Nano Active Stabilization of samples for tomography experiments: A mechatronic design approach

PhD Thesis

By

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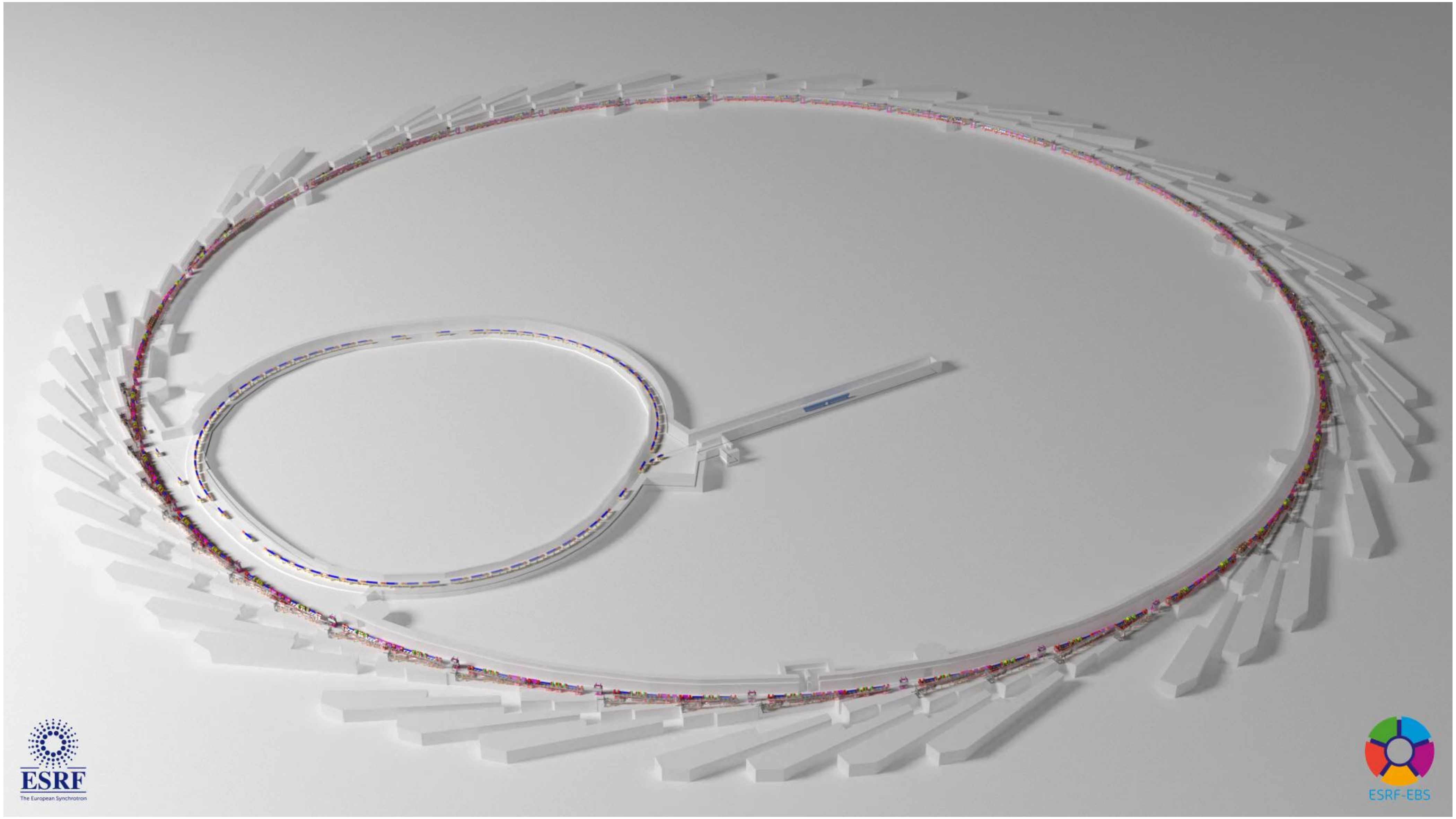
Supervisor: Christophe Collette

fnrs LA LIBERTÉ DE CHERCHER

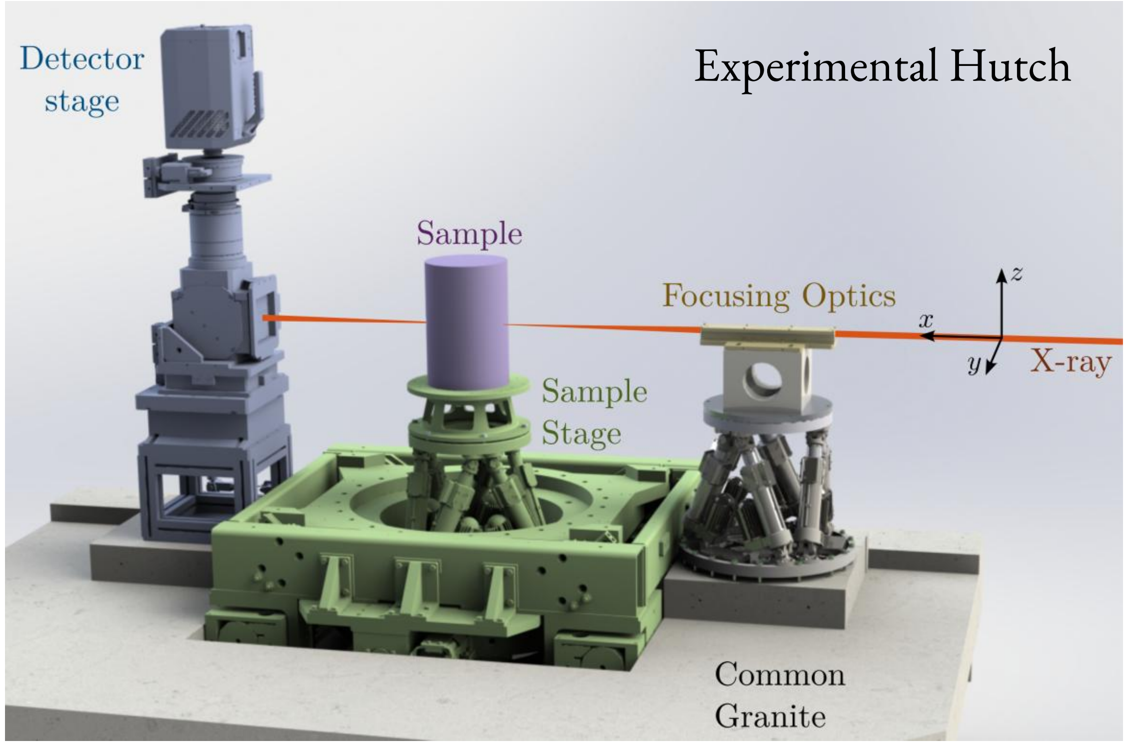
LIÈGE université

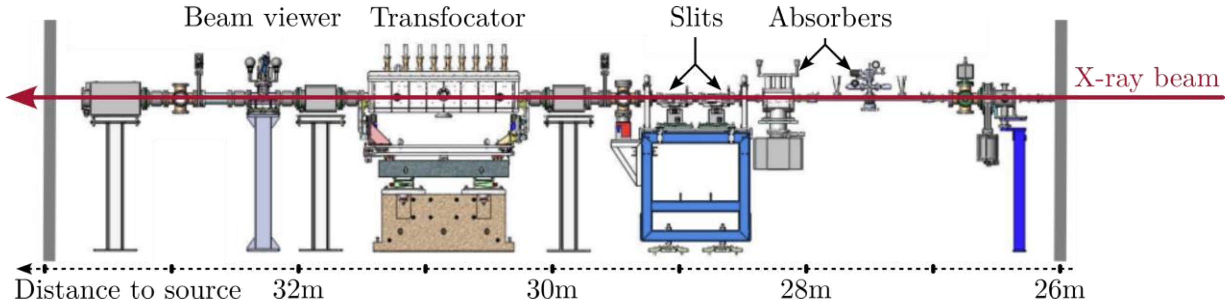
ESRF

The European Synchrotron Radiation Facility (ESRF)

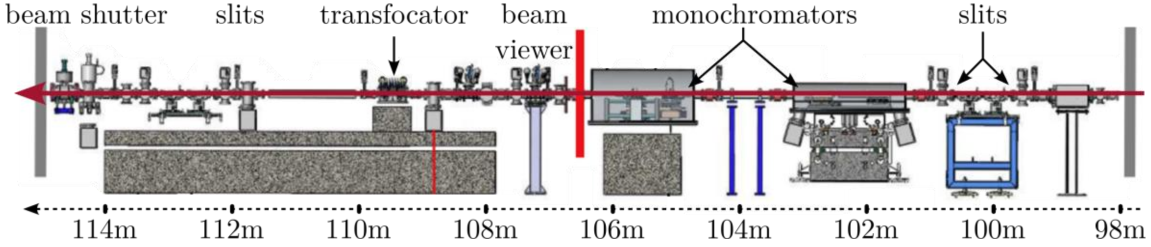


ID31 Beamline





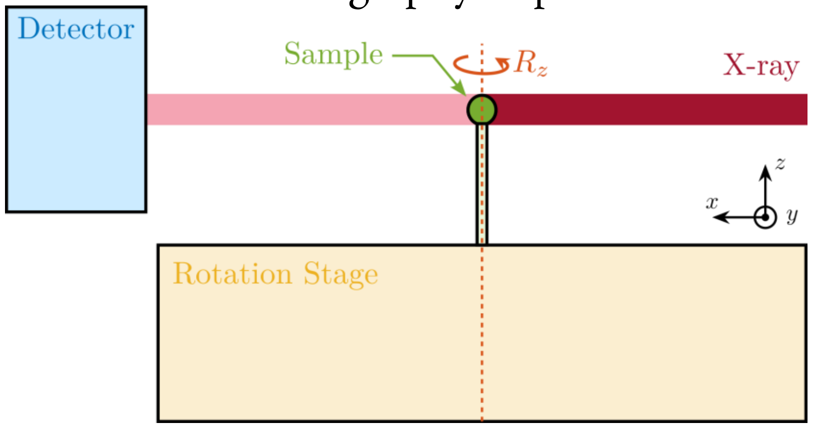
Optical Hutch 1

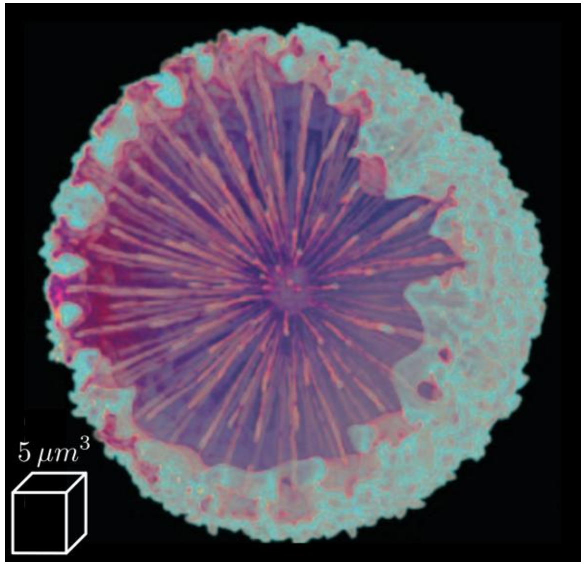


Optical Hutch 2

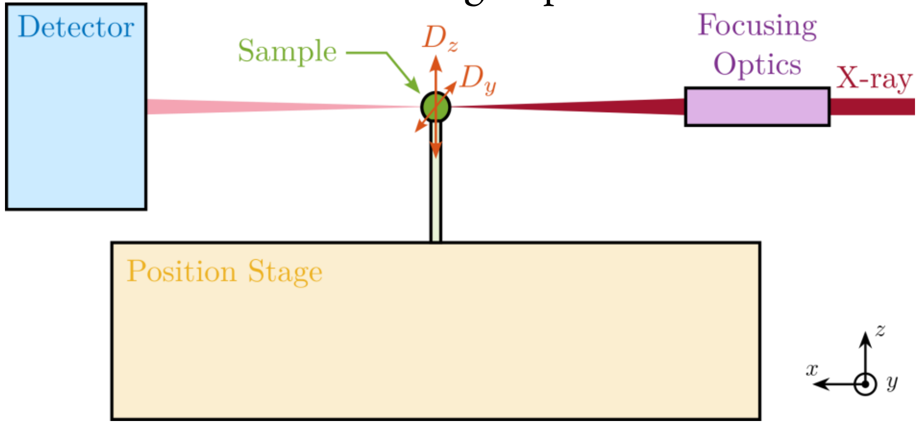
Scientific Examples

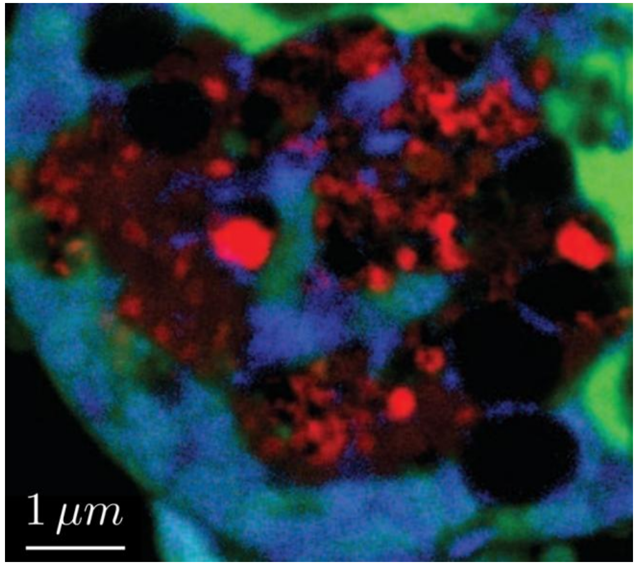
Tomography Experiment



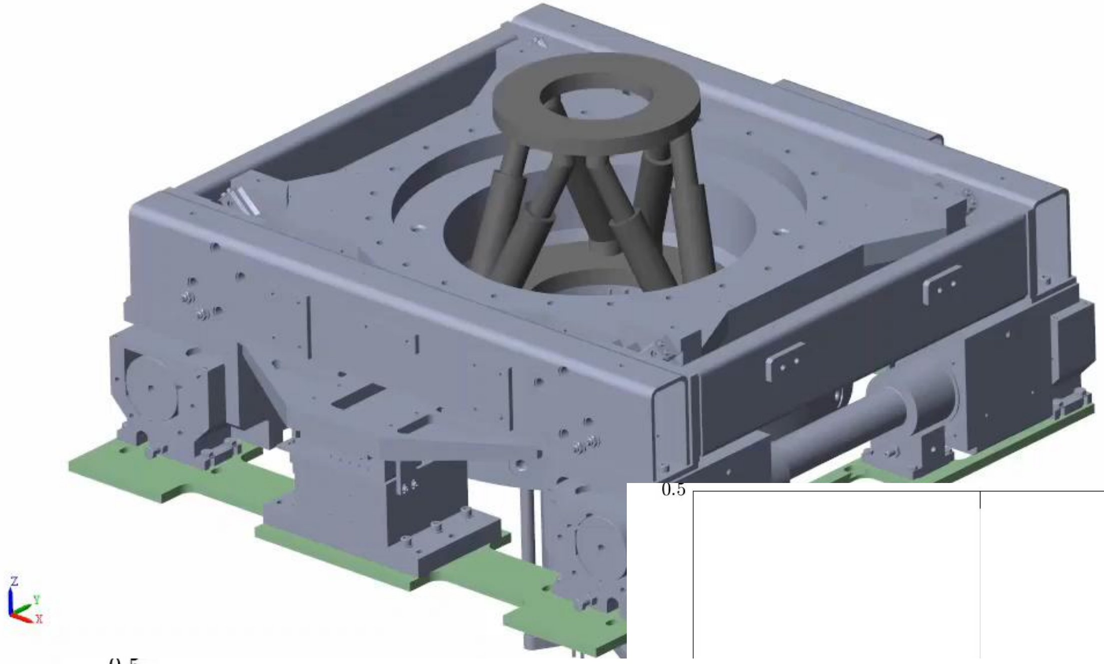


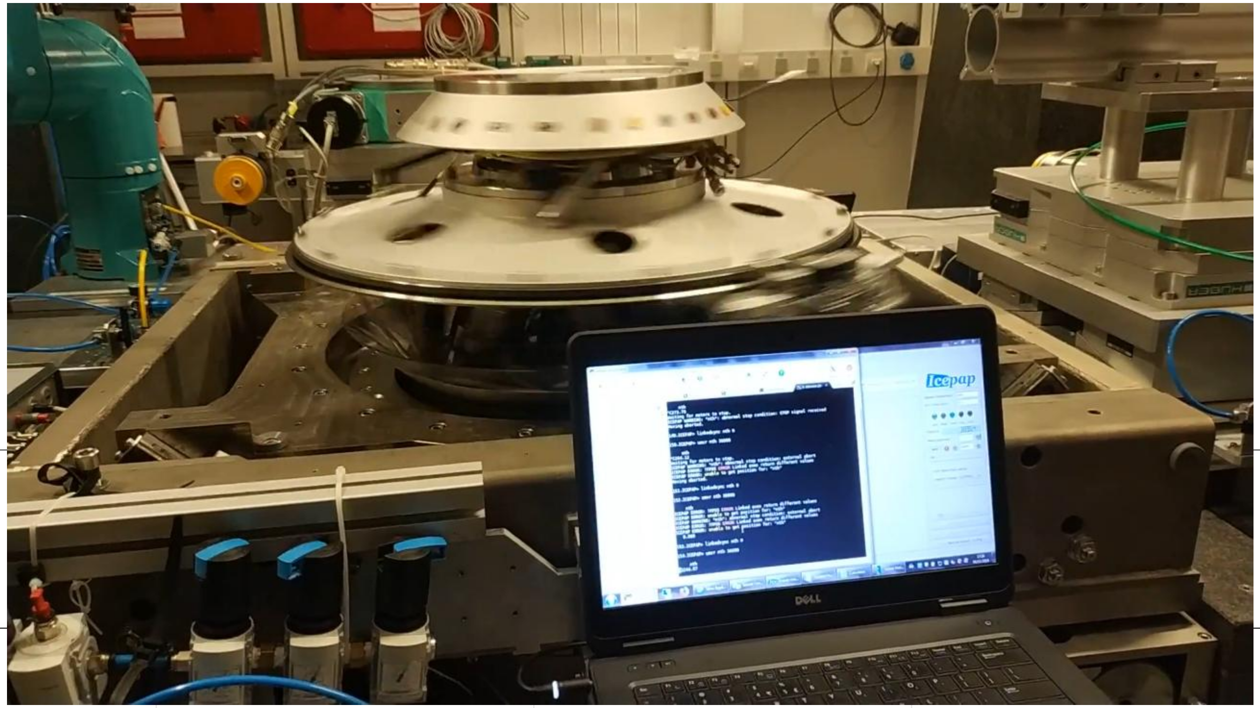
Scanning Experiment

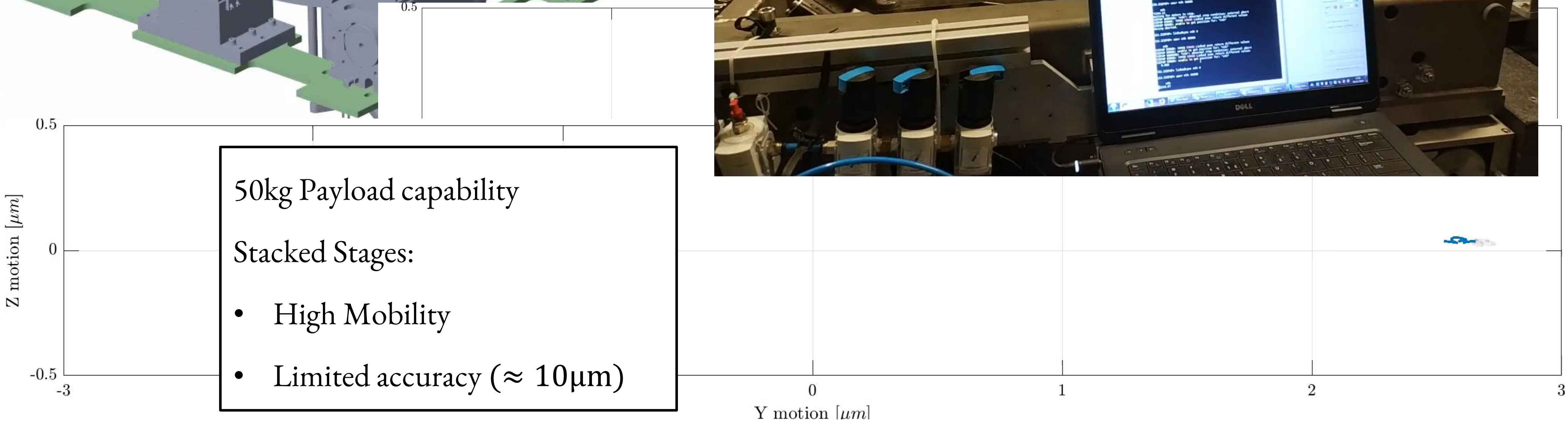




ID31 Positioning Stage: The Micro Station







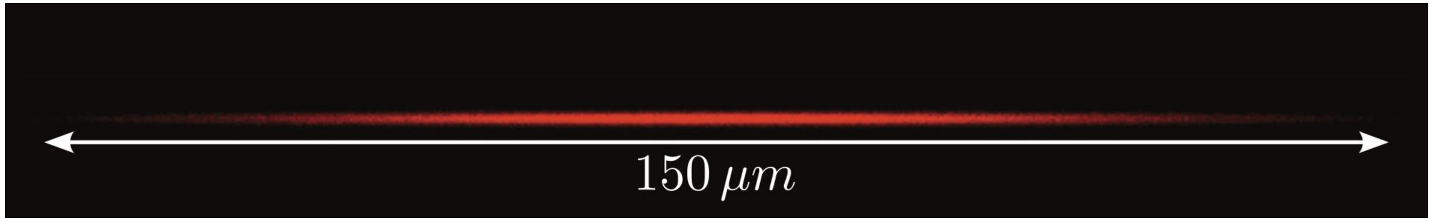
50kg Payload capability

Stacked Stages:

- High Mobility
- Limited accuracy (≈ 10µm)

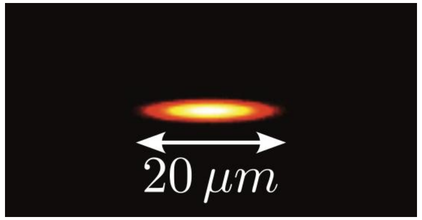
New Positioning Needs: From µm to nm

3^{rd} Generation Light Source

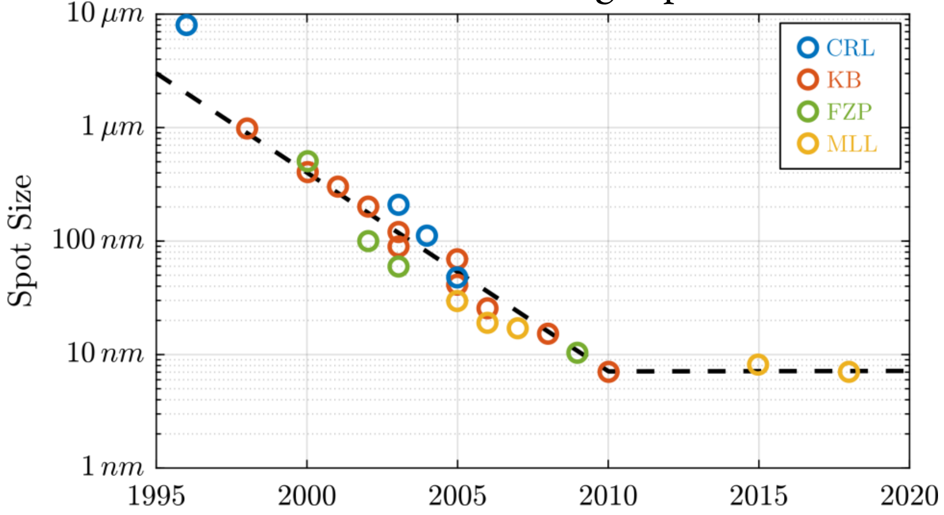


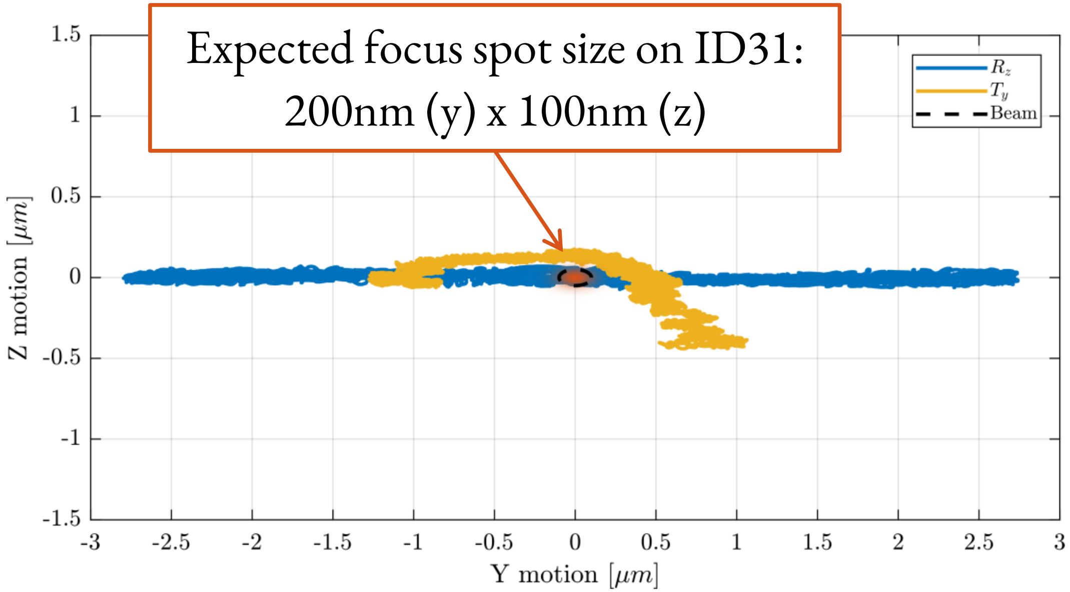
Smaller Light Source →

4^{th} Generation Light Source



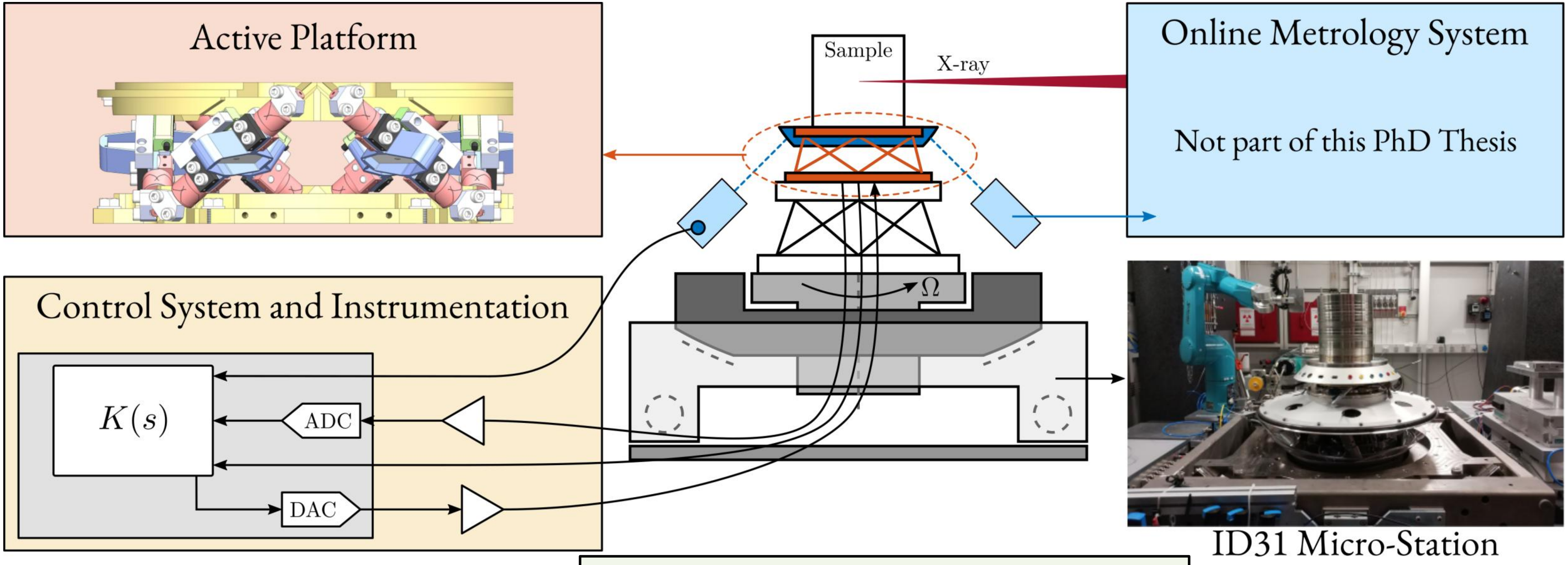
Better Focusing Optics





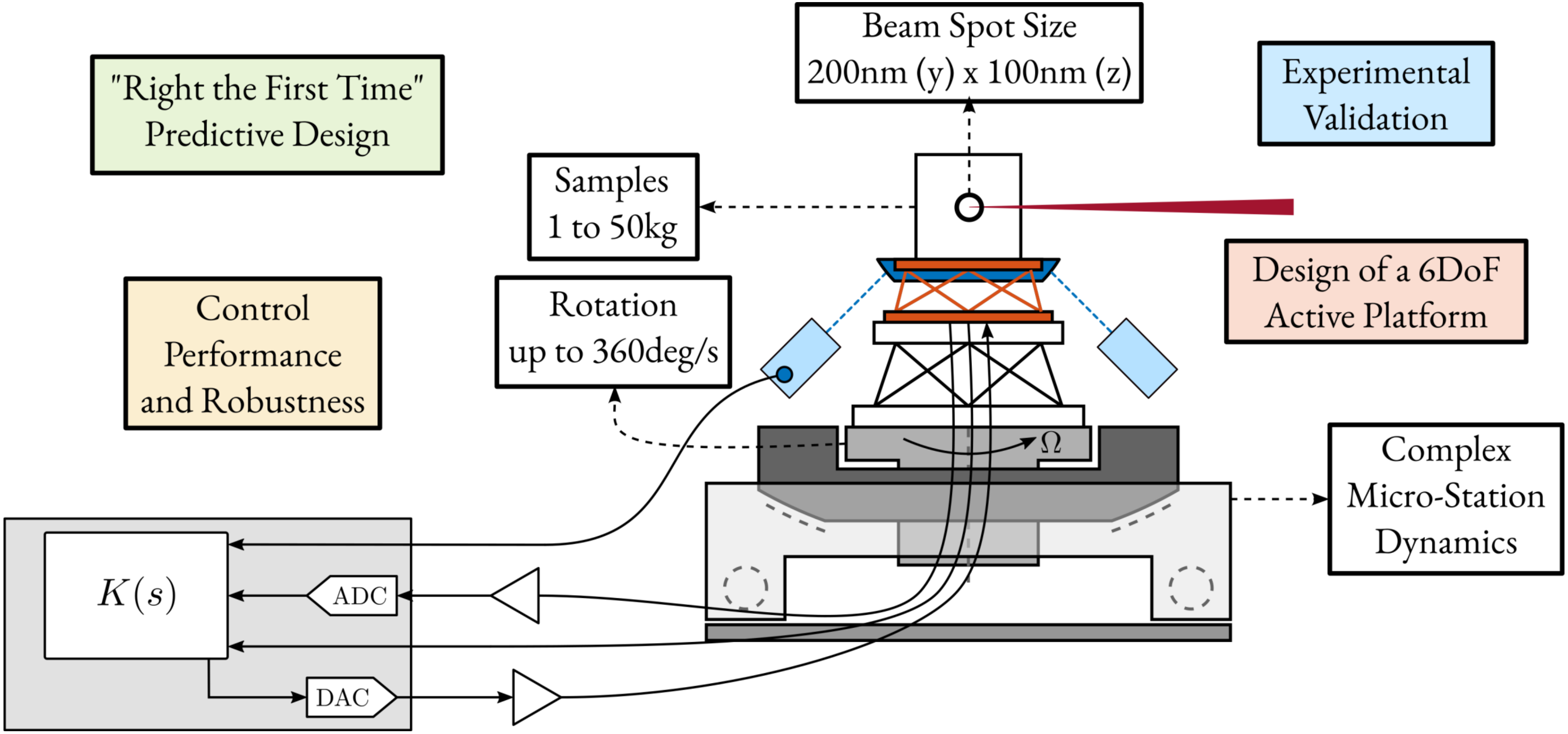
Need to increase the positioning accuracy of the ID31 Micro-station

Nano Active Stabilization System (NASS) - Concept

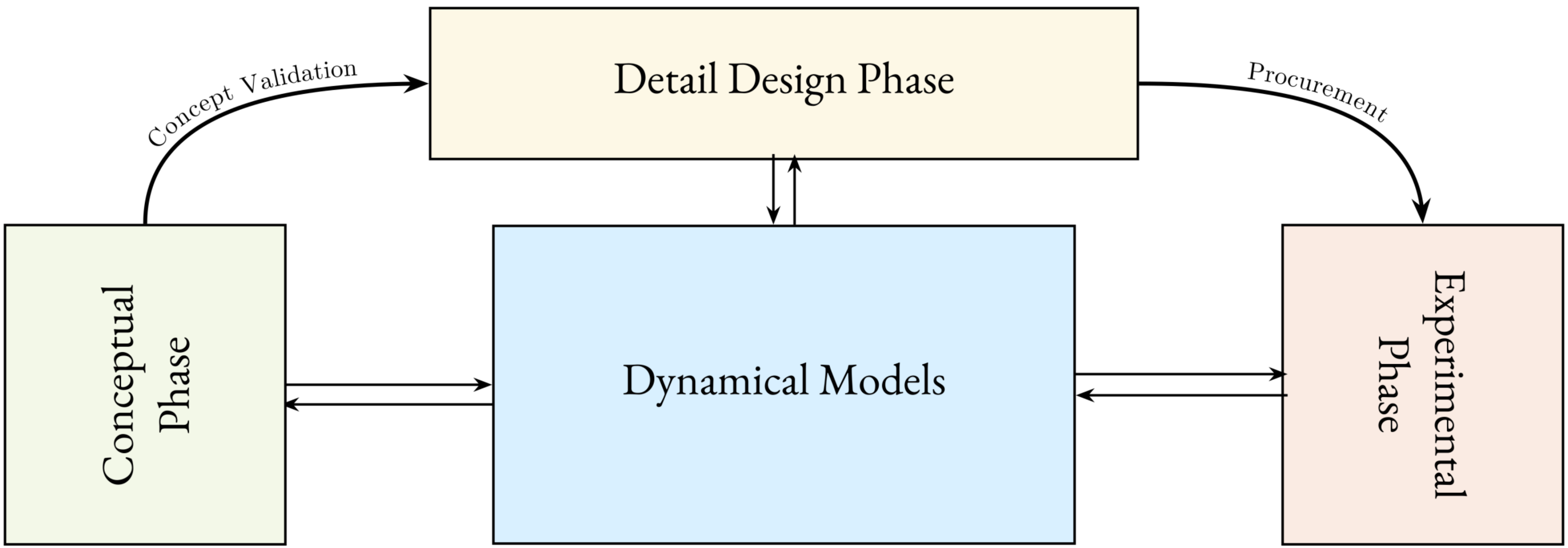


Goal: Keep the PoI of the sample on the beam (200nm x 100nm), as the micro-station is performing scans

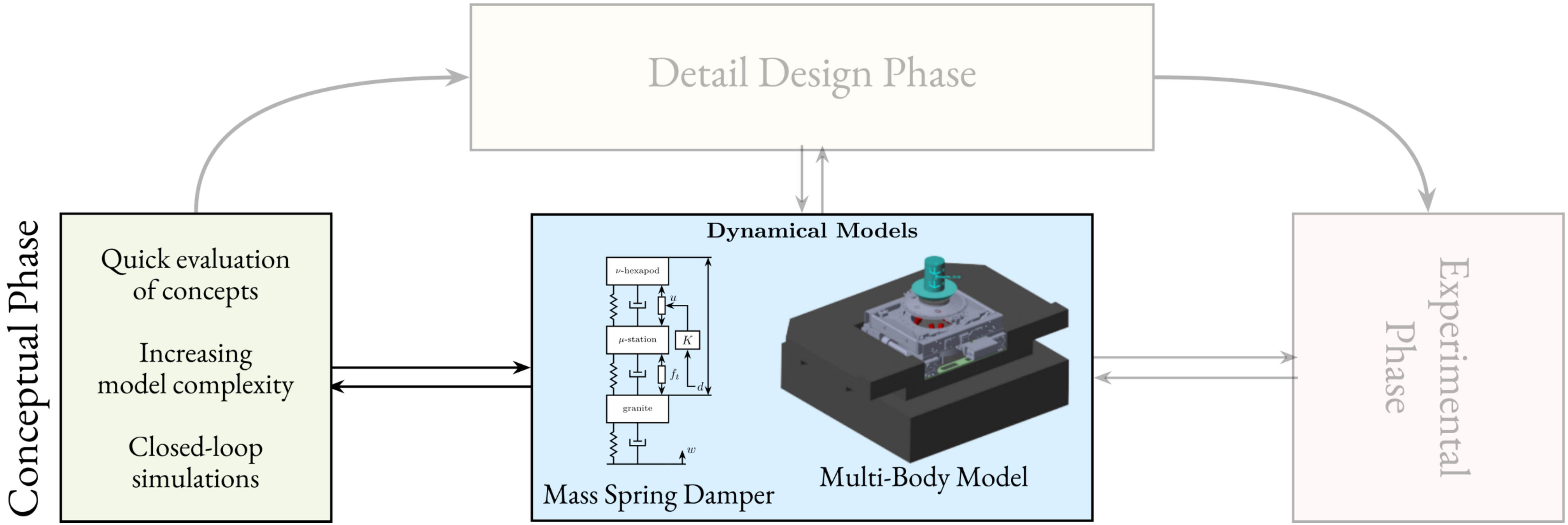
Challenges for the design of the NASS



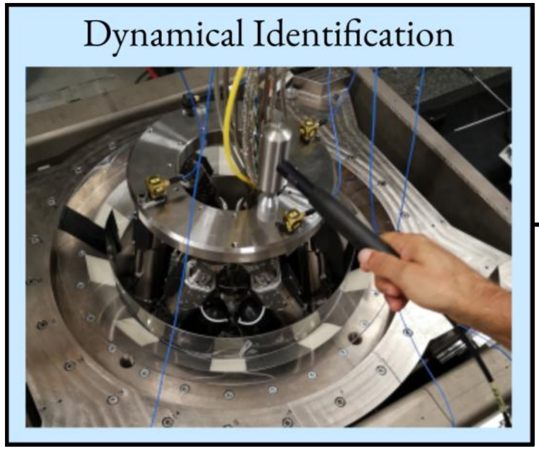
Outline - Design Strategy

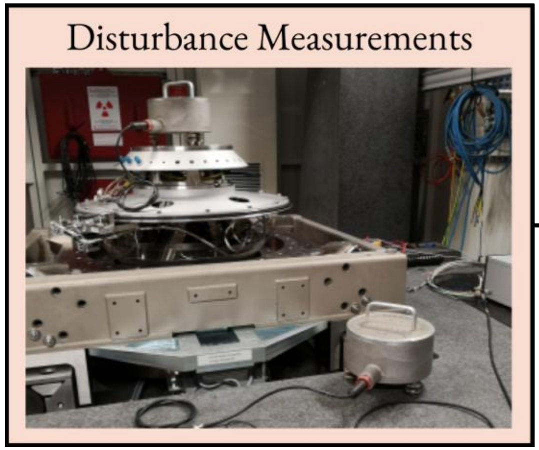


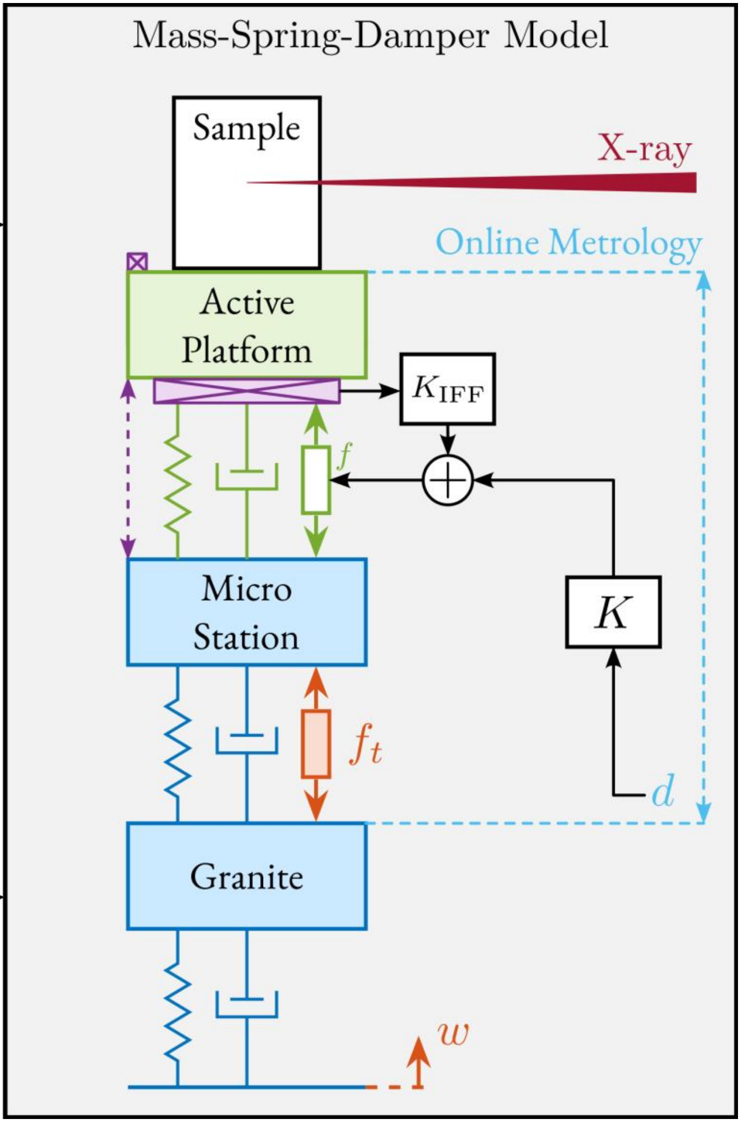
Conceptual Design Development

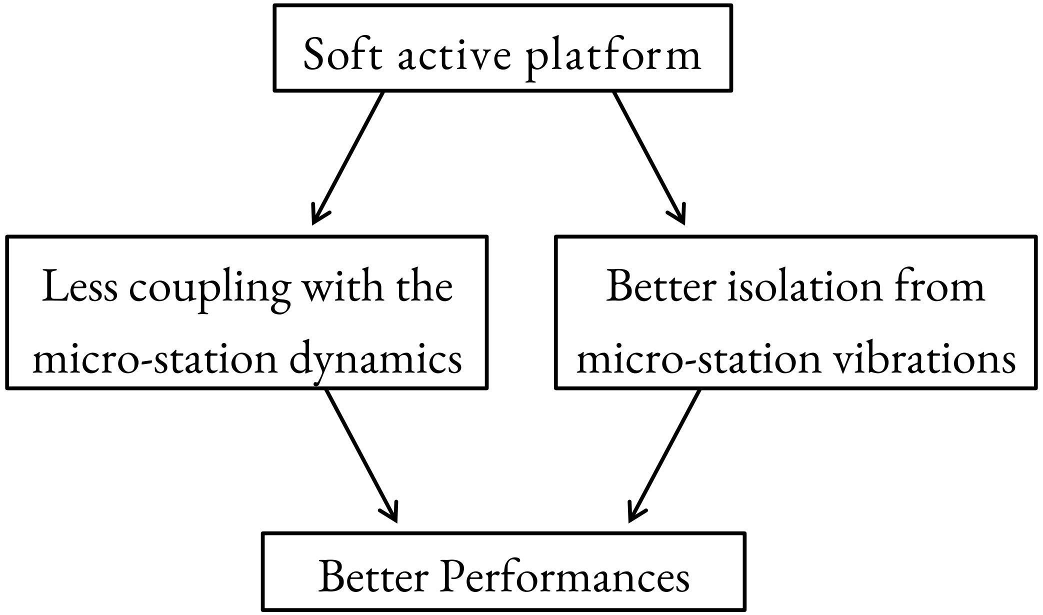


Uniaxial Model

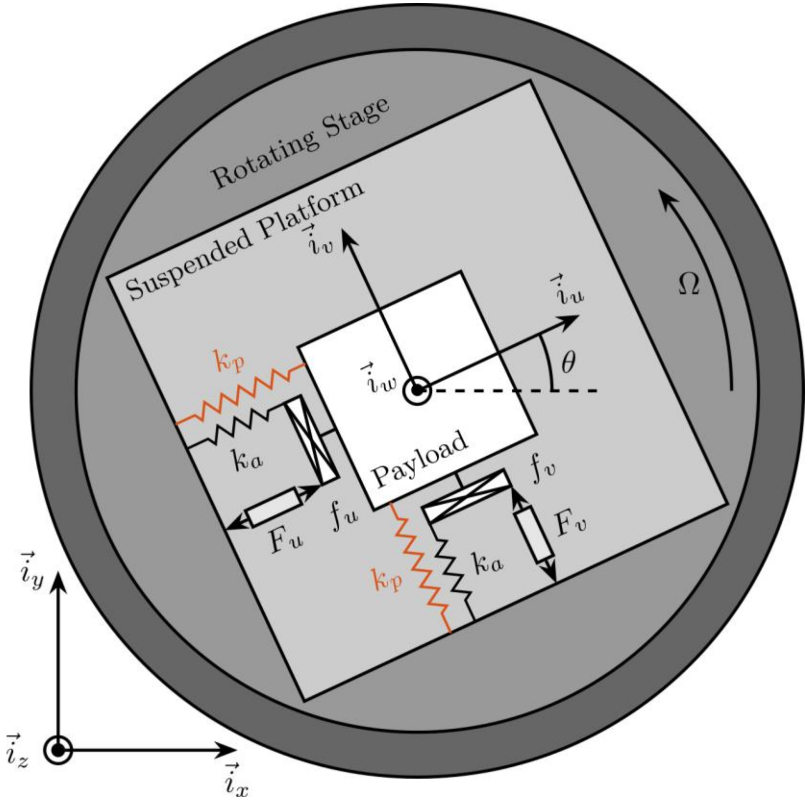








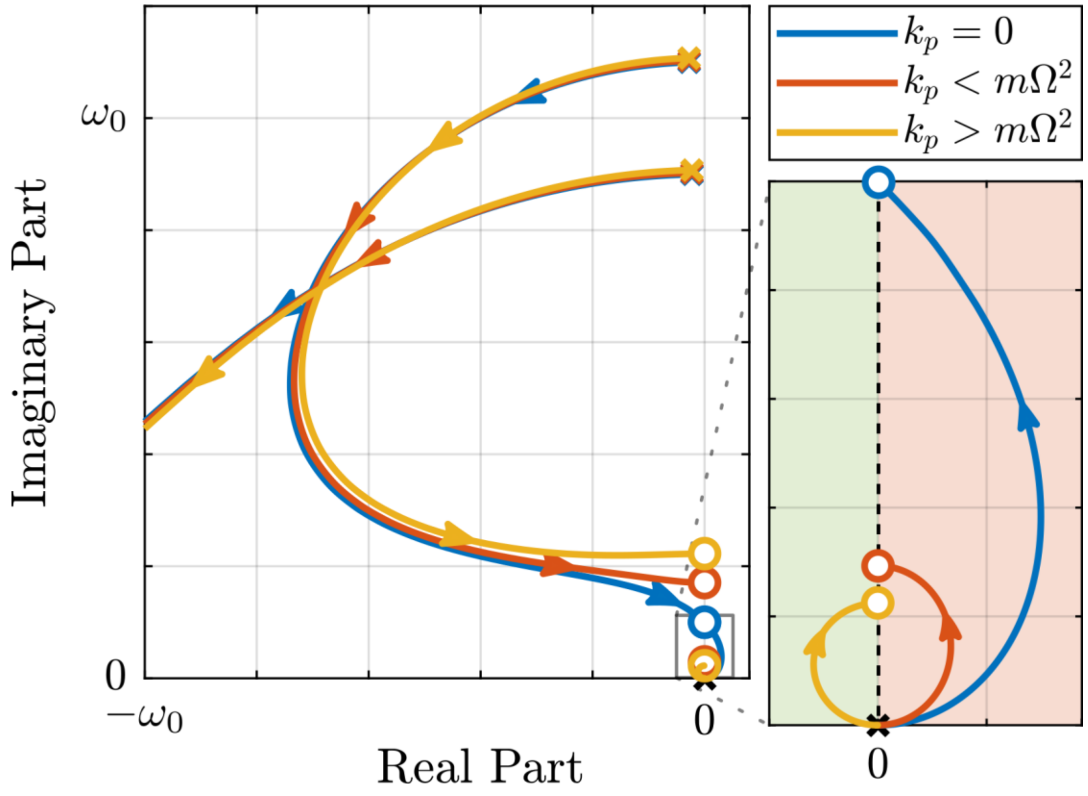
Rotating Model



Centrifugal Forces

Coriolis Effect

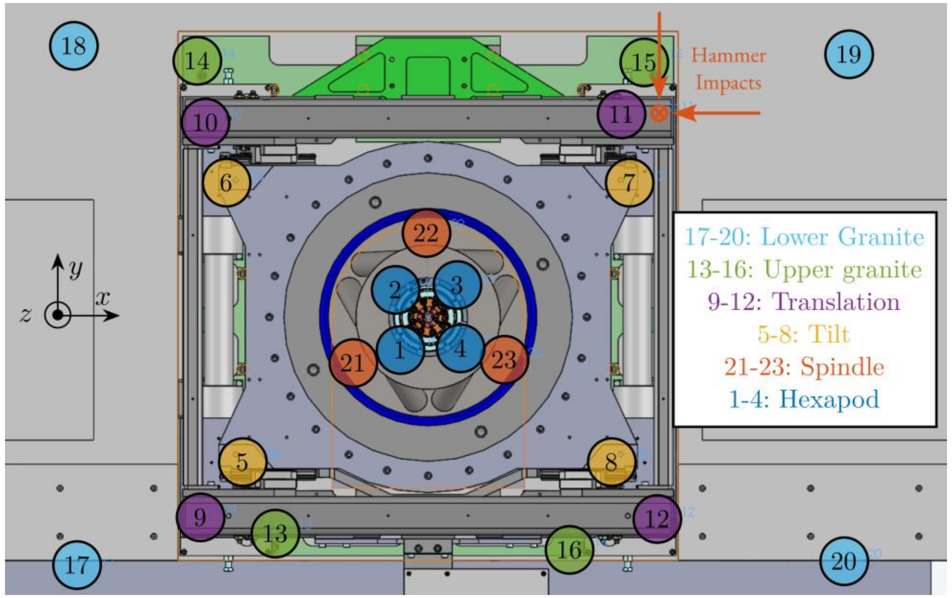
$$m\ddot{d}_u + c\dot{d}_u + (k - m\Omega^2)d_u = F_u + 2m\Omega\dot{d}_v$$
$$m\ddot{d}_v + c\dot{d}_v + (k - m\Omega^2)d_v = F_v - 2m\Omega\dot{d}_u$$

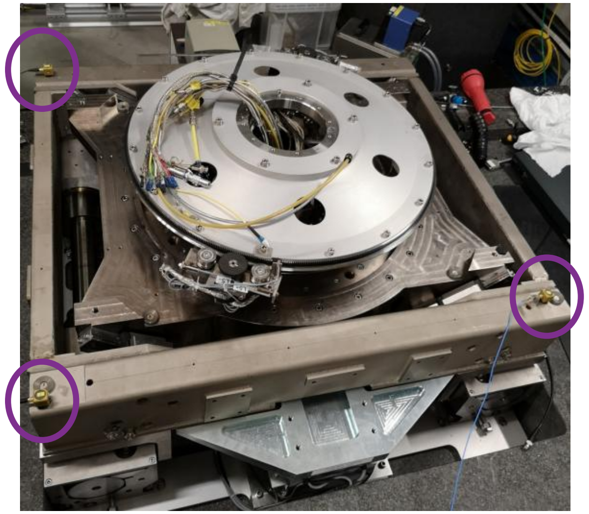


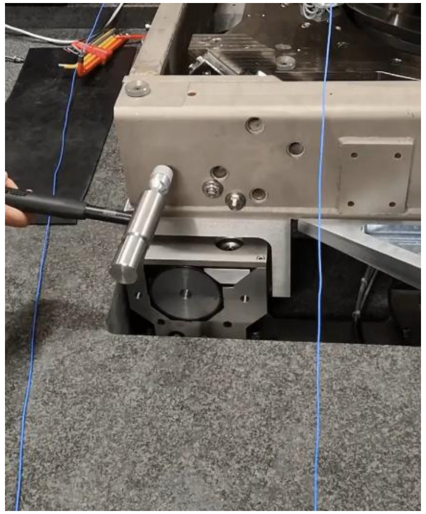
Regained unconditional IFF stability with k_p
Stiff Active Platforms less impacted by Ω

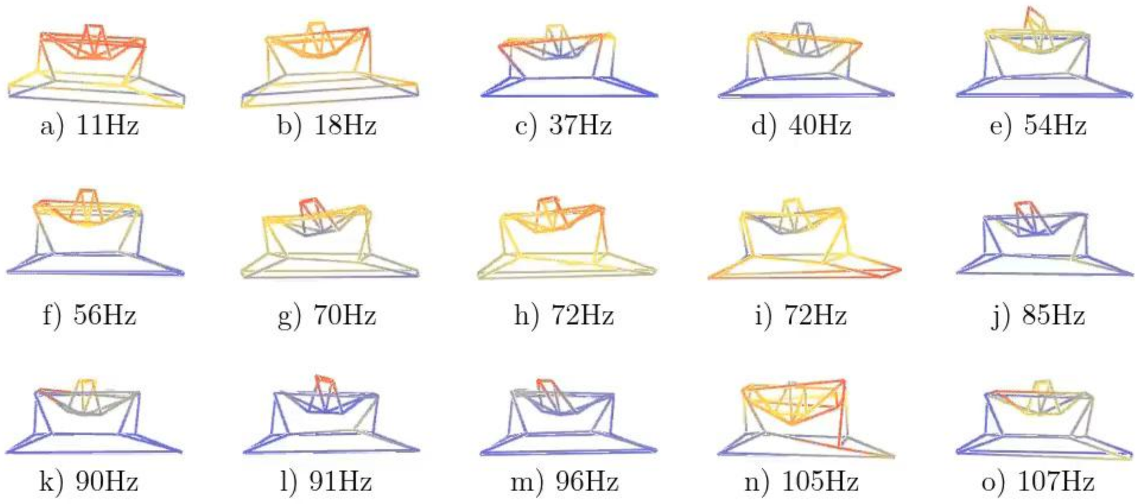
T. Dehaeze and C. Collette.
"*Active Damping of Rotating Platforms Using Integral Force Feedback*".
In Engineering Research Express 2021

Micro-Station – Modal Analysis



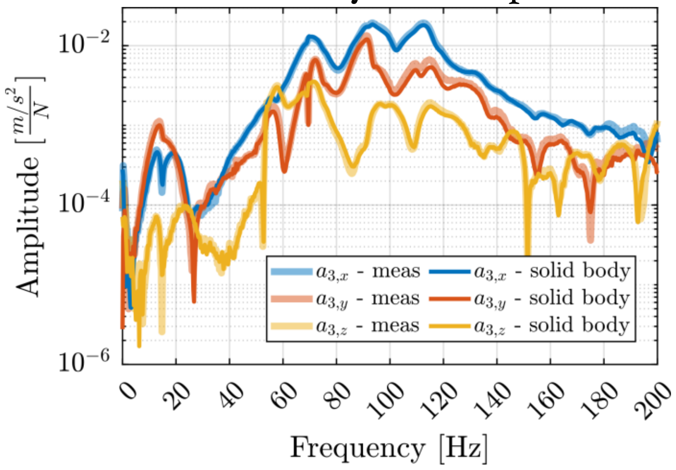






Marc Lesourd

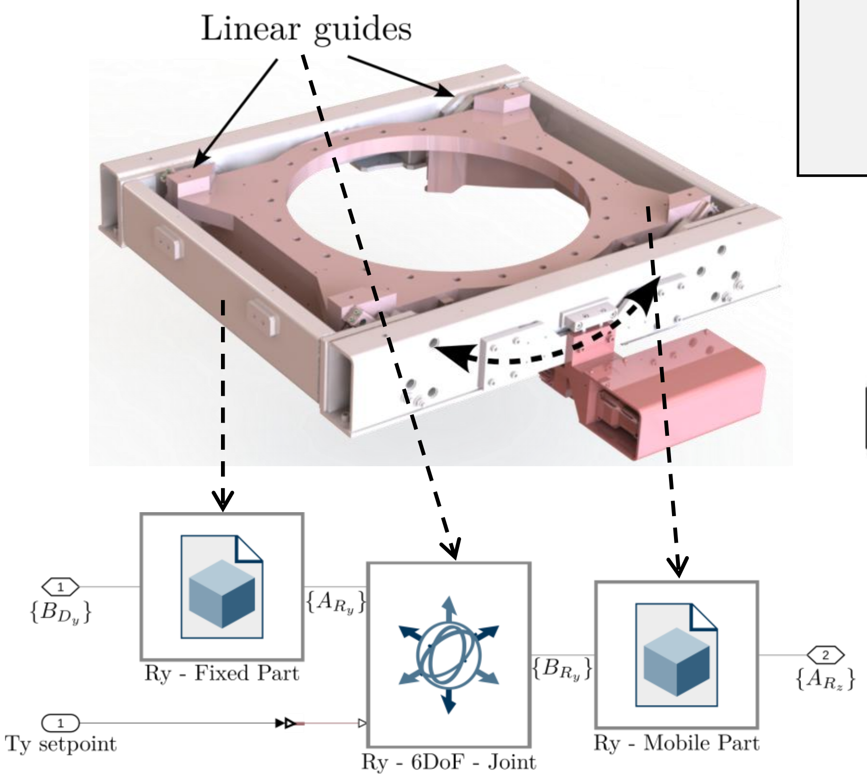
Solid Body Assumption



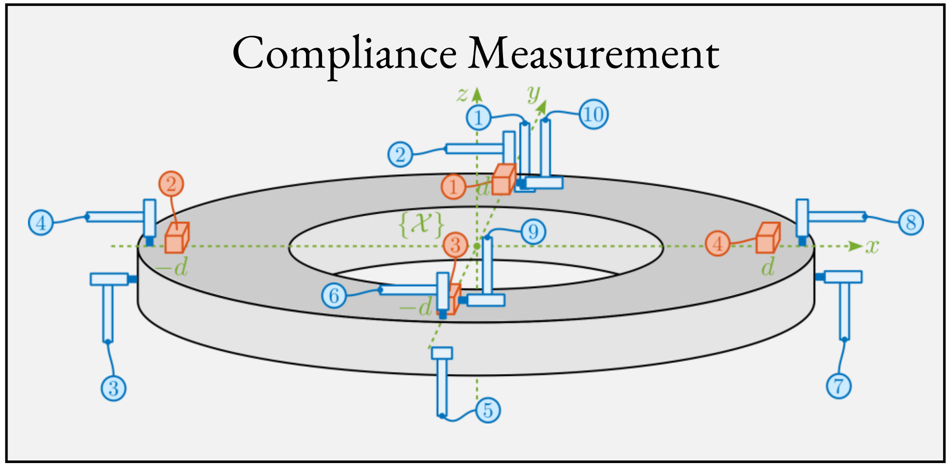
Micro-Station – Multi-Body Model

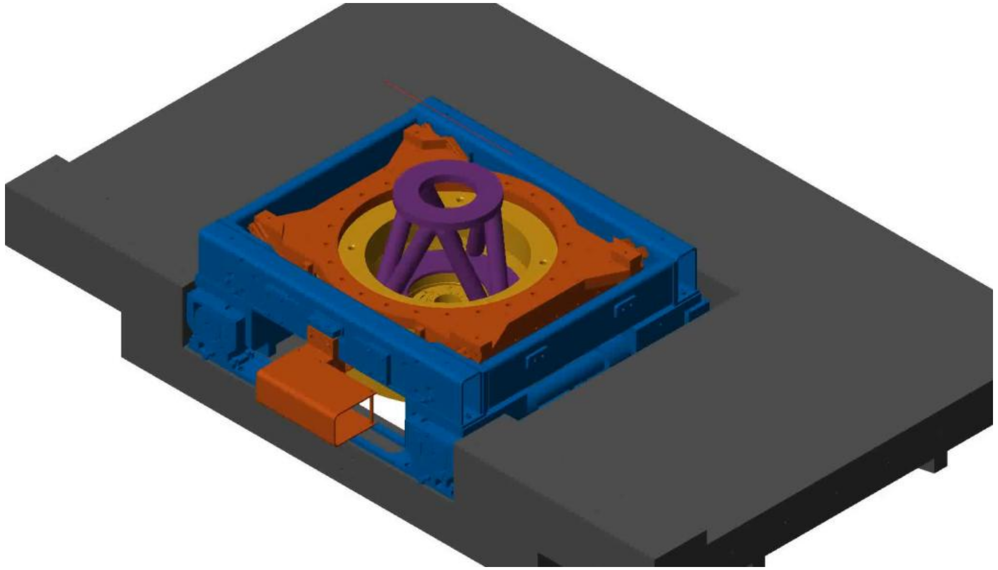
Multi-Body Model

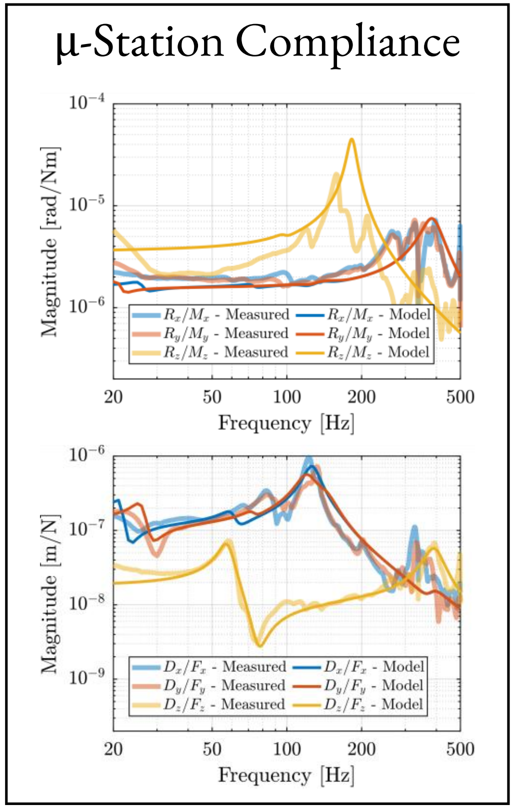
Solid bodies connected by springs and dampers

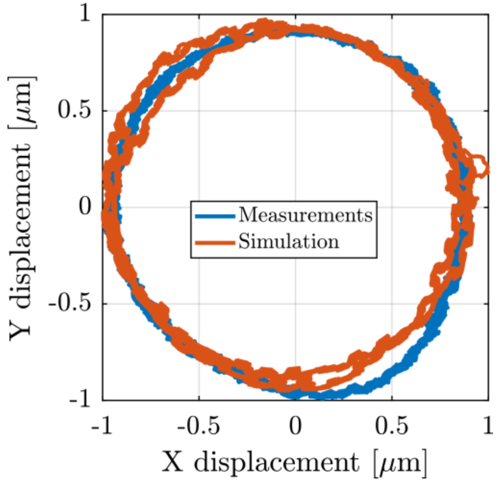


Simulink/Simscape Software

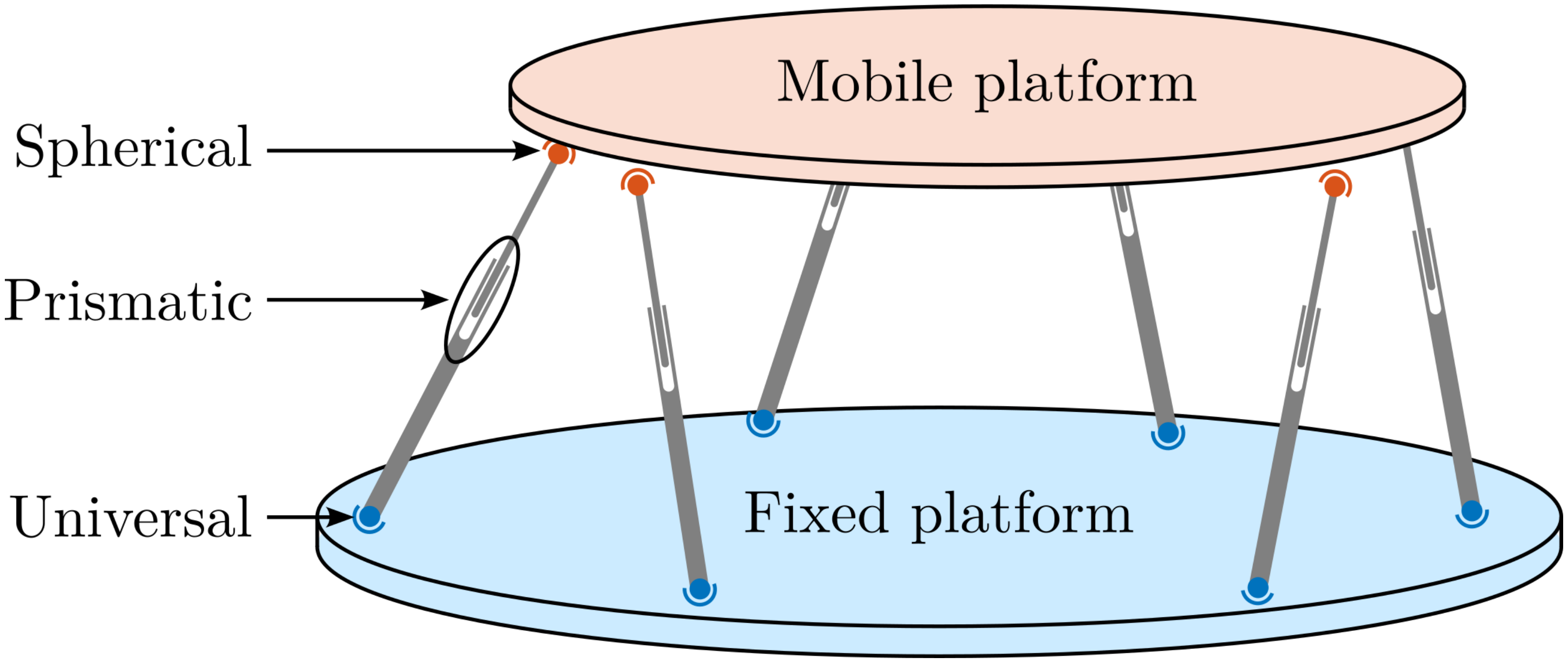




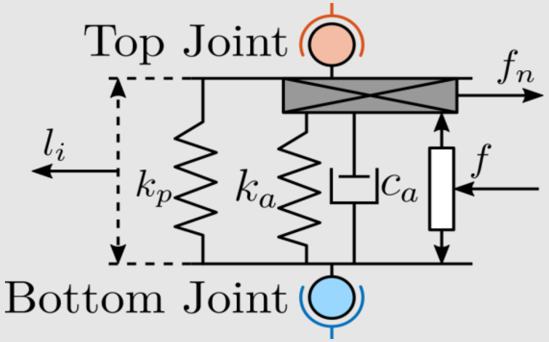




Active Platform – The Gough-Stewart Platform



Multi-Body Model



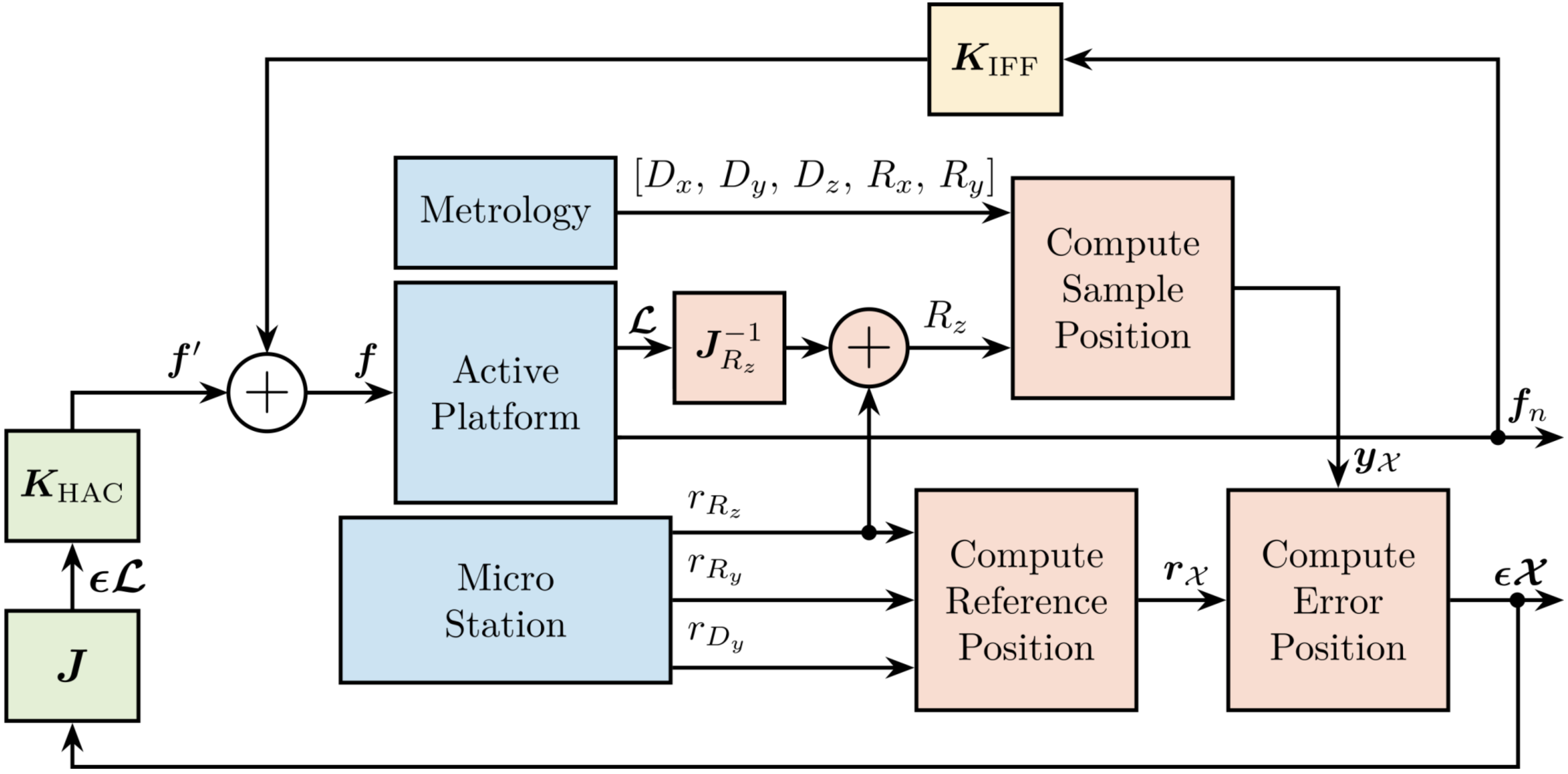
Approximate Kinematic

$$\boldsymbol{\mathcal{X}} = \boldsymbol{J}^{-1} \cdot \boldsymbol{\mathcal{L}}$$

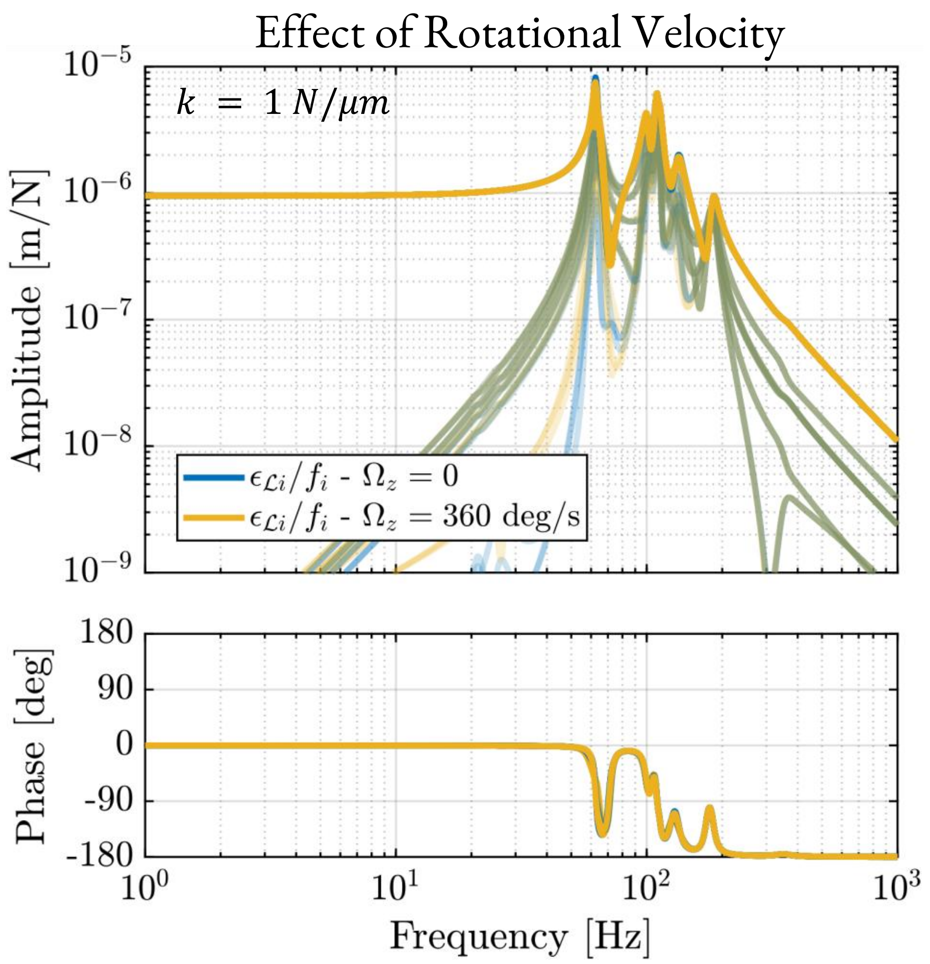
$$\boldsymbol{\mathcal{L}} = \boldsymbol{J} \cdot \boldsymbol{\mathcal{X}}$$

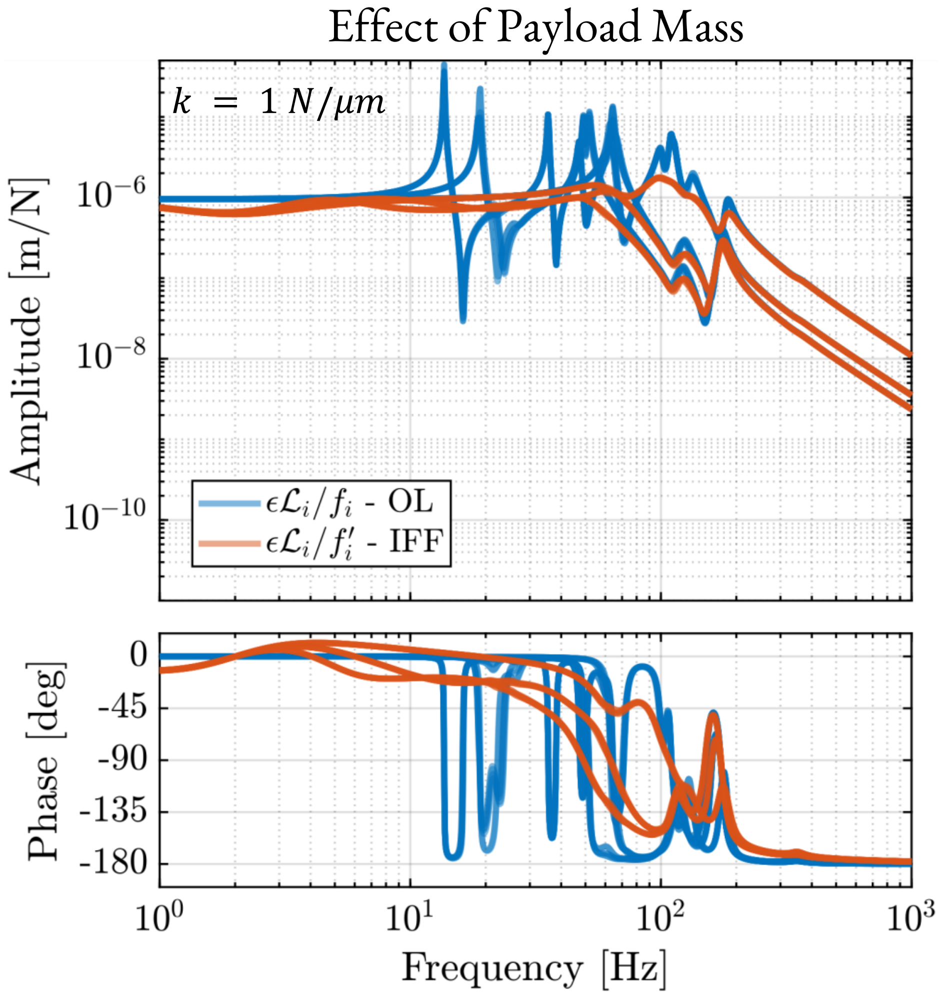
Jacobian Matrix

Control Architecture



Nano Active Stabilization System - Dynamics

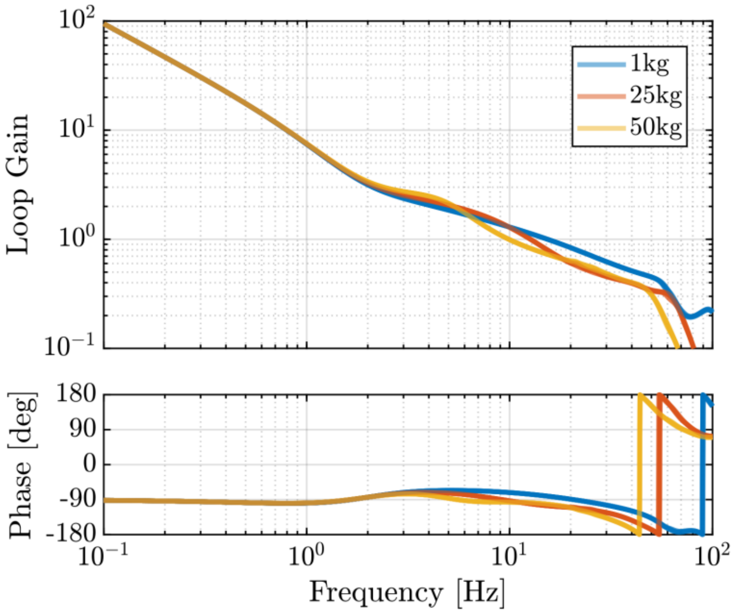


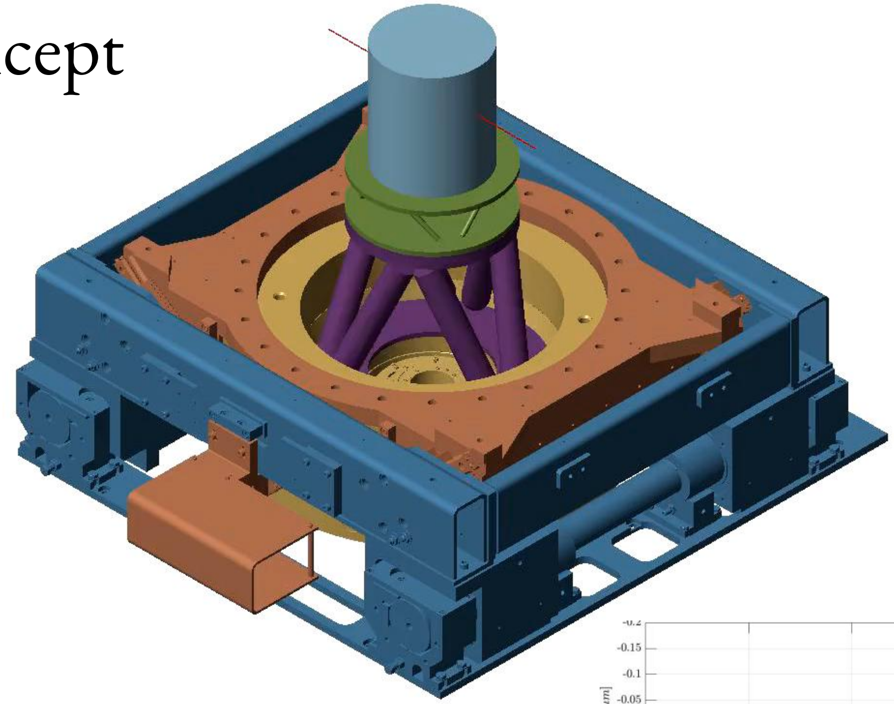


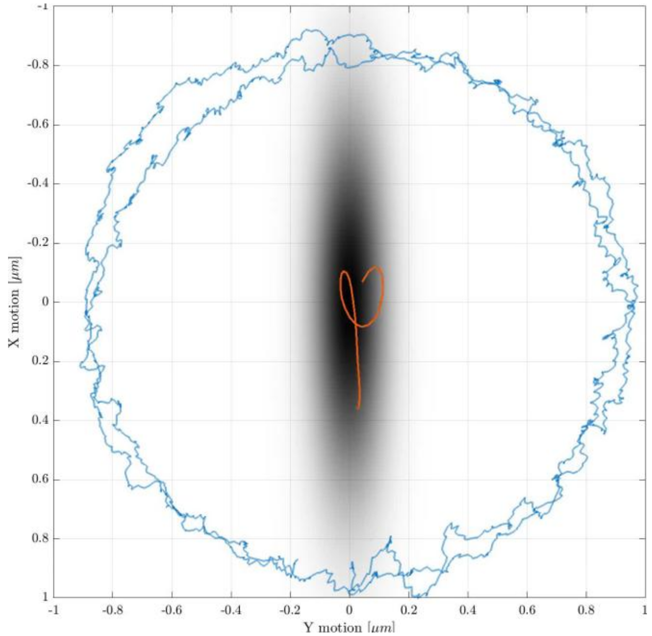
Validation of the Concept

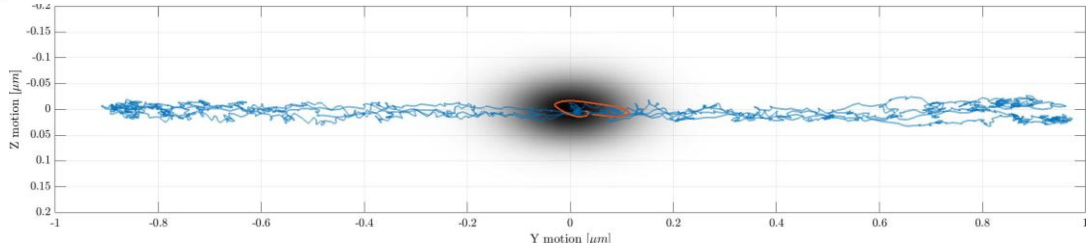
Integrator · Lead · LPF

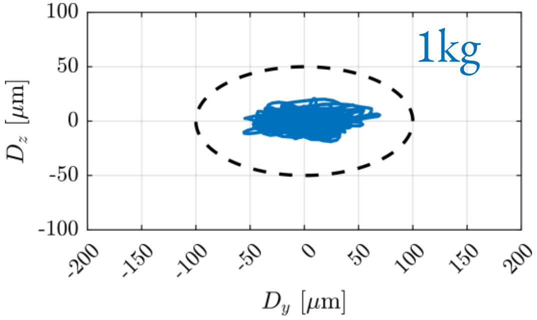
$$K_{\mathrm{HAC}}(s) = g_0 \cdot \frac{\omega_c}{s} \cdot \frac{1}{\sqrt{\alpha}} \frac{1 + \frac{s}{\omega_c/\sqrt{\alpha}}}{1 + \frac{s}{\omega_c\sqrt{\alpha}}} \cdot \frac{1}{1 + \frac{s}{\omega_0}}$$

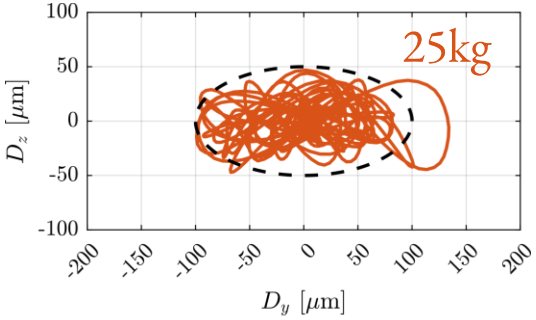


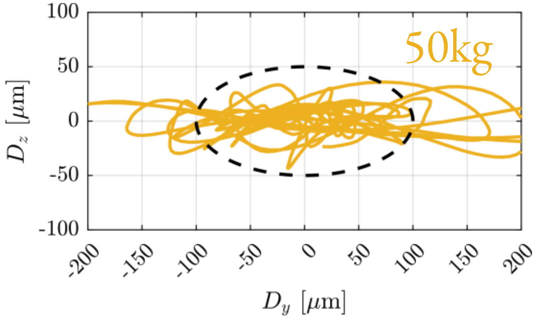




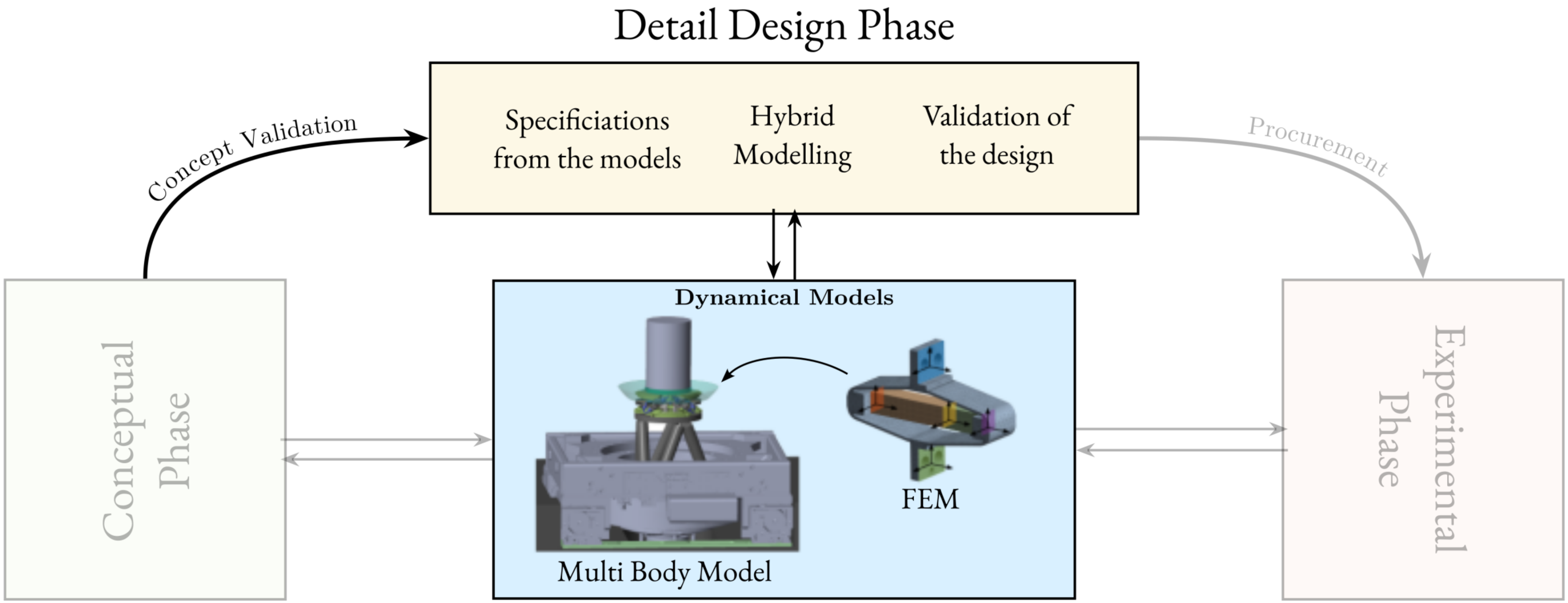








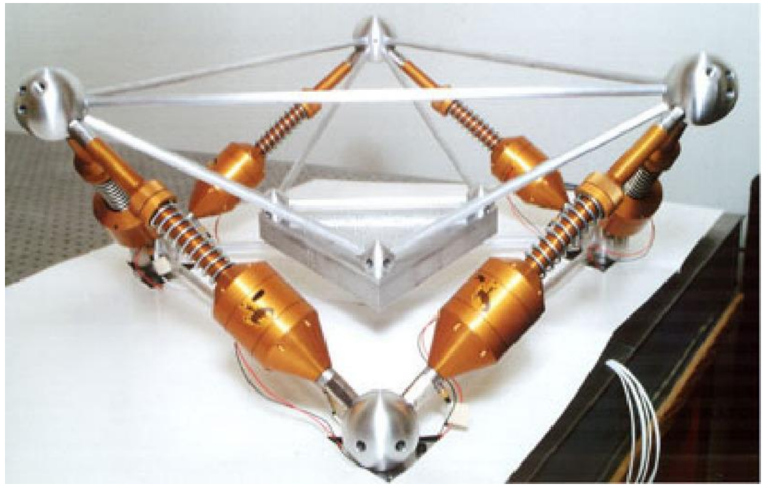
Detail Design



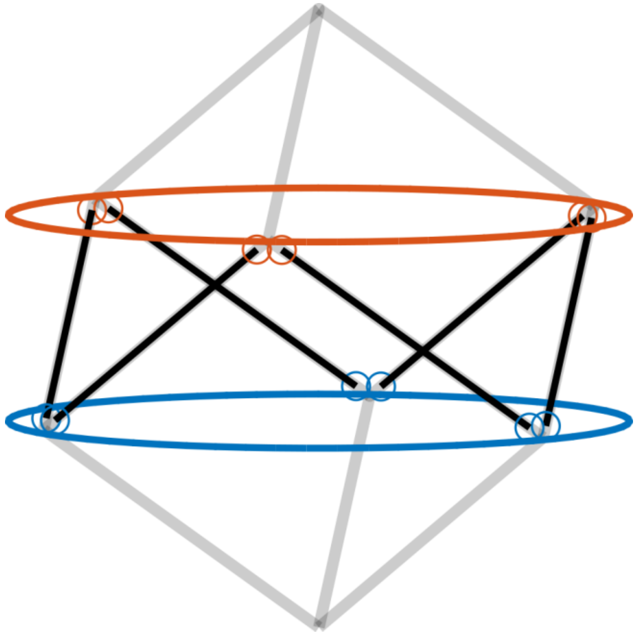
Mechanical Architecture – Optimal Geometry ?

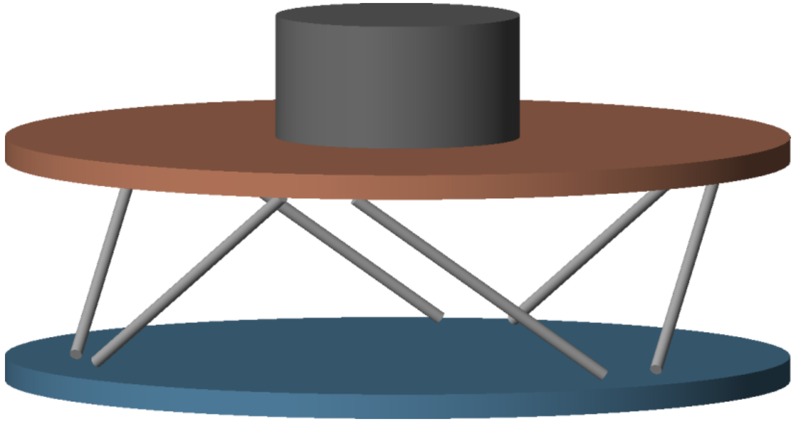
Université Libre de Bruxelles

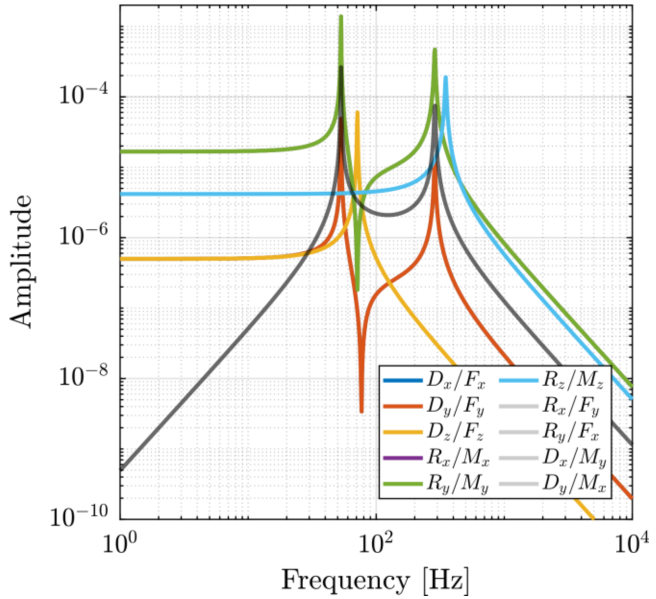
University of Wyoming



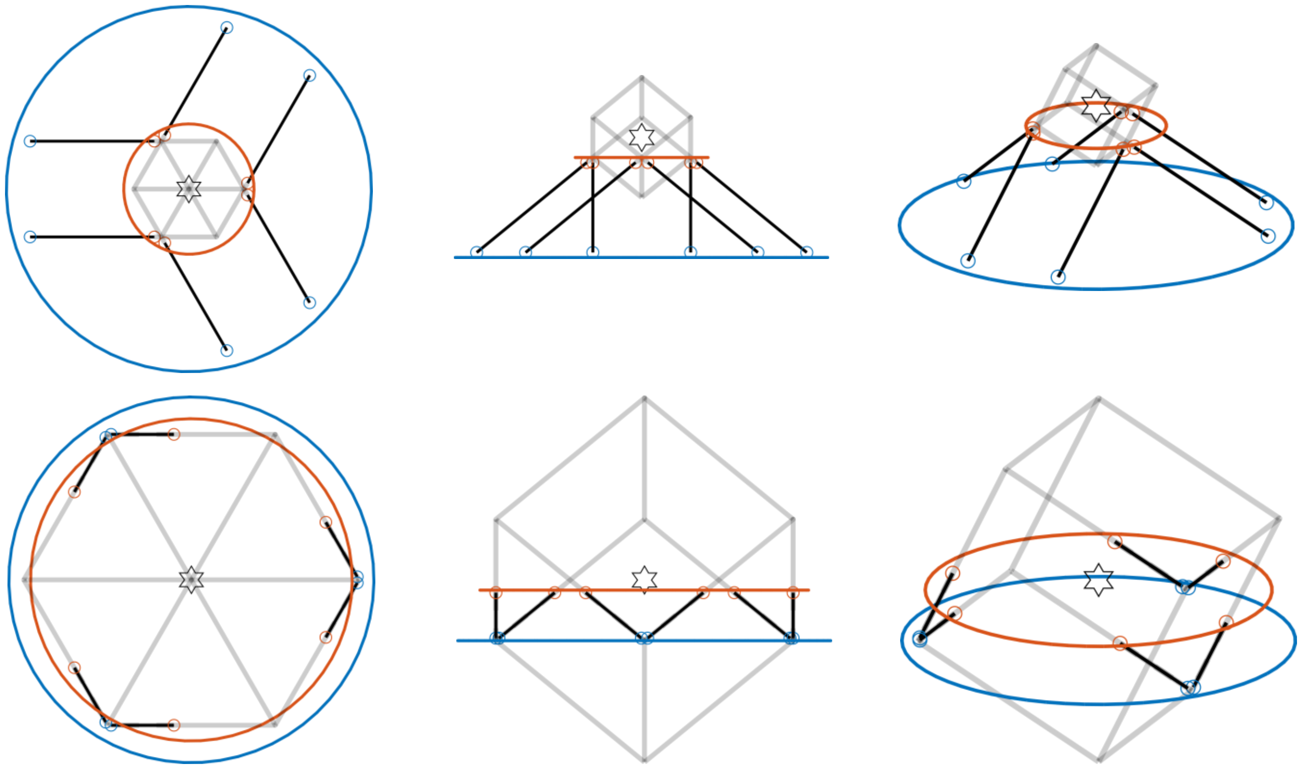
Cubic Architecture







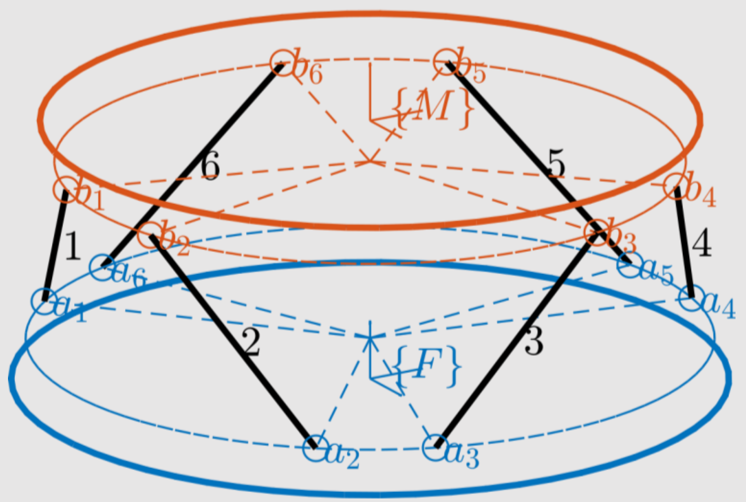
Modified Cubic Architecture



Struts	Vertically Oriented	Increased separation
Vertical stiffness	↗	=
Horizontal stiffness	↘	=
Vertical rotation stiffness	↘	↗
Horizontal rotation stiffness	↗	↗
Vertical mobility	↘	=
Horizontal mobility	↗	=
Vertical rotation mobility	↗	↘
Horizontal rotation mobility	↘	↘

The NASS needs to handle various payloads inertia

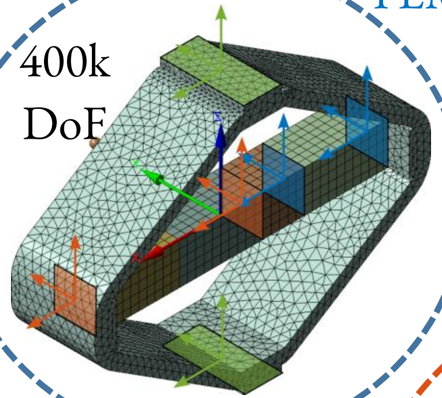
Active Platform Geometry



Component Optimization – Hybrid Modeling

FEM

400k DoF

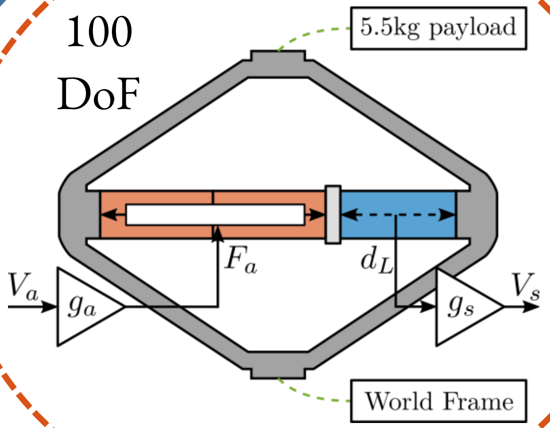


CMS

Reduced Order Flexible Body

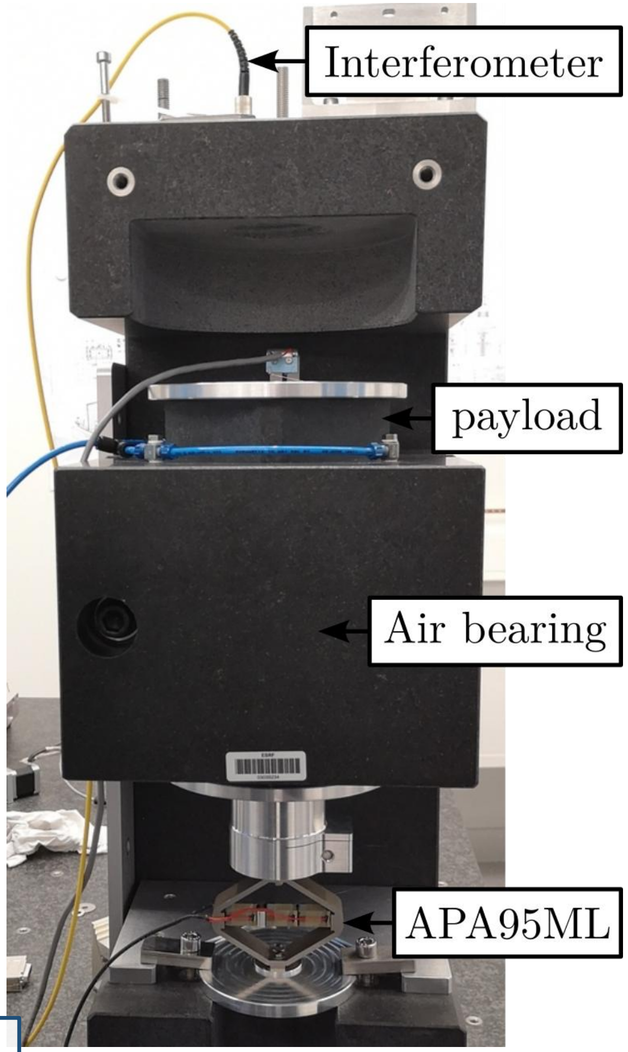
Multi-Body Model

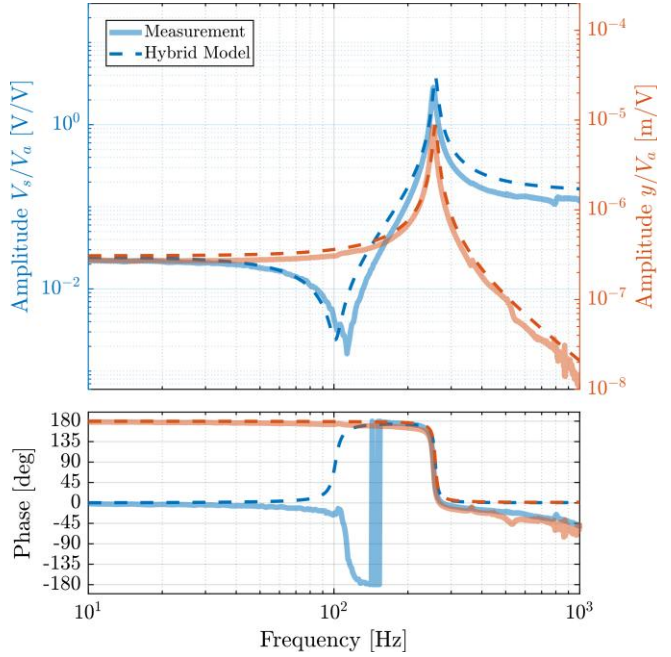
100 DoF

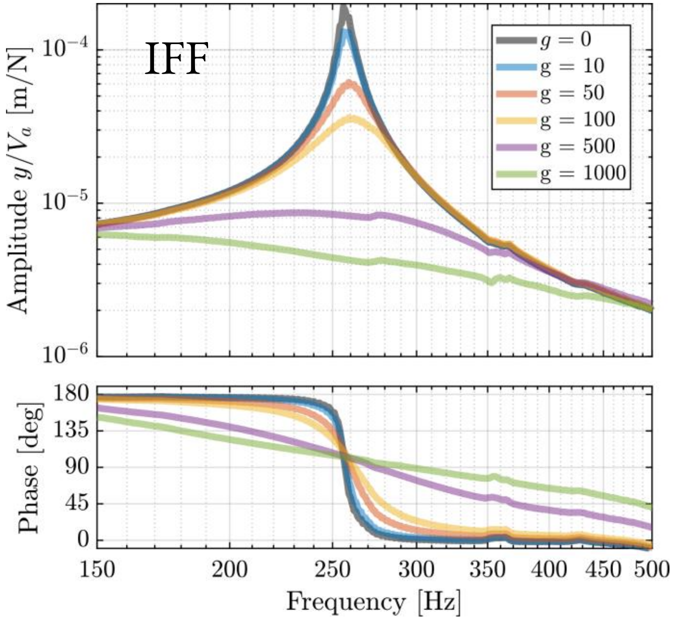


P. Brumund and T. Dehaeze.
"*Multibody Simulations with Reduced Order Flexible Bodies Obtained by FEA*". In MEDSI 2020

Philipp Brumund





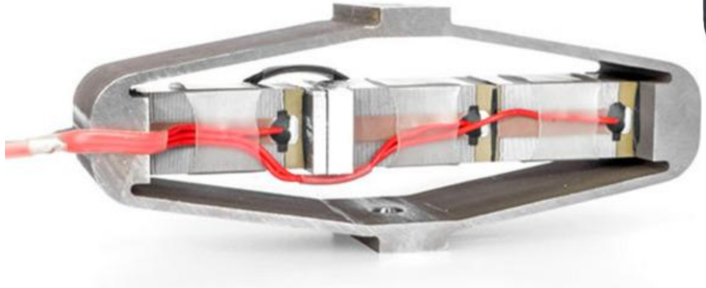


Choice of Actuators and Design of Flexible Joints

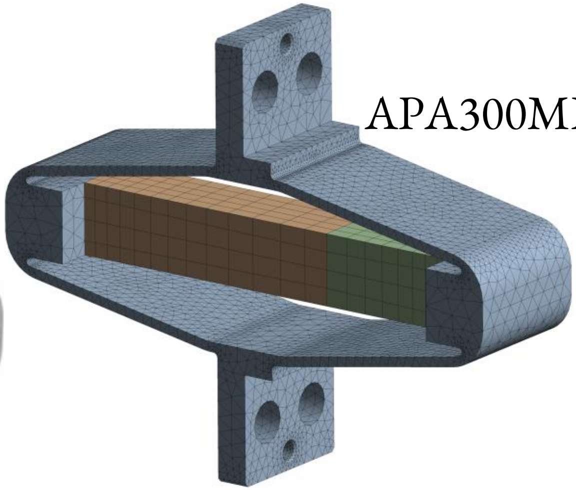
Piezoelectric
Stack Actuator

Voice Coil

Specifications
Stroke > 200 µm
Stiffness ≈ 1 N/µm
Height < 50 mm
Force Sensor



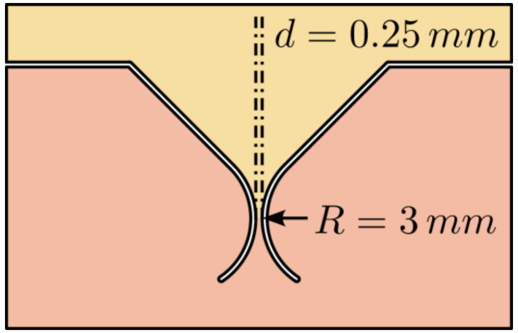
Amplified Piezoelectric Actuator (APA)

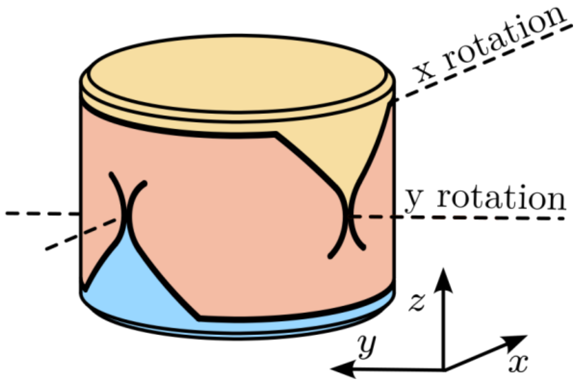


APA300ML

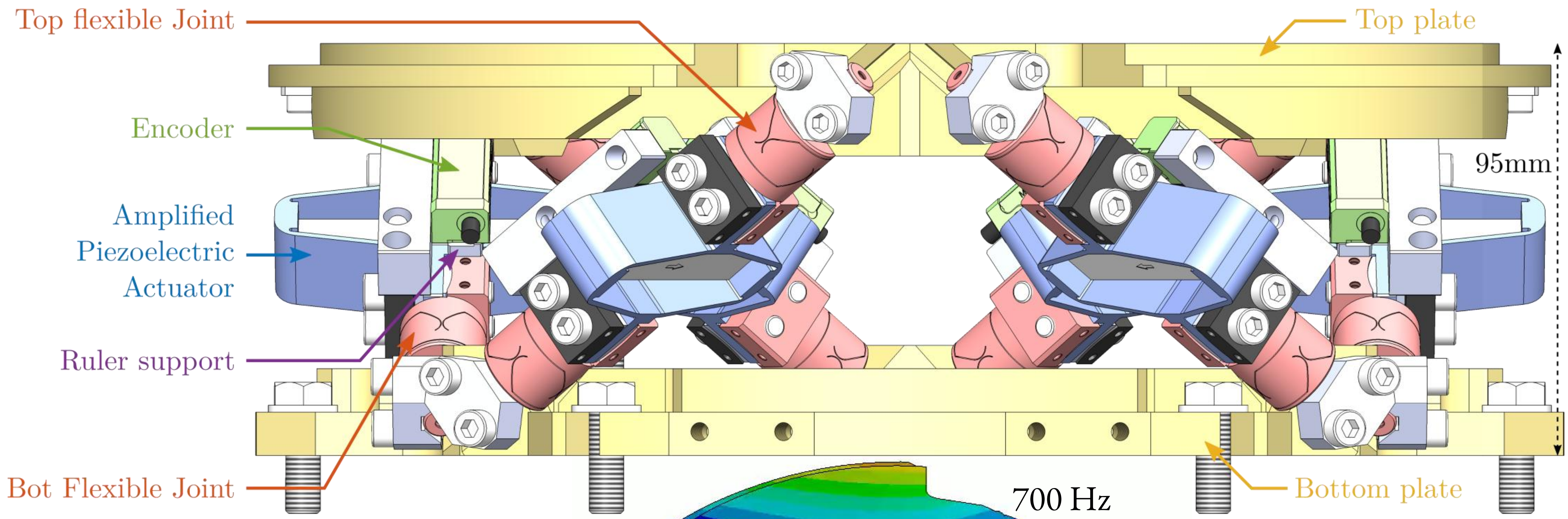
Specifications
Axial Stiffness > 100 N/µm
Bending Stiffness < 100 Nm/rad
Torsion Stiffness < 500 Nm/rad
Bending Stroke > 1 mrad

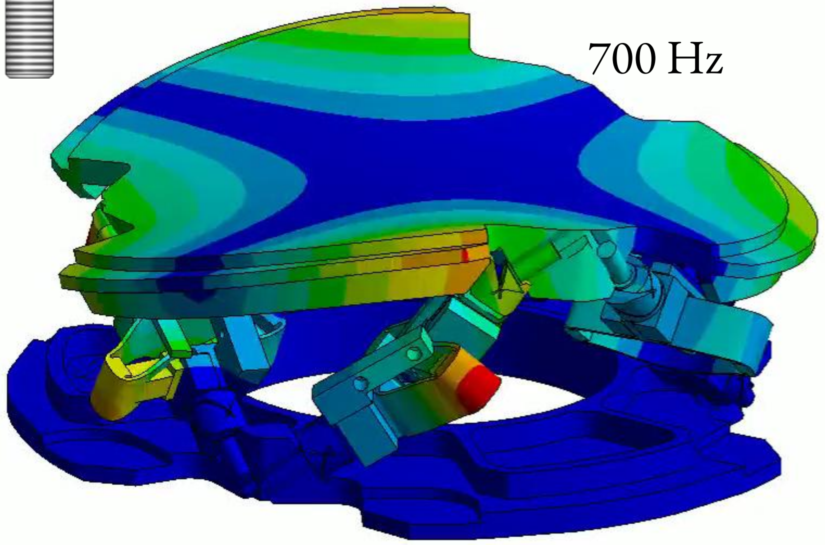
Flexible Joint Geometry



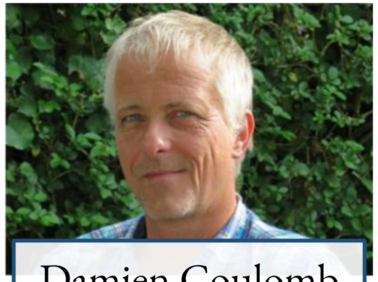


Obtained Design – The “Nano Hexapod”



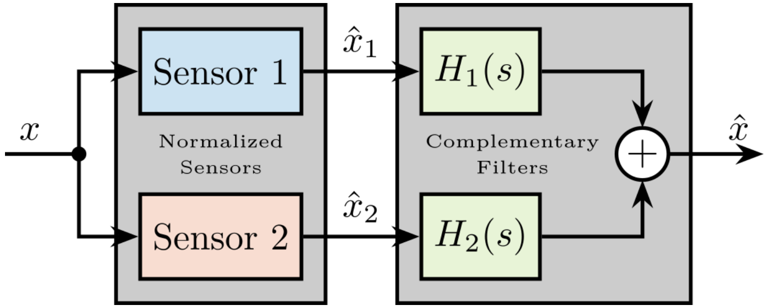


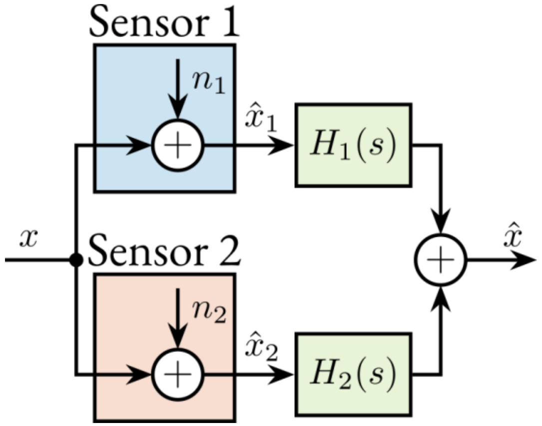
Julien Bonnefoy



Damien Coulomb

Sensor Fusion and Complementary Filters



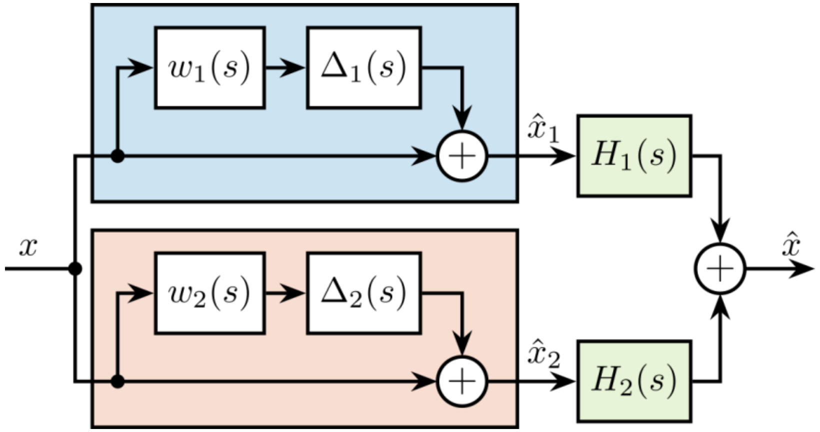


"Fused Sensor" Noise

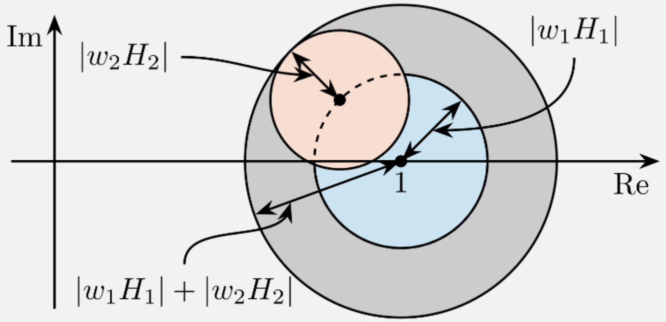
$$\Phi_{\epsilon_x}(\omega) = |H_1(j\omega)|^2 \Phi_{n_1}(\omega) + |H_2(j\omega)|^2 \Phi_{n_2}(\omega)$$

Super Sensor Noise — Noise of Sensor 1 — Noise of Sensor 2

Complementary Filters
$H_1(s) + H_2(s) = 1$

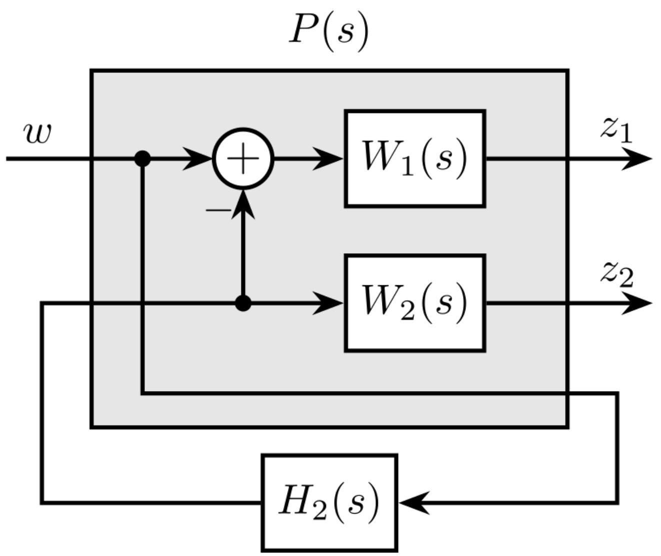


"Fused Sensor" Dynamical Uncertainty



How to design complementary filters by specifying their norms?

Shaping of Complementary Filters



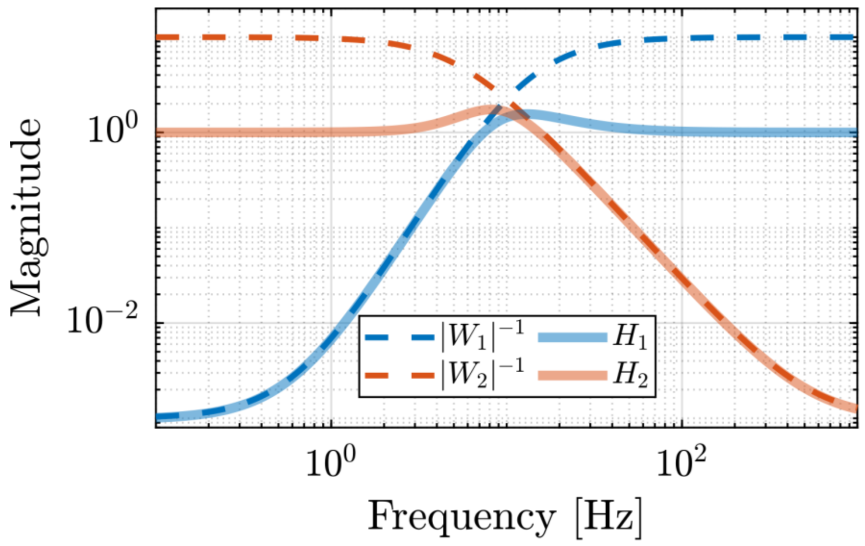
Synthesis Objective

$$H_1(s) + H_2(s) = 1$$
$$|H_1(j\omega)| \leq \frac{1}{|W_1(j\omega)|} \quad \forall\omega$$
$$|H_2(j\omega)| \leq \frac{1}{|W_2(j\omega)|} \quad \forall\omega$$

Mixed Sensitivity H-infinity Synthesis

$$S(s) + T(s) = 1$$
$$|S(j\omega)| \leq \frac{1}{|W_S(j\omega)|} \quad \forall\omega$$
$$|T(j\omega)| \leq \frac{1}{|W_T(j\omega)|} \quad \forall\omega$$

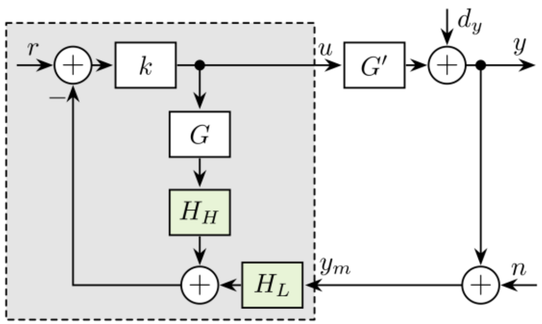
$$\left\| \begin{matrix} (1 - H_2(s))W_1(s) \\ H_2(s)W_2(s) \end{matrix} \right\|_\infty \leq 1 \quad \xrightarrow{H_1(s) \triangleq 1 - H_2(s)} \quad \left\| \begin{matrix} H_1(s)W_1(s) \\ H_2(s)W_2(s) \end{matrix} \right\|_\infty \leq 1$$



T. Dehaeze, M. Verma, and C. Collette.
"Complementary Filters Shaping Using H-Infinity Synthesis". In ICCMA 2019

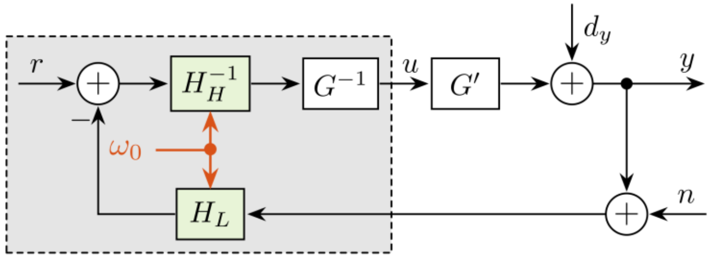
Closed-Loop Shaping using Complementary Filters

Virtual Sensor Fusion



$k \to \infty$

Proposed Control Architecture



$$y = \frac{H_H dy + G' G^{-1} r - G' G^{-1} H_L n}{H_H + G' G^{-1} H_L}$$

$$u = \frac{-G^{-1} H_L dy + G^{-1} r - G^{-1} H_L n}{H_H + G' G^{-1} H_L}$$

$G^{-1} G' \approx 1$

Nominal Case

$S = H_H$ $\quad$ $T = H_L$

$$y = H_H dy \quad + r \quad - H_L n$$

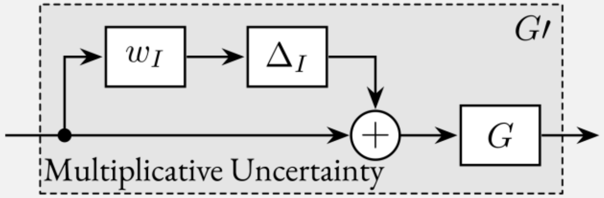
$$u = -G^{-1} H_L dy + G^{-1} r - G^{-1} H_L n$$

Nominal Stability

H_H, H_L, G Stable

H_H, G Minimum phase

Robust Stability



$$|w_I(j\omega) H_L(j\omega)| \leq 1 \quad \forall \omega$$

Nominal Performance

Weighting Functions

$$| w_H(j\omega) \; H_H(j\omega) \, | \leq 1 \quad \forall \omega$$

$$| w_L(j\omega) \; H_L(j\omega) \, | \leq 1 \quad \forall \omega$$

Robust Performance

$$|w_H(j\omega) S(j\omega)| \leq 1 \quad \forall G' \in \Pi_I, \, \forall \omega$$

$$|w_H(j\omega) H_H(j\omega)| + |w_I(j\omega) H_L(j\omega)| \leq 1, \, \forall \omega$$

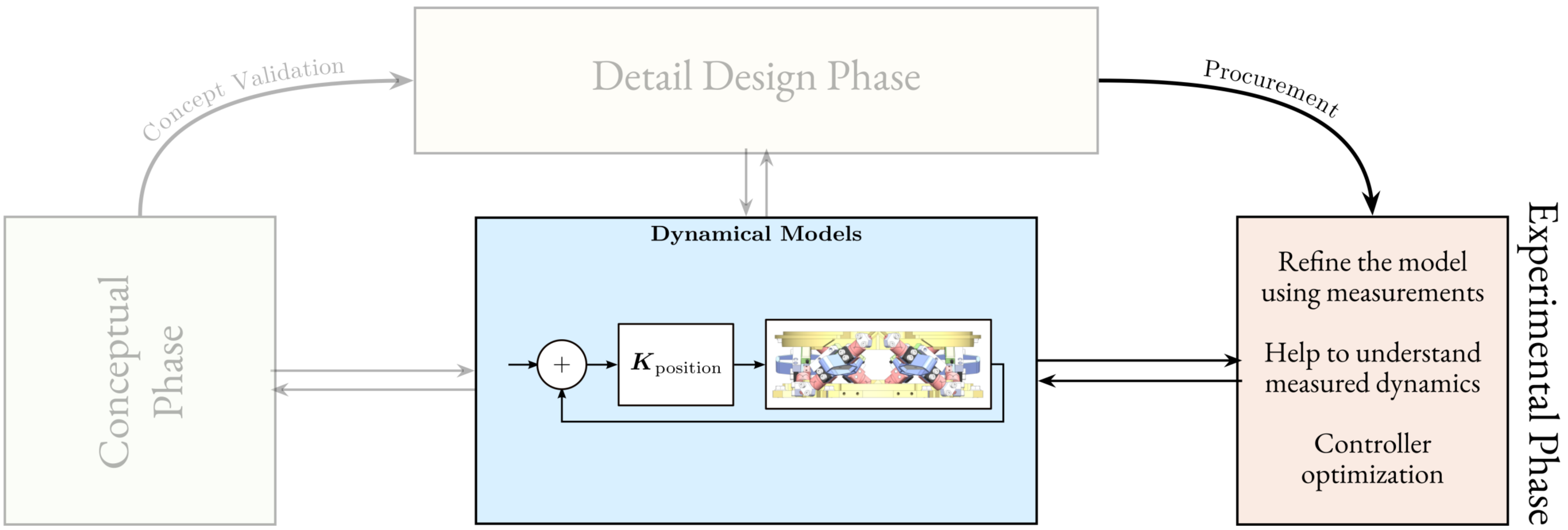
Analytical Formula

$$H_L(s) = \frac{1}{1 + s/\omega_0}$$

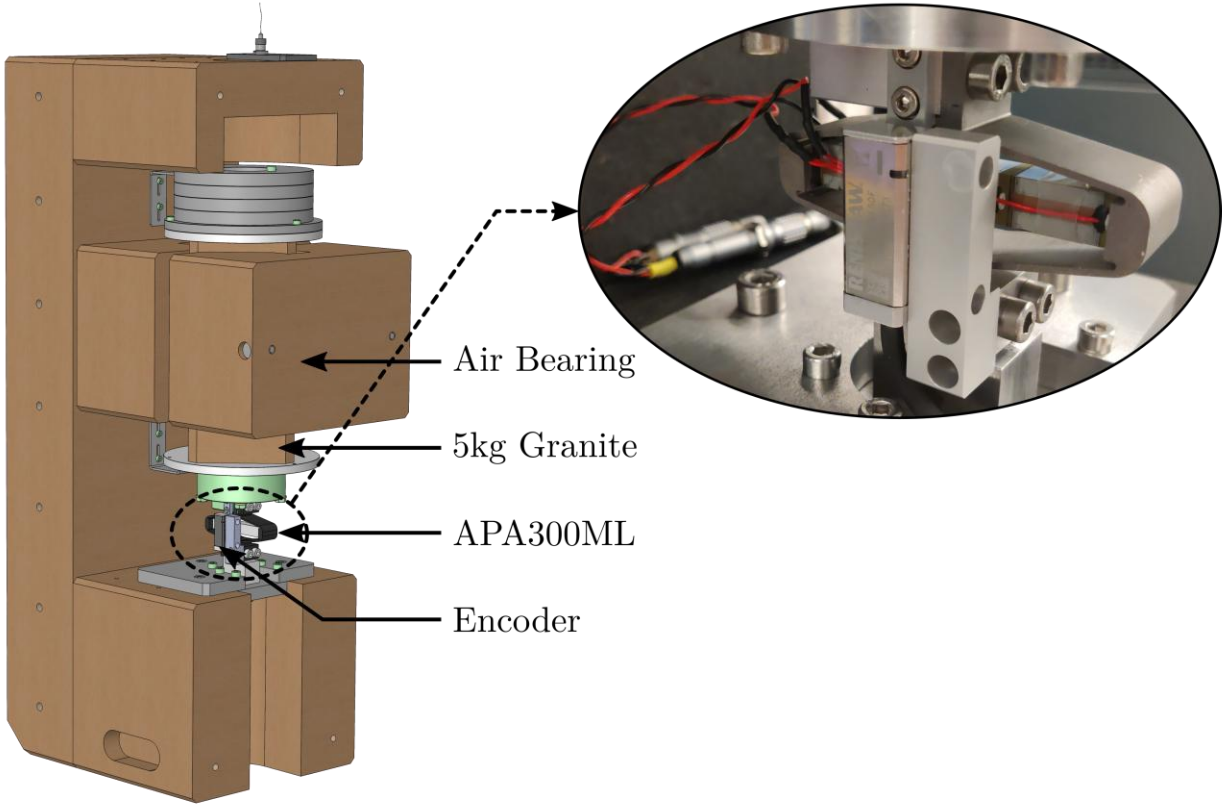
$$H_H(s) = \frac{s/\omega_0}{1 + s/\omega_0}$$

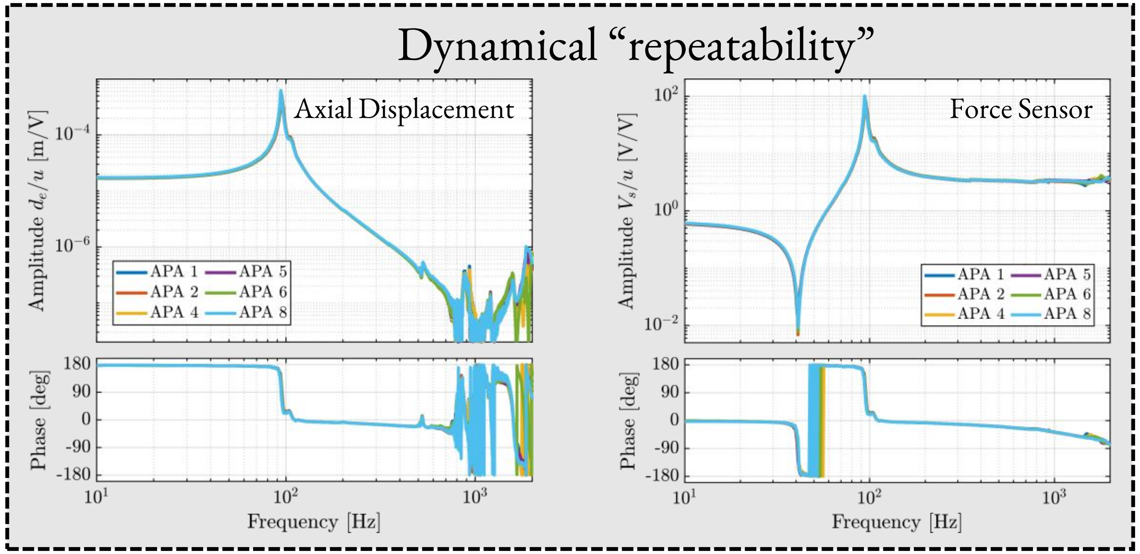
M. Verma, T. Dehaeze, G. Zhao, J. Watchi, and C. Collette.
"*Virtual Sensor Fusion for High Precision Control*". In MSSP 2020

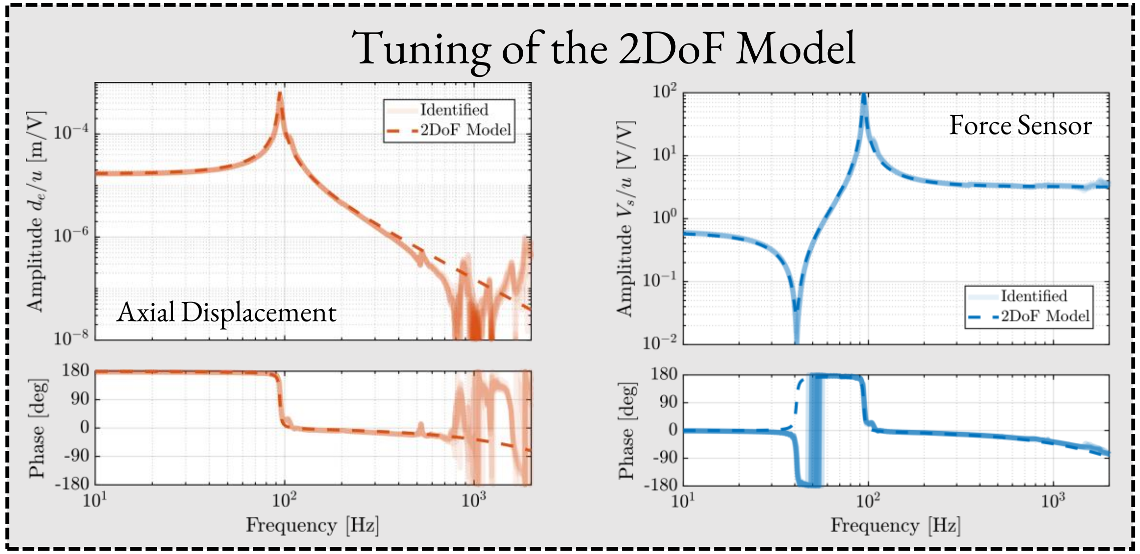
Experimental Validation - Strategy



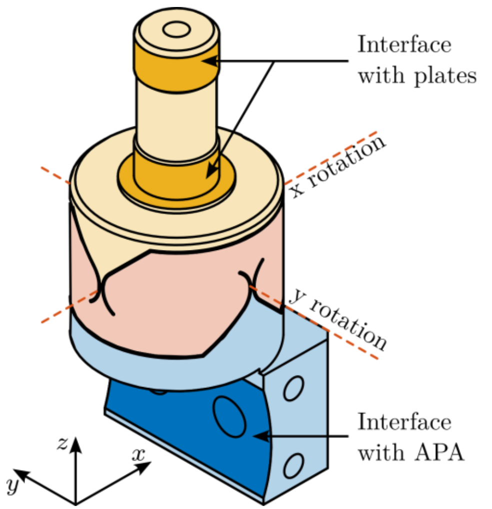
Amplified Piezoelectric Actuator – APA300ML

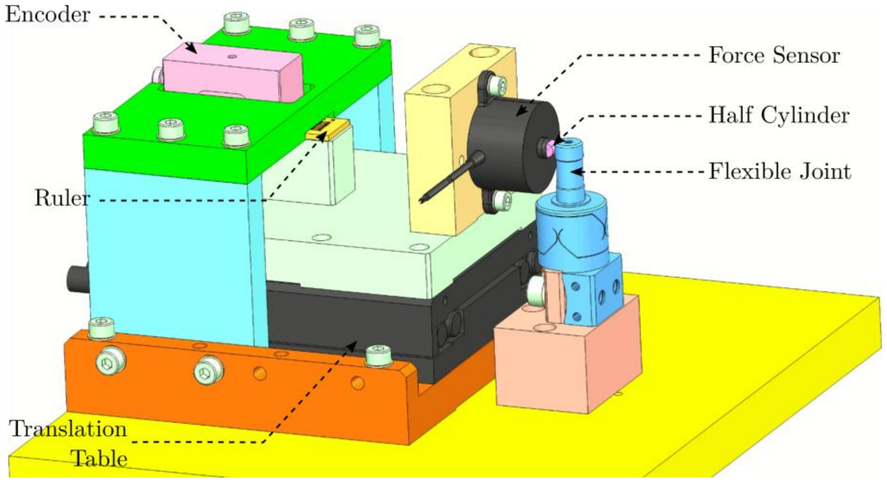


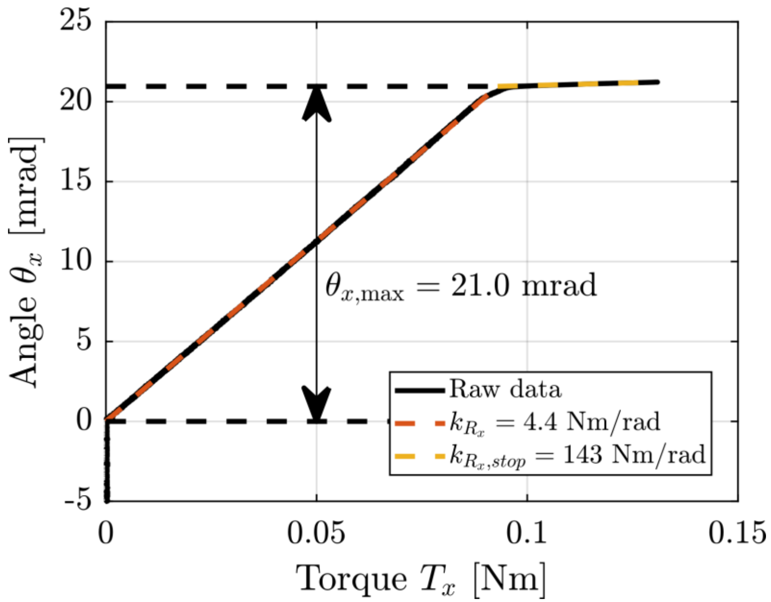


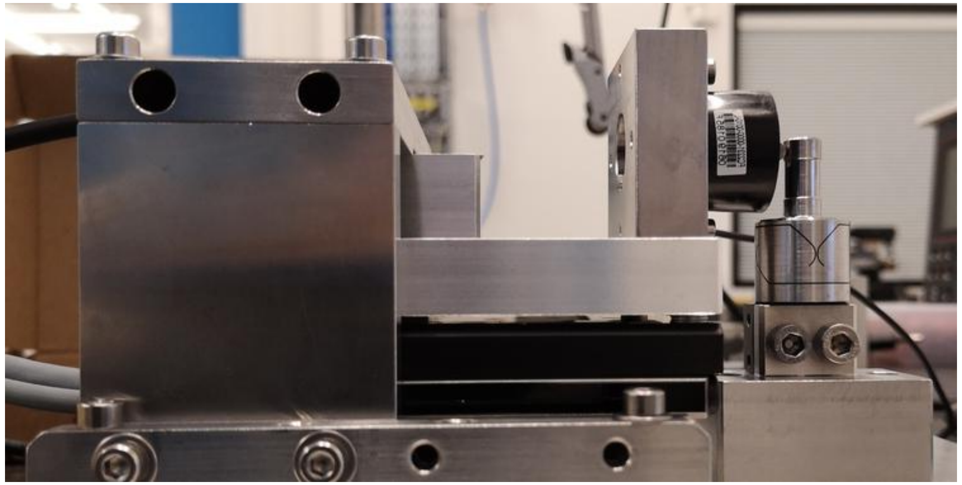


Flexible Joints – Measured Bending Stiffness

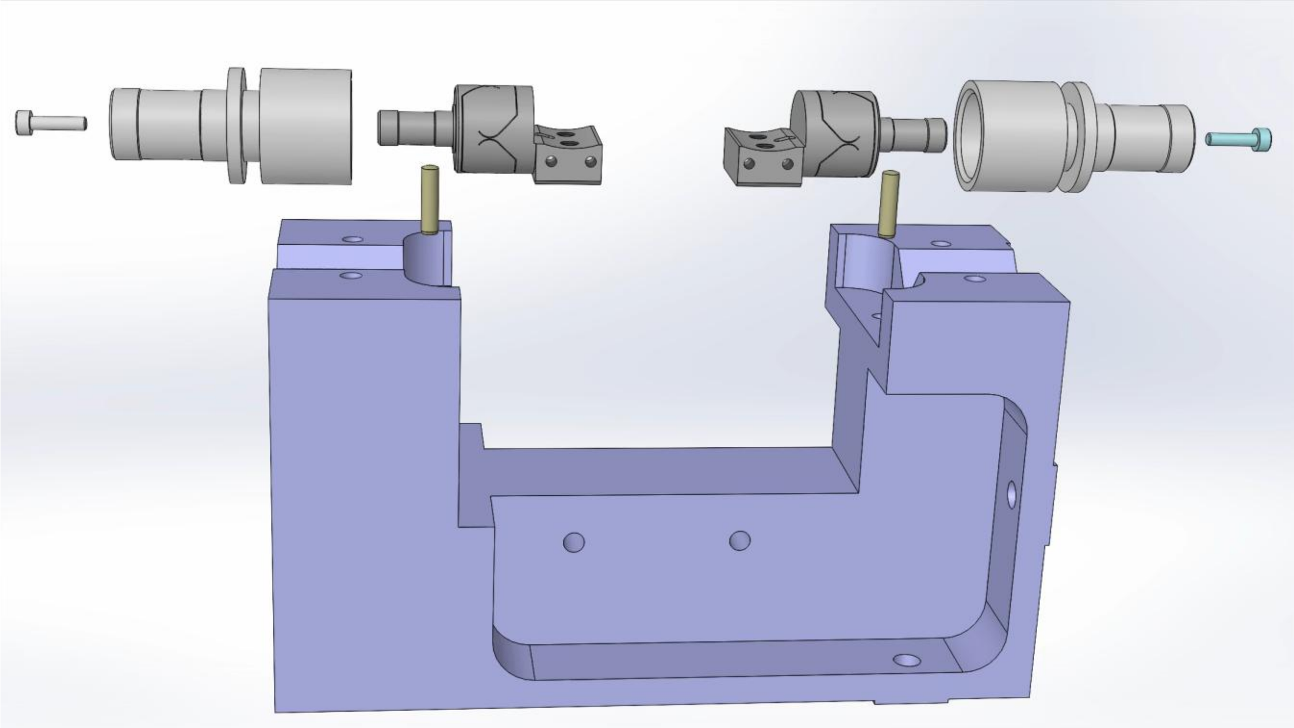


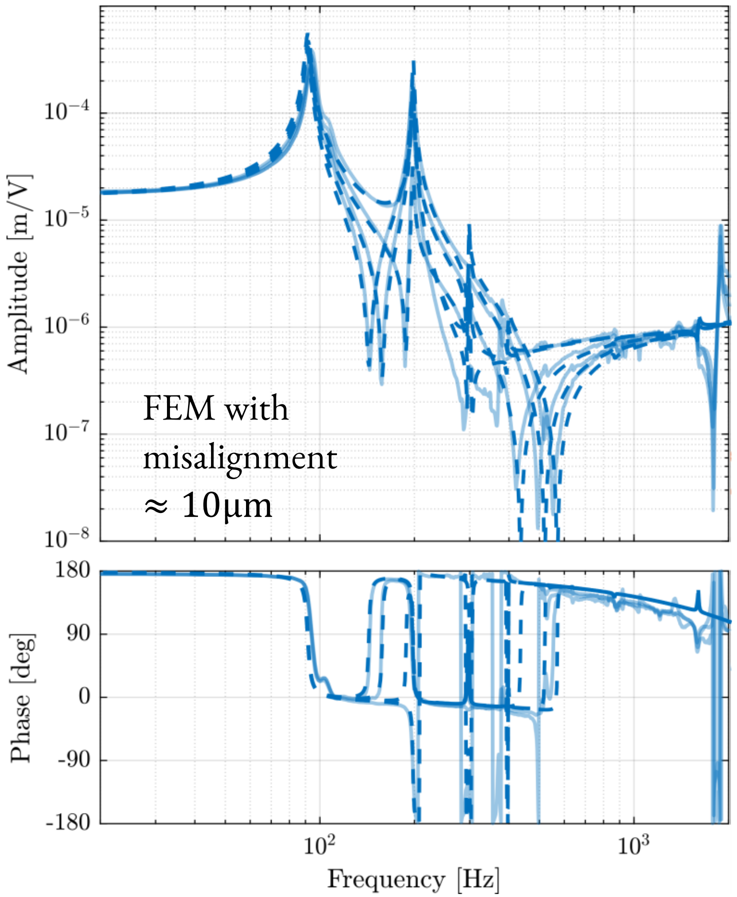


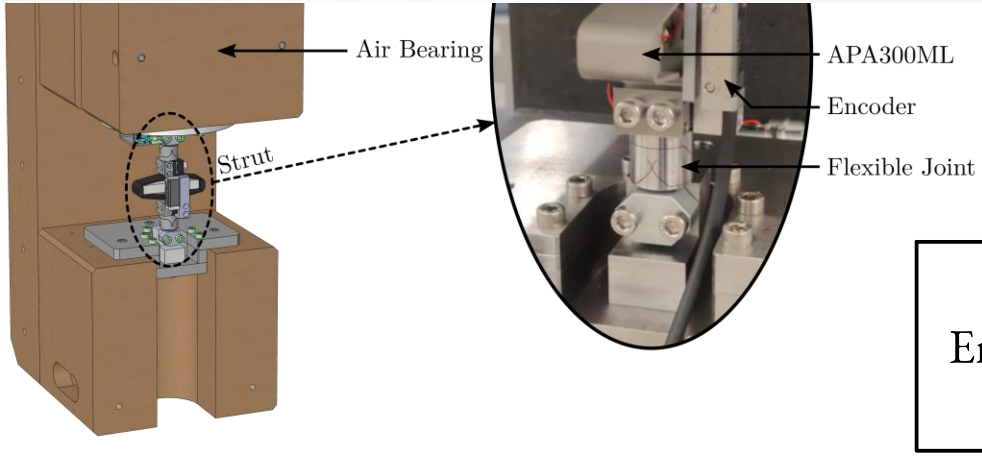


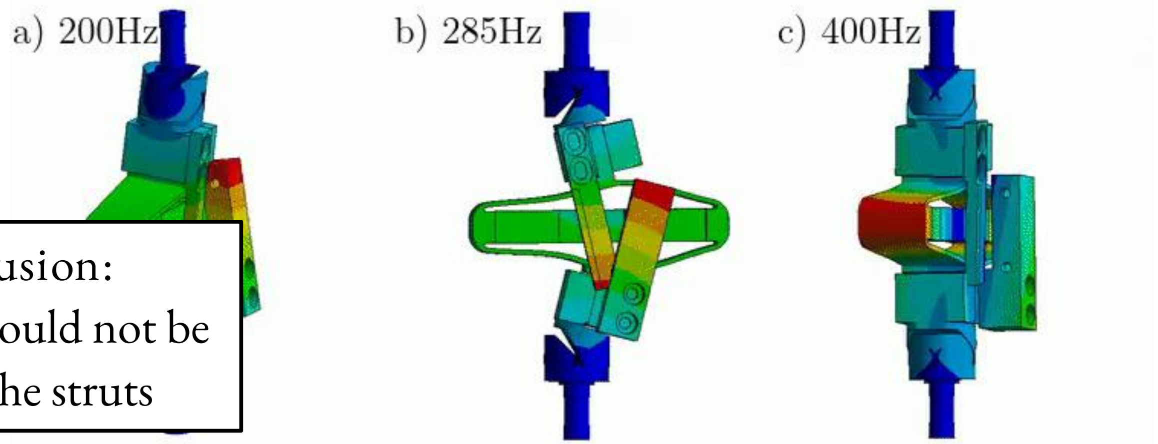


Struts



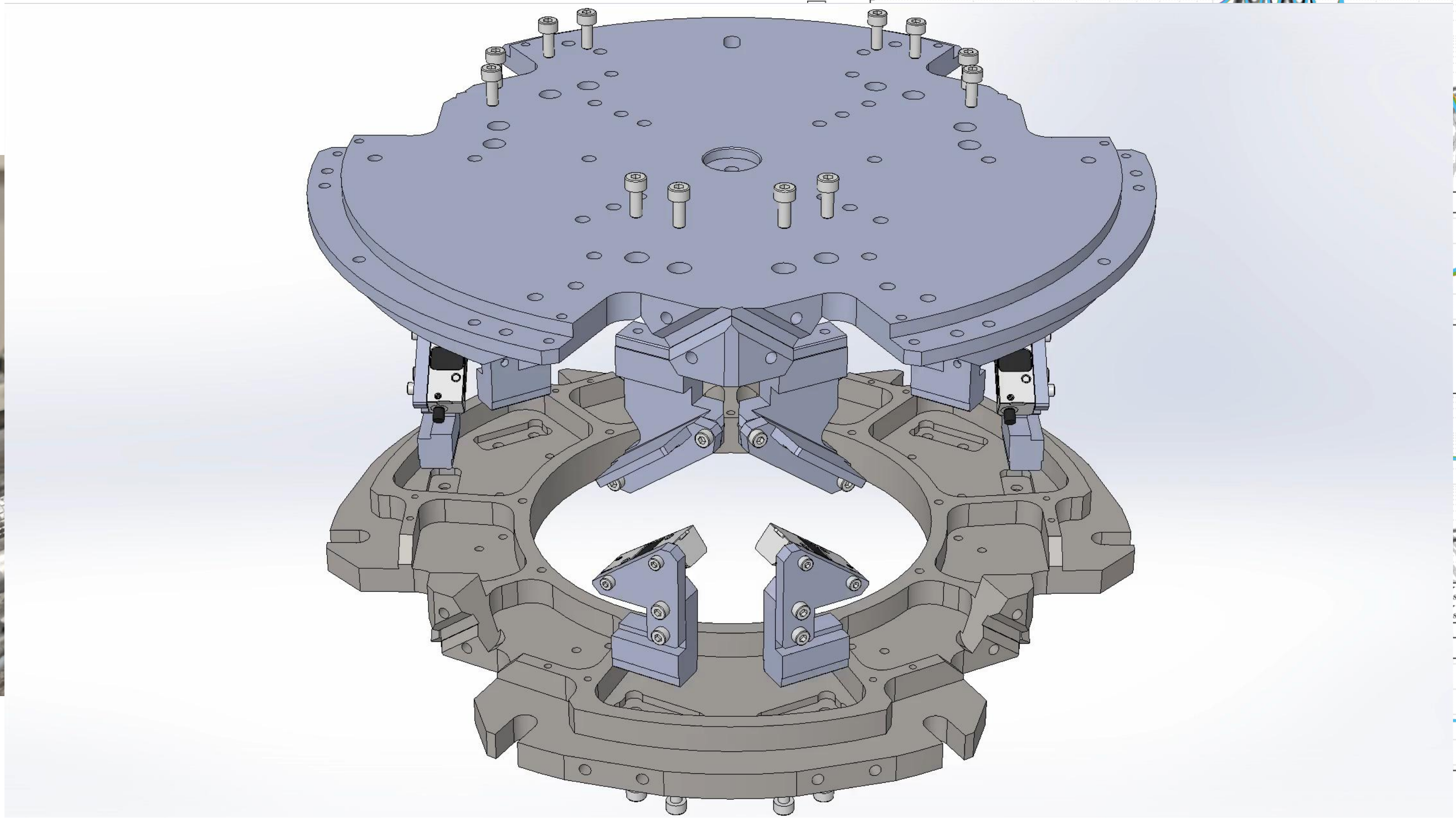


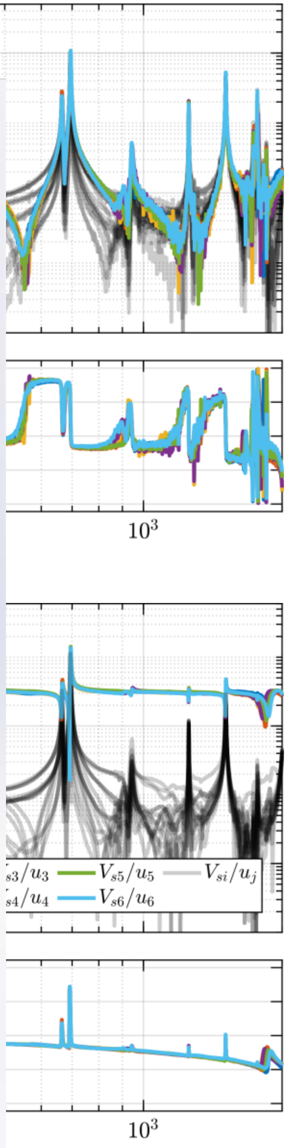




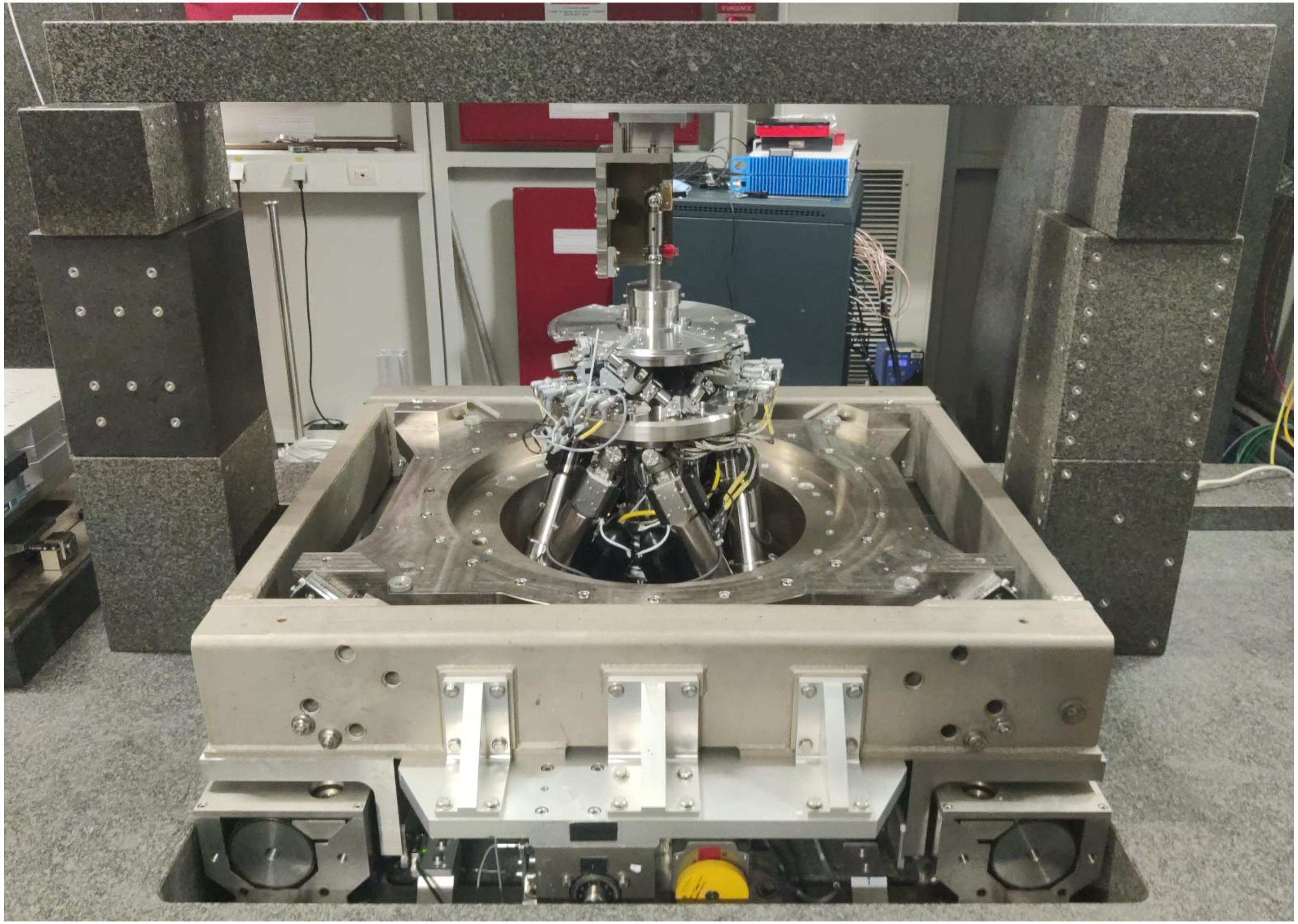
Conclusion:
Encoders should not be fixed to the struts

Nano Hexapod

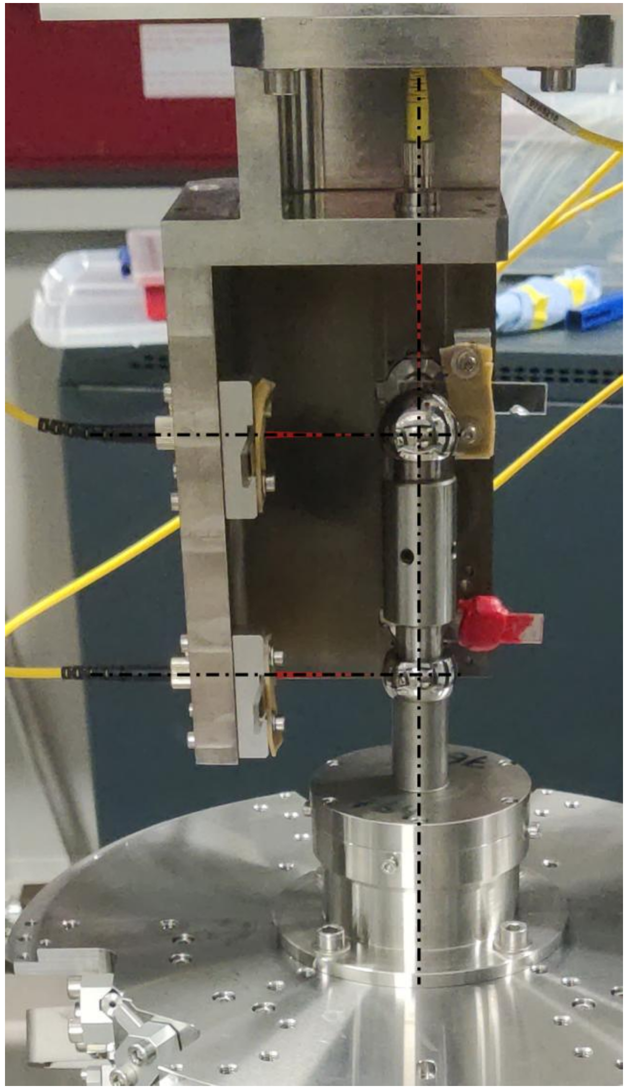


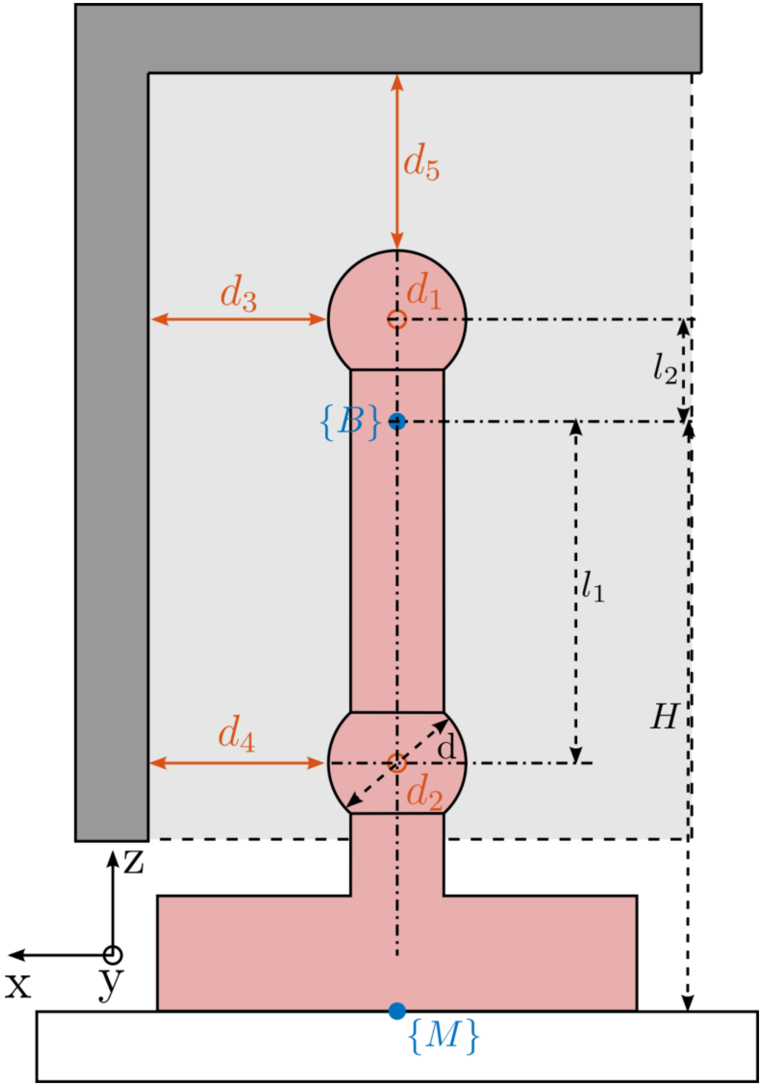


Nano Active Stabilization System – ID31



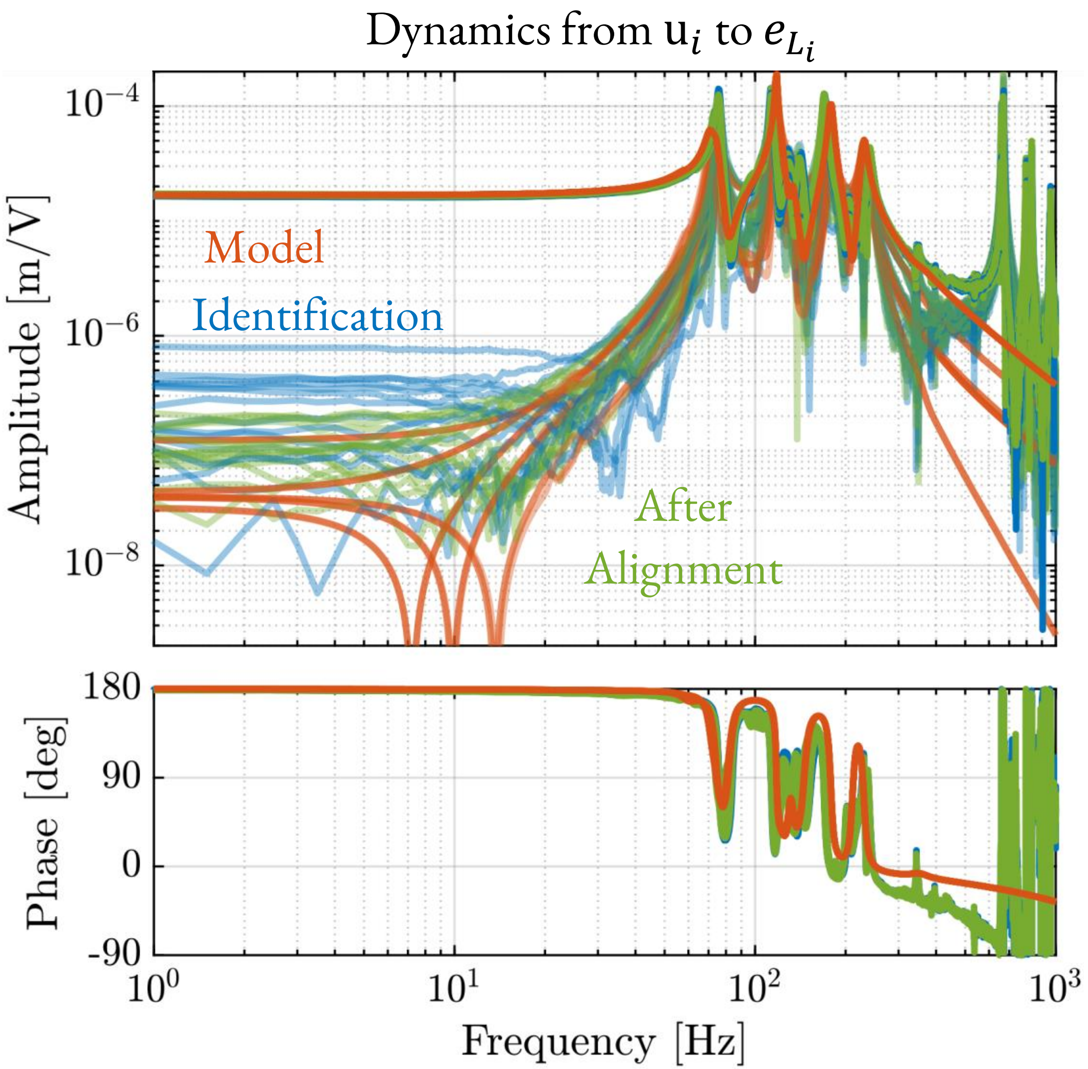
Short Stroke Metrology

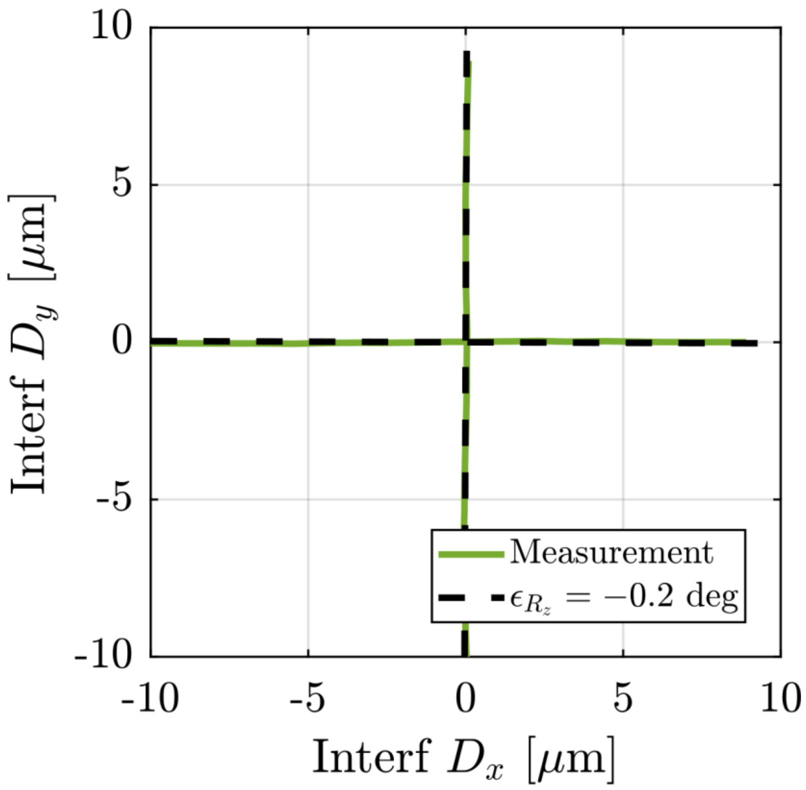




$$\begin{bmatrix} D_x \\ D_y \\ D_z \\ R_x \\ R_y \end{bmatrix} = \underbrace{\begin{bmatrix} 0 & 1 & 0 & -l_2 & 0 \\ 0 & 1 & 0 & l_1 & 0 \\ -1 & 0 & 0 & 0 & -l_2 \\ -1 & 0 & 0 & 0 & l_1 \\ 0 & 0 & -1 & 0 & 0 \end{bmatrix}^{-1}}_{\boldsymbol{J_d}} \cdot \begin{bmatrix} d_1 \\ d_2 \\ d_3 \\ d_4 \\ d_5 \end{bmatrix}$$

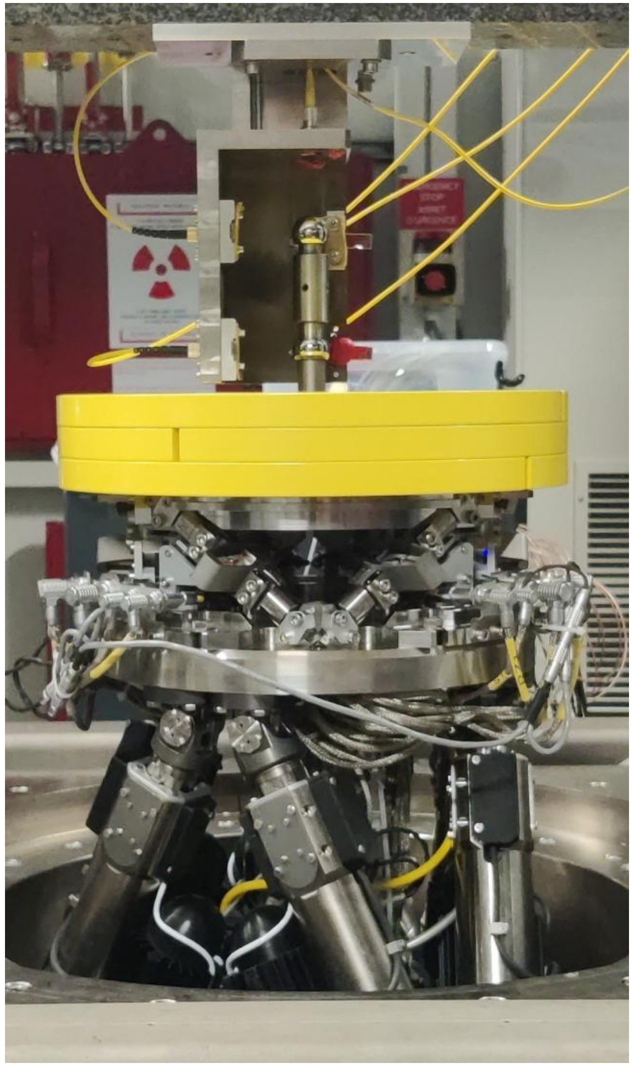
Plant Dynamics

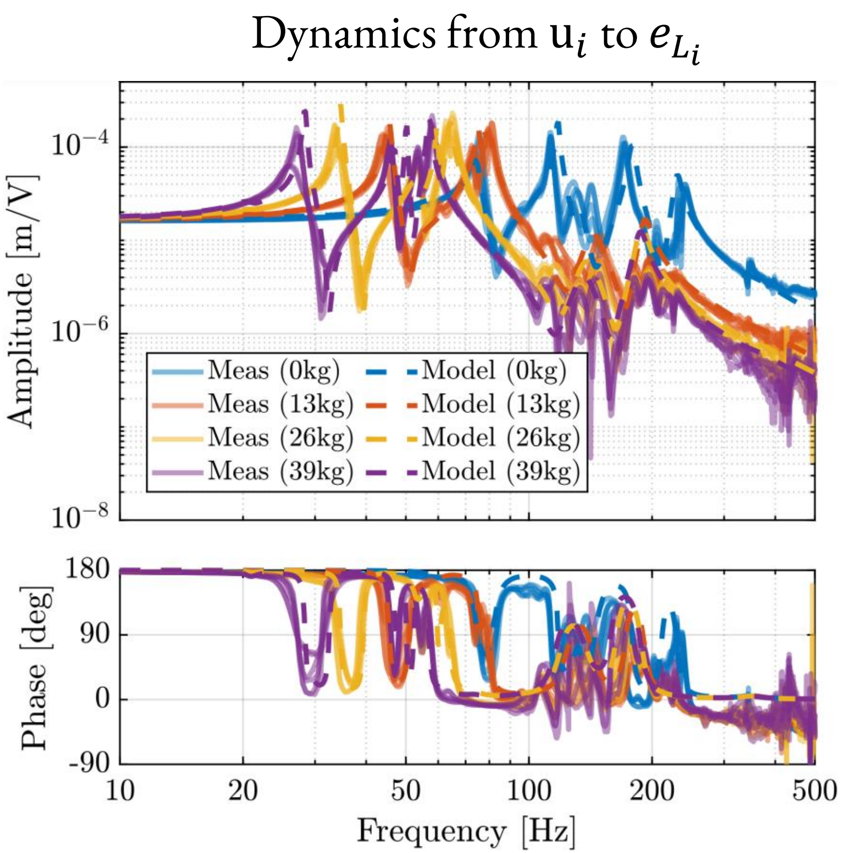


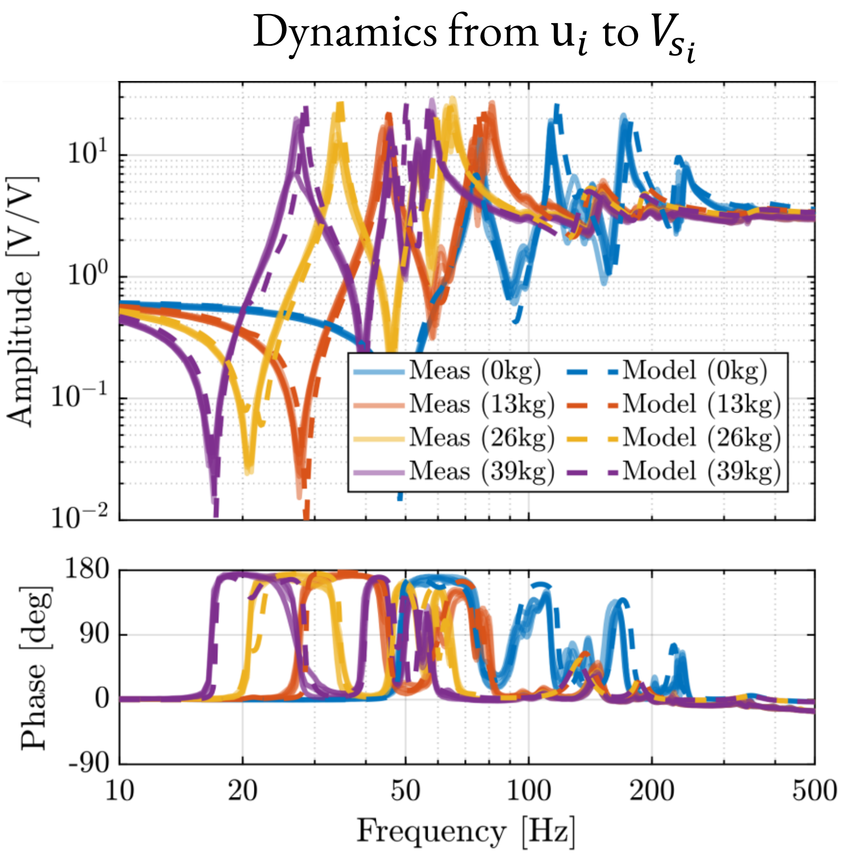


Comparing the measurements with the model can help detect potential issues

Effect of Payload Mass

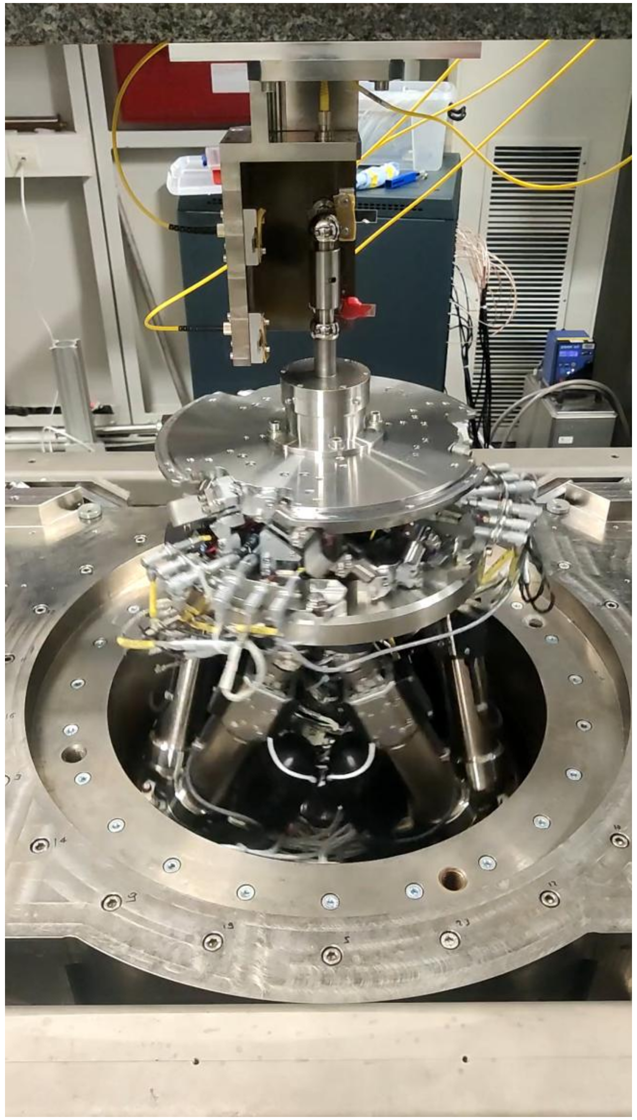


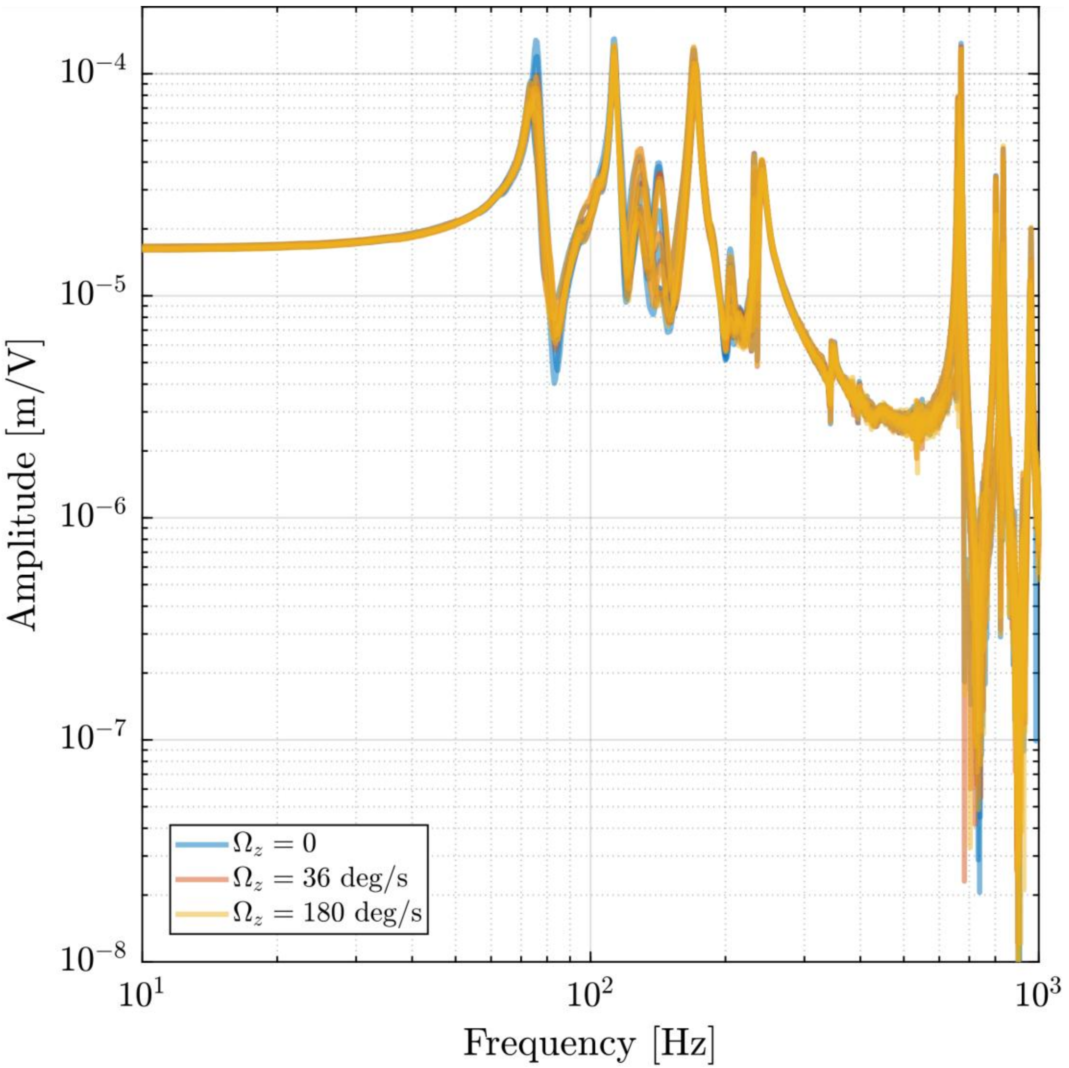




Integral Force Feedback should be robust to the change of payload

Effect of Rotational Velocity

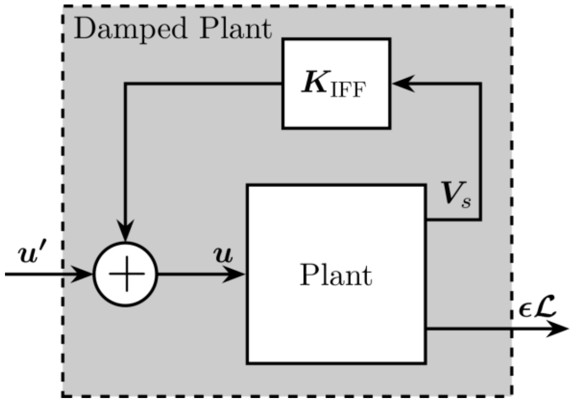




Dynamics not affected by the rotation

Validates the control kinematics

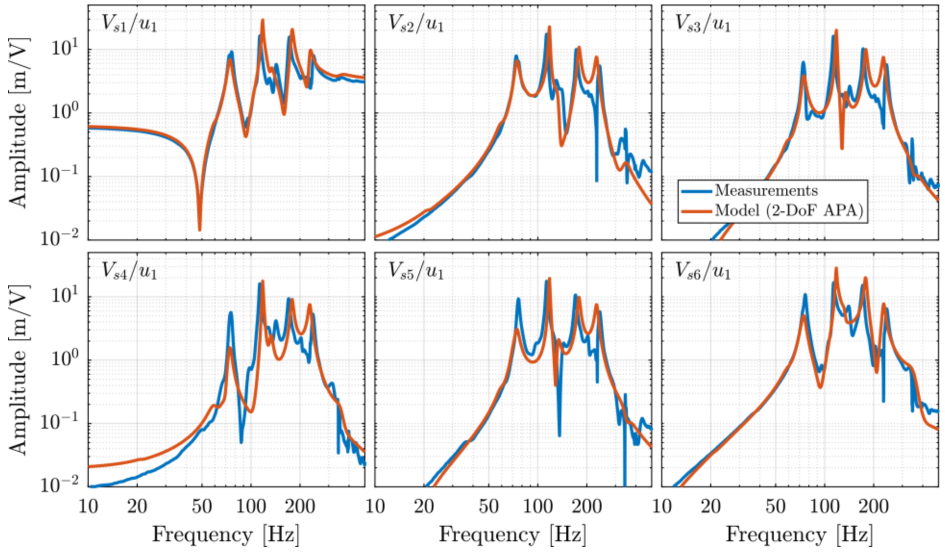
Decentralized Integral Force Feedback (IFF)



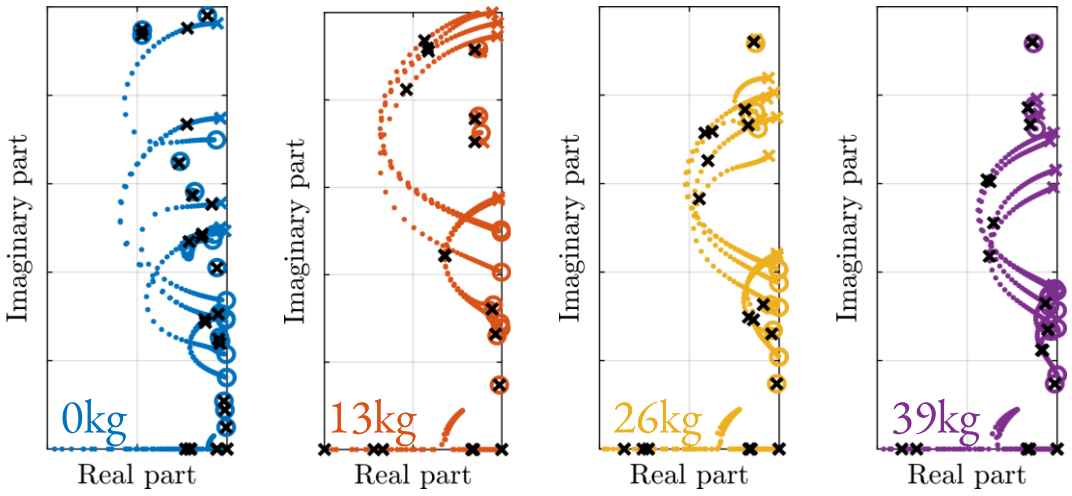
$$\boldsymbol{K}_{\text{IFF}} = K_{\text{IFF}} \cdot \boldsymbol{I}_6 = \begin{bmatrix} K_{\text{IFF}} & & 0 \\ & \ddots & \\ 0 & & K_{\text{IFF}} \end{bmatrix}$$

$$K_{\text{IFF}} = g_0 \cdot \frac{1}{s} \cdot \frac{s^2/\omega_z^2}{s^2/\omega_z^2 + 2\xi_z s/\omega_z + 1}$$

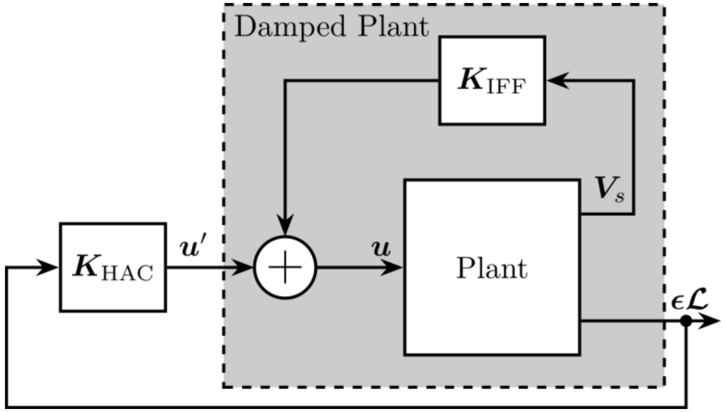
Modeling of dynamical coupling



Root Locus: Estimation of obtained damping



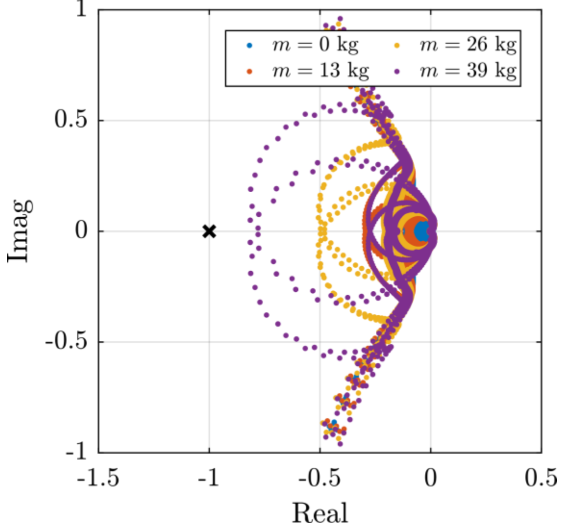
High Authority Controller (HAC)



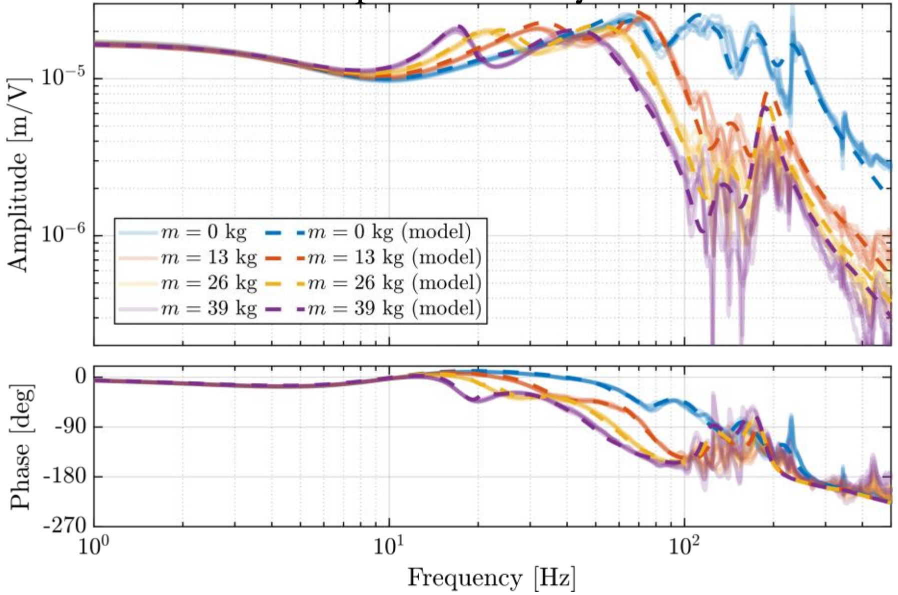
$$\boldsymbol{K}_{\text{HAC}} = \begin{bmatrix} K_{\text{HAC}} & & 0 \\ & \ddots & \\ 0 & & K_{\text{HAC}} \end{bmatrix}$$

$$K_{\text{HAC}}(s) = g_0 \cdot \underbrace{\frac{\omega_c}{s}}_{\text{int}} \cdot \underbrace{\frac{1}{1 + \frac{s}{\omega_0}}}_{\text{LPF}}$$

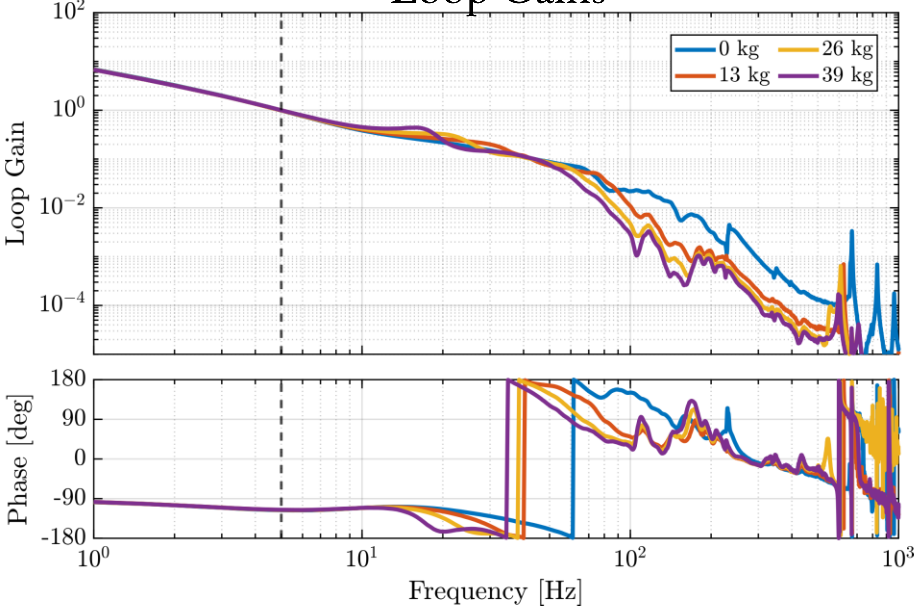
Characteristic Loci



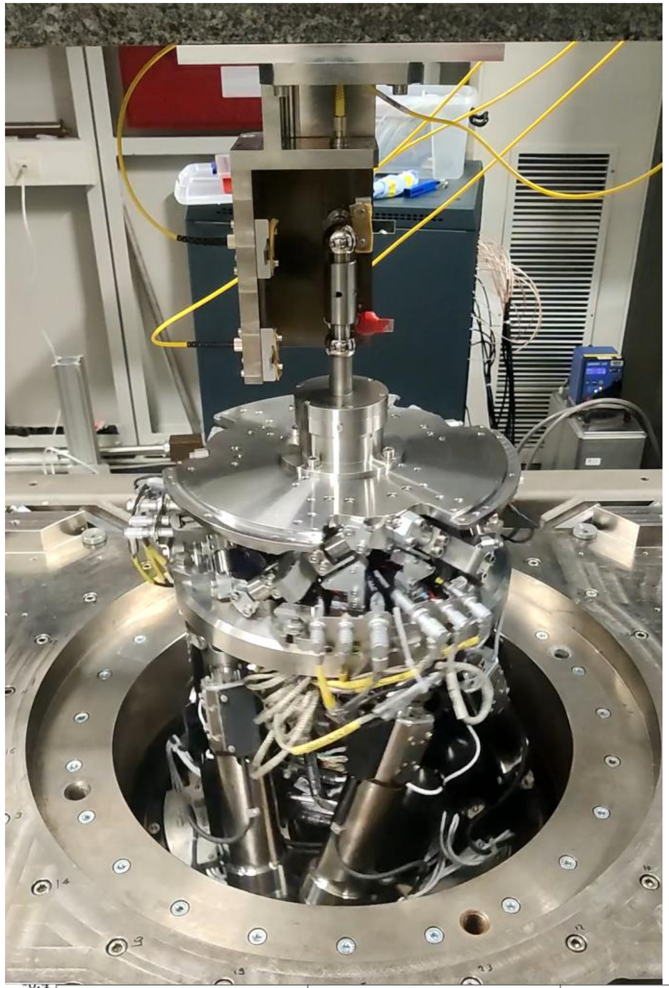
Damped Plant Dynamics

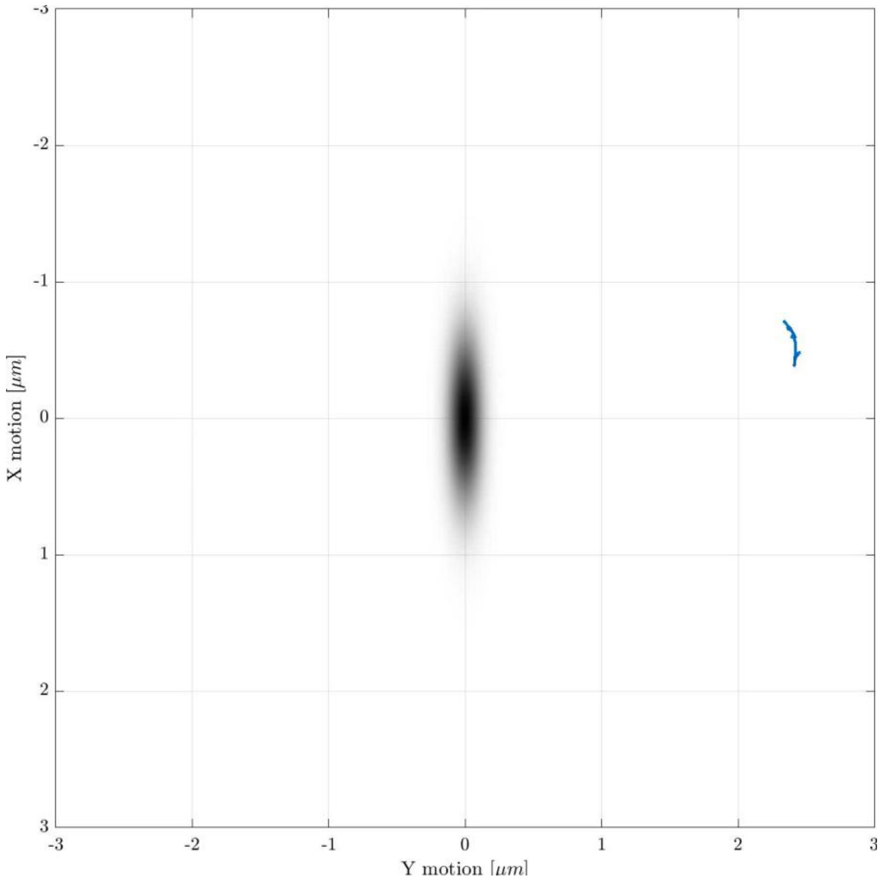


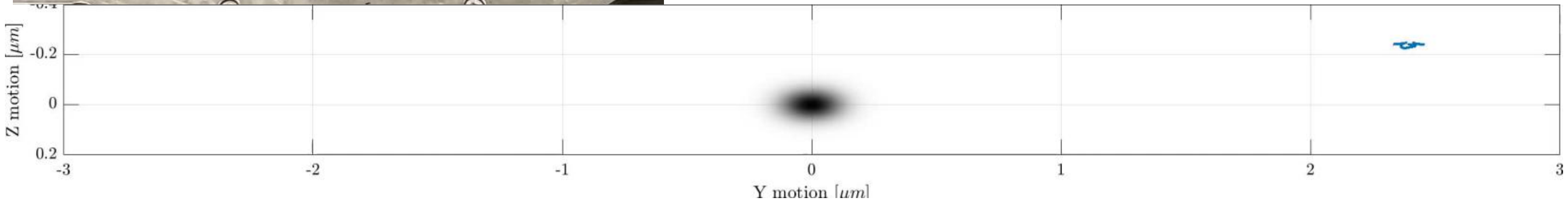
Loop Gains



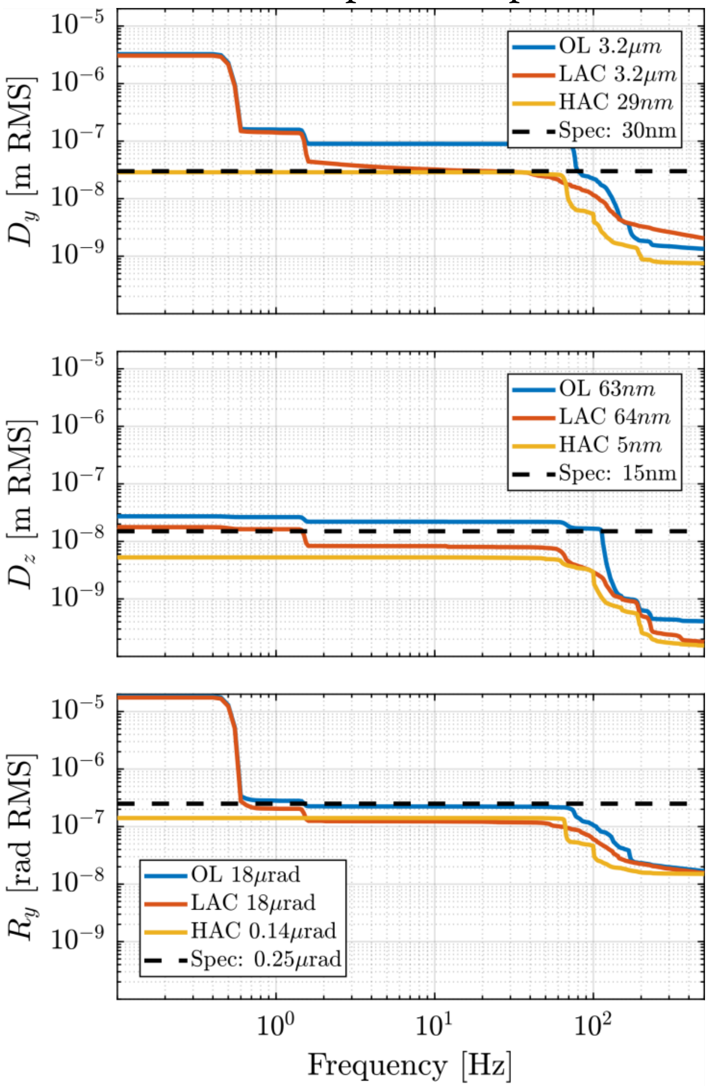
Tomography Experiments



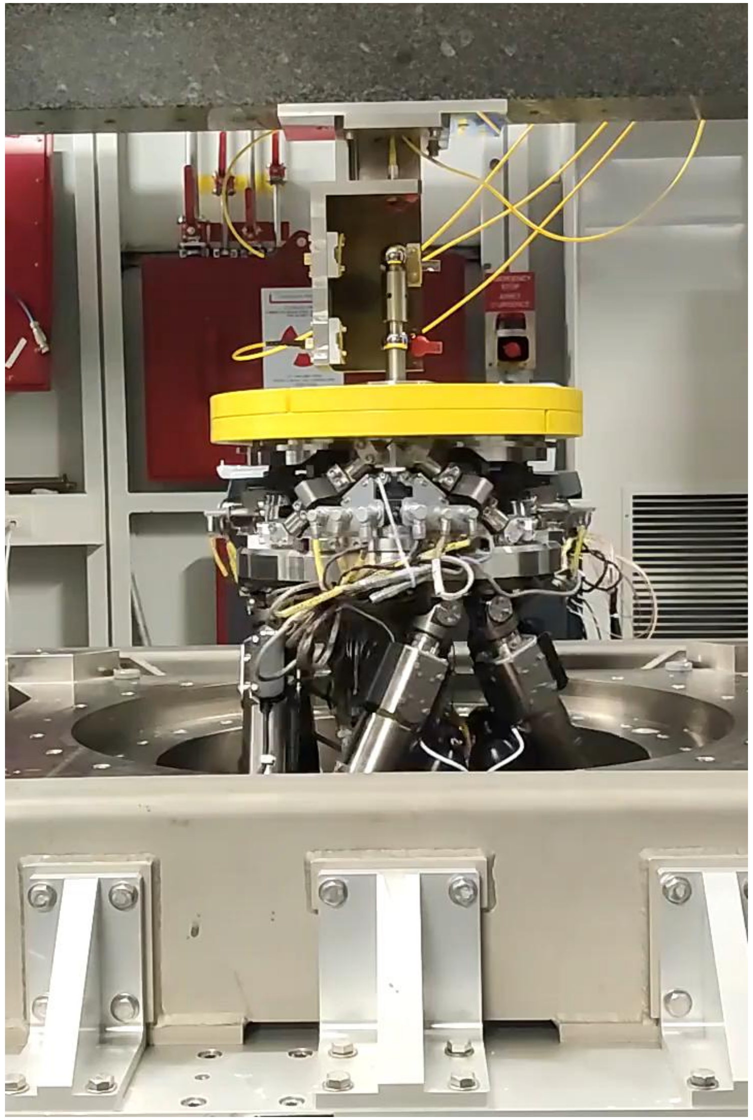


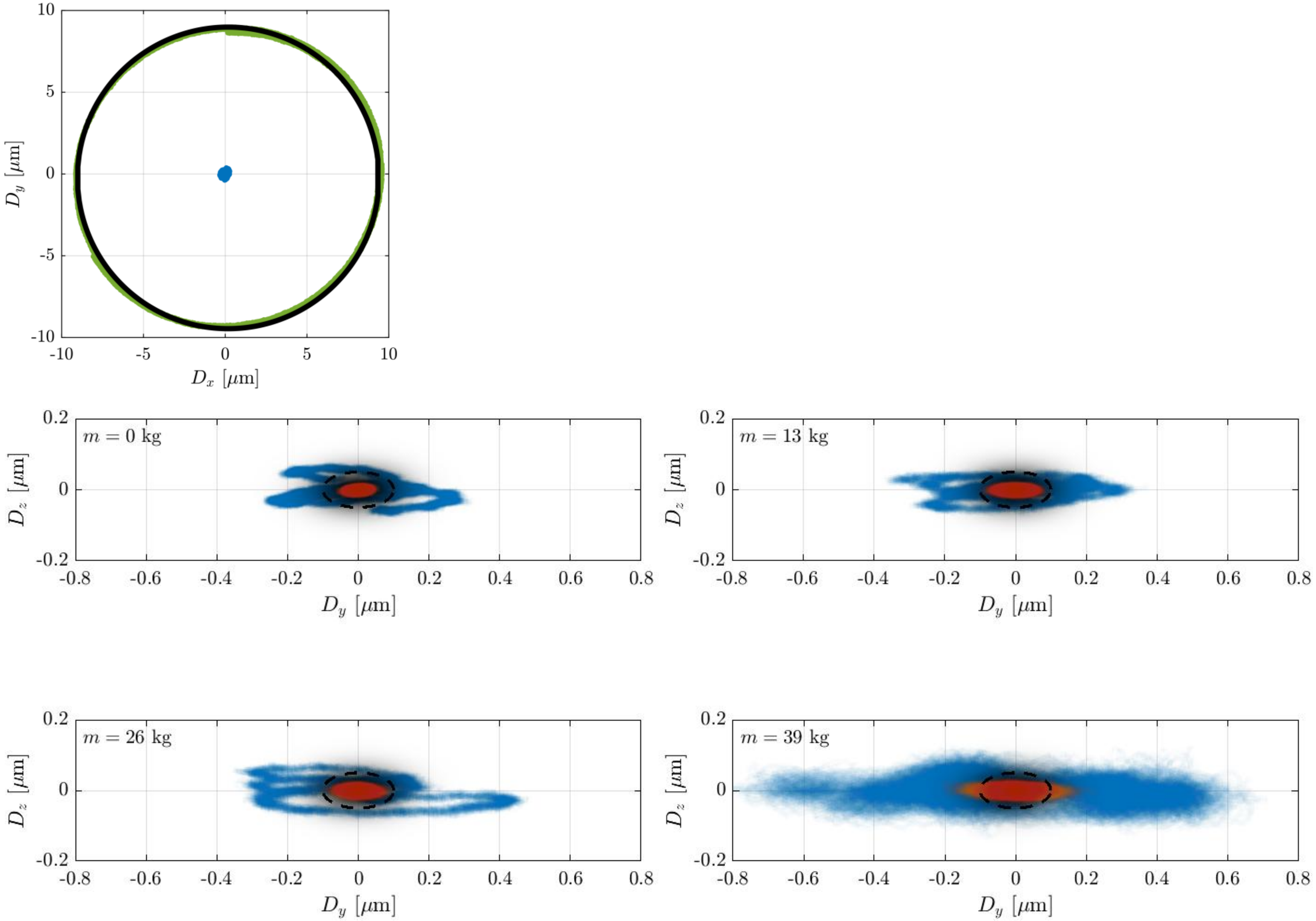


Cumulative Amplitude Spectrum

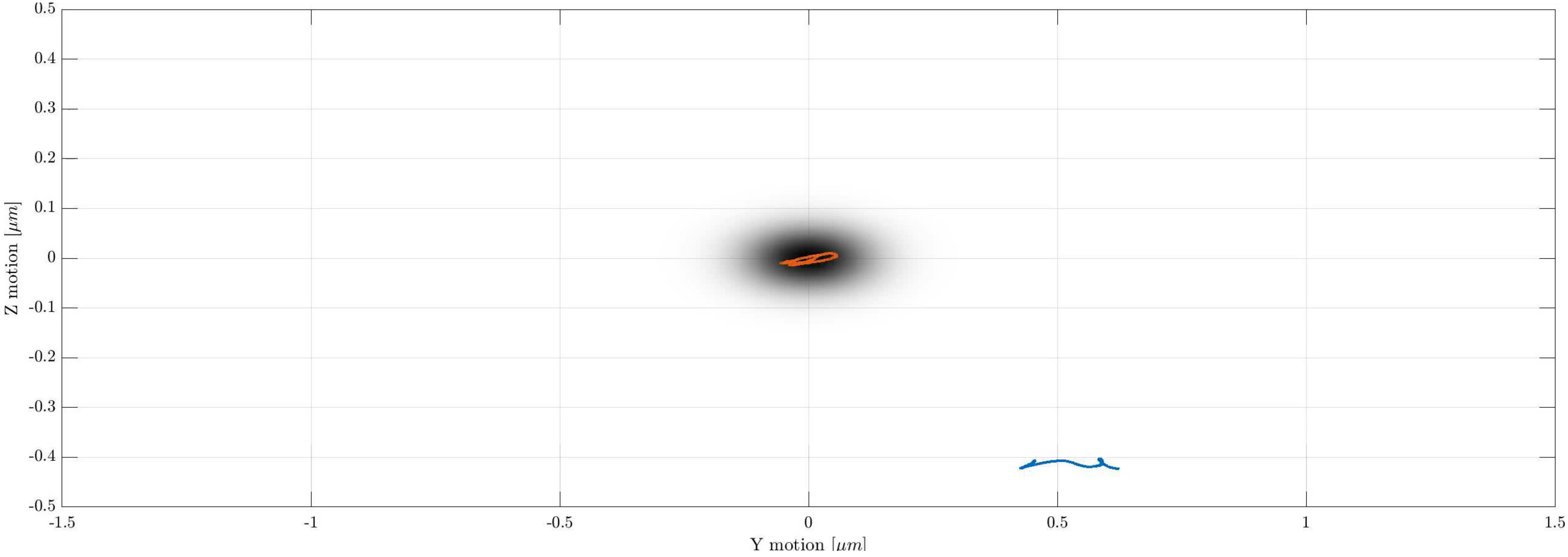


Tomography Experiments – Robustness to Change of Payload





Lateral Scans

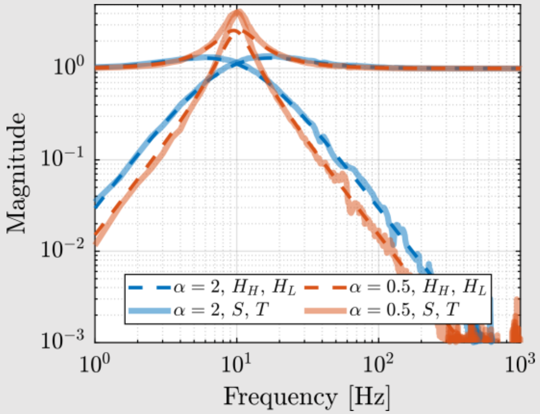


Closed-Loop Shaping with Complementary Filters

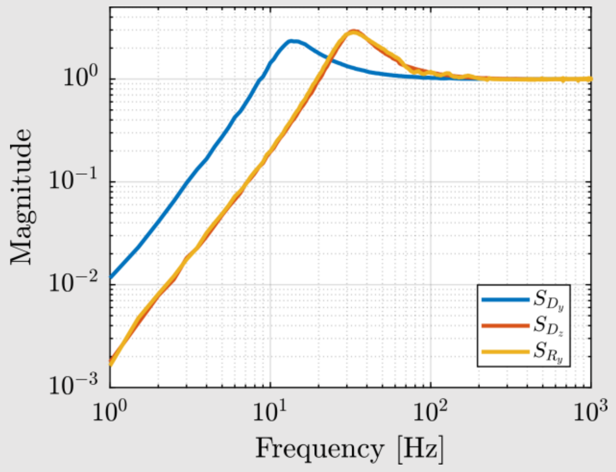
Complementary Filters Formula

$$H_L(s) = \frac{(1+\alpha)(\frac{s}{\omega_0}) + 1}{\left((\frac{s}{\omega_0}) + 1\right)\left((\frac{s}{\omega_0})^2 + \alpha(\frac{s}{\omega_0}) + 1\right)}$$

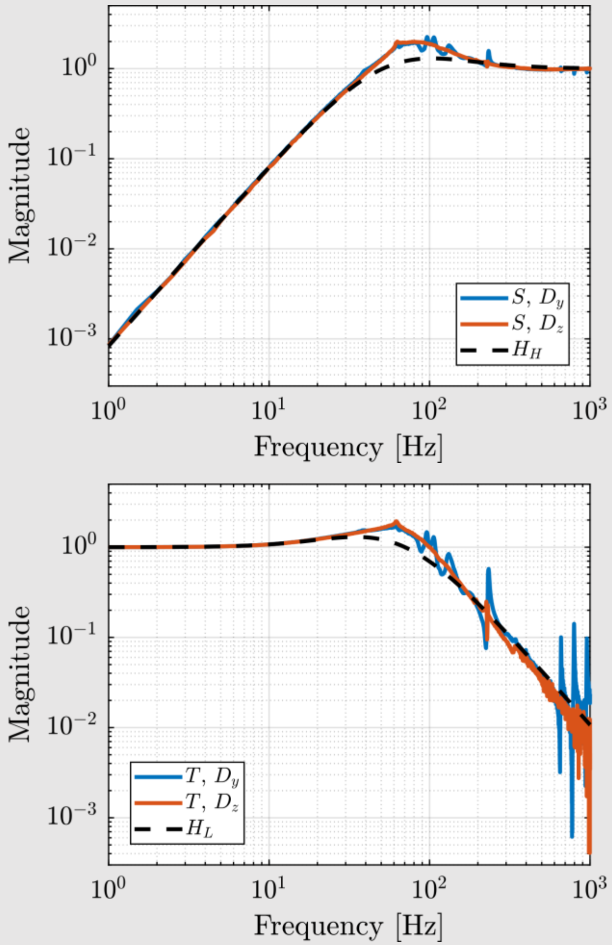
$$H_H(s) = \frac{(\frac{s}{\omega_0})^2\left((\frac{s}{\omega_0}) + 1 + \alpha\right)}{\left((\frac{s}{\omega_0}) + 1\right)\left((\frac{s}{\omega_0})^2 + \alpha(\frac{s}{\omega_0}) + 1\right)}$$

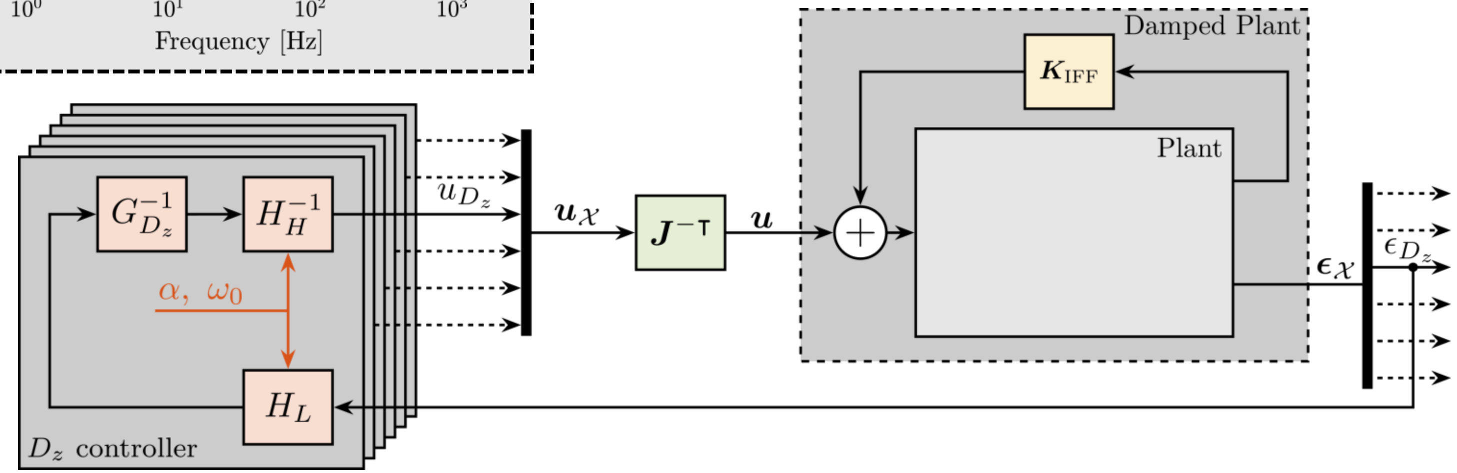


Different Bandwidth



Highest Achieved Bandwidth



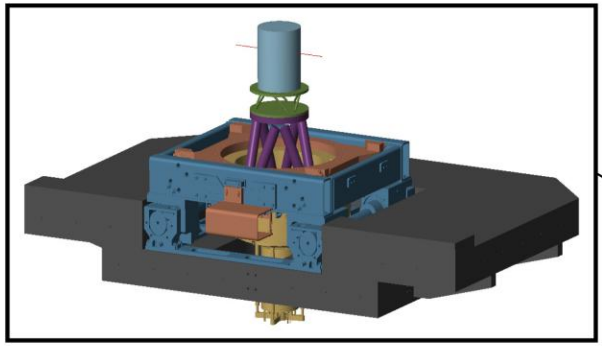


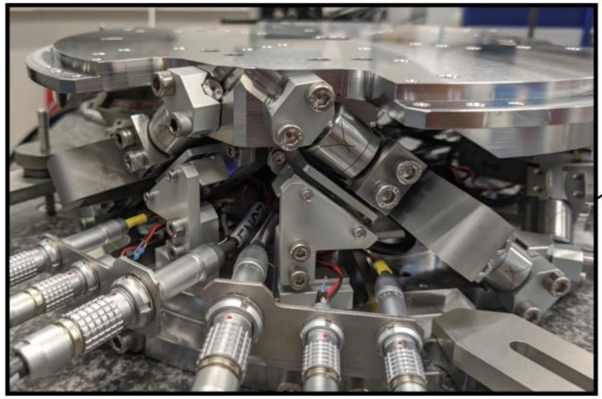
Conclusion

Goal

Improve the Micro-Station accuracy
from ≈ 10µm down to ≈ 100nm
without impacting the mobility
and payload capability

Challenges





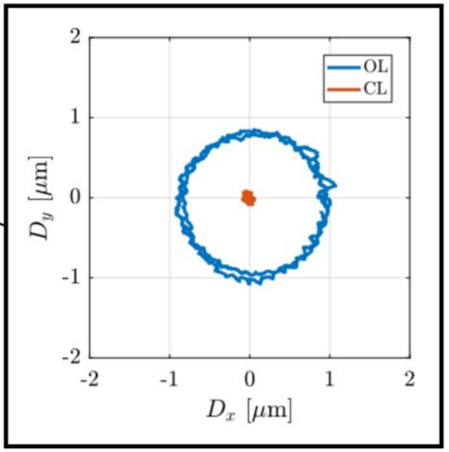
Predictive Design
"Right the First Time"

Control
Performance
and Robustness

Design of a rotating
6DoF Active Platform

Experimental
Validation

"Robustness by design"
Closed-Loop Shaping



Conclusion

Validated Concept
Unique Positioning-Station:
High mobility / High Accuracy / 50kg payload capability
New scientific oppotunities on ID31

Perspectives

Better addressing the change of Payload

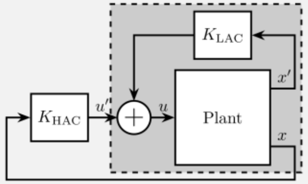
Robust Control
$\mathcal{H}_\infty / \mu$-synthesis

Linear Parameter-Varying
(LPV)
Control

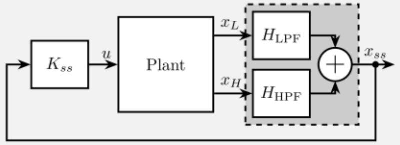
Automatic tuning
after change of payload

Better use of sensors

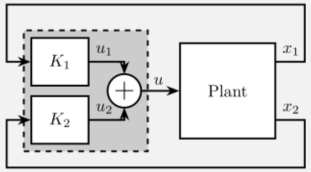
HAC-LAC



Sensor Fusion

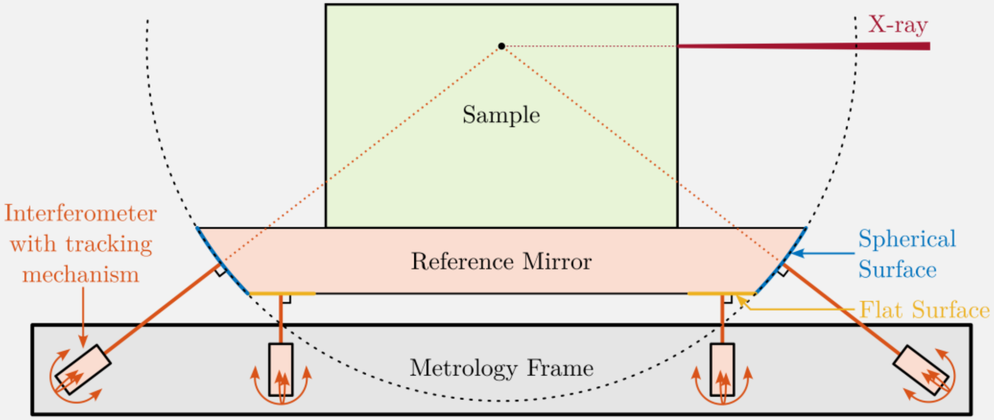


Two sensor Control

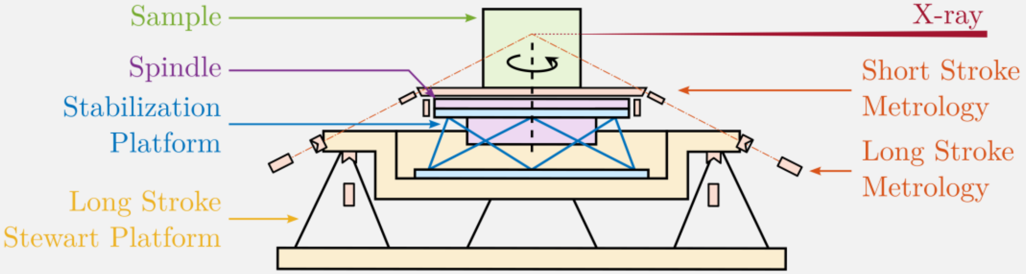


Extend the design methodology to other high precision instruments and complete Beamlines

Long Stroke Metrology System



Change of Design Approach: Alternative Architecture



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Thank You !