



# Design workflow of digital controllers for high-performance mechatronic systems at Sirius' beamlines

Advanced Control Workshop  
September 21<sup>st</sup>, 2025

---

**Gabriel O. Brunheira**

Control and Integration | Beamlines Engineering Division

Brazilian Synchrotron Light Laboratory | LNLS



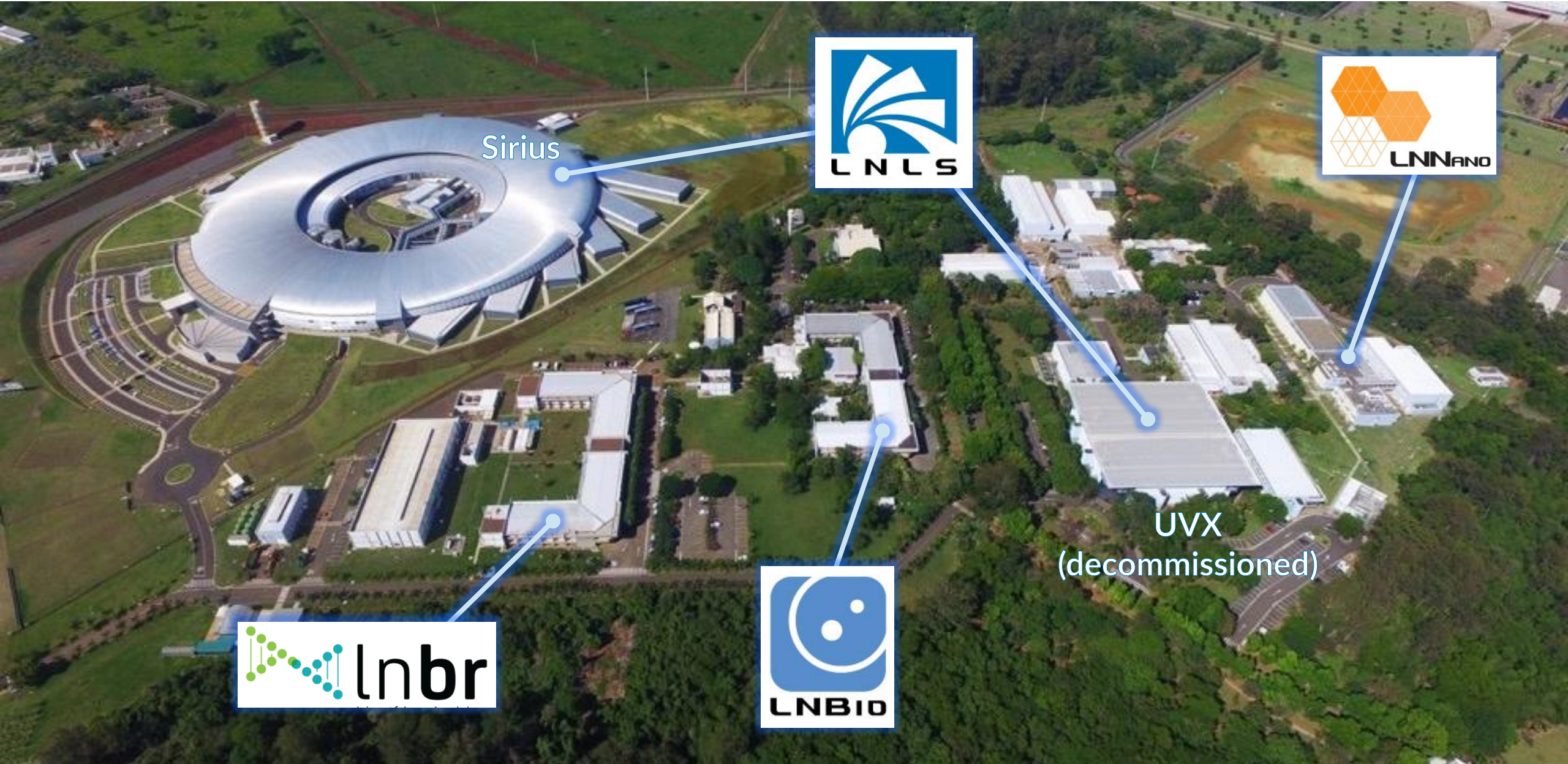
MINISTRY OF  
SCIENCE TECHNOLOGY  
AND INNOVATION



# CNPEM & LNLS



CNPEM



Sirius

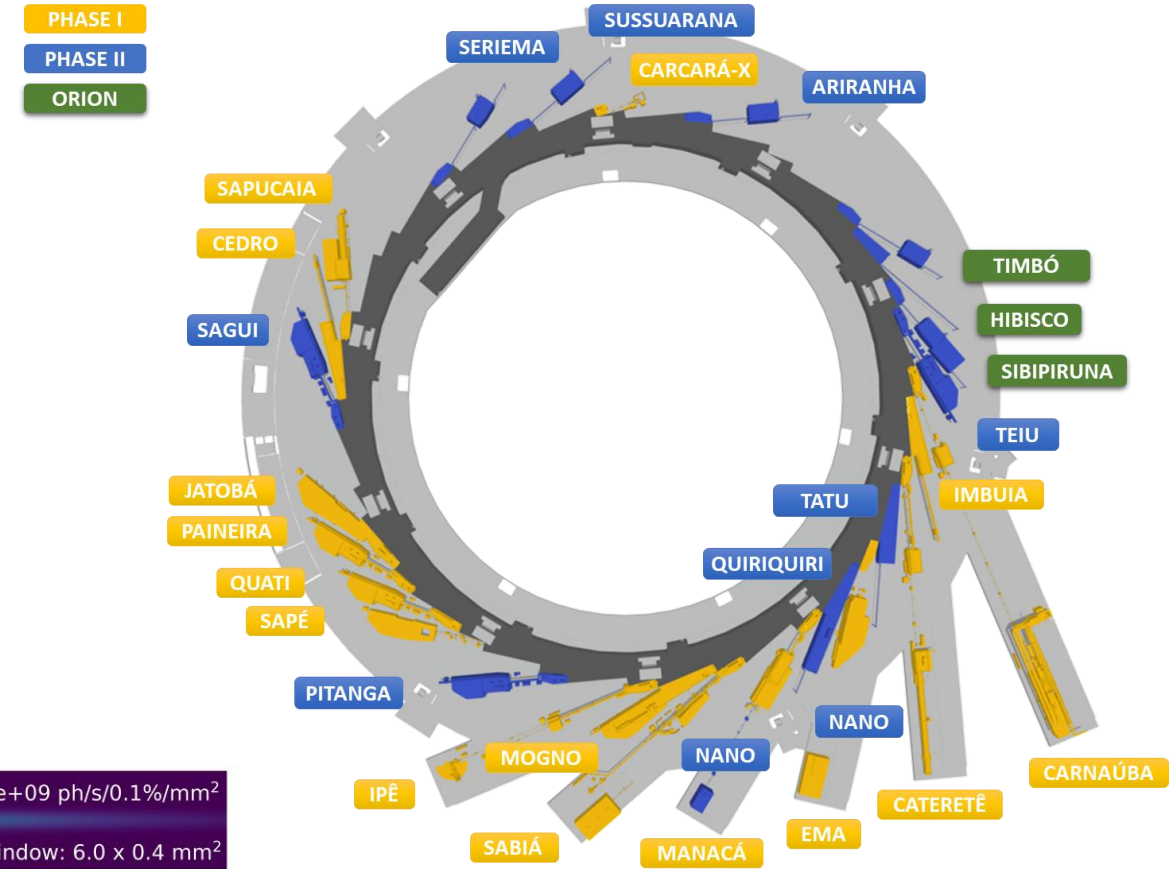


UVX  
(decommissioned)



# Sirius – 4<sup>th</sup> generation light source

- Increased brilliance/flux
  - ✓ Smaller sources → **Higher stability**
  - ✓ Higher flux → **Faster processes**
- Increased coherence fractions
  - ✓ Coherence-based methods (ptycho)
  - ✓ **Higher stability** requirements



UVX	Max. Intensity = $1.7 \times 10^9$ ph/s/0.1%/mm <sup>2</sup>
	Window: 6.0 x 0.4 mm <sup>2</sup>
Sirius	Max. Intensity = $6.6 \times 10^{16}$ ph/s/0.1%/mm <sup>2</sup>
	Window: 6.0 x 0.4 mm <sup>2</sup>

Beamsizes at LNLS: UVX (2<sup>nd</sup> gen) vs. Sirius (4<sup>th</sup> gen)

# Design of high-performance mechatronics at LNL



### 2.2. The 11 Design Principles

Design of High Precision Machines:

1. Structure (symmetry, stiffness, dynamics, damping)
2. Kinematic/Semi-kinematic design (isostatic)
3. Abbé Principle (metrology)
4. Direct measurement
5. Metrology frames (isolated from force frames)
6. Bearings
7. Transmission drives
8. Thermal effects
9. Control
10. Error Budgeting (static, dynamic, thermal)
11. Error Compensation

and many others...

### 2.3. Mechanical: Sensors

Critical aspects:

- Absolute vs Relative
- Measurement range
- Communication protocol
- Measurement bandwidth
- Noise levels
- Non-linearities
- Vacuum compatibility
- Temperature compatibility

Autocollimator

### 2.3. Mechanical: Actuators

Critical aspects:

- Actuation principle
- Force levels
- Actuation range
- Noise levels
- Non-linearity
- Vacuum comp.
- Temperature

### 2.3. Mechanical: Flexural Mechanisms

PROs:

- Predictable behavior/modeling
- Less dependent of friction
- Higher repeatability and resolution (reduced friction effects)
- Free of lubrication
- Lower (or negligible) level of maintenance

CONs:

- Limited motion range
- Limited load capacity
- Non-linear behavior

### 2.3. Mechanical: Control of Degrees of Freedom (DoF)

Restriction of Degrees of Freedom by single-point contact:

- Hertz contact theory
- Friction/preload based
- Limited stiffness

Overconstraining = deformation

### 2.5. Thermal: Fundamentals

Expansion approximation:

$$\Delta L = L_0 \cdot \alpha \cdot \Delta T$$

E.g.:

- $L = 25 \text{ mm}$
- $\Delta T = 0.1 \text{ K}$
- $\alpha = 20 \mu\text{m/m} \cdot \text{K (Al)}$
- $\Delta L = 50 \text{ nm!}$

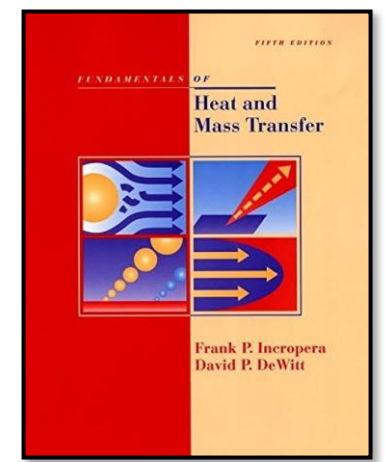
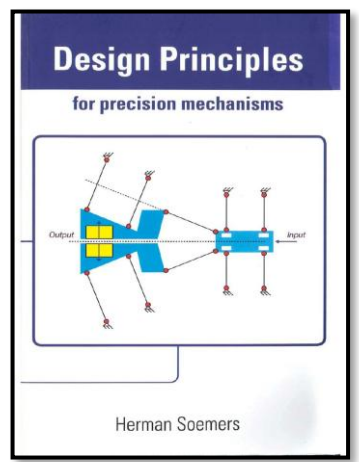
### 2.3. Mechanical Metrology: Abbé

Options:

- Reduction of lever-arms as much as possible;
- Measurement of additional DoFs;
- Calibration.

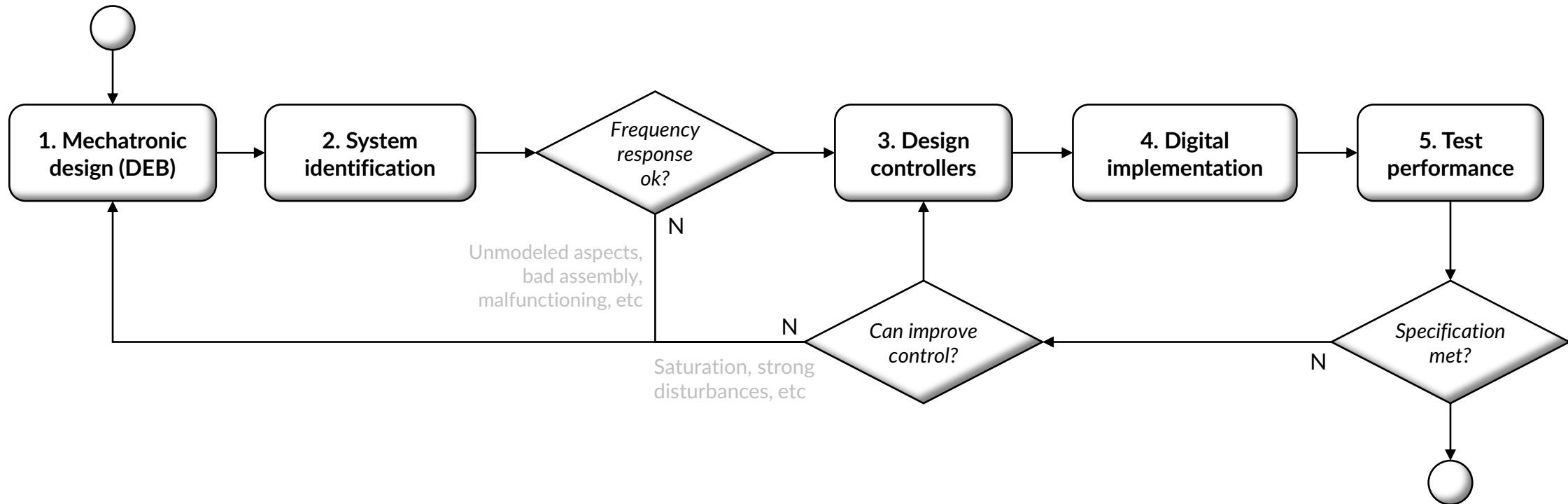
E.g.:

- $L = 25 \text{ mm}$
- $\theta = 1 \mu\text{rad}$
- $\epsilon = 25 \text{ nm!}$

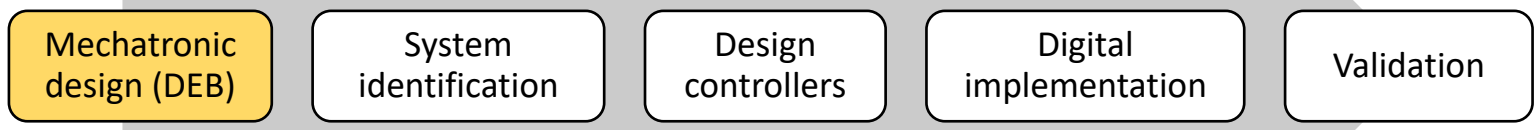


Geraldes, R.R., THKAM01, MEDSI 2023

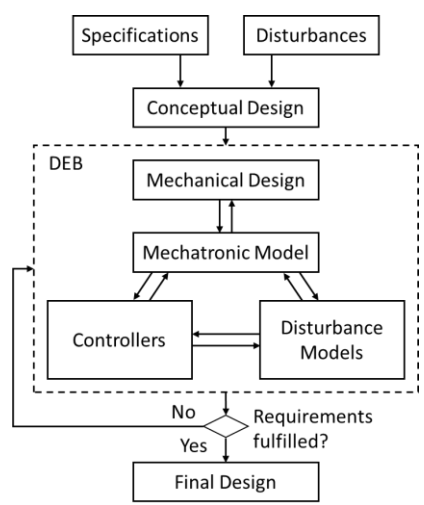
# Control design workflow



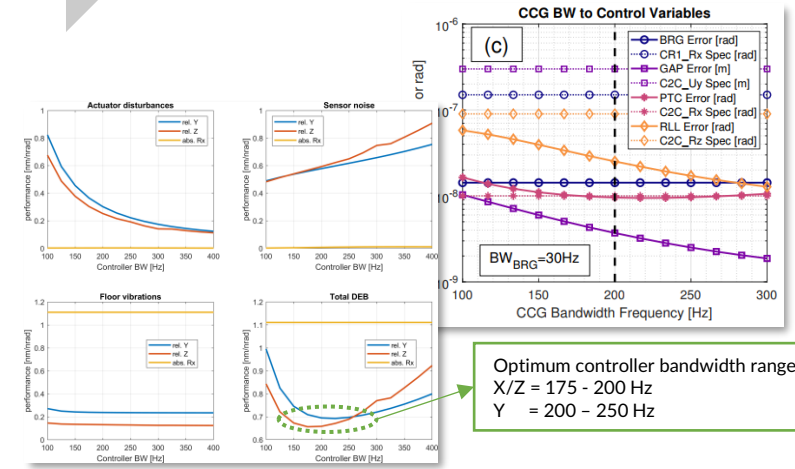
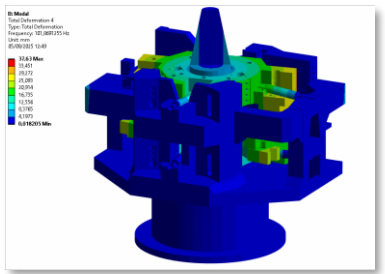
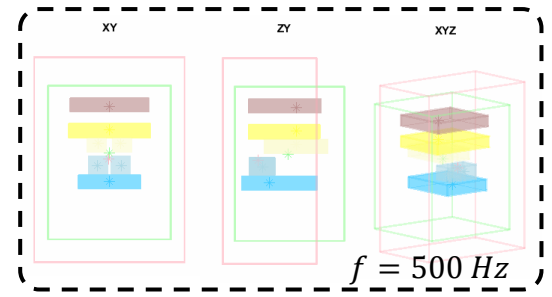
# System design with Dynamic Error Budgeting (DEB)



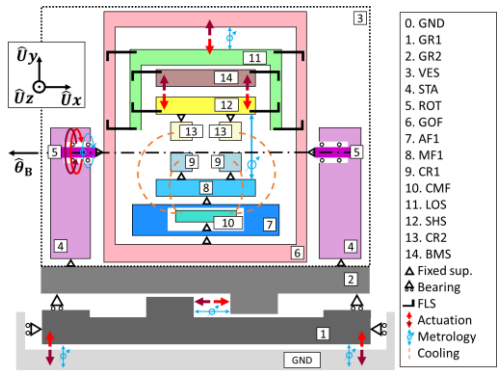
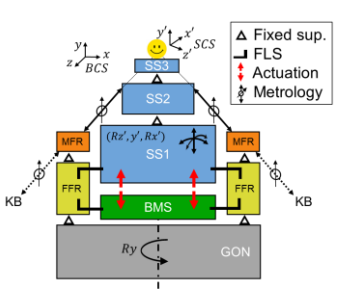
## DEB Framework



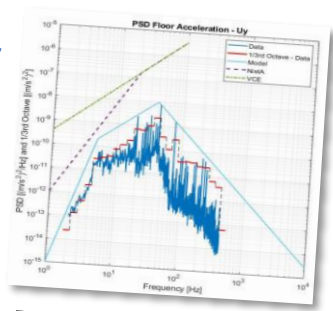
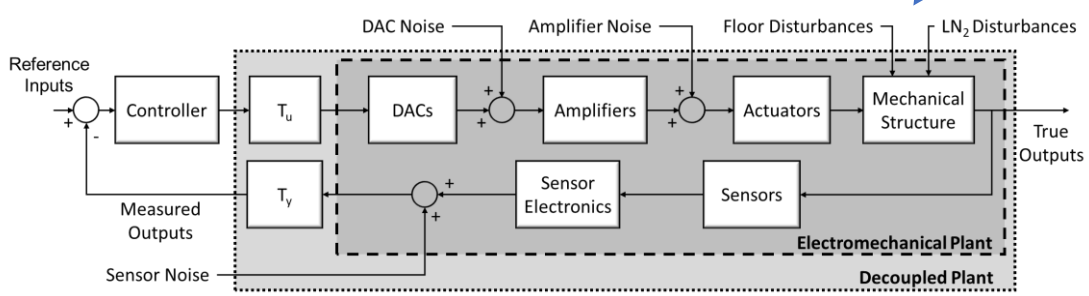
## Mode Shapes



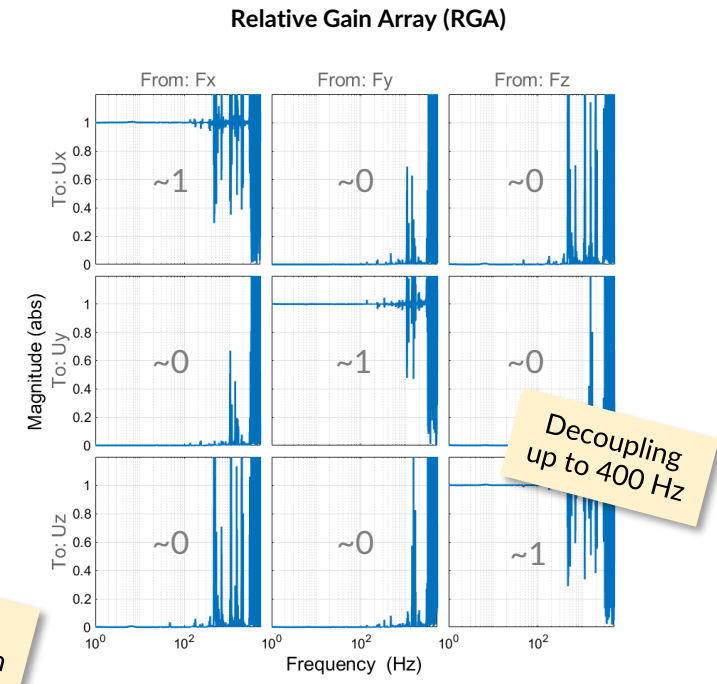
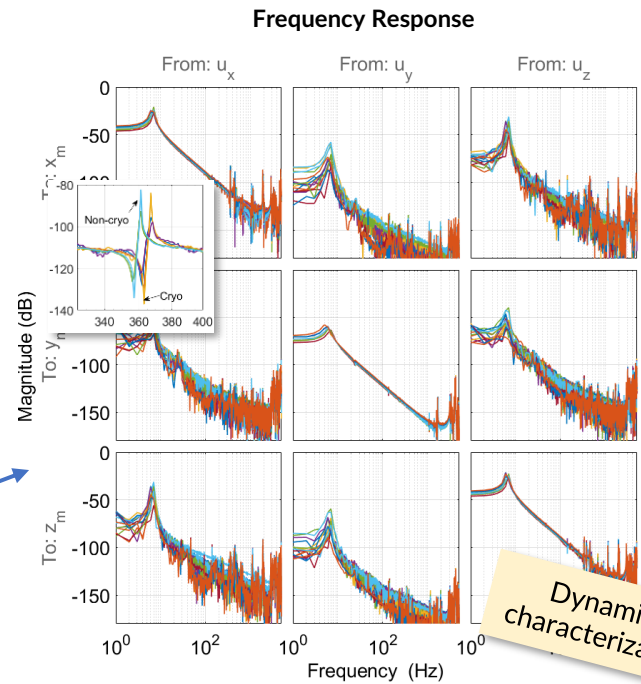
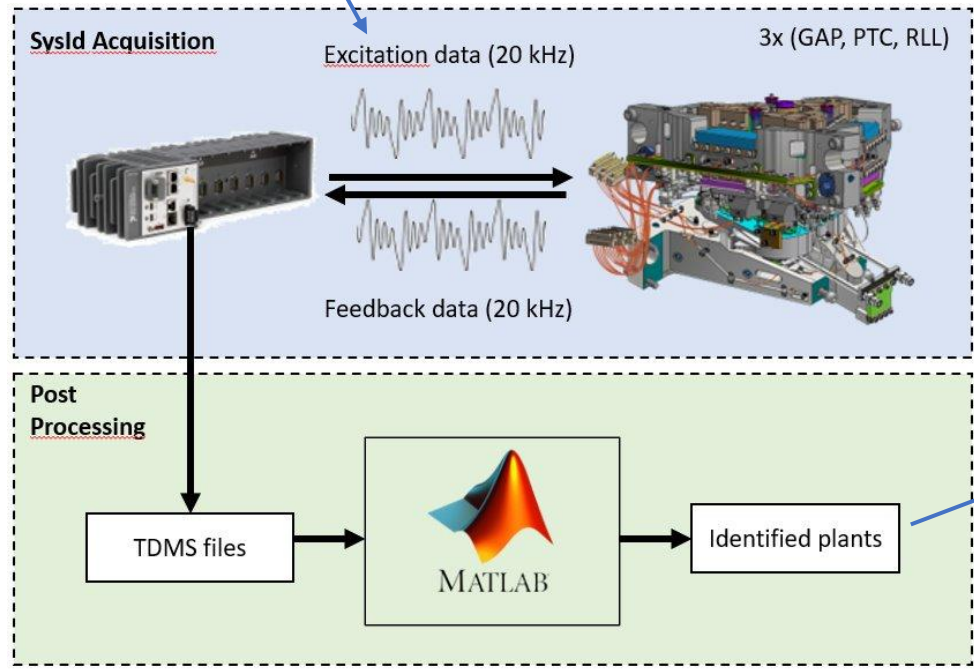
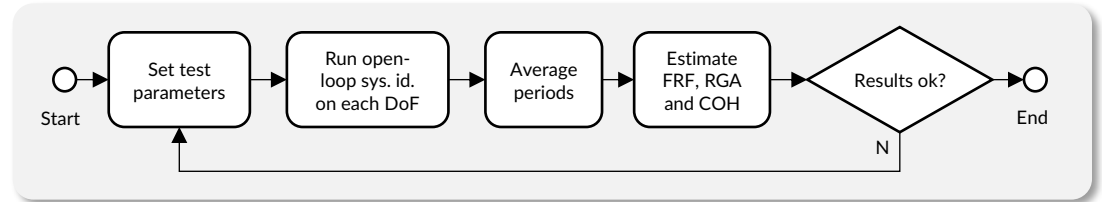
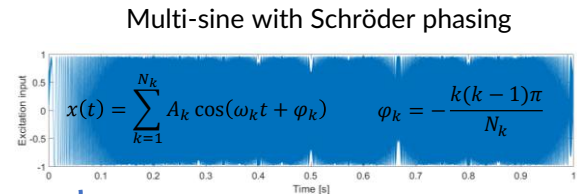
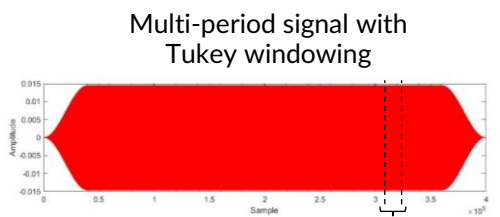
## Lumped Mass Model



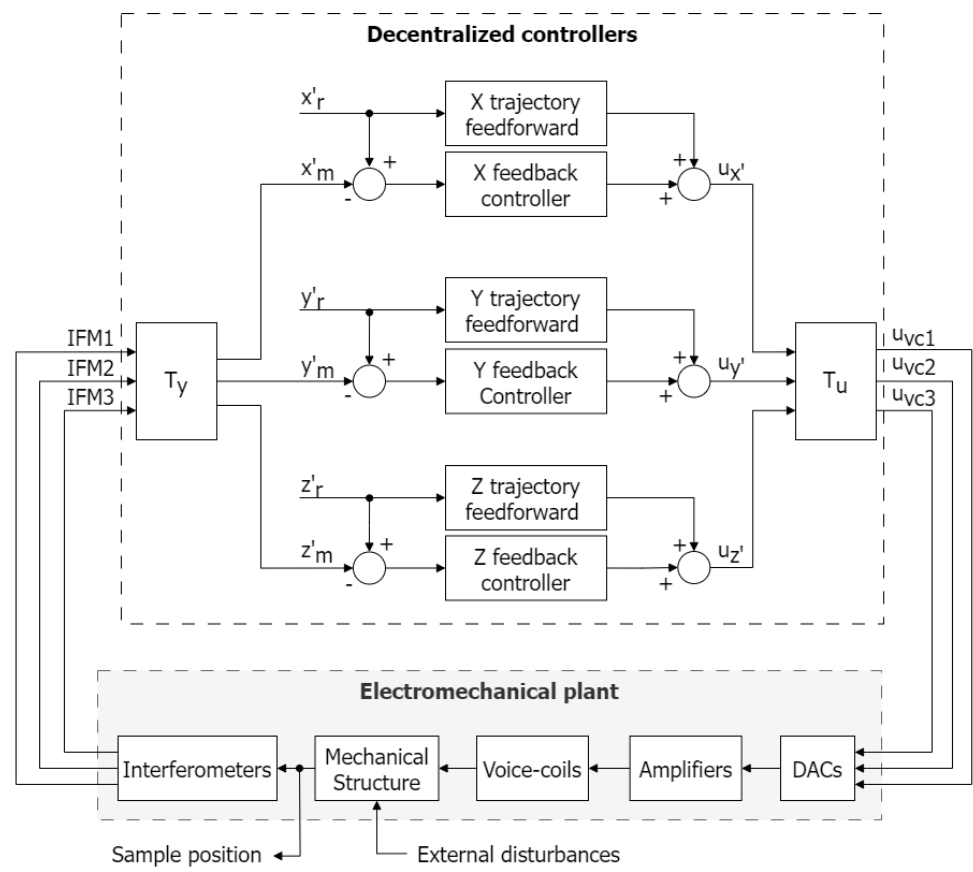
## Fixed feedback control loop structure + disturbances



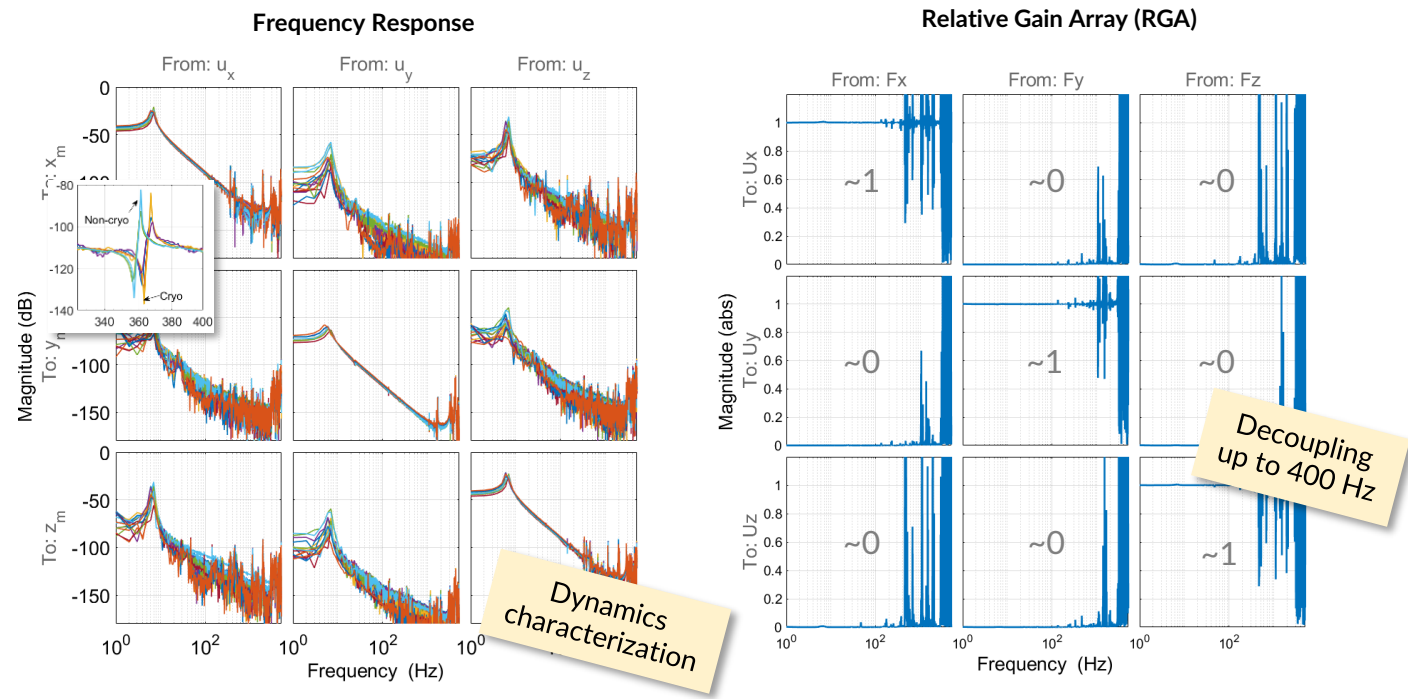
# Non-parametric system identification



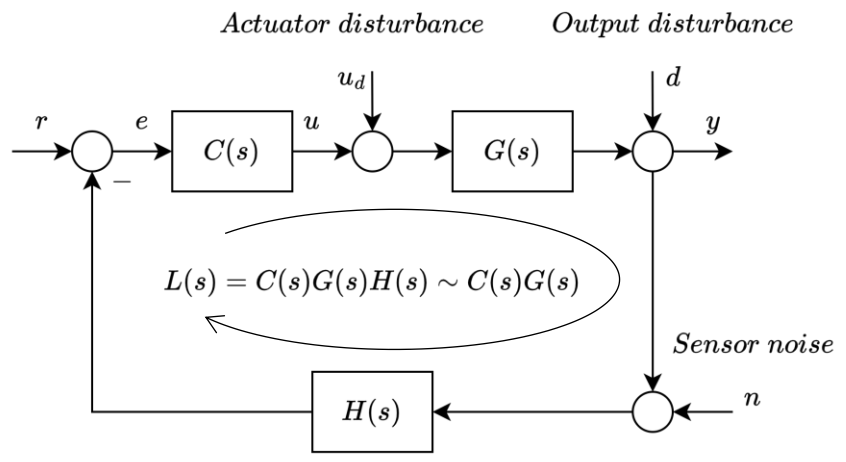
# Decentralized control for SISO design



- MIMO systems are already designed to minimize crosstalk between degrees-of-freedom, envisioning decentralized control
- Homogeneous transformation from sensors ( $T_u$ ) and actuators ( $T_u$ ) position act as the steady-state decoupling matrices



# Loop-gain trade-off



$$T = \frac{y}{r} = \frac{y}{n} = \frac{L}{1+L}$$

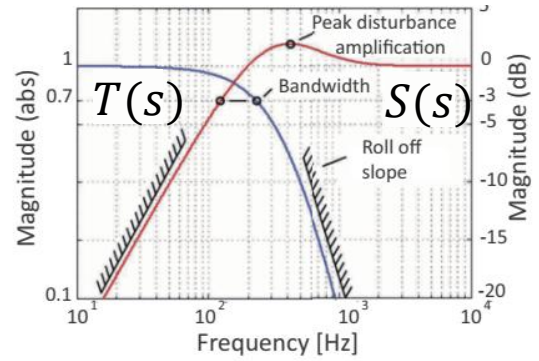
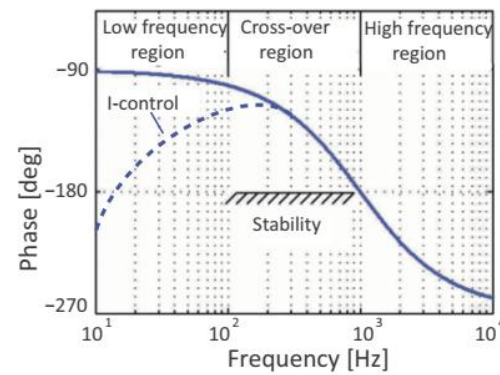
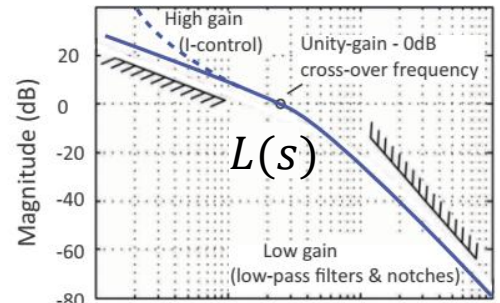
$$S = \frac{y}{d} = \frac{e}{r} = \frac{1}{1+L}$$

$$P = \frac{y}{u_d} = \frac{G}{1+L}$$

$$K = \frac{u}{r} = \frac{u}{n} = \frac{C}{1+L}$$

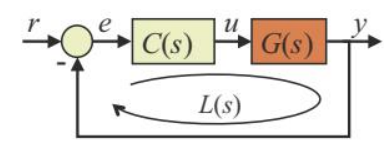
Solution -  $L(s)$  has:

- High gain at low frequencies
- Low gain at high frequencies



Design goals trade-off:

- $L$  large for good reference tracking :  $T \rightarrow 1 \Rightarrow y \rightarrow r$
- $L$  small to reject sensor noise at output :  $T \rightarrow 0 \Rightarrow y \rightarrow 0$
- $L$  large for disturbances rejection :  $S, P \rightarrow 0 \Rightarrow y \rightarrow 0$
- $C$  (and  $L$ ) small to reduce actuator signal :  $K \rightarrow 0 \Rightarrow u \rightarrow 0$



[Schmidt, 2020]

# Feedback controller with loop shaping method



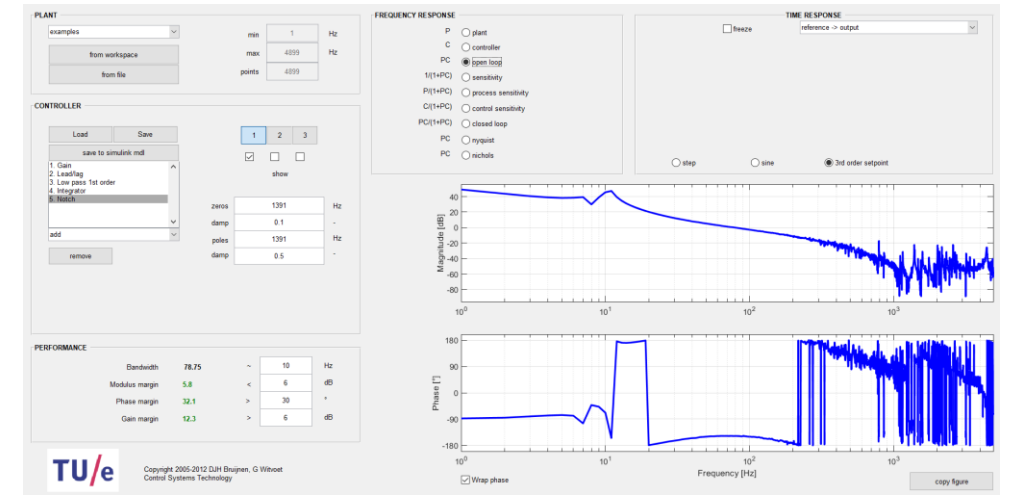
Manual tuning with Shapelt for MATLAB  
(Eindhoven University of Technology)

Fixed PID-like structure, formed by 2<sup>nd</sup> order blocks:

- Intuitive design
- Discretization into Second-order Sections (SOS) for higher numerical stability

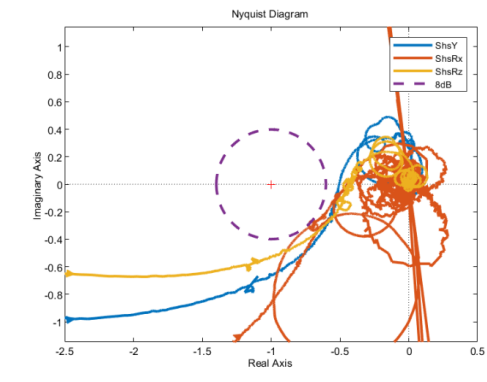
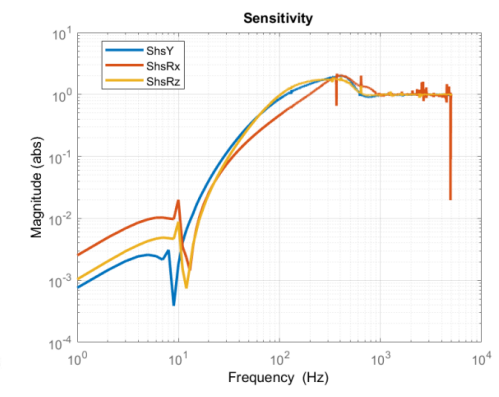
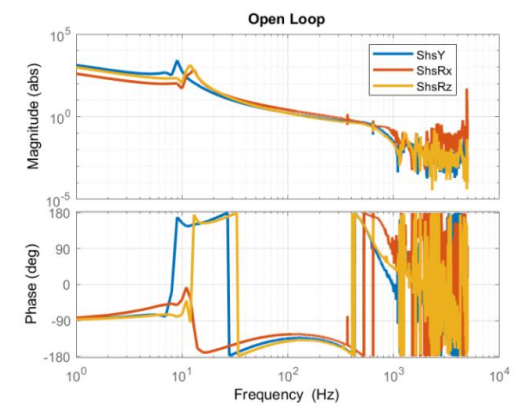
$$C(s) = k_{bw} \cdot \frac{s + z_i}{s} \cdot \frac{s + z_l}{s + p_l} \cdot \frac{\omega_{LP}^2}{s^2 + 2\xi\omega_{LP}s + \omega_{LP}^2} \cdot \frac{s^2 + 2\alpha\xi_{n1}\omega_{n1}s + \omega_{n1}^2}{s^2 + 2\xi_{n1}\omega_{n1}s + \omega_{n1}^2} \cdot \frac{s^2 + 2\alpha\xi_{n2}\omega_{n2}s + \omega_{n2}^2}{s^2 + 2\xi_{n2}\omega_{n2}s + \omega_{n2}^2} \dots$$

Prop. gain
Integrator
Lead comp.
Low-pass filter
Notch filter 1
Notch filter 2

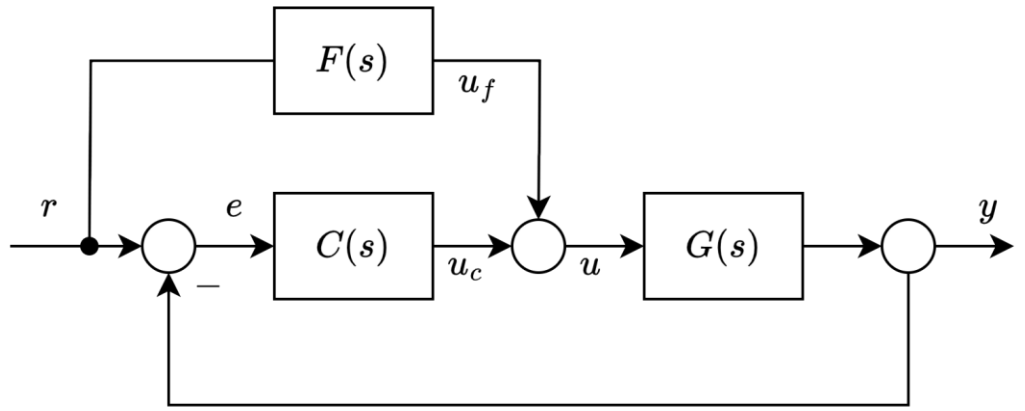


Design specifications:

- Bandwidth : above disturbances (~100 – 300 Hz)
- Modulus margin (S peak) : < 6 dB
- Phase margin : > 30°
- Gain margin : > 6 dB



# Reference feedforward for trajectory tracking



$$T(s) = \frac{y}{r} = \frac{FG + CG}{1 + CG}$$

Ideal feed-forward by model inversion:

$$F(s) = G^{-1}(s) \Rightarrow \begin{cases} T \rightarrow 1 \\ y \rightarrow r \end{cases}$$

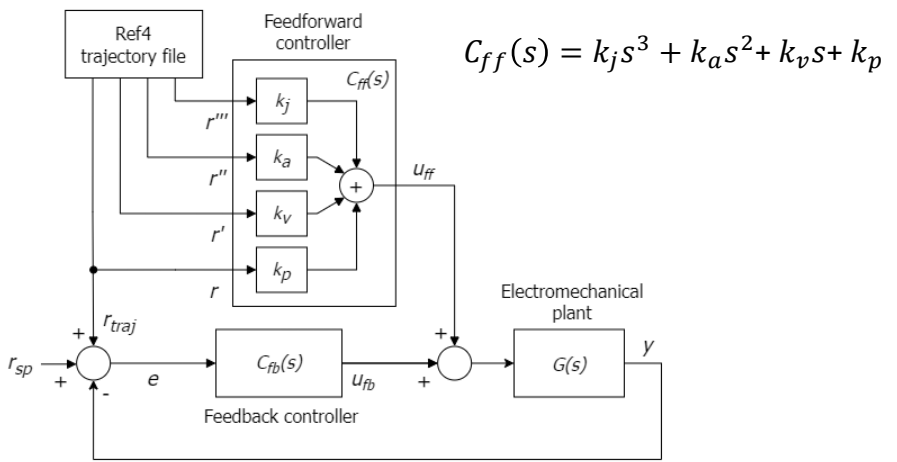
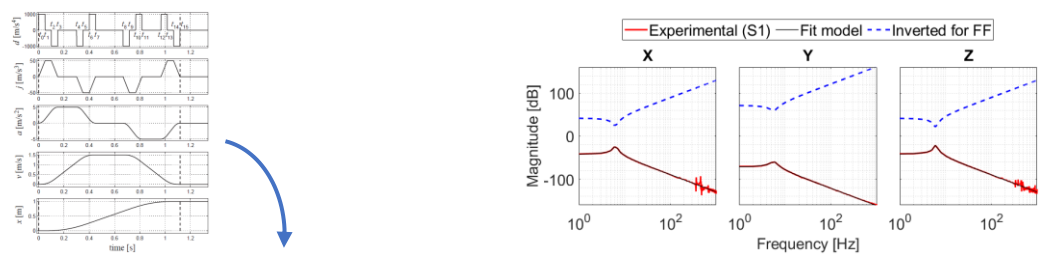
- Most of control effort comes from feedforward effort
- Feedback deals with steady-state error and disturbance rejection
- Inversion is not possible for strictly proper system (practically all physical systems), requiring additional poles to  $F(s)$
- Robust performance limited by model uncertainty

# Reference feedforward for trajectory tracking



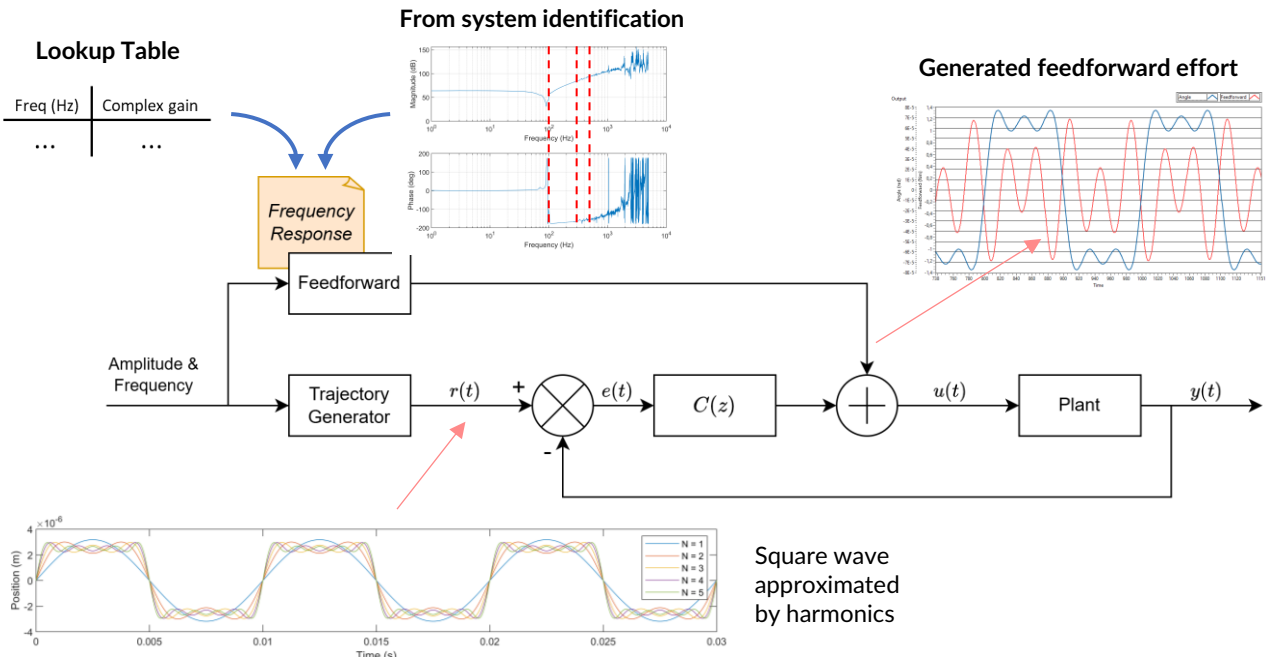
## Method 1: S-curves trajectory files

- Smooth motion by reducing high frequency energy
- Parametrization from physical aspects (max velocity, etc)
- Direct feedforward effort, given all derivative terms

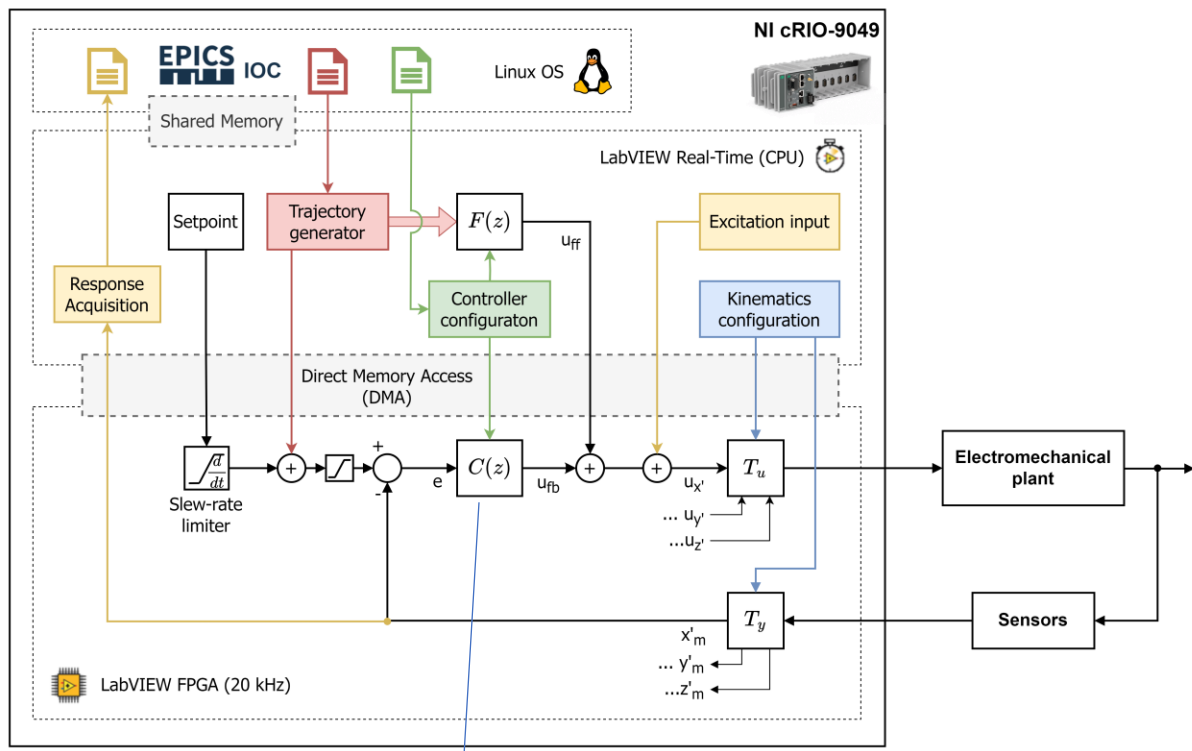
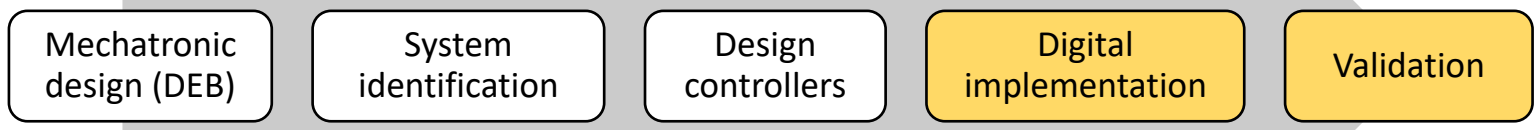


## Method 2: Periodic references

- Periodic trajectory is generated from fundamental and desired harmonics
- Gain and phase for each component from inverse of measured frequency response (complex numbers)
- Work-in-progress: online estimation of gain and phase response



# Digital implementation

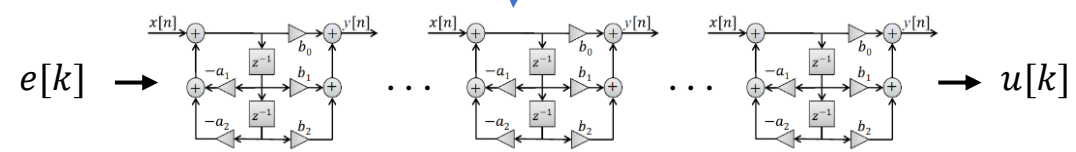


## Feedback controller discretization

- 20 kHz sampling frequency
- Each block of the “PID” controller is discretized separately to improve numerical stability
- Tustin discretization (pre-warping on notch filters)

## Implementation in NI CompactRIO platform

- Double-precision floating-point arithmetic (64 bits)
- Custom TF solver for LabVIEW FPGA
- Reconfigurable Direct Form II IIR filters in series for each DoF
- System identification and acquisition functionalities for validation and experimental usage



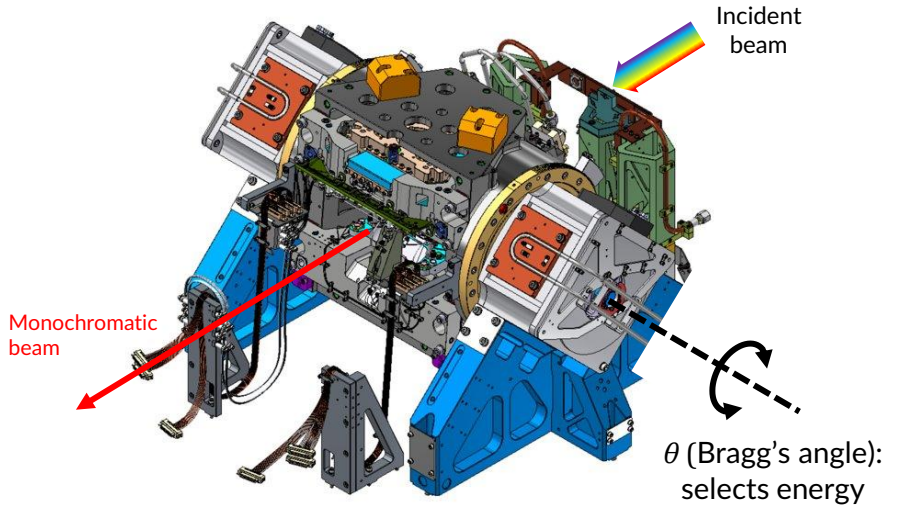
$C(z)$ : Second-order sections IIR filters in series



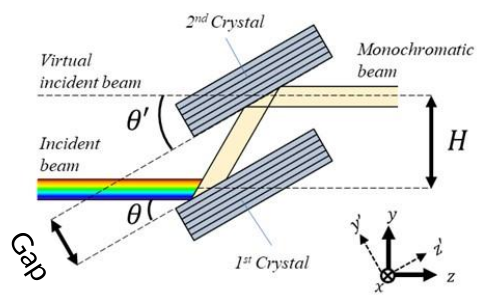
CNPq

# Applications in beamline systems at LNLS/Sirius

# High-Dynamic Double Crystal Monochromator (HD-DCM-Lite)



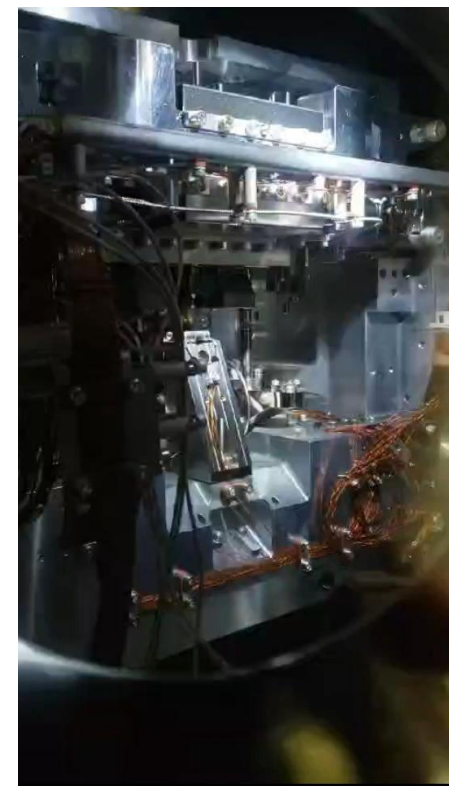
Short-stroke - keeps H constant



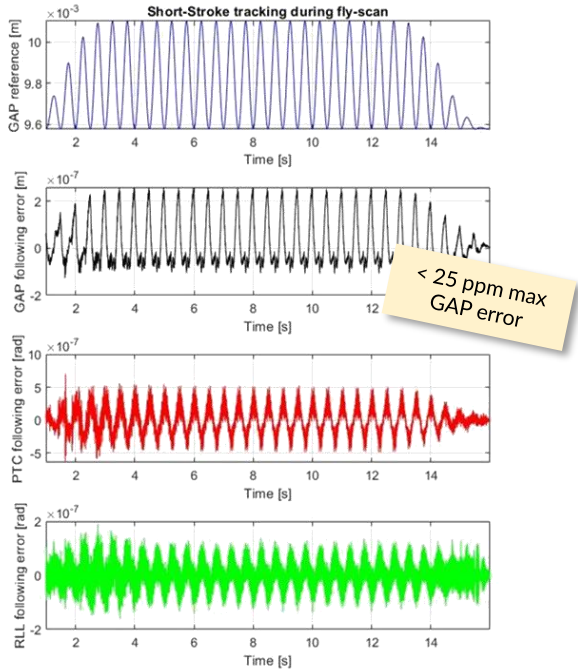
Fast energy scans (sinusoidal)

1.75 Hz, 13° (p2p)

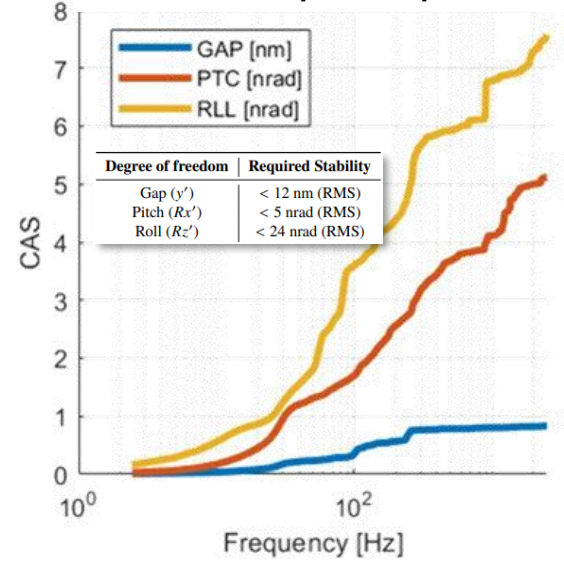
10 Hz, 0.3° (p2p)



Short-stroke scan error (2 Hz)



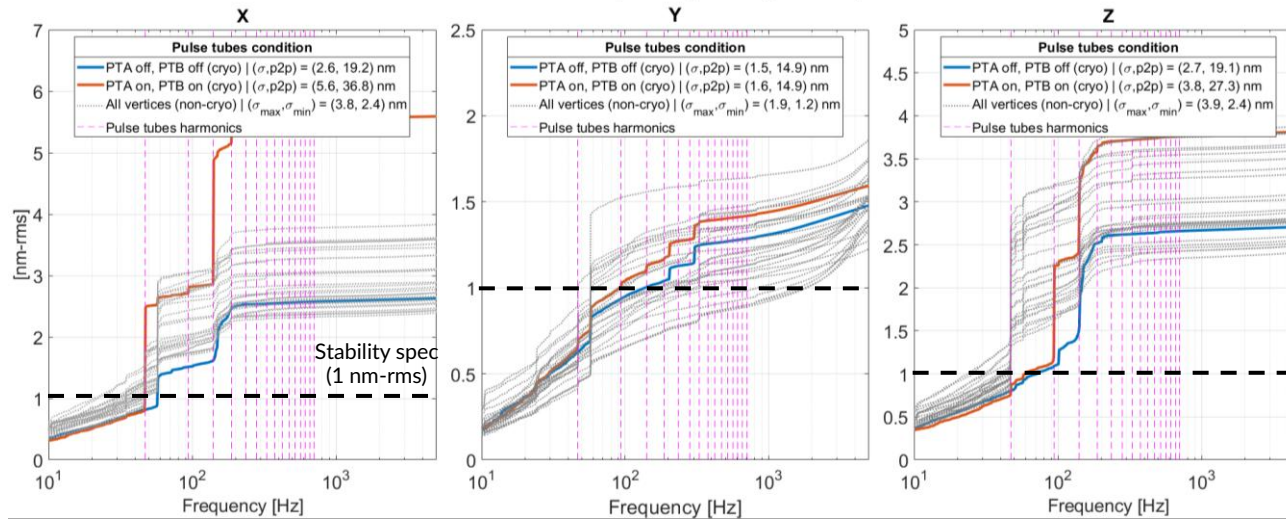
Short-stroke (In-position) cumulative amplitude spectrum



# SAPOTI Cryogenic Sample Stage (CARNAÚBA)

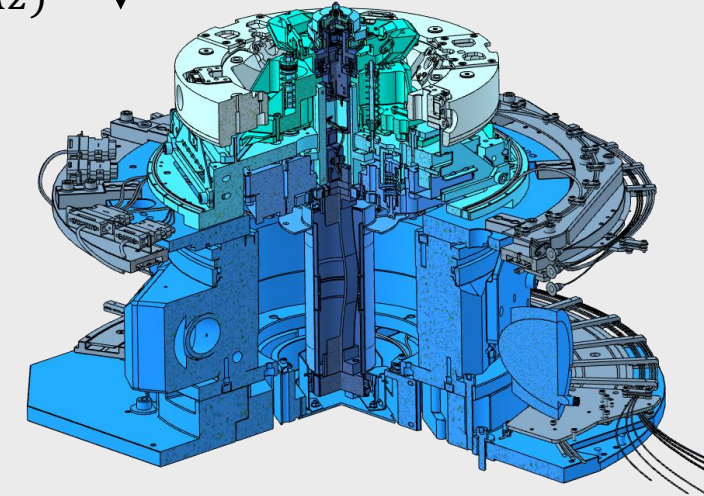


Sample stage (in-position stability) - Cumulative amplitude spectrum

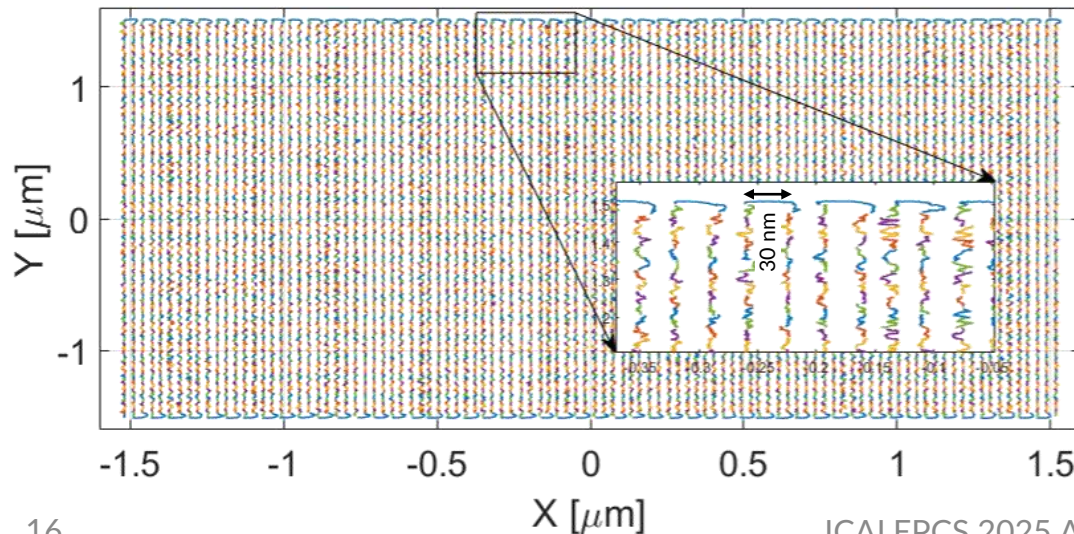


$x, y, z$   
 $(y, Rx, Rz)$

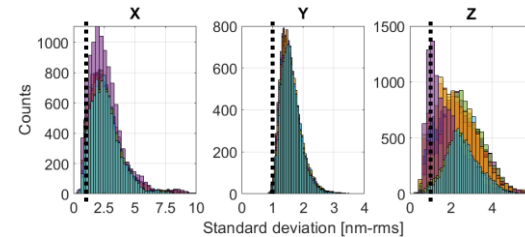
Parameter	Value
Vacuum level	~ 1e-9 mbar
Sample Temperature	100 to 300 K
2D mapping range (XY)	+/- 1.5 mm
2D mapping stab. (XY)	1 nm RMS
2D mapping acc. (XY)	< 10 nm
2D mapping repeat. (XY)	5 nm
Mapping velocity	≤ 50 μm/s
Main rotation range (Ry)	±110°
Main rotation stab. (Ry)	2 μrad
Main rotation acc. (Ry)	100 μrad
Main rotation repeat. (Ry)	10 μrad



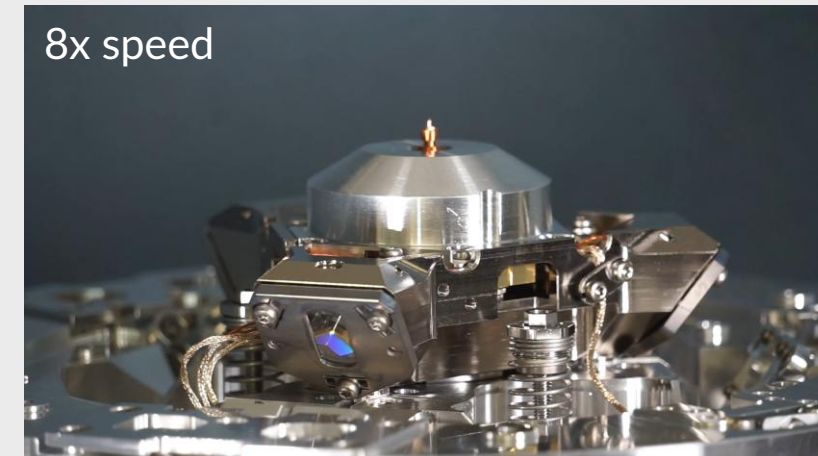
Sample position 2D raster fly-scan ( $3 \times 3 \mu\text{m}^2$ ) - 104 seconds



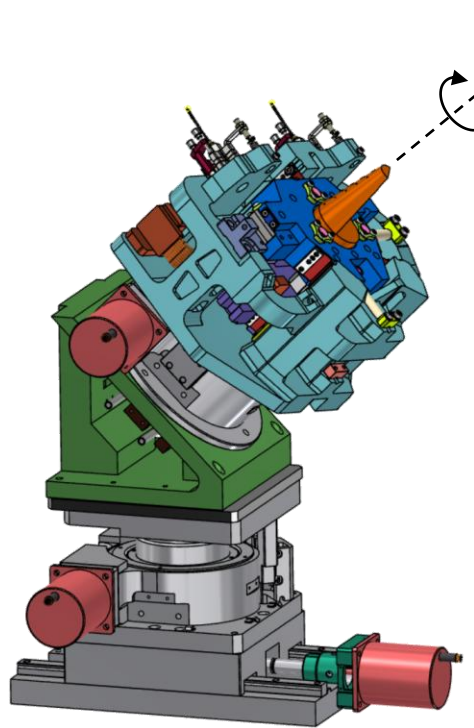
Histogram of RMS error per pixel (27 positions)



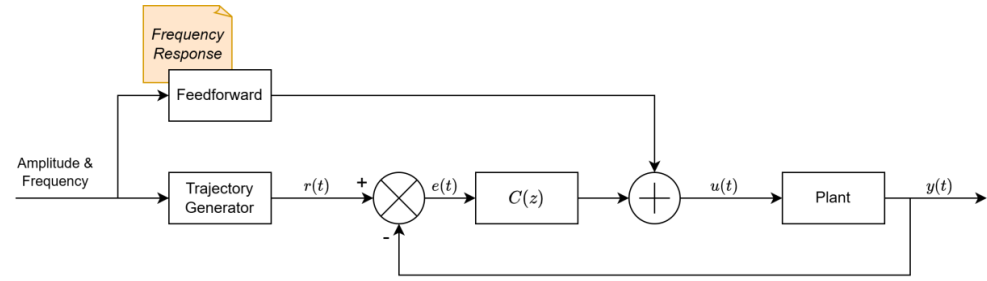
8x speed



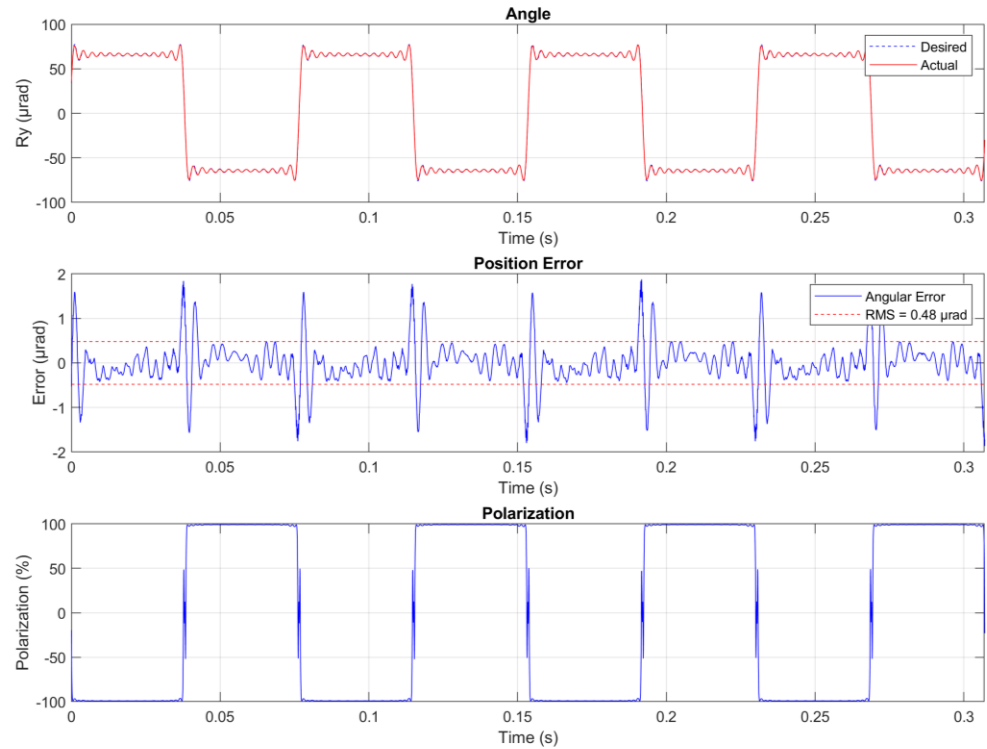
# Quarter-Wave Plate for XMCD experiments (EMA)



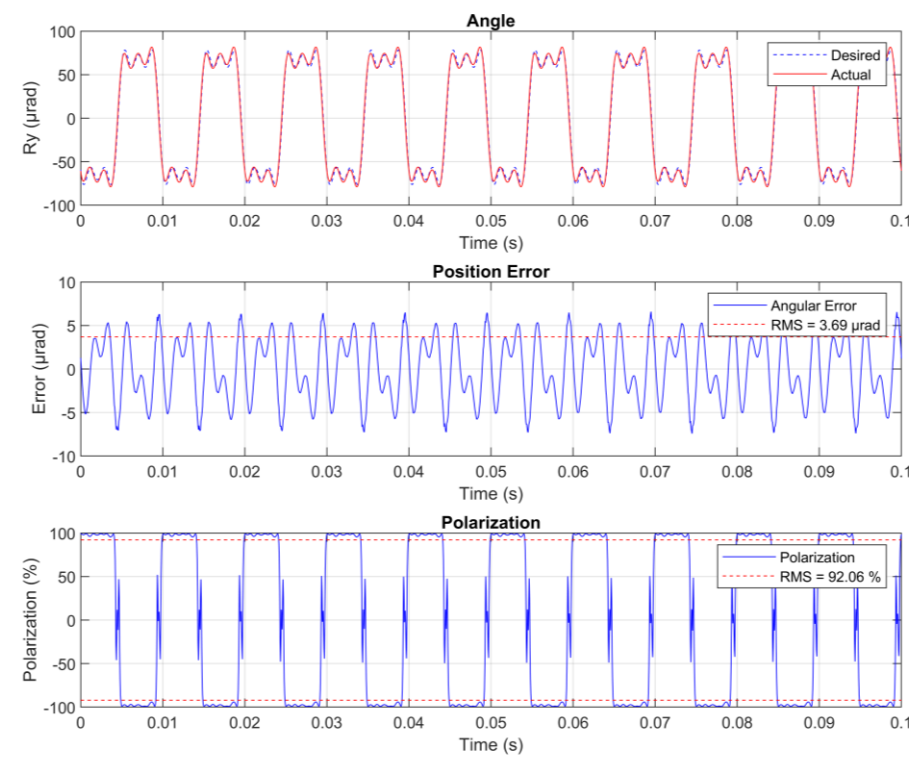
Ry: selects light polarization



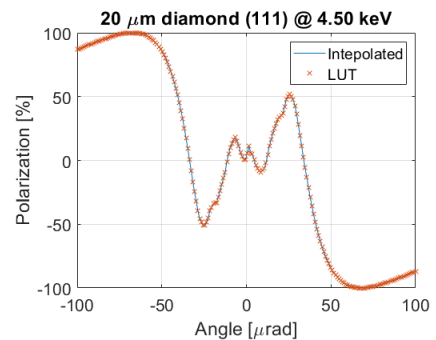
13 Hz XMCD with 200 μm Diamond @ 10 keV



100 Hz Lock-In with 200 μm Diamond @ 10 keV



New QWP for EMA beamline



\* Results with prototype

1. R.R. Geraldes, "Nanopositioning at Sirius/LNLS Beamlines - a Review and Future Opportunities", presented at the 12th Int. Conf. Mech. Eng. Design Synchrotron Radiat. Equip. Instrum. (MEDSI'23), Beijing, China, Nov. 2023, paper THKAM01
2. R. Geraldes, M. Moraes, G. Witvoet, and J. Vermeulen, "Predictive Modeling through Dynamic Error Budgeting Applied to the High-Dynamic Double-Crystal Monochromator for Sirius Light Source," *Precision Engineering*, vol. 77, pp. 90–103, 2022.
3. S. Skogestad and I. Postlethwaite, *Multivariable Feedback Control: Analysis and Design*. John Wiley & Sons, Inc., 2005
4. T. R. S. Soares, J. L. B. Neto, J. P. S. Furtado, and R. R. Geraldes, "System Identification Embedded in a Hardware-Based Control System with CompactRIO," in *Proc. ICALEPCS'23*, Cape Town, South Africa, 2023, pp. 489–493.
5. D. Bruijnen, R. van de Molengraft and M. Steinbuch, "Optimization aided loop shaping for motion systems," 2006 IEEE Conference on Computer Aided Control System Design, 2006 IEEE International Conference on Control Applications, Munich, Germany, 2006, pp. 255-260
6. P. Lambrechts, M. Boerlage, and M. Steinbuch, "Trajectory Planning and Feedforward Design for Electromechanical Motion Systems," *Control Engineering Practice*, vol. 13, pp. 145–157, 2005

# Thank you

---

Gabriel Oehlmeyer Brunheira  
[gabriel.brunheira@lnls.br](mailto:gabriel.brunheira@lnls.br)



Sign up to receive  
newsletters  
about **CNPEM**  
and its units

[cnpem.br](http://cnpem.br)



**CNPEM**  
Brazilian Center for Research  
in Energy and Materials

MINISTRY OF  
SCIENCE TECHNOLOGY  
AND INNOVATION

