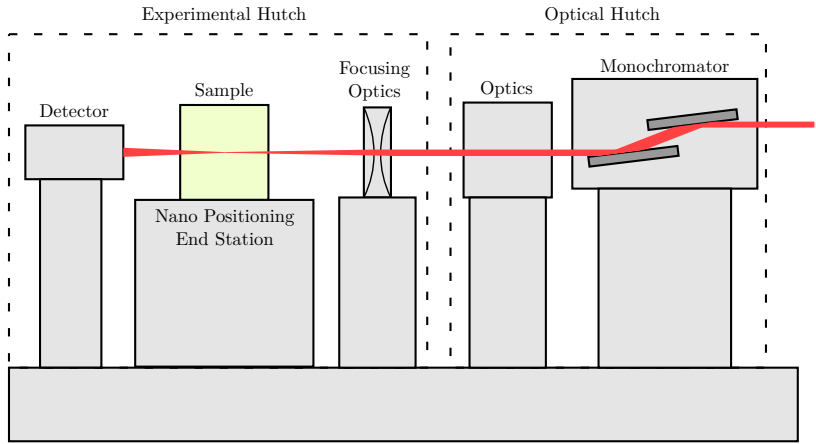
Mechatronics Developments for Nano-Positioning

X-ray Nano Probe Day Out

Dehaeze Thomas

15-09-2023

Typical Nano-Probe Beamline



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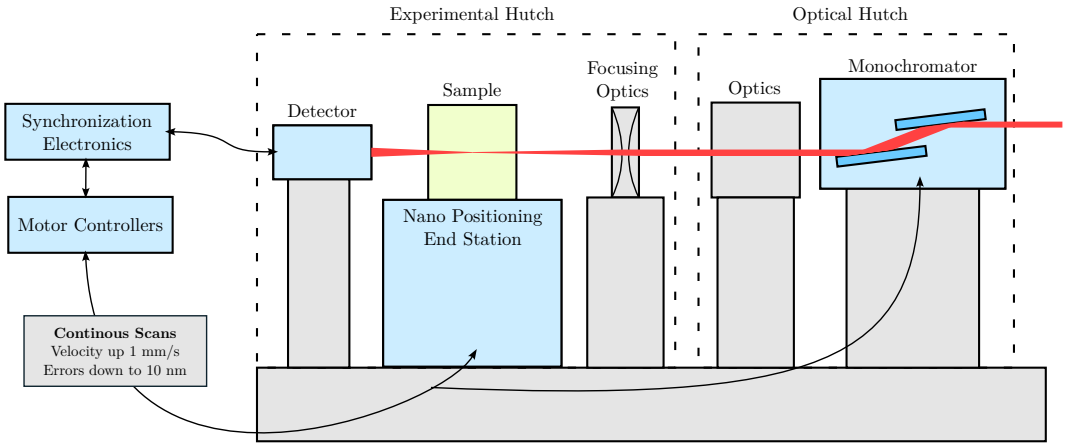
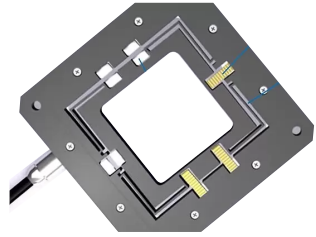


Outline

Outline

Positioning Stages - Key elements



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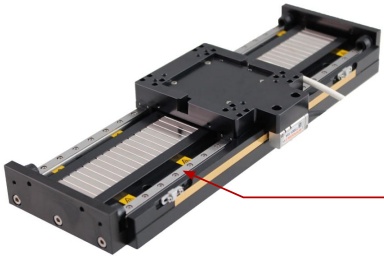
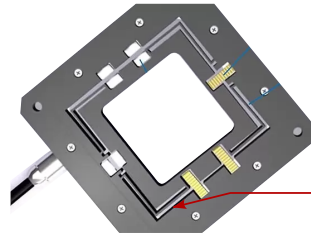
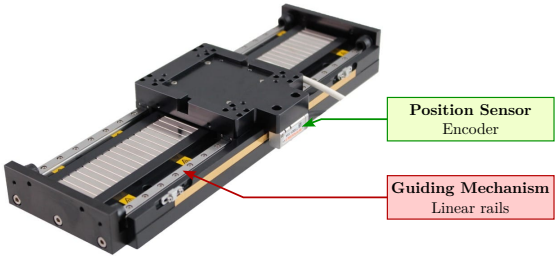


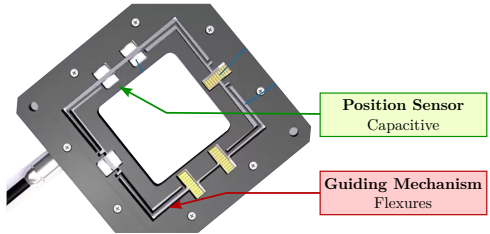
Guiding Mechanism
Linear rails



Guiding Mechanism
Flexures

Positioning Stages - Key elements





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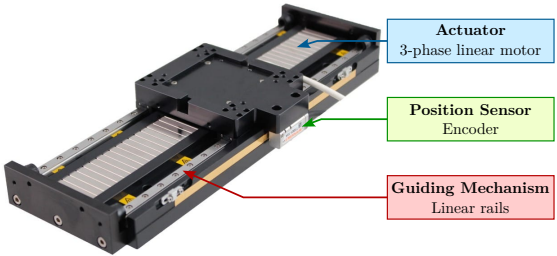

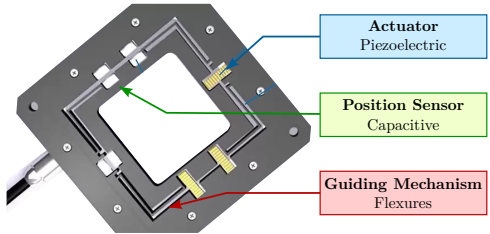

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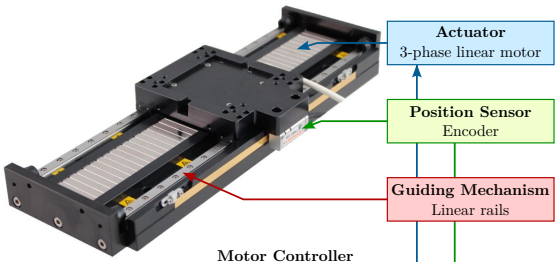


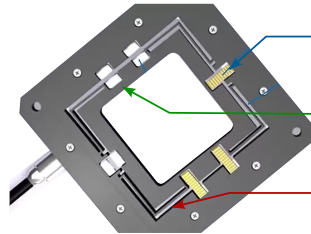
Actuator
3-phase linear motor

Position Sensor
Encoder

Guiding Mechanism
Linear rails

Motor Controller

Feedback Control



Actuator
Piezoelectric

Position Sensor
Capacitive

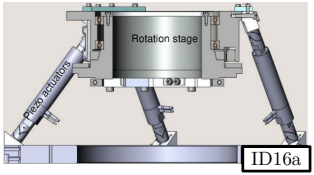
Guiding Mechanism
Flexures

Motor Controller

Feedback Control

Guiding mechanisms

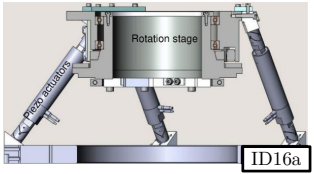
Mechanical Bearing



Long Stroke, Vacuum compatible
Poor dynamical performances
Limited accuracy and lifetime

Guiding mechanisms

Mechanical Bearing



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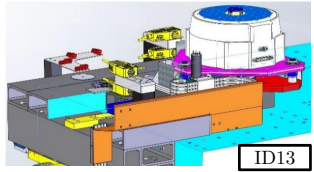
Air Bearing



Long stroke, Good accuracy
Not vacuum compatible
Stack stages: degraded performances

Guiding mechanisms

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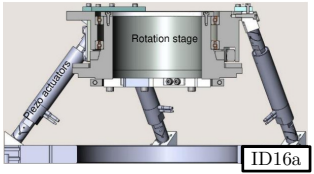

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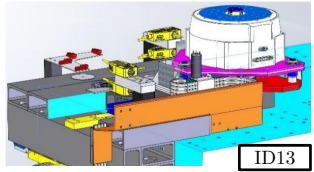

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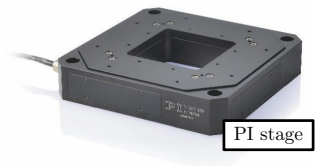
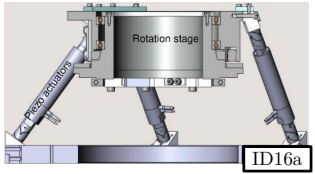
Flexure Bearing



Good accuracy, Vacuum compatible
Short stroke
High vibration transmissibility

Guiding mechanisms

Mechanical Bearing



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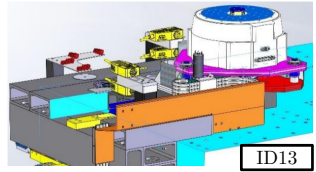

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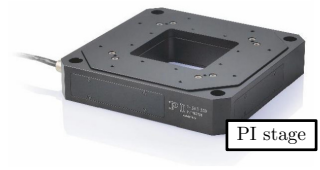
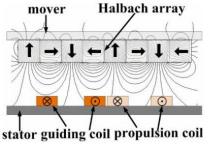


Good accuracy, Vacuum compatible
Short stroke
High vibration transmissibility

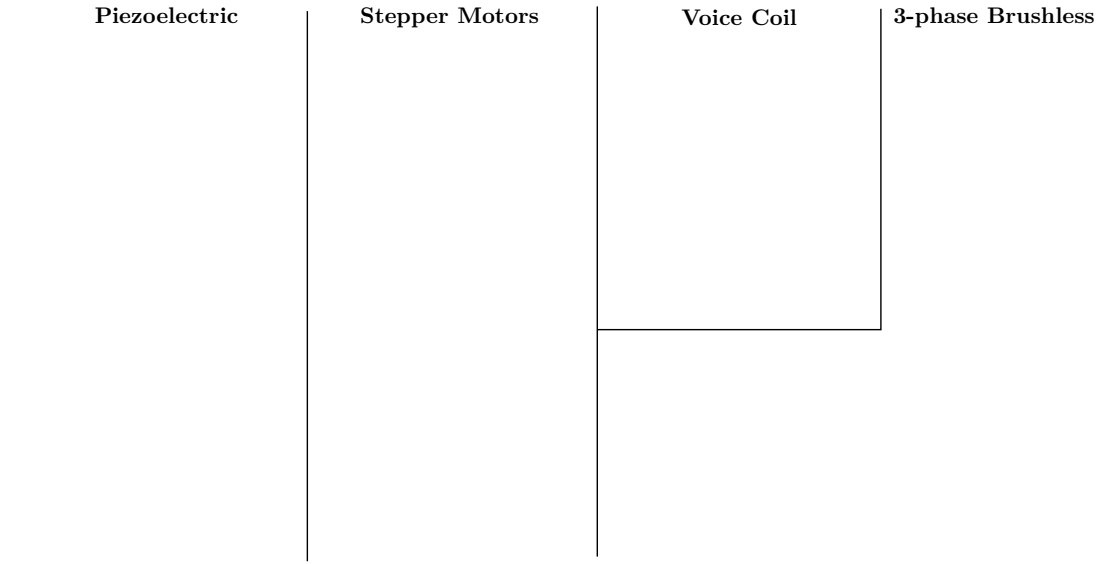
Magnetic Levitation



Non-contact motion: excellent accuracy and dynamics
Bearings and motors combined: compact design
Multi DoF in one stage
Long stroke
Vacuum compability
Inherent vibration control

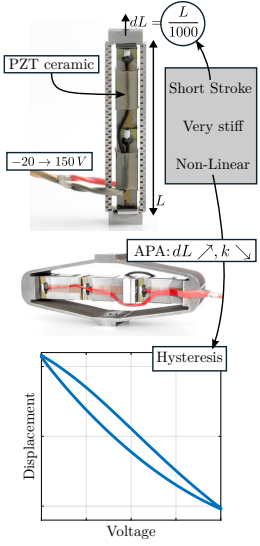
Some challenges have to be addressed
Development project

Actuator technology



Actuator technology

Piezoelectric



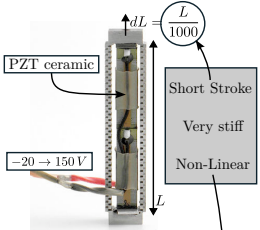
Stepper Motors

Voice Coil

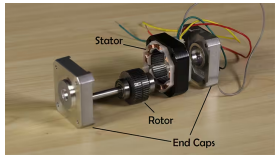
3-phase Brushless

Actuator technology

Piezoelectric



Stepper Motors

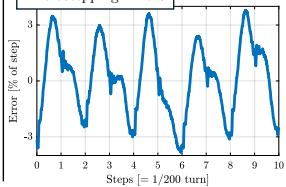


Open-Loop capable
(200 steps per turn)

Good for static positioning
(esp. with linear encoder)

Not suitable for continuous scans

Microstepping Errors



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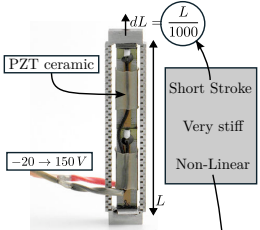

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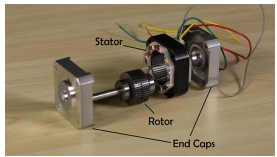

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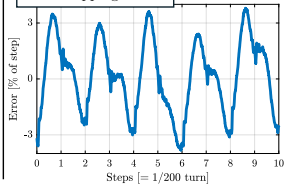


Voice Coil

Non contact
(Stiffness brought by feedback)

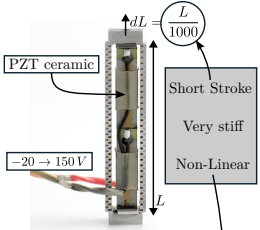
Limited to ~10 mm

Very linear and good dynamics

3-phase Brushless

Actuator technology

Piezoelectric



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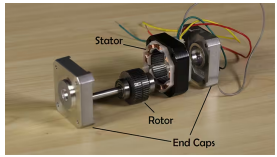

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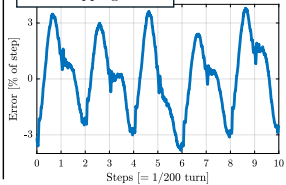


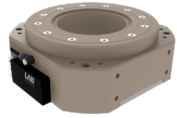
Voice Coil

Lorentz Force

Non contact
(Stiffness brought by feedback)

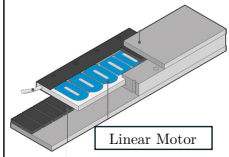
Limited to ~10 mm

Very linear and good dynamics



Air bearing Spindles

3-phase Brushless



Linear Motor

Small torque motors

Less vibration (smooth motion)

Higher velocity than Stepper

Requires feedback sensor

Sensors for nano-positioning

Fig.: Capacitive Sensor

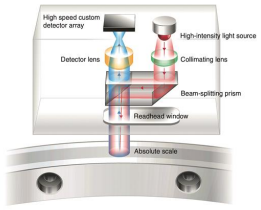


Fig.: Encoder

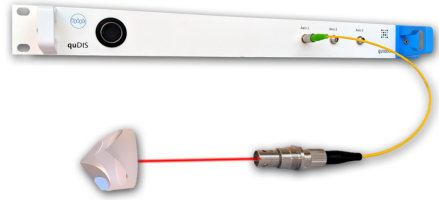


Fig.: Interferometer

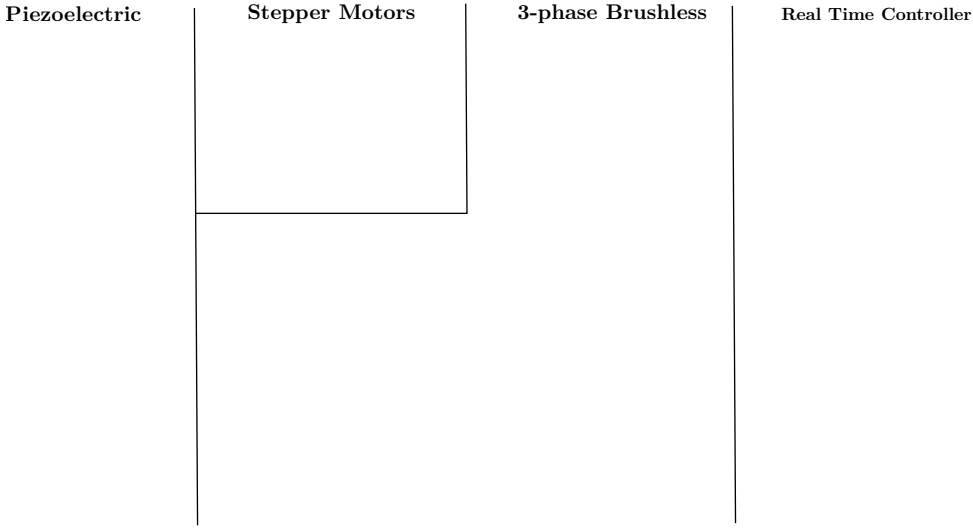
	Capacitive	**Encoder**	**Interferometer**
Range	$<$ 1mm	$>$ 1m	$>$ 1m
Resolution	$2\,nm$ at $100\mu m$	$5\,nm$	$0.5\,nm$
Accuracy	0.1%	$< 5\,\mu m/m$	$< 1\,\mu m/m$
Price	1-3k	1k	5k
Usage	Short stroke Piezo stages	1-DoF	multi-DoF In vacuum

Interferometers: Air effect

Working distance 100mm:

- $\Delta T = 0.1^oC \Rightarrow 10nm$
- $\Delta P = 1hPa \Rightarrow 27nm$
- $\Delta RH = 10\,\% \Rightarrow 10nm$

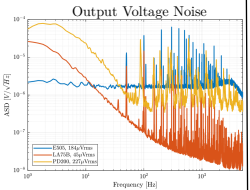
Control Electronics



Control Electronics

Piezoelectric

Performance:
Bandwidth & Voltage noise



Stepper Motors

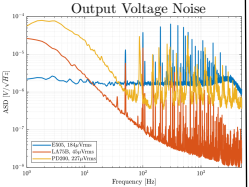
3-phase Brushless

Real Time Controller

Control Electronics

Piezoelectric

Performance:
Bandwidth & Voltage noise



Stepper Motors

Inhouse, standard solution !

3-phase Brushless

Real Time Controller

Control Electronics

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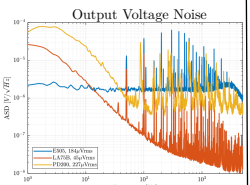

Stepper Motors

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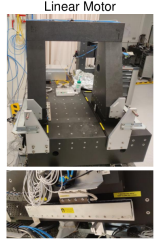
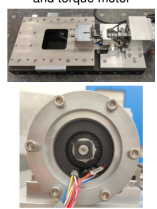
3-phase Brushless

No standard solution yet ...

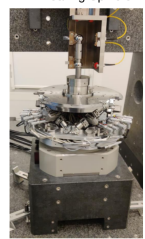
Air Bearing Gantry with Linear Motor



Linear stage with cross-roller bearing, rollvis and torque motor



Air Bearing Spindle



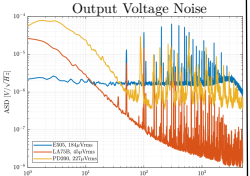
Real Time Controller

Control Electronics

Piezoelectric

Performance:
Bandwidth & Voltage noise

Output Voltage Noise



Stepper Motors

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3-phase Brushless

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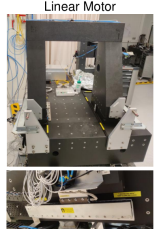
Air Bearing Gantry with Linear Motor



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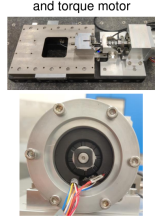
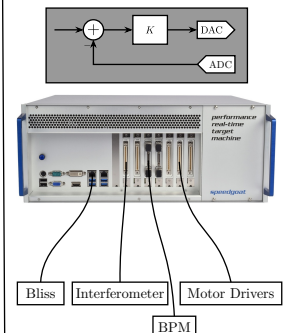


Air Bearing Spindle

Real Time Controller



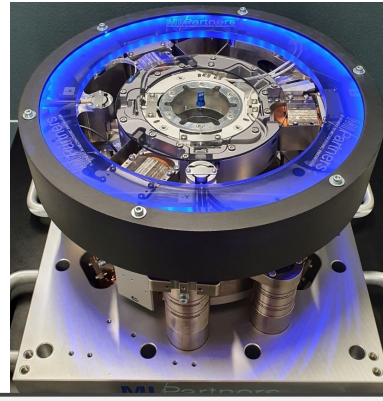
Very versatile (simulink)

Lots of Inputs/Output options

Well suited for mechatronics systems

When is Mechatronics needed?

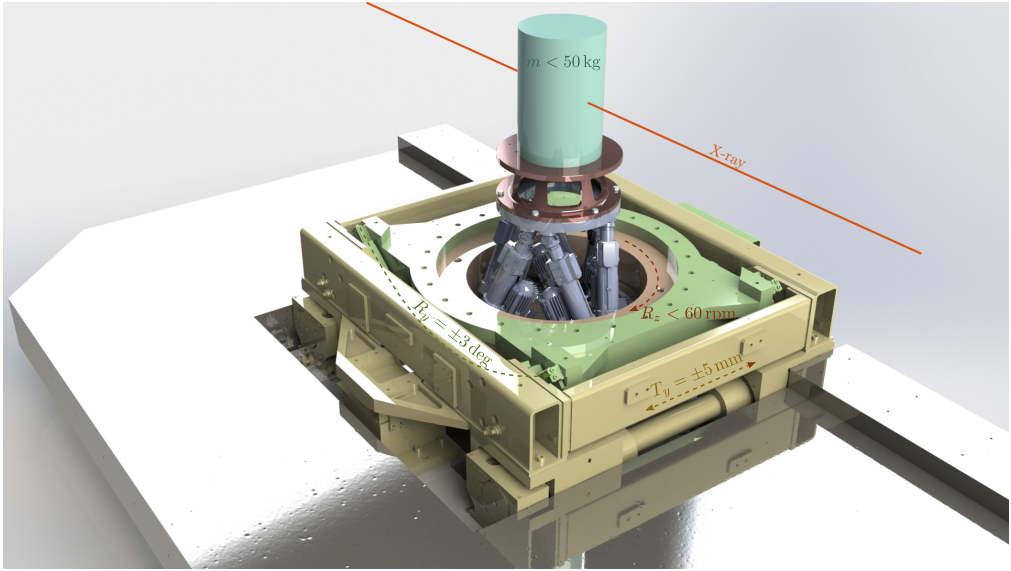
- **Static** Positioning
- Mech./Elec./Control are decoupled
- "Traditional" design possible



- **Dynamic** Positioning
- Complex integrated system
- Requires a **mechatronics approach**

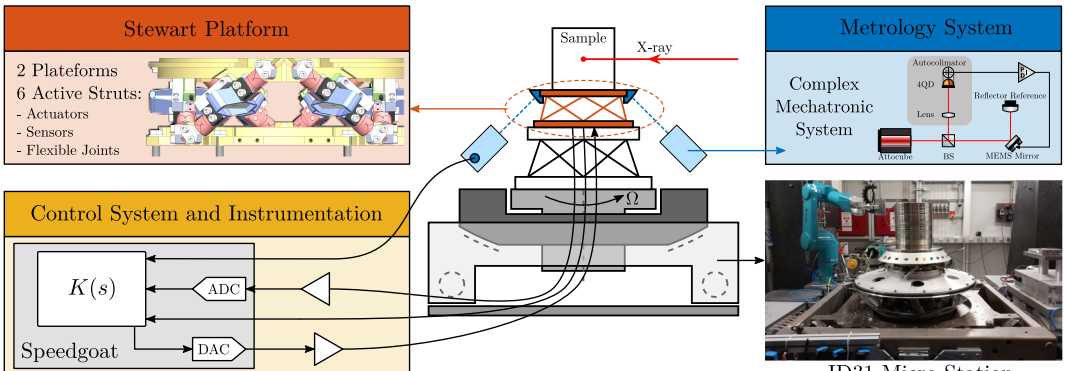
Outline

The ID31 Micro Station



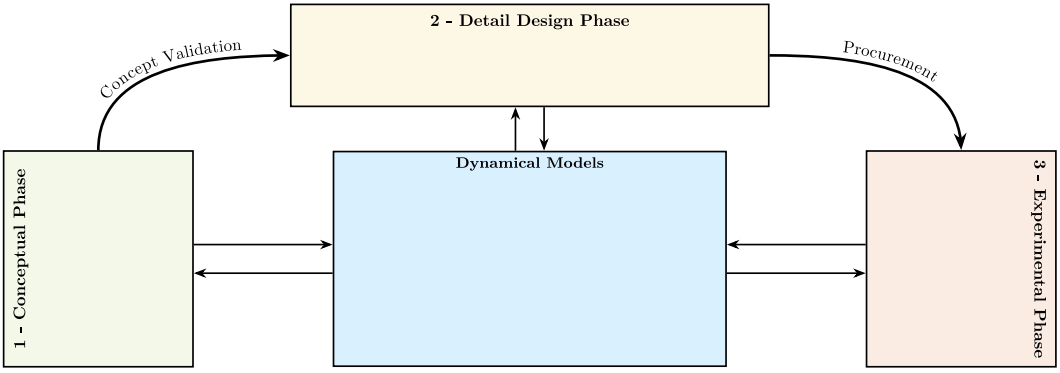
The Nano Active Stabilization System (NASS)

Objective: Improve position accuracy from $\approx 10\,\mu m \Longrightarrow 10\,nm$
Design approach: "Model based design" / "Predictive design"

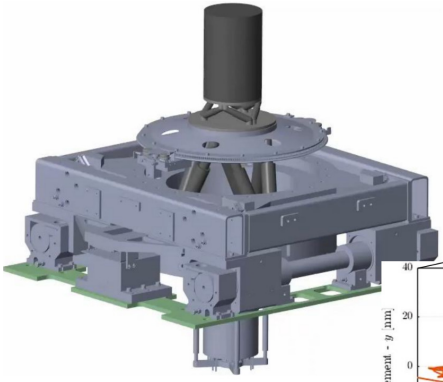


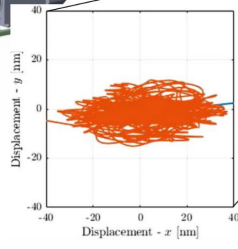
ID31 Micro-Station

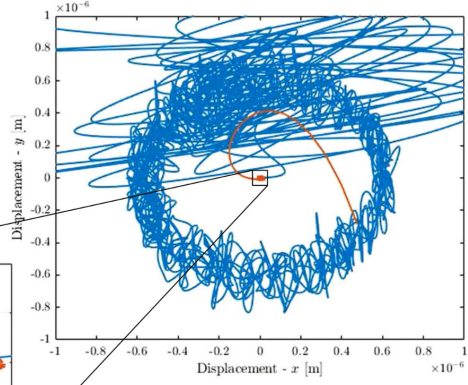
Mechatronics Approach / Model Based Design



Multi-Body Model - Simulations

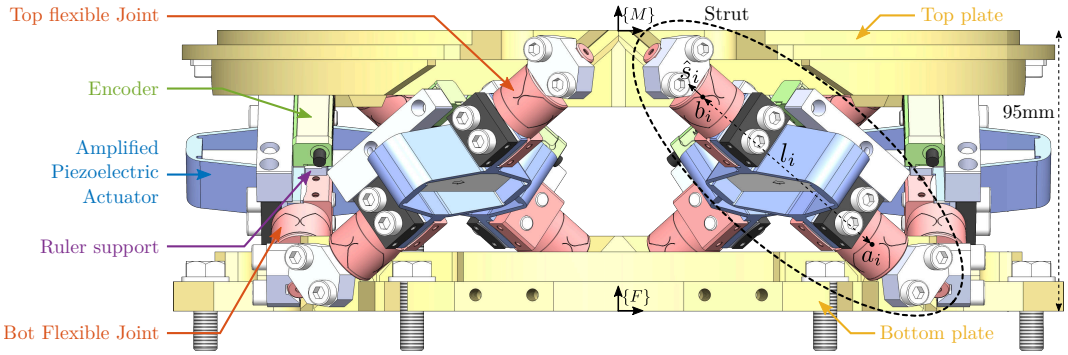






Validation of the concept

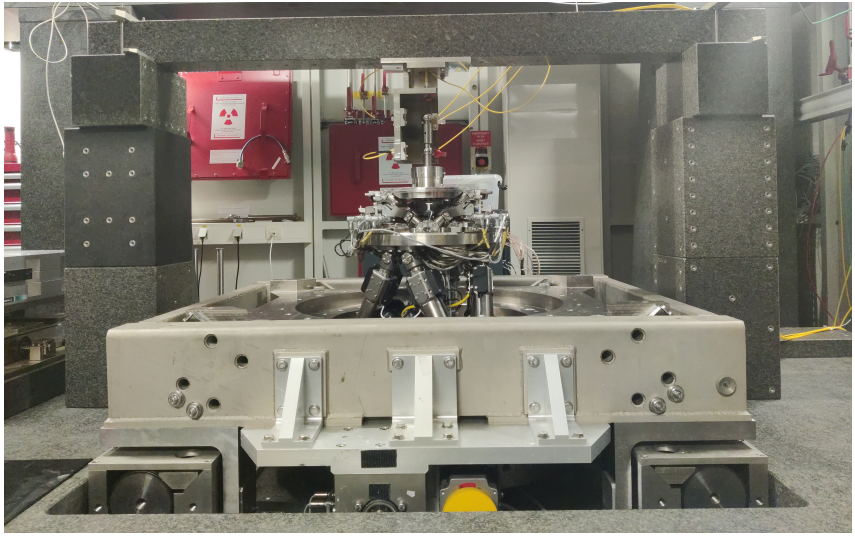
Detail Design Phase: Nano-Hexapod



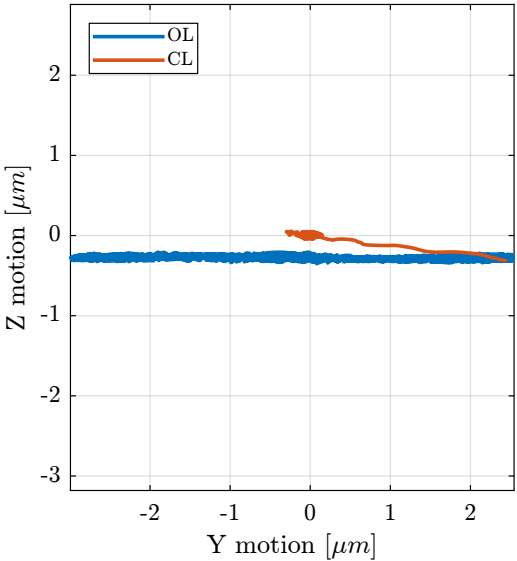
General Specifications

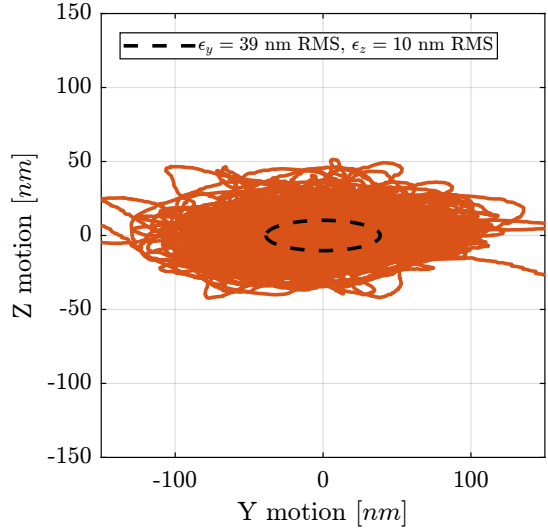
- Flexible modes as high as possible
- Only flexible elements (no backlash, play, etc.)
- Integrated Force Sensor and Displacement Sensor
- Predictable dynamics

Tests on ID31 End Station

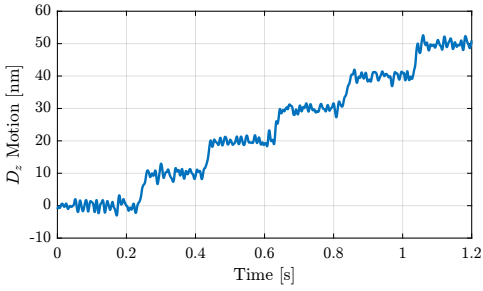


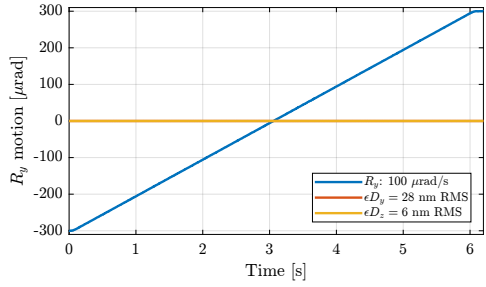
Tomography Scan

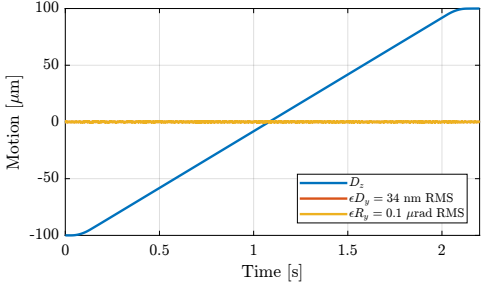




"Dirty layer" (D_z) and reflectivity (R_y) scans





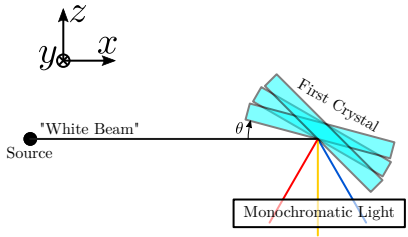


Mechatronics approach

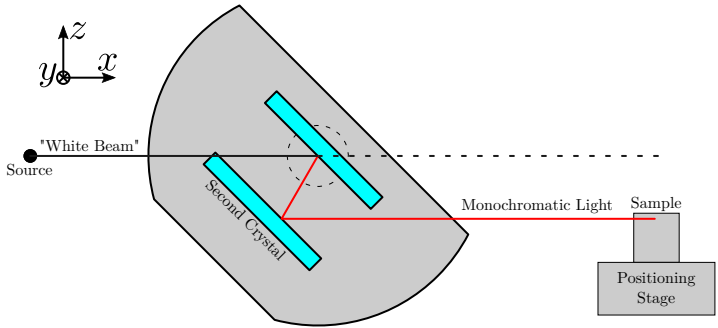
- Use of dynamical models (mechanics, electronics, control, disturbances, ...)
- Predictive design
- High versatility of the system

Outline

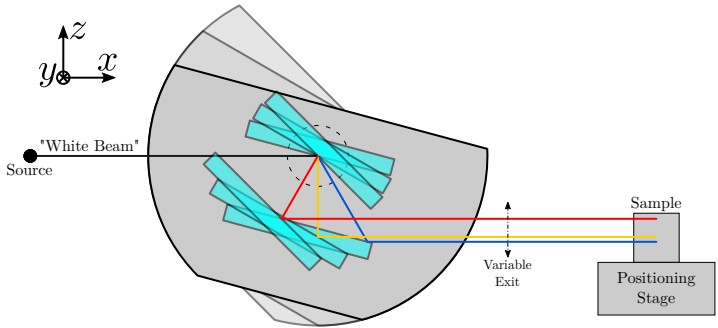
DCM Architecture



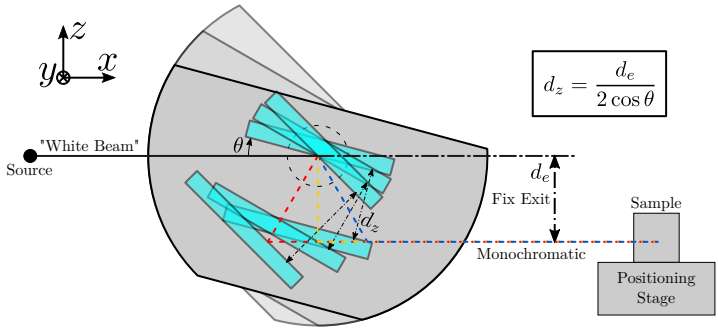
DCM Architecture



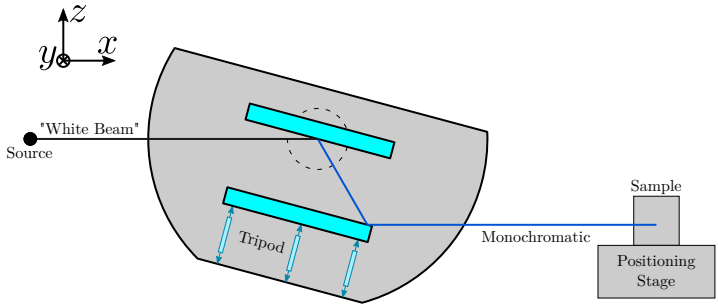
DCM Architecture



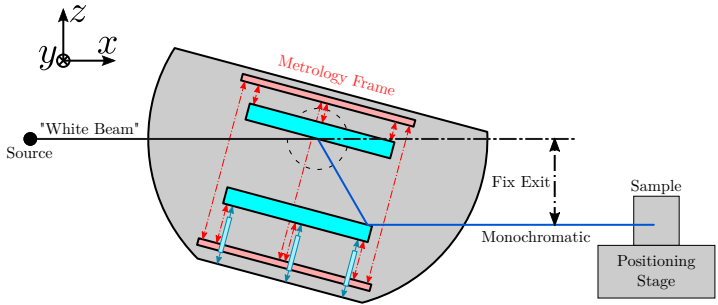
DCM Architecture



DCM Architecture



DCM Architecture

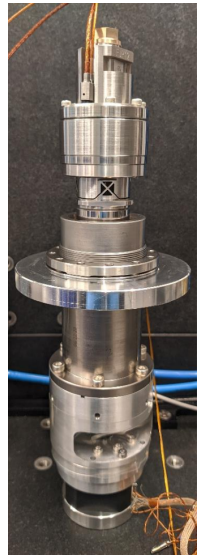


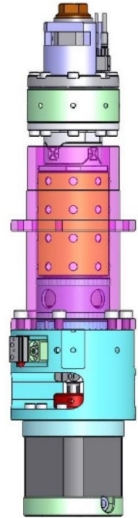
Fast Jack Actuator - Hybrid Approach

	Specifications
Stroke	$30\,mm$
Velocity	**1 mm/s**
Errors	**<5 nm RMS**
Stiffness	$> 10\,\mu m/N$
Payload	10kg
Robustness	10 million cycles
Environment	UHV

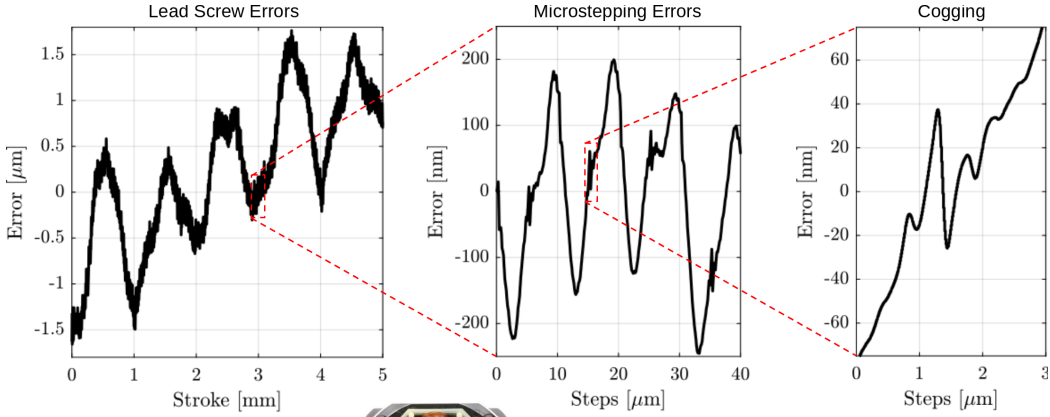
Hybrid design:

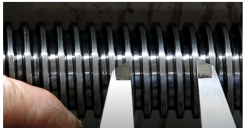
- Stepper for long stroke
- Piezo for error control

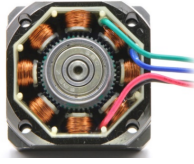




Open-Loop Errors

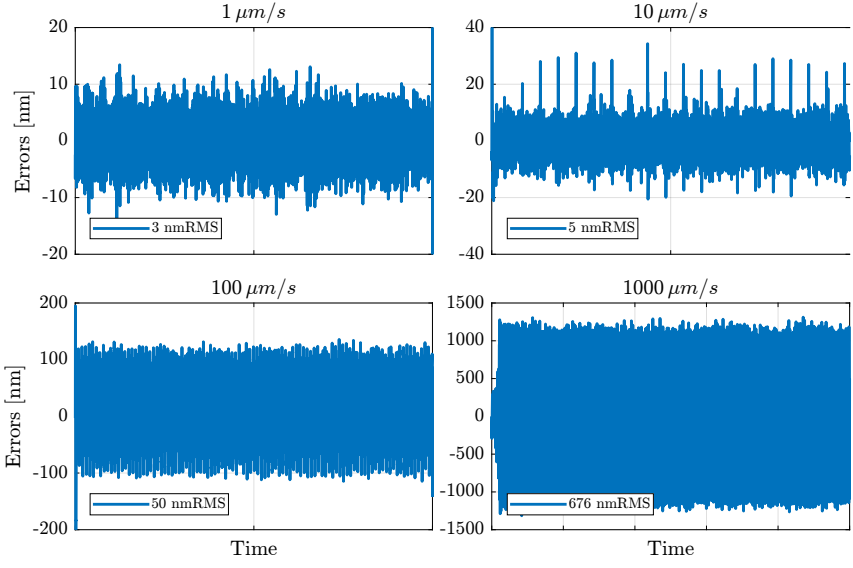




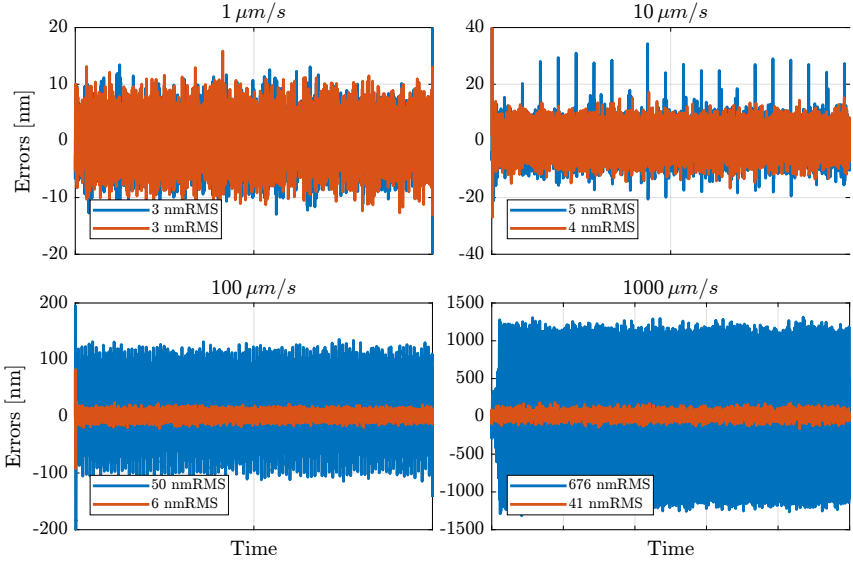


- Errors linked to spatial effects
- At $1\,mm/s$, $\mu-$stepping errors at $200\,Hz$

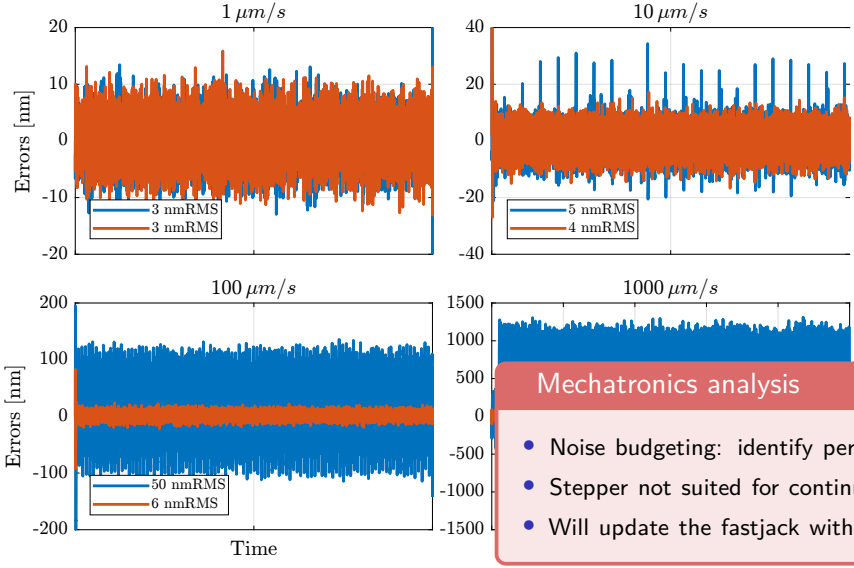
Closed-Loop Errors - Limitation due to stepper motor



Closed-Loop Errors - Limitation due to stepper motor



Closed-Loop Errors - Limitation due to stepper motor



Mechatronics analysis

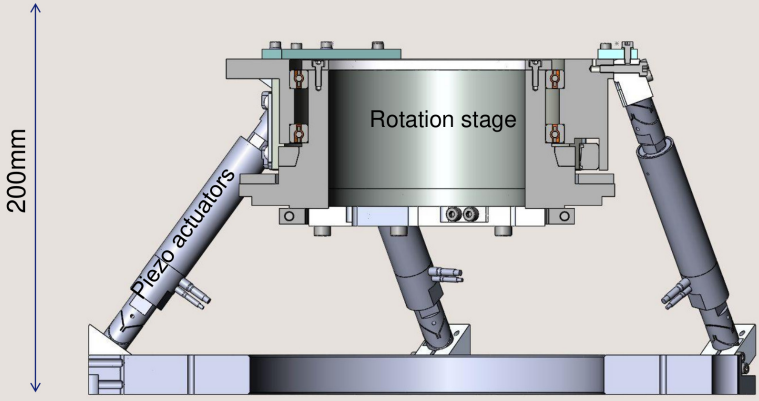
- Noise budgeting: identify perf. limitation
- Stepper not suited for continuous scans
- Will update the fastjack with better actuators

Outline

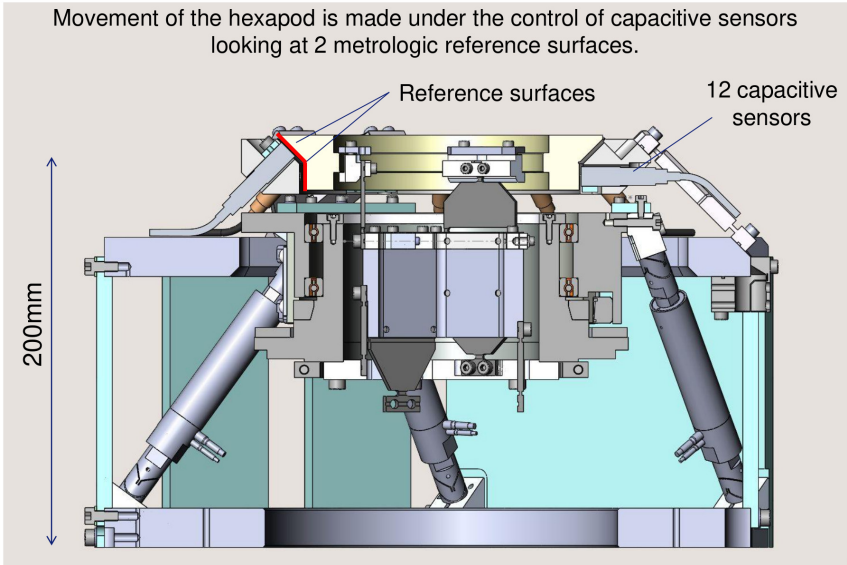
Mechanical Architecture

Vacuum + parasitic movements < 50nm

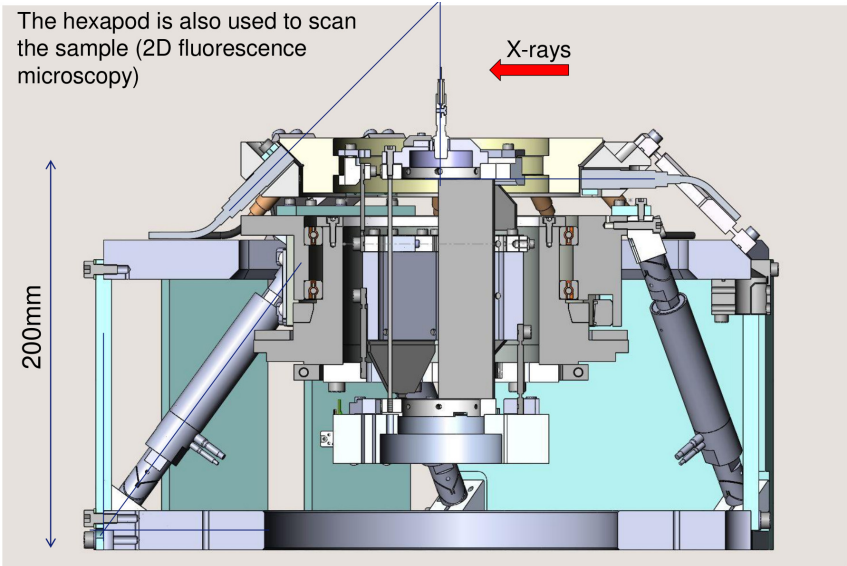
Correction of the guiding errors of a rotation stage by piezo actuators



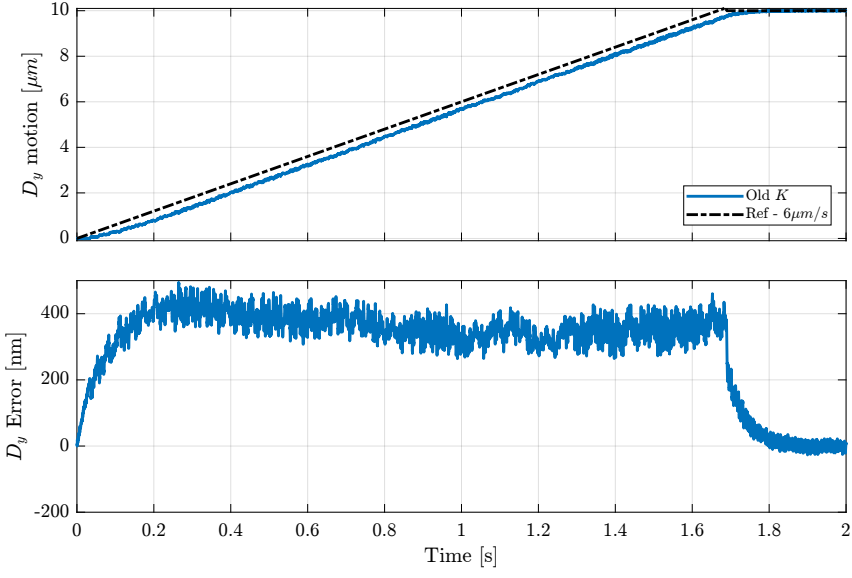
Mechanical Architecture



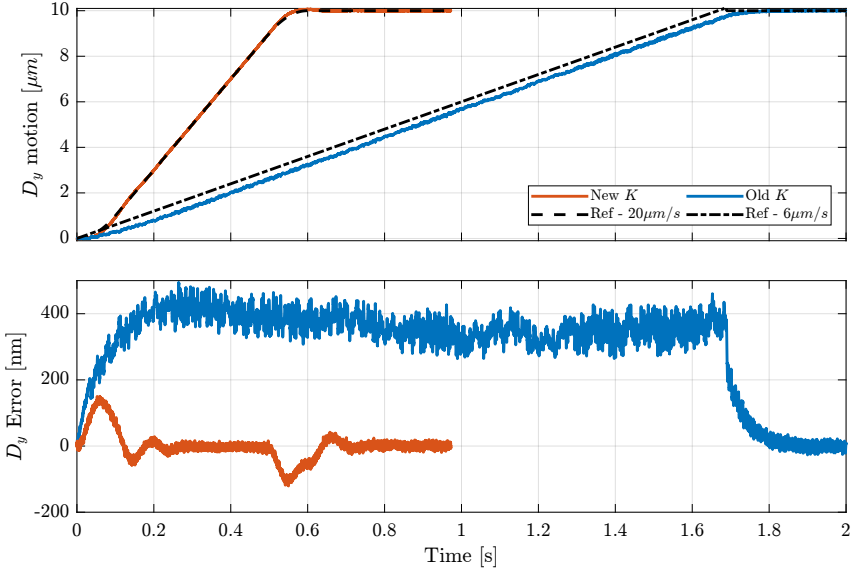
Mechanical Architecture



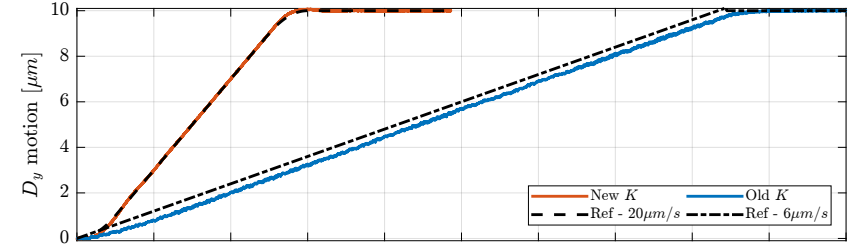
Scanning performances - Improvement with new controller

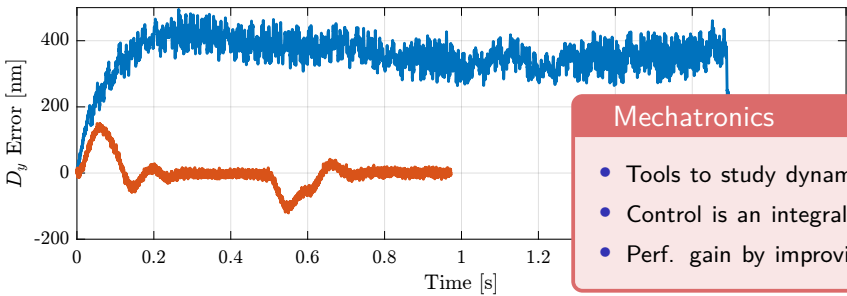


Scanning performances - Improvement with new controller



Scanning performances - Improvement with new controller





Mechatronics

- Tools to study dynamics of systems
- Control is an integral part of the system
- Perf. gain by improving the control

Outline

Conclusion

Design of nano-position systems

- Adapting our design approach by using mechatronics tools
- Lead to better performing systems
- Need better collaboration between MEG/EU/BCU (“mechatronics entity” ?)

Conclusion

Design of nano-position systems

- Adapting our design approach by using mechatronics tools
- Lead to better performing systems
- Need better collaboration between MEG/EU/BCU (“mechatronics entity” ?)

What are your nano-positioning/mechatronics challenges?

- Come talk with us so that we better understand your needs
- Adapt our mechatronics developments for the beamlines
- Please submit projects (even just preliminary studies)

Resources

Mechatronics:

- Schmidt, R. M., Schitter, G., & Rankers, A. (2020). The design of high performance mechatronics
- Steinbuch, M., & Oomen, T. (2016). Model-based control for high-tech mechatronics systems

Position Sensors:

- Fleming, A. J. (2013). A review of nanometer resolution position sensors: operation and performance.

Feedback Control:

- Skogestad, S., & Postlethwaite, I. (2007). Multivariable feedback control: analysis and design

Parallel Robots:

- Taghirad, H. (2013). Parallel robots : mechanics and control