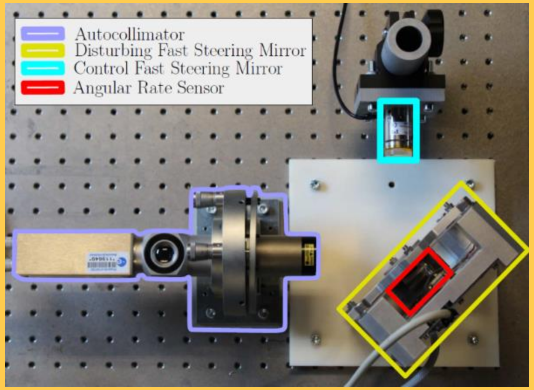
Controls Structures Interactions at the interface of Disciplines
is a Major Issue
in Complex Aerospace Systems
It needs to be managed with Formal Tools

PROBLEM STATEMENT: FAST LAB

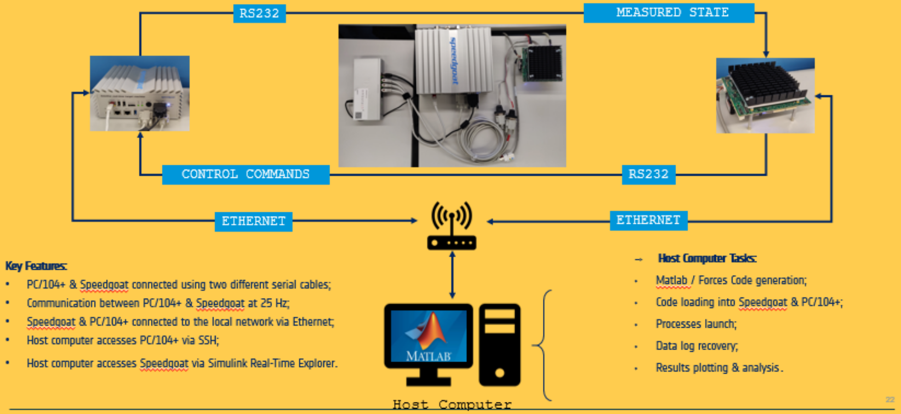
Motivation:

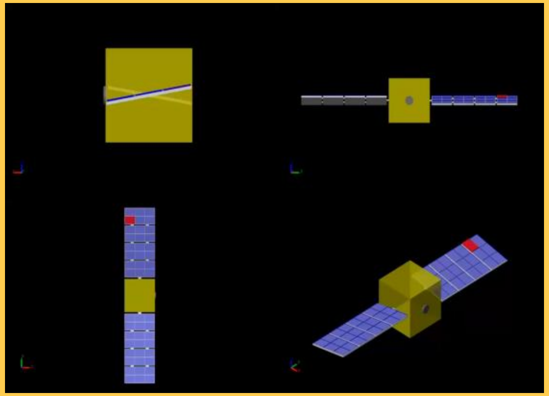
- Build up in-house competences for the pre-development of active control demonstrators
- Build high performance robust/adaptable MIMO controls, system identification and V&V.
- Innovate towards future R&D activities, Foster collaborations & Industrialise





Behind the scene:





MAIN CONTRIBUTORS

Valentin Preda
GNC System Engineer

Fabrice Boquet
AOCS System Engineer

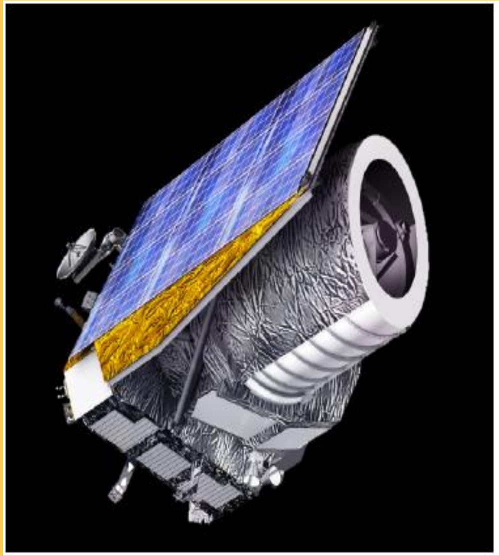
[1] V. Preda, J. Cieslak, D. Henry, S. Bennani, and A. Falcoz, “Robust microvibration mitigation and pointing performance analysis for high stability spacecraft,” *Int. J. Robust Nonlinear Control*, Dec. 2018, doi: 10.1002/rnc.4338.
[2] V. Preda, J. Cieslak, D. Henry, S. Bennani, and A. Falcoz, “A H-infinity/mu solution for microvibration mitigation in satellites: A case study,” *J. Sound Vib.*, 2017, doi: 10.1016/j.jsv.2017.03.015.
[3] F. Sanfedino, V. Preda, V. Pommier-Budinger, D. Alazard, F. Boquet and S. Bennani, "Robust Active Mirror Control Based on Hybrid Sensing for Spacecraft Line-of-Sight Stabilization," in *IEEE Transactions on Control Systems Technology*, vol. 29, no. 1, pp. 220-235, Jan. 2021, doi: 10.1109/TCST.2020.2970658

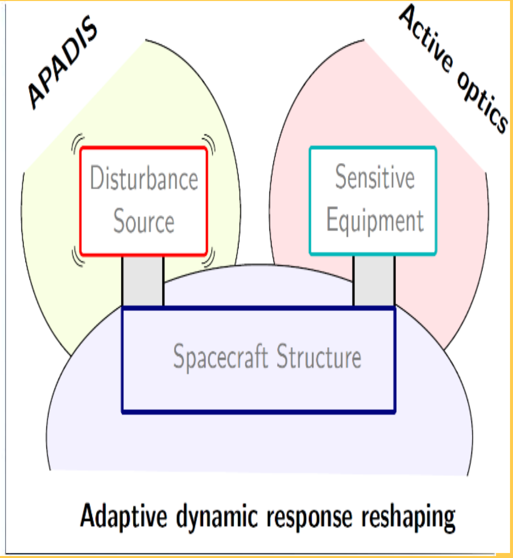
PROBLEM STATEMENT: APPLICATION CASE

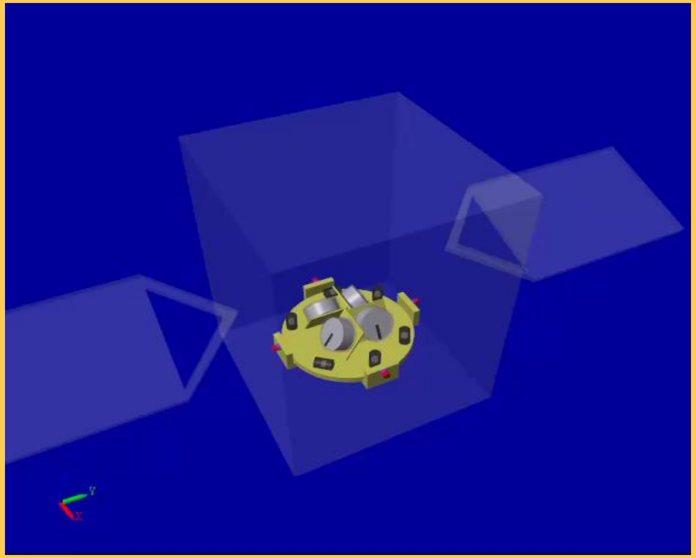
→ **Future missions:** High precision pointing systems

→

- Larger, lighter, more flexible structures
- Higher pointing accuracy, robust, adaptable and affordable







Crucial to understand and mitigate on-board the impact of **micro-vibrations**

SOLUTIONS

1. **Problem Statement**
2. **Solutions**
3. **Tools Used**
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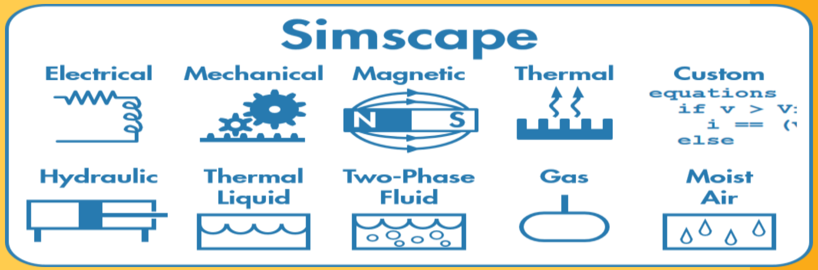
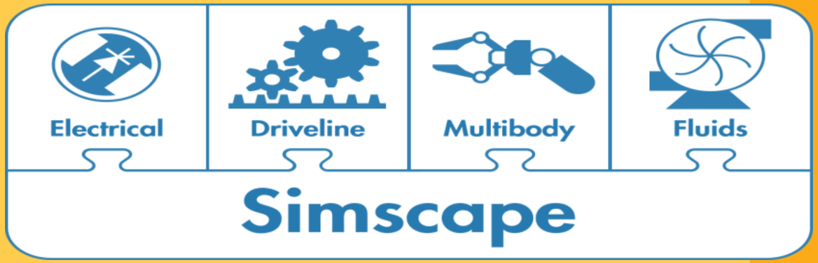
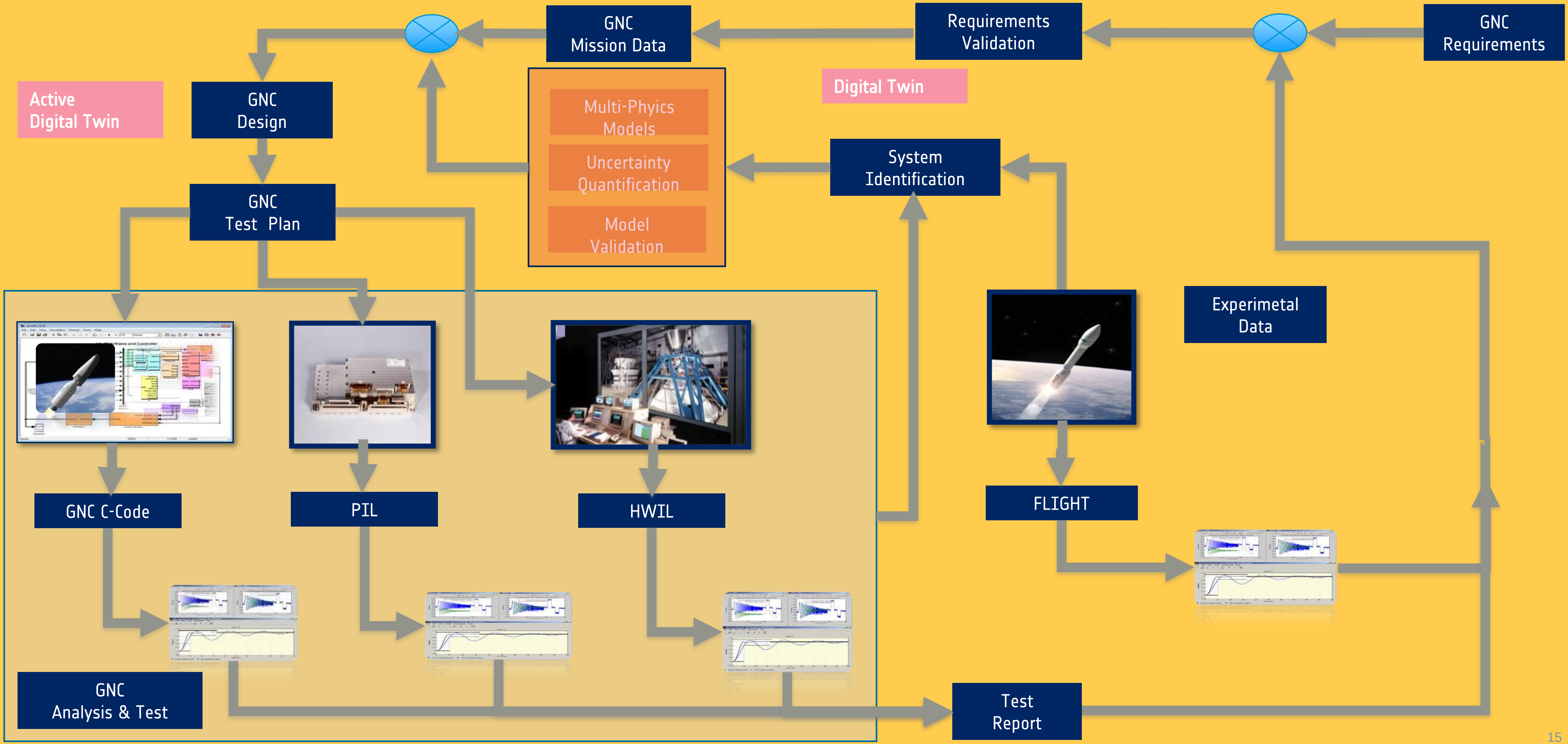




SOLUTION / E2E PROCESS



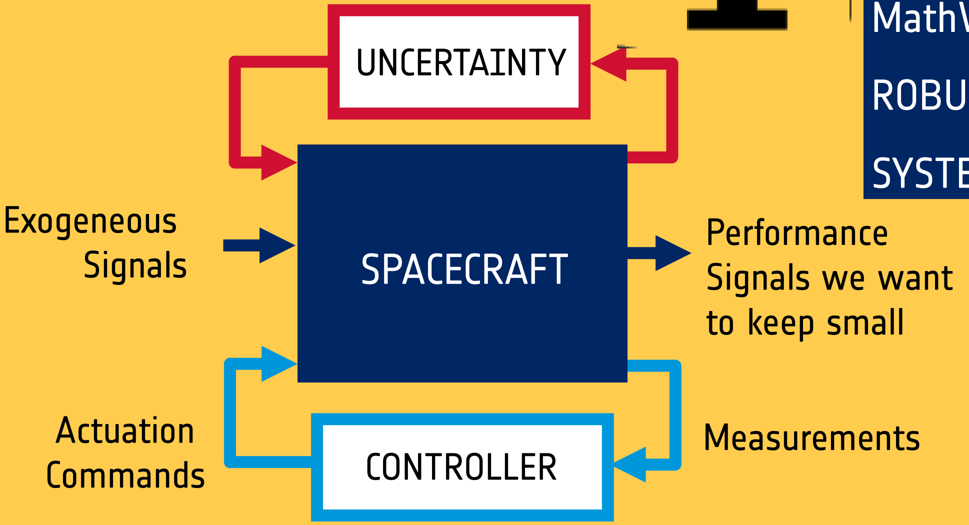
SOLUTION: ACTIVE CONTROL

- → Limit the influence of disturbances on key performance signals
- → Uncertainty = adversary in the loop.
- → Trade-off between performance & robustness.
- → Manual tuning around nominal conditions => poor peformance & robusness.
- → Robust control = using modern optimisation algorithms to manage perfomance and robustness trade-offs. (Systune !!!!)

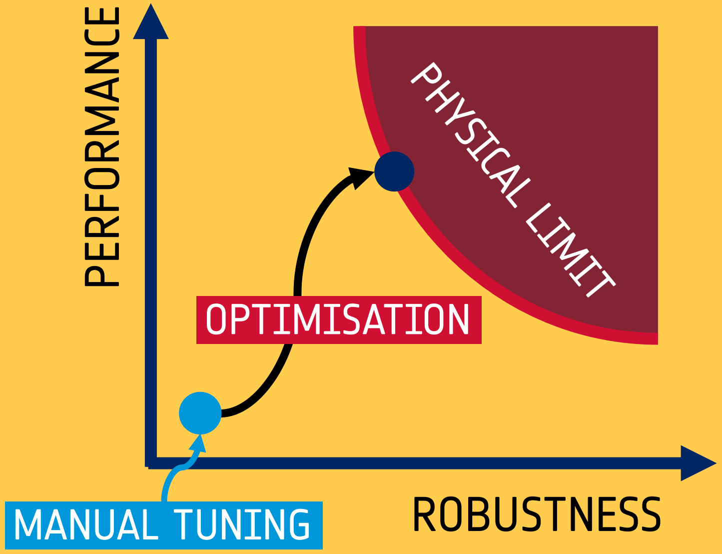
MathWork

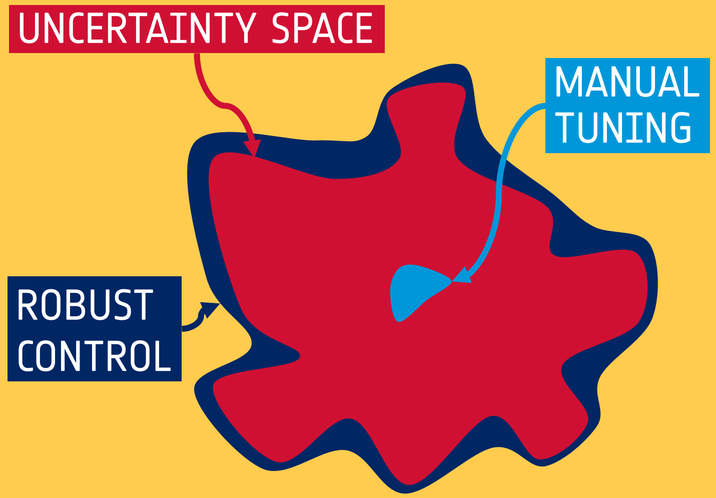
ROBUST CONTROL Toolbox

SYSTEM IDENTIFICATION Toollbox



Physical Model
Digital Twin





TOOLS USED

1. Problem Statement
2. Solutions
3. Tools Used
4. Results
5. Benefits
6. Takeaways/Conclusion

MODEL BASED DEIGN TOOLS USED

- **Modelling**
  - Physical / Cross Domain / Digital Twin
  - Requirements Formalised
- **Control Design**
  - Analysis Model / Synthesis Models
- **Simulation**
  - Virtual HWIL / PIL testing
  - Optimization Driven Simulation
  - V&V
- **Implementation Level**
  - Auto-coding HWIL
  - Optimization based Testing
  - On-line Design
  - System Identification & Model Validation

Requirements	Experiment Preparation	Physical Systems
Physical Model Digital Twin	System Identification	Auto-Coding Algorithms
Uncertainty Modelling	Uncertainty Quantification	Target Processor
Control Design	Model Validation	Target Computer
Simulation	V&V	Testing

RESULTS

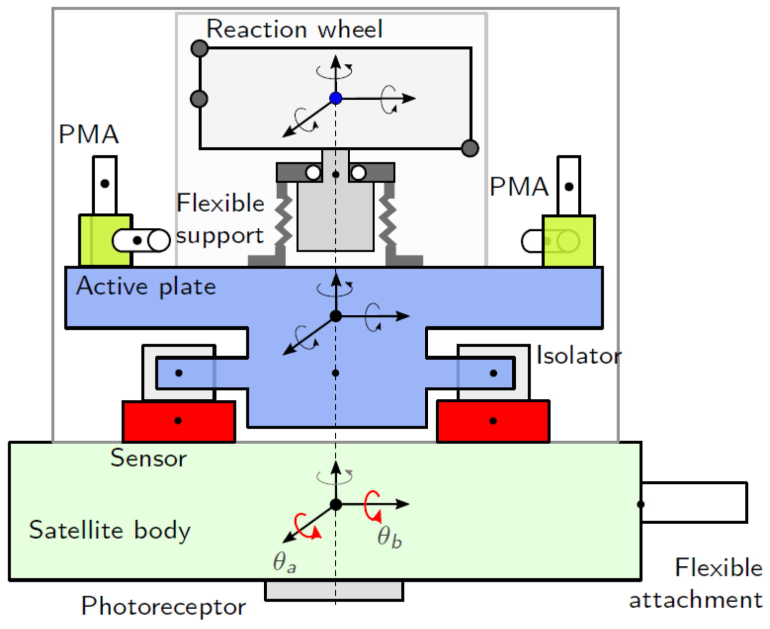
- Problem Statement
- Solutions
- Tools Used
- Results
- Benefits
- Takeaways/Conclusion

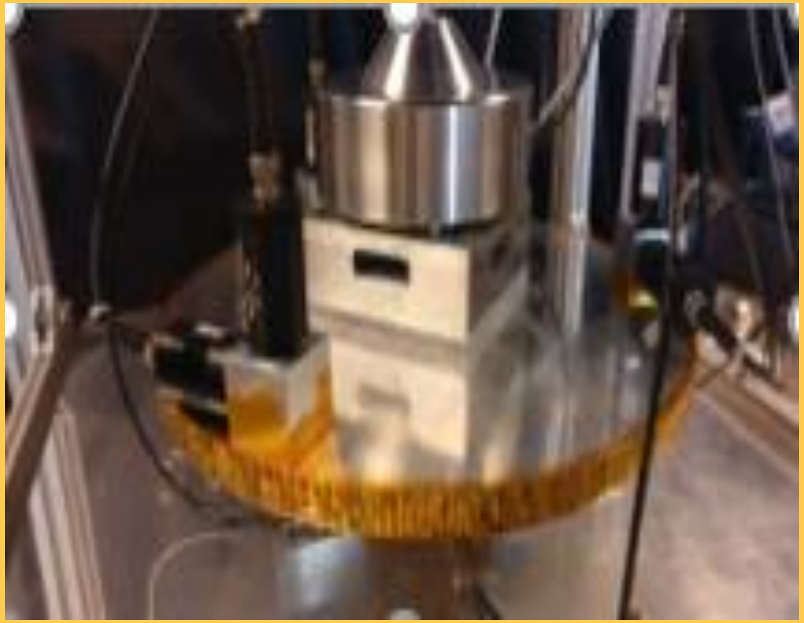
ROBUST MICROVIBRATION CONTROL & WORST-CASE ANALYSIS FOR HIGH POINTING STABILITY SPACE MISSIONS

→ **Motivation:** Reduce impact of microvibrations generated by reaction wheels (key technology for the future).

Approach:

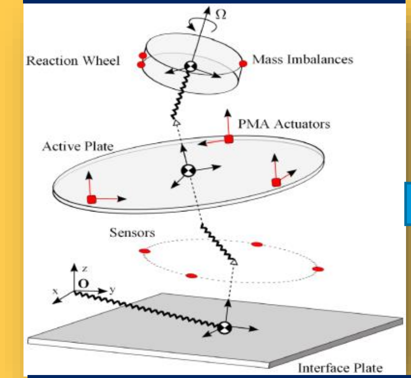
- Digital Twin Modelling Apparatus
- Wheel on an platform actively controlled using a set of shakers.
- Passive isolators attenuate high frequency.
- Sensors measure forces transmitted to base.
- Robust controller that adapts to gyroscopic effects and guarantees worst-case pointing performance
- Key techniques: structured H infinity design, LPV control, LFT modeling, mu/IQC analysis.





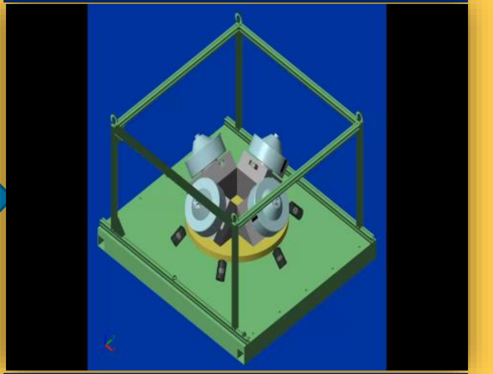
ACTIVE CONTROL FOR HIGH POINTING STABILITY

Modelling



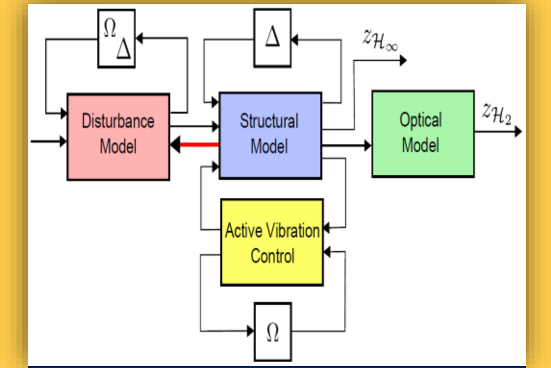
Analytic Model

Simulation



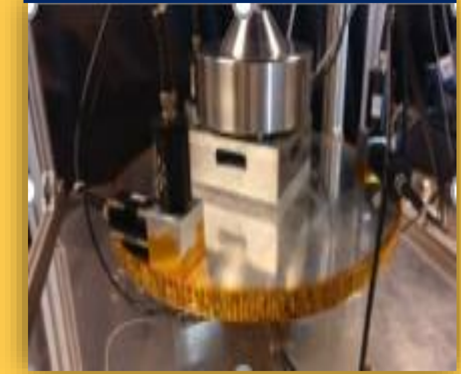
Digital Twin

Design



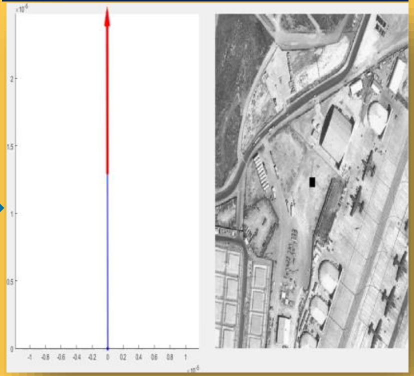
Active Digital Twin

Testing

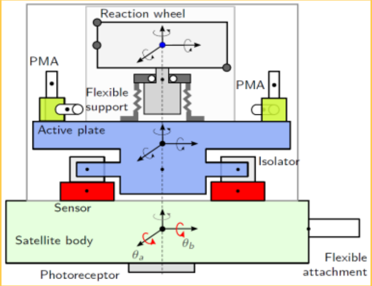


Physical Systems

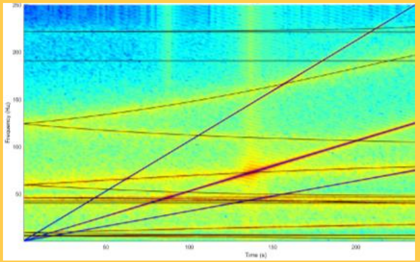
Validation



Optical Performance



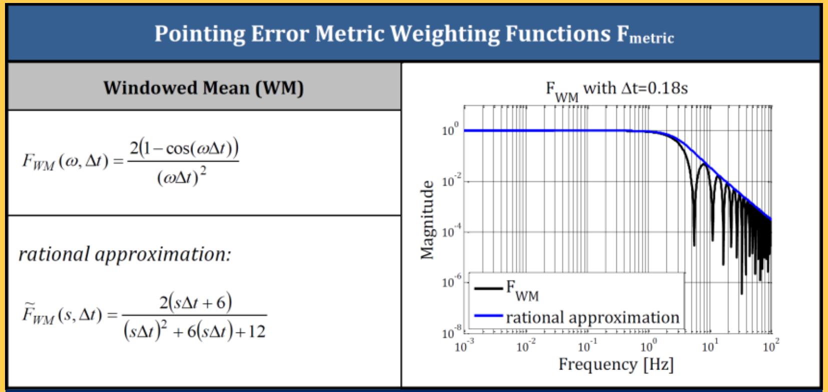
Development of analytical models that support high-performing control design



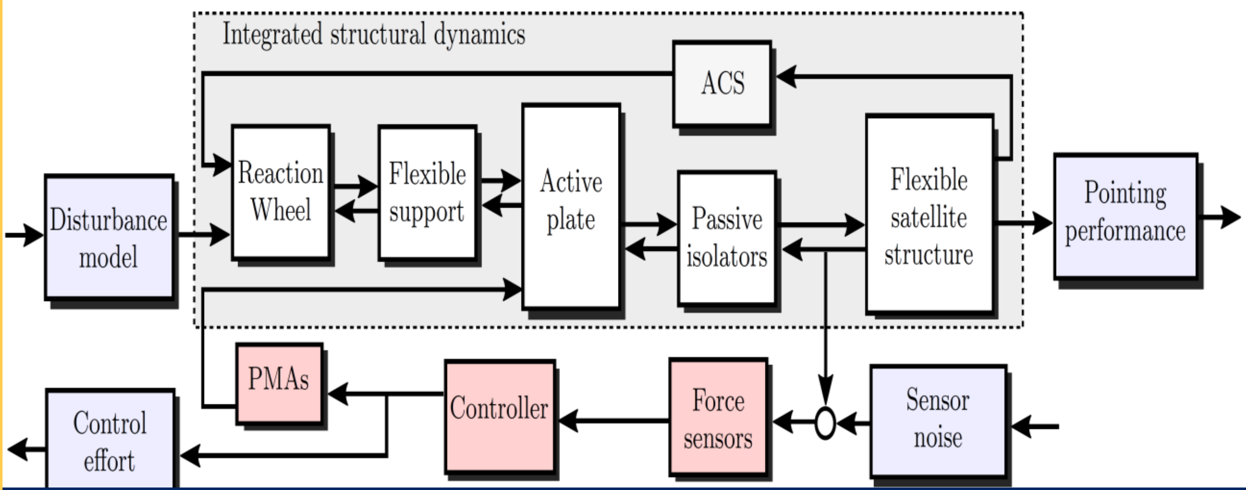
Spectral Signature

END-TO-END MODEL

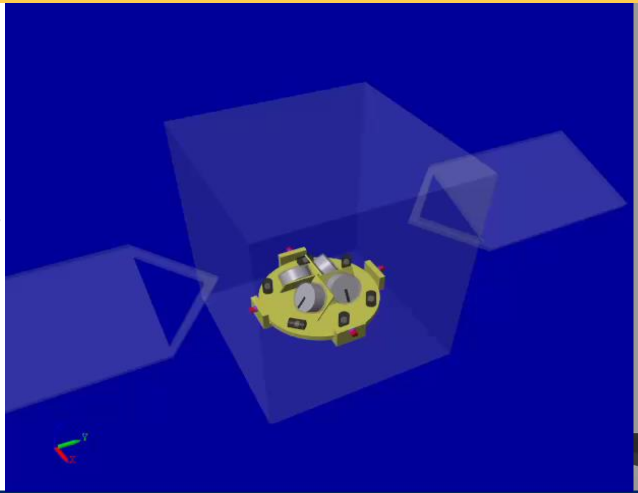
- Physical model is developed to perform an end-to-end mapping from disturbances to pointing performance
- Pointing performance weights are based on rational approximations of the windowed mean and variance



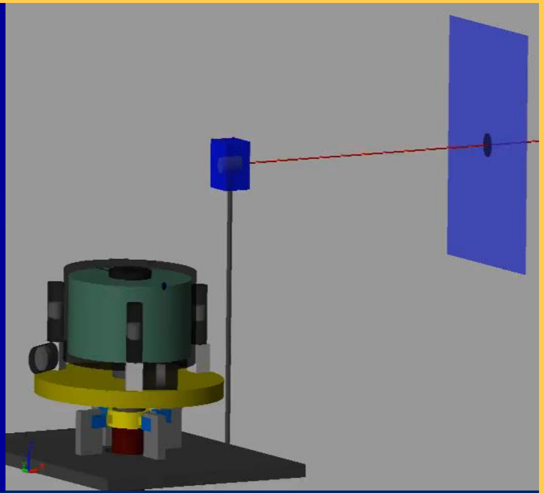
Pointing Error Metric



End2End System



E2E Digital Twin

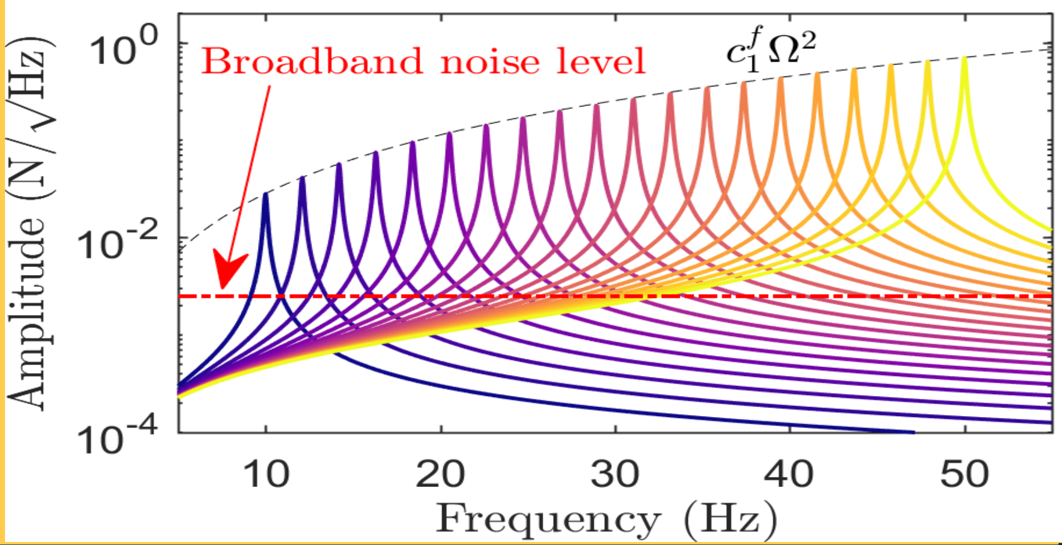


Digital Twin

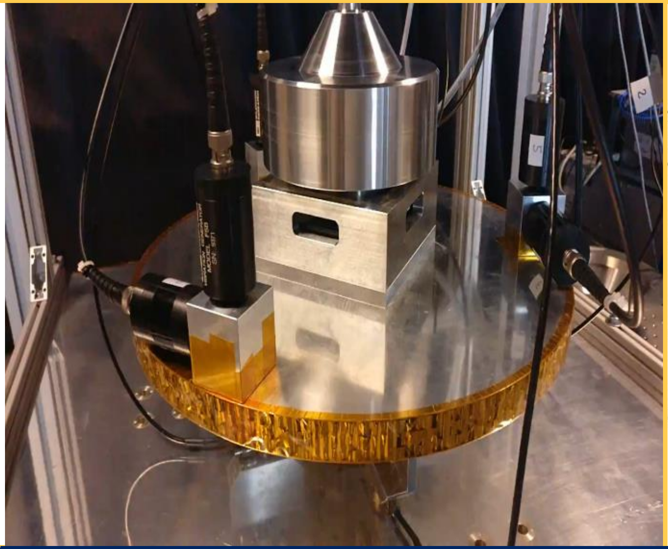
LPV DYNAMICS AND DISTURBANCE SPECTRUM

Harmonic perturbations induced by wheel imperfections grow **Quadratically** with the wheel rate

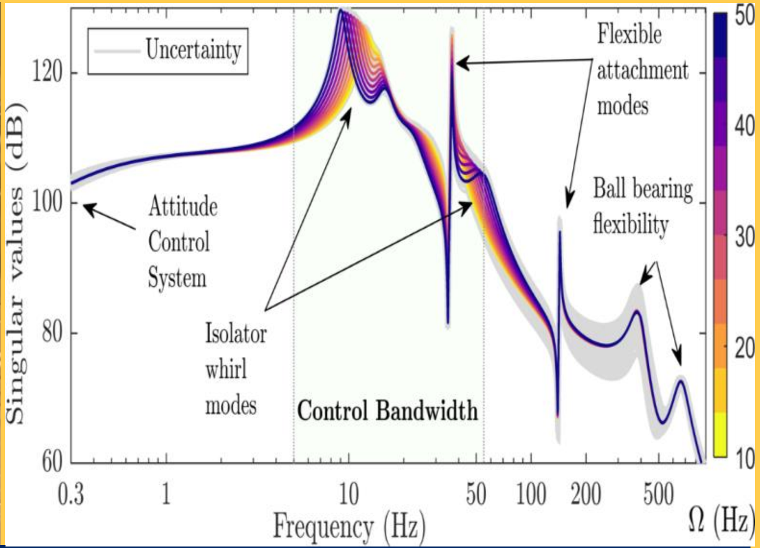
Time Varying Dynamics depending on Wheel Speed



Input Spectrum



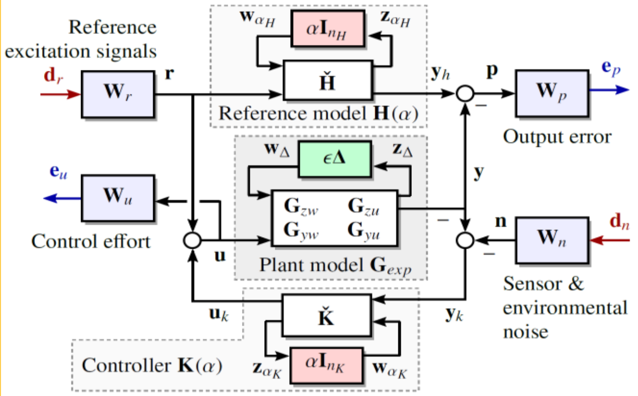
System Identification

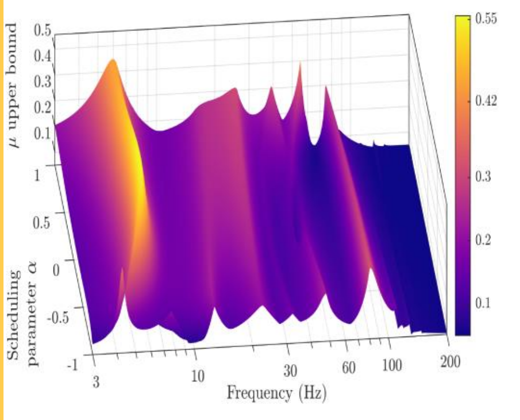


Output Spectrum

RESULTS: CONTROL DESIGN

- Requirements formalized as weight and **are all of physical in nature**
- Relate the Spectral Densities of the input/output signals
- Model mismatch via uncertainty model
- Desired Reference Model and Controller are LPV





Digital Twin

Embeds

Δ

Robust Synthesis Model

Physics / Uncertainties / Operational Plant Changes / Requirements

Controller

Globally Guaranteed System Performance Robustness

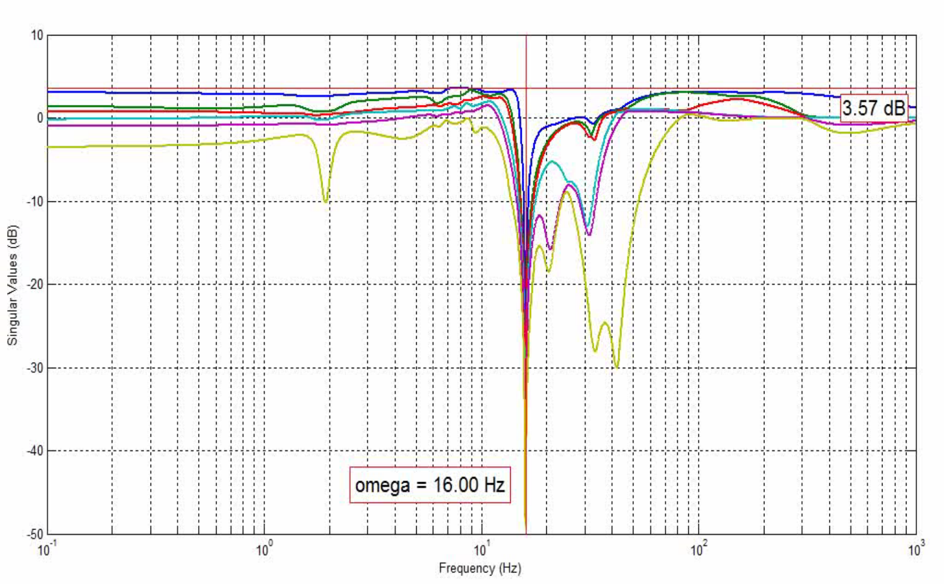
Active Digital Twin

Gives us

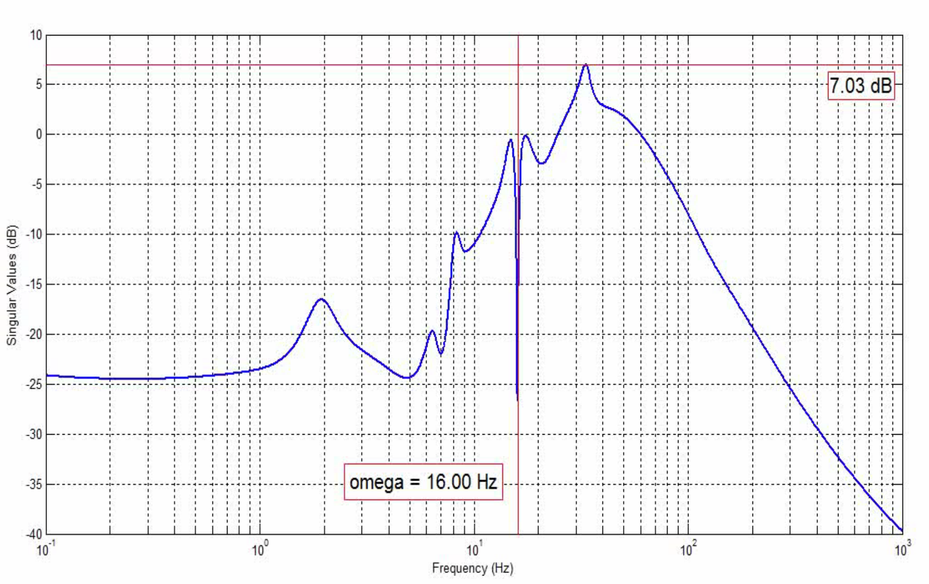
Desired Behavior

H/W IN THE LOOP RESULTS

Closed-Loop Response to Input Spectrum with harmonic perturbation corresponding to the wheel rate

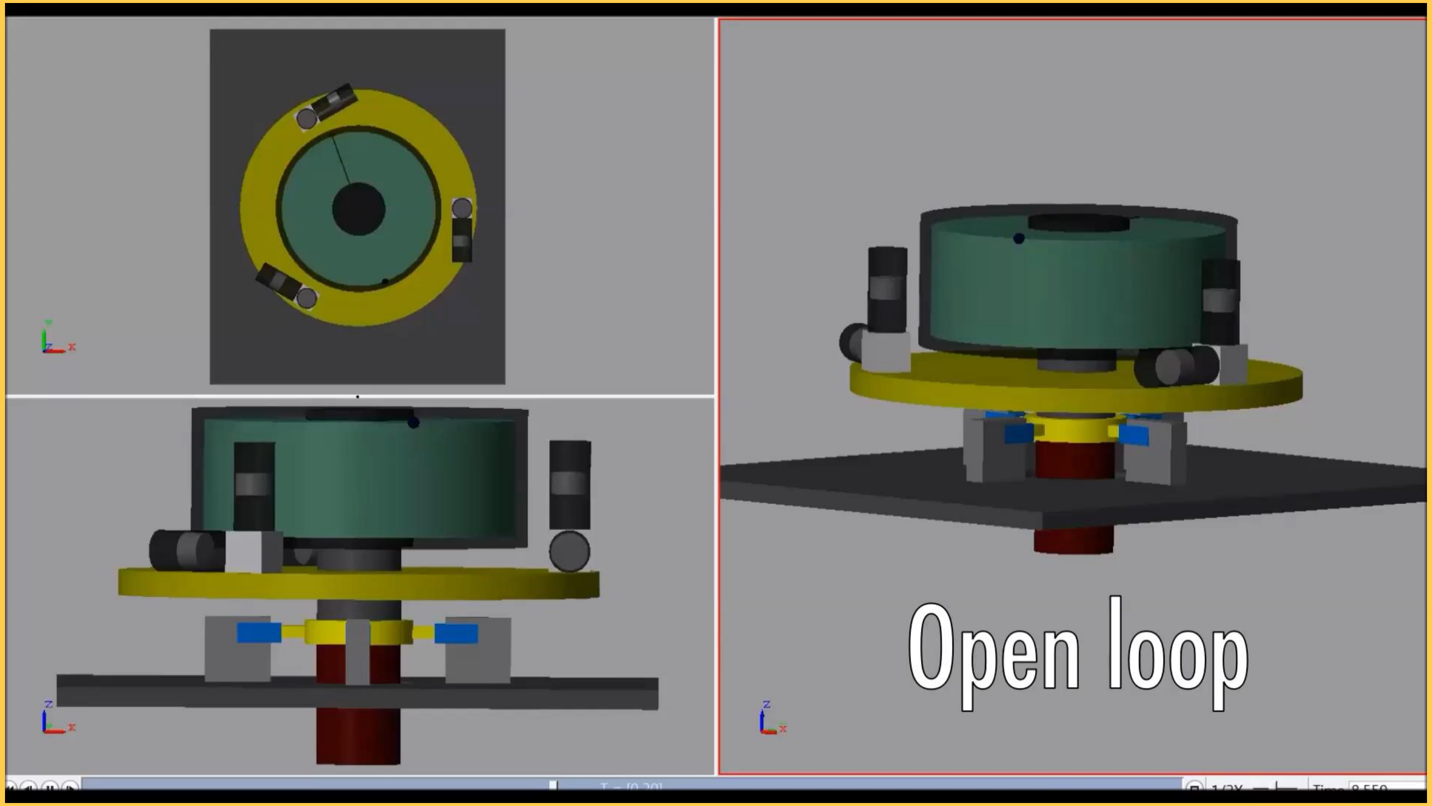


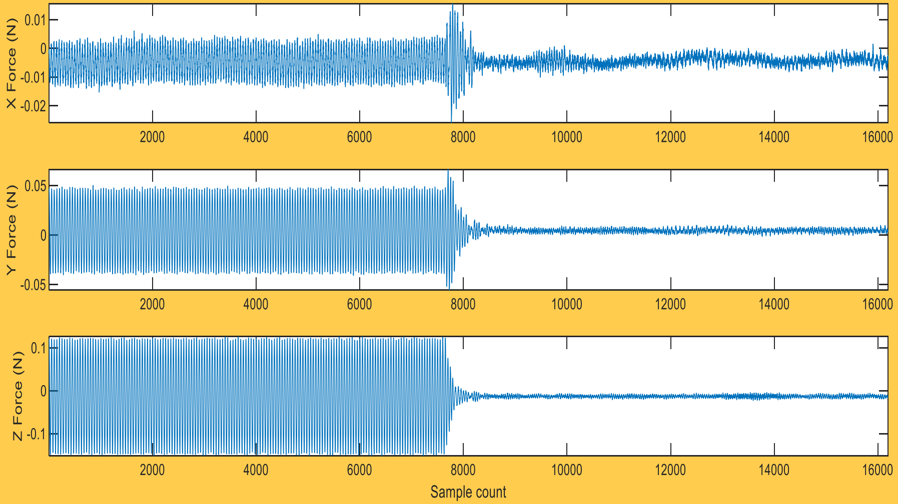
Adaptive Sensitivity (e/d) Transfer Function



Adaptive Disturbance to Output (y/d) Transfer Function

RESULTS





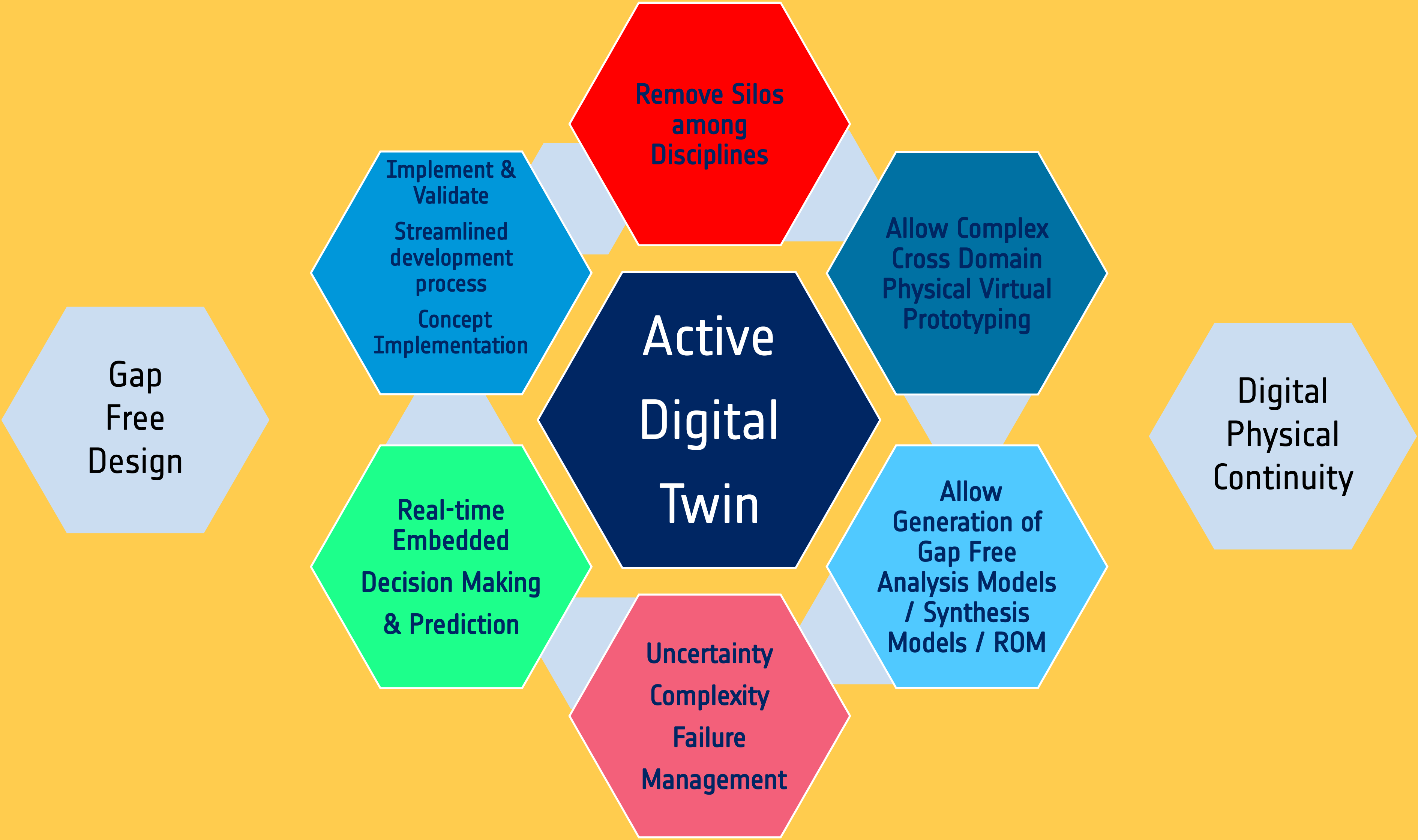
Simscape

Results using LPV controller demonstrate up to **40 dB attenuation performance** in some frequency ranges

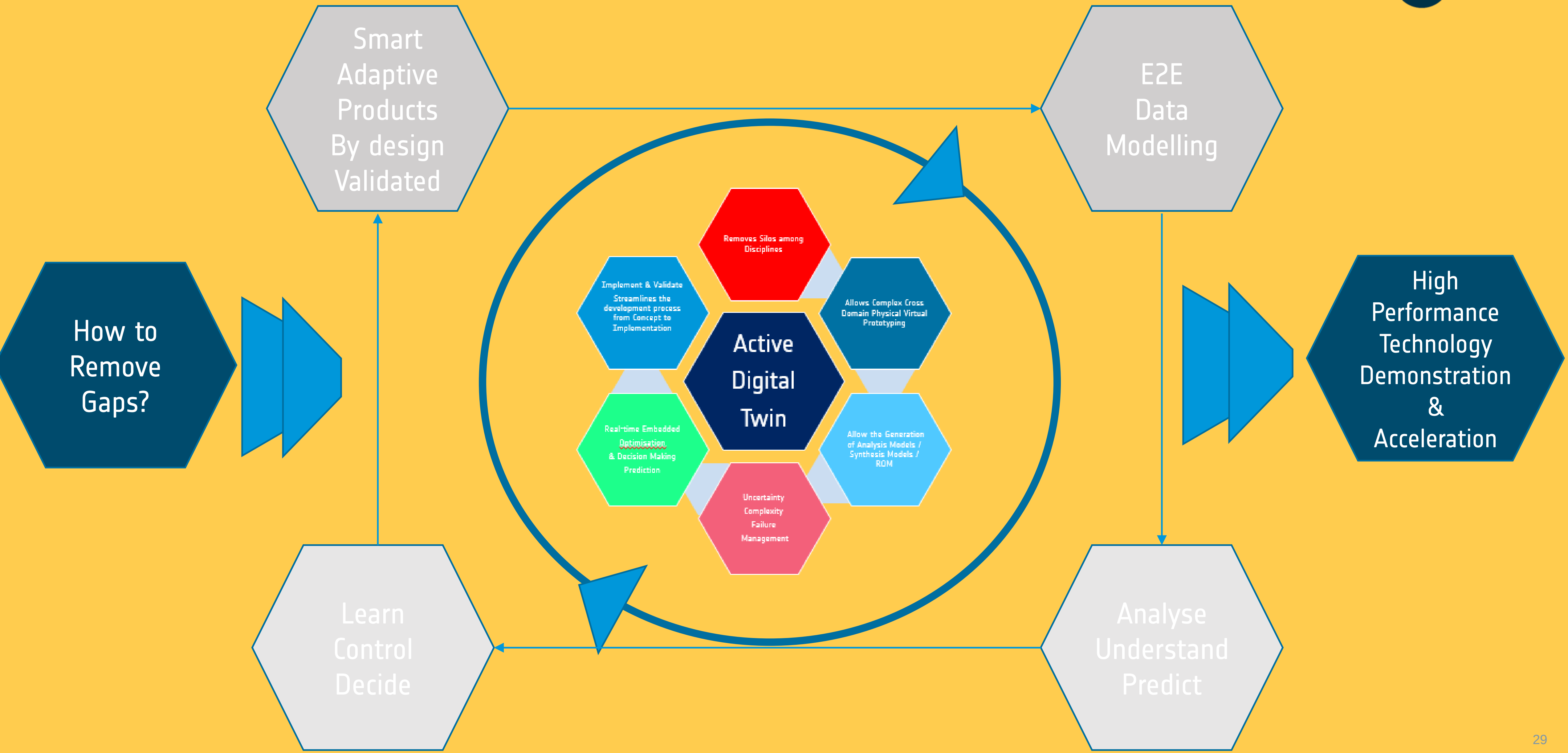
BENEFITS

- **Problem Statement**
- **Solutions**
- **Tools Used**
- **Results**
- **Benefits**
- **Takeaways & Conclusion**

BENEFITS ACTIVE DIGITAL TWINS

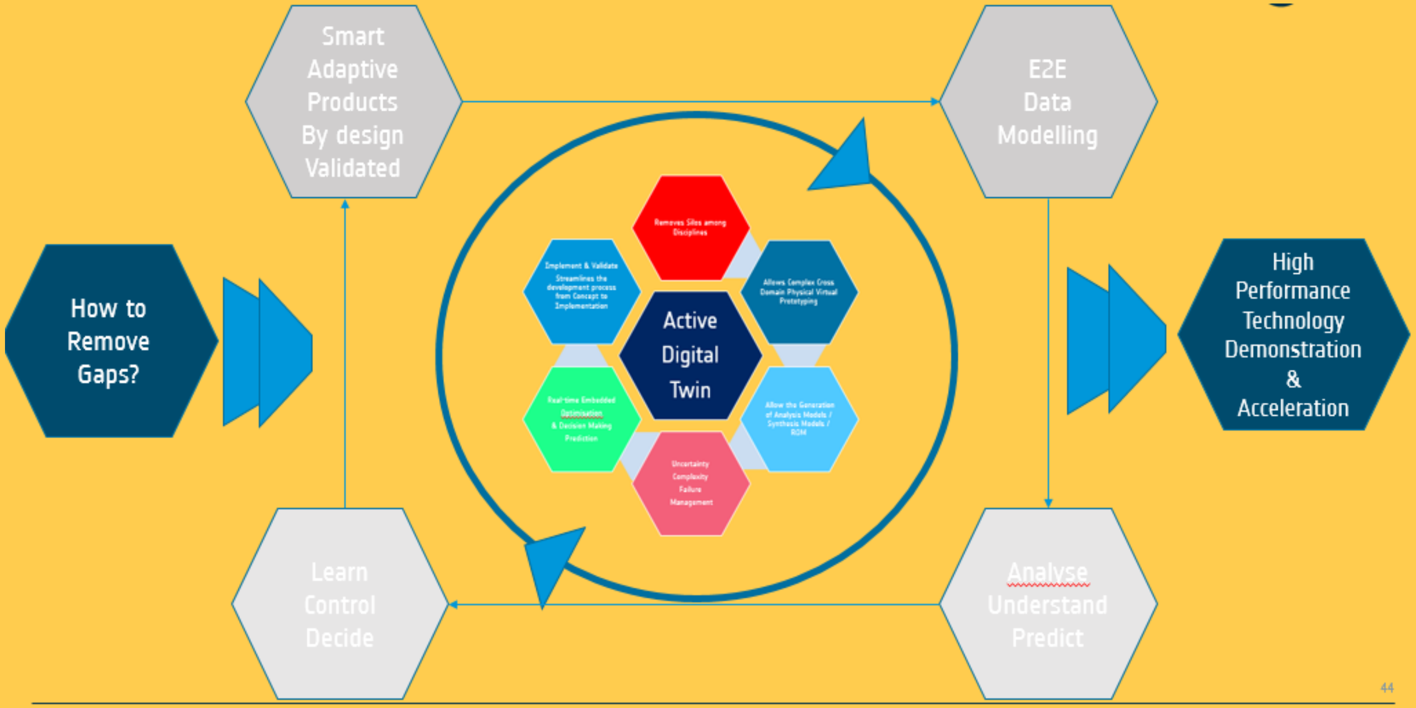


BENEFITS



Smart Adaptive Products By design Validated
E2E Data Modelling
How to Remove Gaps?
High Performance Technology Demonstration & Acceleration
Learn Control Decide
Analyse Understand Predict
Active Digital Twin
Removes Silos among Disciplines
Allows Complex Cross Domain Physical Virtual Prototyping
Allow the Generation of Analysis Models / Synthesis Models / ROM
Uncertainty Complexity Failure Management
Real-time Embedded Optimisation & Decision Making Prediction
Implement & Validate Streamlines the development process from Concept to Implementation

BENEFITS ACTIVE DIGITAL TWINS



This was only possible via an integraged tool chain

TAKEAWAYS

- Digital Twins (DT) are crucial for Active Controls of innovative concepts
    - From Concept Design to HW Implementation in matter of weeks (fast iteration cycle)
    - DT reveal Complex inter-dynamic couplings and system wide design drivers
    - Uncertainty management with Robust Modelling Analysis and Control
- Digital Twins within the MathWorks Toolchain
    - Estimated Time & Cost saving factor about 10
    - Demonstrated Broad Band Adaptive Active Isolation improvement factor 100
    - Developed innovative technology concept adaptable to any of our missions

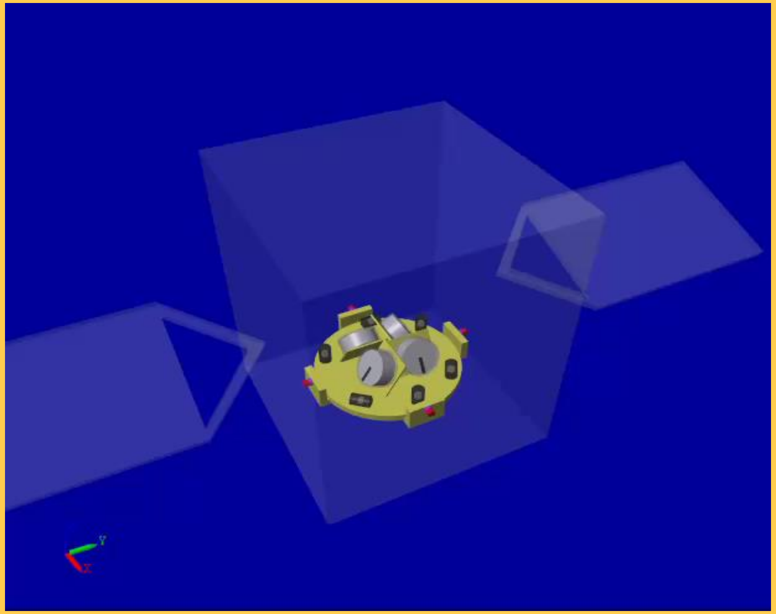
→ Main tools used: Simulink, Simscape, Robust Control Toolbox, System Identification Toolbox

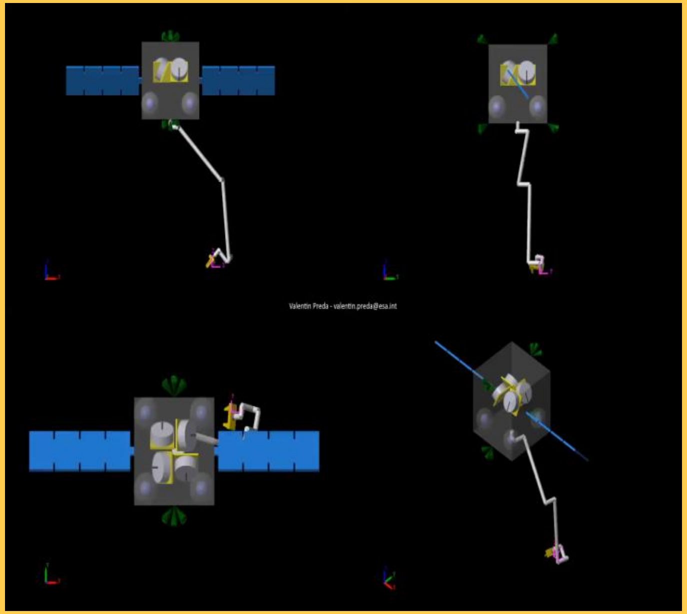
ONGOING ACTIVITIES

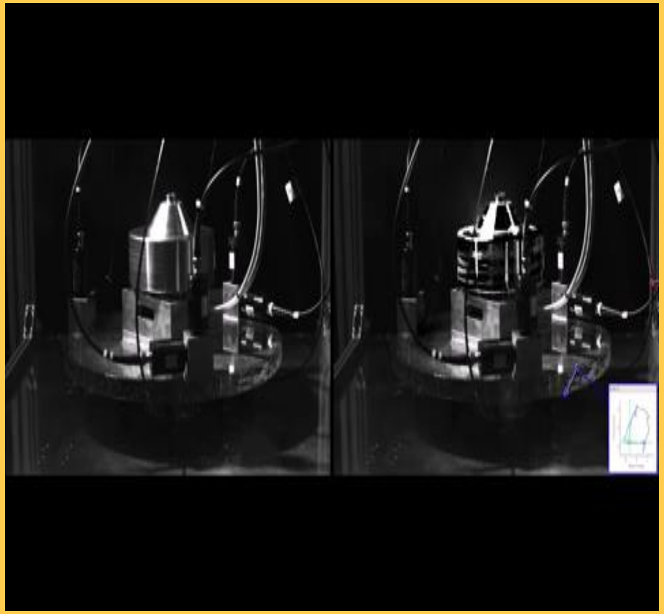
- Developing a Physics Informed and Dynamical Systems Based Machine Learning Design Framework (PDE, Hybrid Systems, from Non-Linear to Linear, incl. Neural ODE's, Implicit Equilibrium NN..)
- Active Digital Twins evolve from an off-line into an embedded Design and Validation process
  - The Digital Twin Modelling process is now performed via a Physics Informed and Real-Time driven System Identification Process
  - We develop a Guaranteed Online Decision Process using well founded theoretical and numerical results from robust control theory and real-time optimisation.
  - The unknown unknowns are managed online....
- Development of analysis tools from Robust Controls assessing robustness Neural Nets (deployed as surrogates for complexity)

Towards Robust & Autonomous Space Systems

DIGITAL TWINS IN ACTION







DON'T PANIC! WE ARE IN CONTROL

THANKS TO THE ENTIRE ESA GNC TEAM !!!!!