3D METROLOGY CONFERENCE

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Precision Design Principles. Does the size matter? A methodological approach

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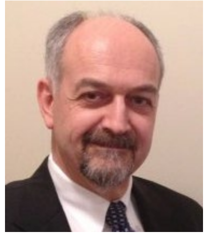
1542

Special thanks to …

Presentation based on previous works:

- JA Yagüe-Fabra, W Gao, A Archenti, E Morse, A Donmez. "Scalability of precision design principles for machines and instruments" CIRP annals 70 (2), 659-680, 2021.



- José A. Albajez. Univ. Zaragoza
- Marta Torralba, Lucía C. Díaz. PhD thesis. UZ.



- Unai Mutilba. PhD thesis. Tekniker

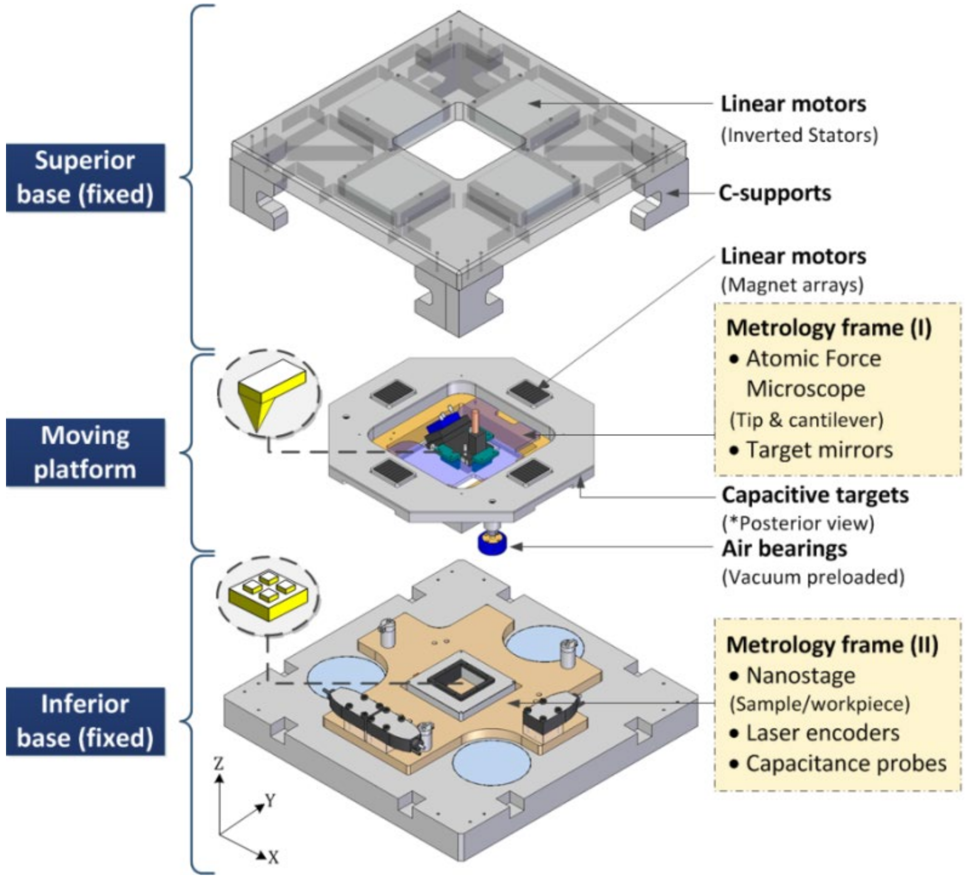
- Alberto Mendikute. PhD thesis. Ideko

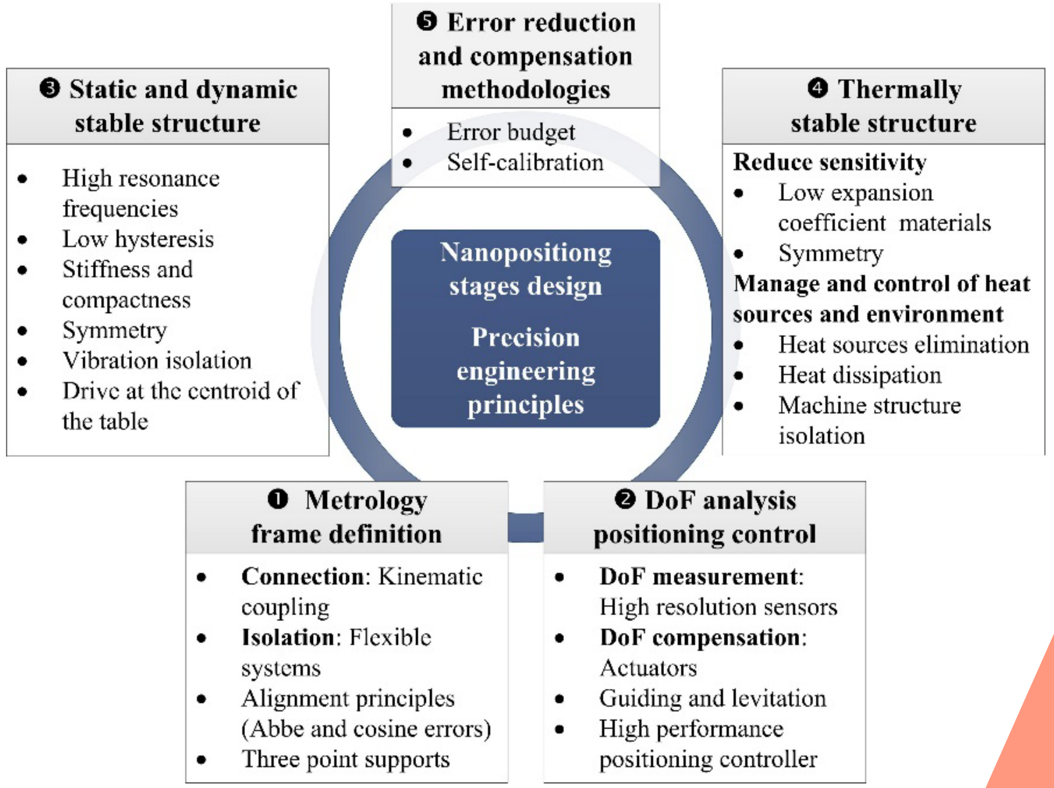
1. Introduction

Does the size matter?

Precision engineering is significant in practically every field and industrial sector, from semiconductor industry, power generation, to astronomy and gravitational research.

Introduction / Example: nanopositioning stage (NanoPla)





Small range: NanoPla

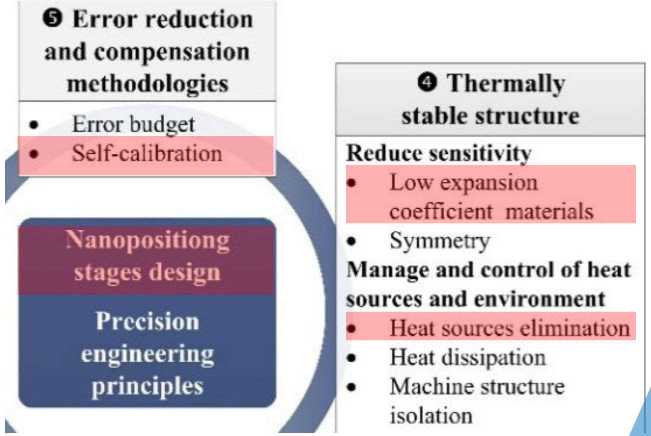
Universidad Zaragoza

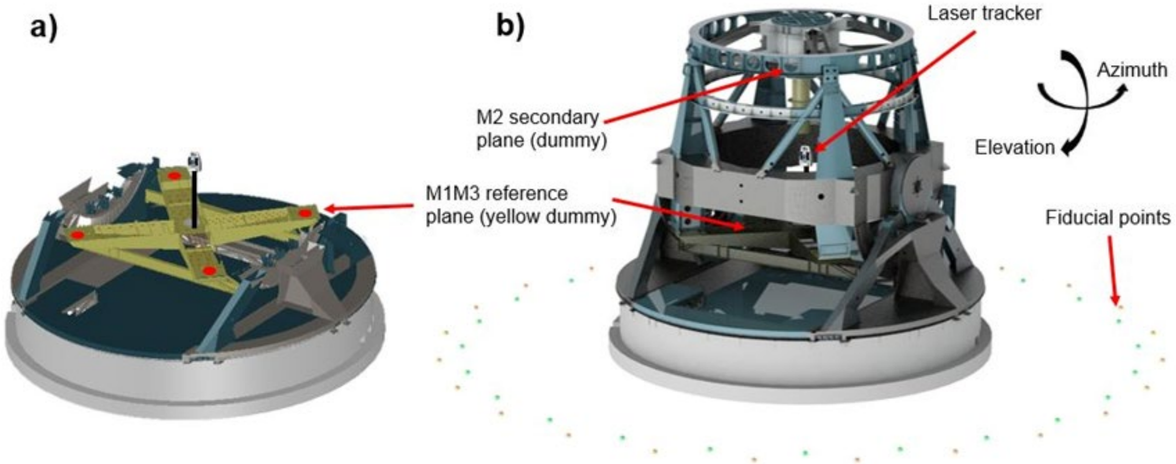
M Torralba, M Valenzuela, JA Yagüe-Fabra, JA Albajez, JJ Aguilar “Large range nanopositioning stage design: A three-layer and two-stage platform” Measurement 89, 55-71

Introduction / Example: large range precision system

Large Synoptic Survey Telescope [2]

- 16 m diameter
- 375 tones
- 8.4 m mirror
- 3200-megapixel camera





Tekniker
MEMBER OF BASQUE RESEARCH & TECHNOLOGY ALLIANCE

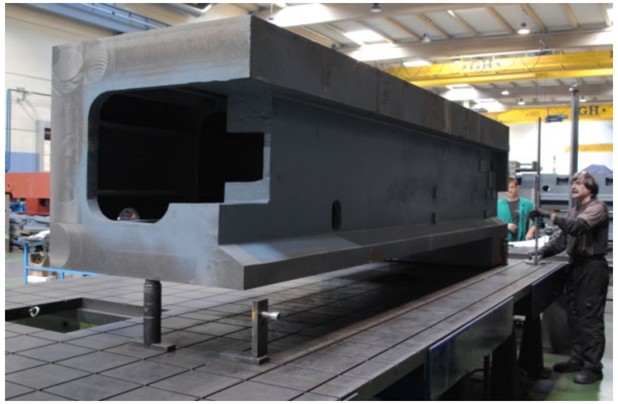
Large range

U Mutilba, G Kortaberria, F Egaña, JA Yagüe-Fabra “3D metrology simulation and relative pointing error verification of the Telescope Mount Assembly subsystem for the Large Synoptic Survey Telescope” Sensors 2018, 18, 3023

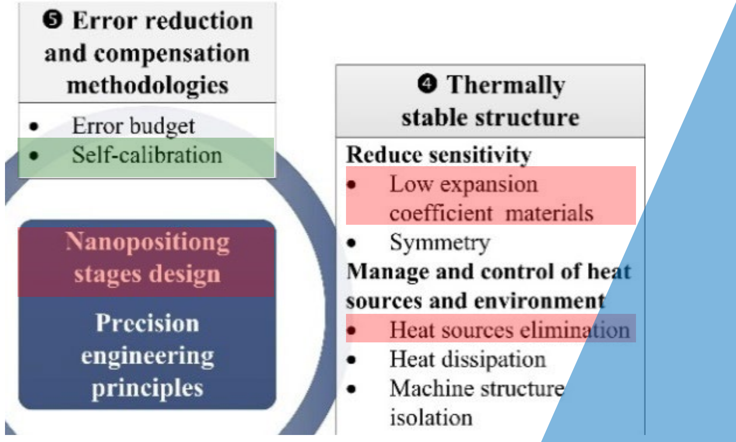
Introduction / Example: large range precision system

Development of a solution based on **photogrammetry to increase the efficiency** of a **dimensional metrology** process that limits the productivity achievable in the manufacturing of **large components**: the blank part alignment process.

Dimensional Control



Alignment references calculation



In machine alignment before machining

IDEKO
MEMBER OF BASQUE RESEARCH & TECHNOLOGY ALLIANCE

A Mendikute, I Leizea, JA Yagüe-Fabra, M Zatarain "Self-calibration technique for on-machine spindle-mounted vision systems" Measurement, 113, 71-81, 2018

Introduction / Scalability

- Precision Design principles applied for all the “precision systems” are basically the same.
- But there are also some interesting and important differences when designing a precision system with a small, medium, or large working range.
- For instance: structural design, sensors used, error compensation, etc. are applied in different ways depending on the size of the system (instrument or machine).

Scalability:

- Scalability describes the degree to which the application of the precision design principles is independent on the working range of the system.
- A design principle is considered scalable when its applicability is independent of the working range of the precision system in an adaptable, flexible, and robust way.

Outline

1. Introduction
2. Precision design principles
3. Classification of machines and instruments
4. Structure and alignment principles
5. Motion measurement and control principles
6. Error mitigation principles
7. Conclusions

2. Precision design principles for machines and instruments

- General "Map" of Precision engineering design principles (starting point): McKeown, 1987; Schellekens, 1998

1. Structure / Symmetry (Schellekens)
2. Kinematic/Semi-Kinematic Design
3. Abbe Principle
4. "Direct" Displacement Transducers
5. Metrology Frames
6. Bearings
7. Drives/Carriages
8. Thermal Effects
9. Servo-Drives, Control / Vibr. Control
10. Error Budgeting / Repeat. (Schellek.)
11. Error Compensation / Vibr. Control

Structure and alignment principles

Motion measurement and control principles

Error mitigation principles

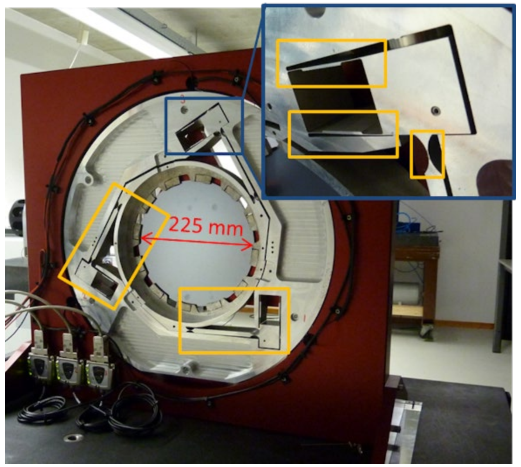
3. Classification of machines and instruments

Classification criterion: maximum range reachable by the system; (machining range for MT, measuring range for CMS, focal length for vision systems, etc.):

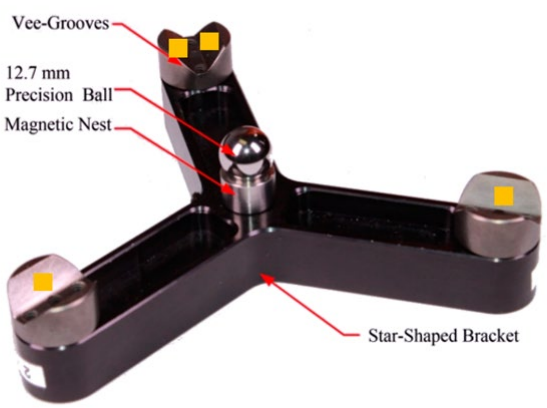
- Small range machines and instruments (< 100 mm)
- Medium range machines and instruments (100 mm – 5 m)
- Large range machines and instruments (> 5 m)

4. Structure and alignment principles

- **Assembly** → Flexure mechanisms are often applied to obtain precise and repeatable movement → Systems running under low-speed and low-acceleration conditions.
- Alignment: Abbe offsets → Monolithic designs or kinematic couplings.
- Serial vs Parallel Kinematic Systems



Dynamic masking stage with a flexure guiding system actuated by voice coil actuators, designed by JPE



Kinematic coupling (Maxwell kinematic system consists of three spheres mated with three female vees) platform according to Gaudreault et al.

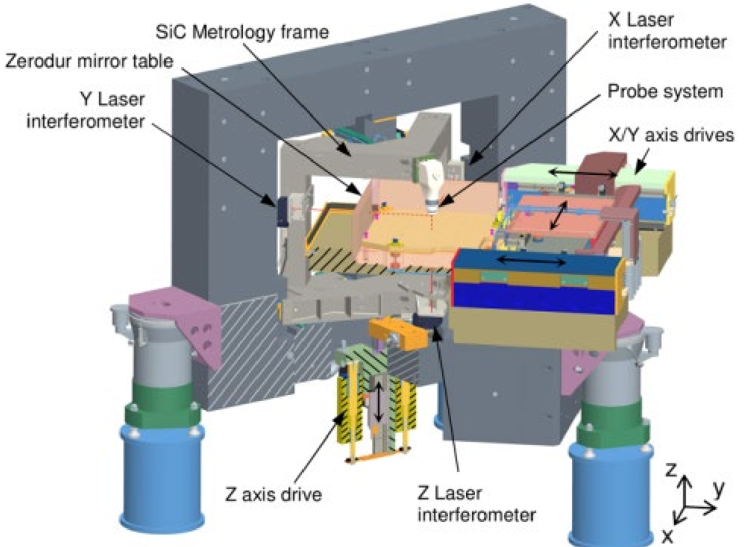
Stewart platform multi-axis positioning system from Physik Instrumente

- **Metrology loops/frames** → Minimize effects of forces and heat → **Symmetry** → **Isolation of error forces** (*Invar, Zerodur*, Athermal designs, On-line compensation techniques, …)

Structure and alignment principles / Medium range systems

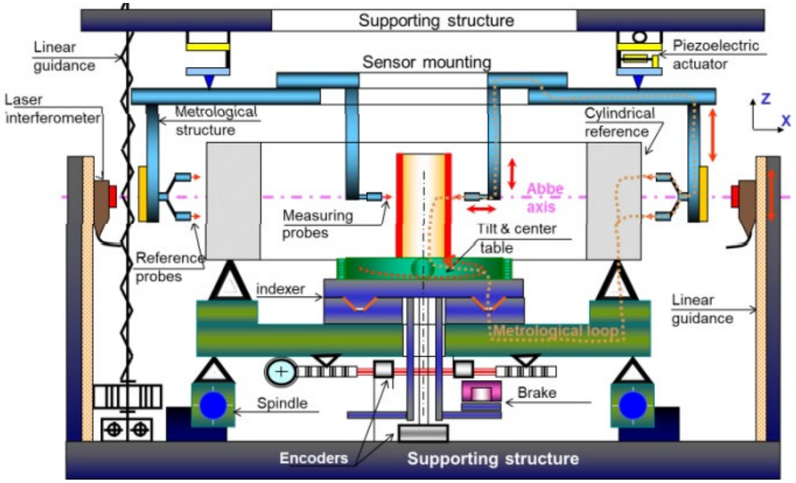
- Ultra-precision CMMs: metrology frame (materials), Abbe principle, air bearings, capacitive probes, …
- Lithography scanners: overlay error better than 2 nm, full-wafer critical dimension (CD) uniformity of less than 0.5 nm → Metrology frame (Invar), vibration isolated, stiff encoder grid plates made of Zerodur are kinematicaly mounted on the metrology frame, the short beam interferometers reduce sensitivity to the refractive index changes, …

ISARA 400 CMM



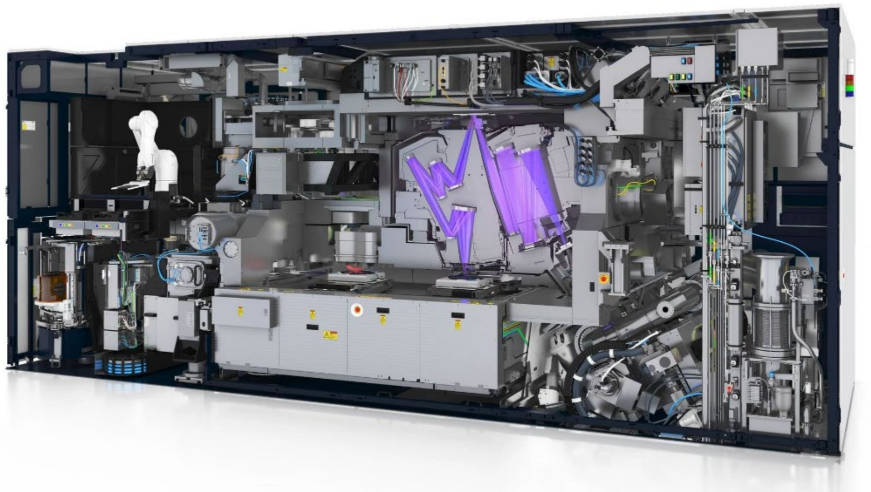
R.L. Donker, et al., 2009, Realization of Isara 400: a large measurement volume ultra-precision CMM, in Proc. of the 24th Annual Meeting of The ASPE.

LNE Ultra-precision CMM



Toguem, S.-C.T., et al., 2019, Design of an ultra-high precision machine for form measurement, Procedia CIRP, 84:942–947

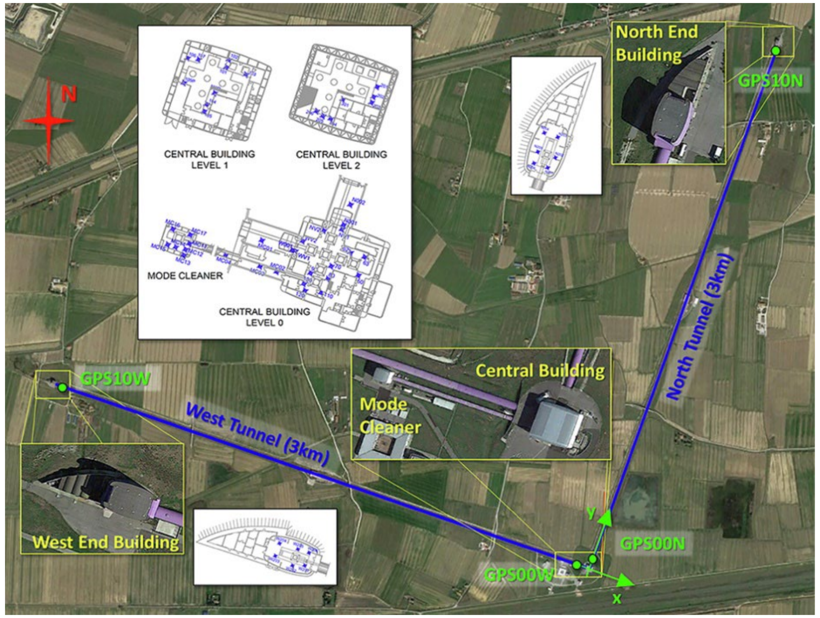
ASML EUV lithography



Structure and alignment principles / Large range systems

- Research frontier: increase non-linearly with size
- LIGO & Virgo:
  - Michelson laser interferometer (4 km) + resonant Fabry-Perot cavity + ultra-high vacuum pipes + anti-seismic dampers inside vacuum enclosures → length measurement resolution 10^{-18} m.
  - Even though the mirrors and test masses are in a vacuum and thermally isolated from the environment, the high-power laser beams can change the lenses radius of curvature, thus affecting the detector's sensitivity → Thermal compensation is required.
  - Virgo: Global Navigation Satellite System (GNSS) baselines, used for the alignment of equipment and for the determination of the position of internal components of the system.
- Large Hadron Collider (LHC) uses metrology frames and combine different types of measurements to get redundancy.

Virgo gravitational wave detector



Marsella, M., et al., 2020, Geodetic measurements to control a large research infrastructure: The Virgo detector at the European Gravitational Observator, Measurement, 151

Structure and alignment principles / Discussion

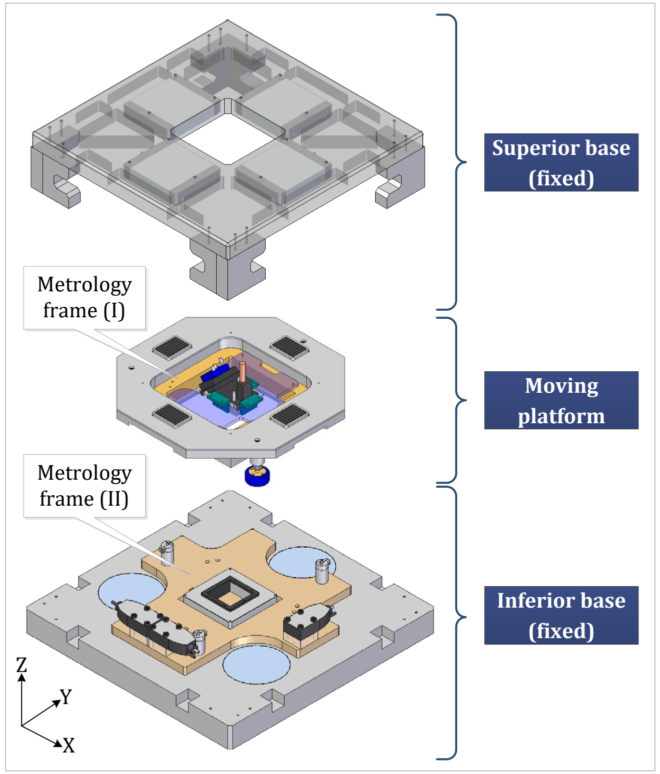
Applicability of structure and alignment precision design principles:

Precision Design Principles	Small range systems	Medium range systems	Large range systems
Symmetry	●	●	◕
Kinematic Design	●	◑	◔
Abbe Principle	●	◕	◔
Metrology Frames	●	◕	◕
Thermal effects	●	◕	◔

Legend: the blacker the circle is the more often the principle is applied in the indicated range

- Small range systems: usually most of them are applied.
- Medium range systems: machine volume and the economical restrictions → error correction or compensation techniques.
- Large range systems, the thermal effects and the structure’s own weight deformations may cause important loss of precision → Error compensation techniques.
- High precision large-scale systems, especially in singular scientific facilities, show very interesting applications of the mentioned precision design principles.

Small range systems. Example: nanopositioning stage (NanoPla specs)



Technical features

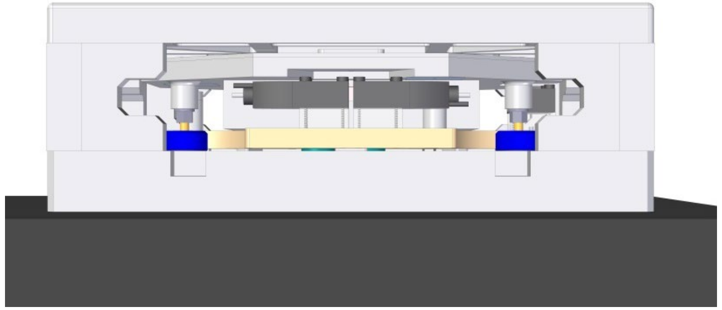
Travel range = 50x50 mm^2
Resolution ≈ 10 nm
Positioning error ≈ 25 nm
Stability ≈ 10 nm
Scanning speed > 2 mm/s

Design considerations

Commercial components
Open design
First prototype
Two-stage architecture
Coarse & fine motion

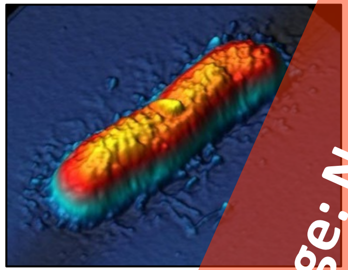
Applications

AFM
Topographic profile mapping of **larger sample areas**: silicon wafers, solar cells, ...



NanoPla first prototype

AFM system
Nanotec S.L.



AFM image
http:/www.icmm.csic.es/

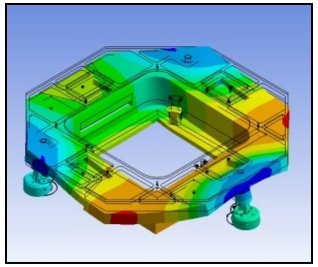
Small range: NanoPla

Nanopositioning stage development

Structure and alignment principles

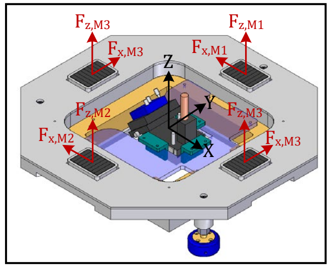
Motion measurement and control principles

Error mitigation principles



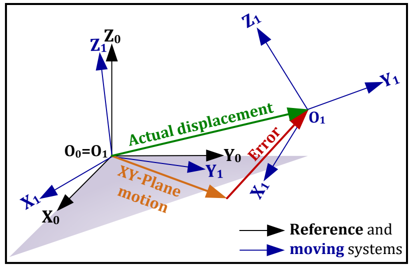
System design

- Instrument overview
- First prototype description
- Finite element analysis



Drive & control system

- Linear motors characterization
- 1D-control loop
- 2D-long range stage strategy

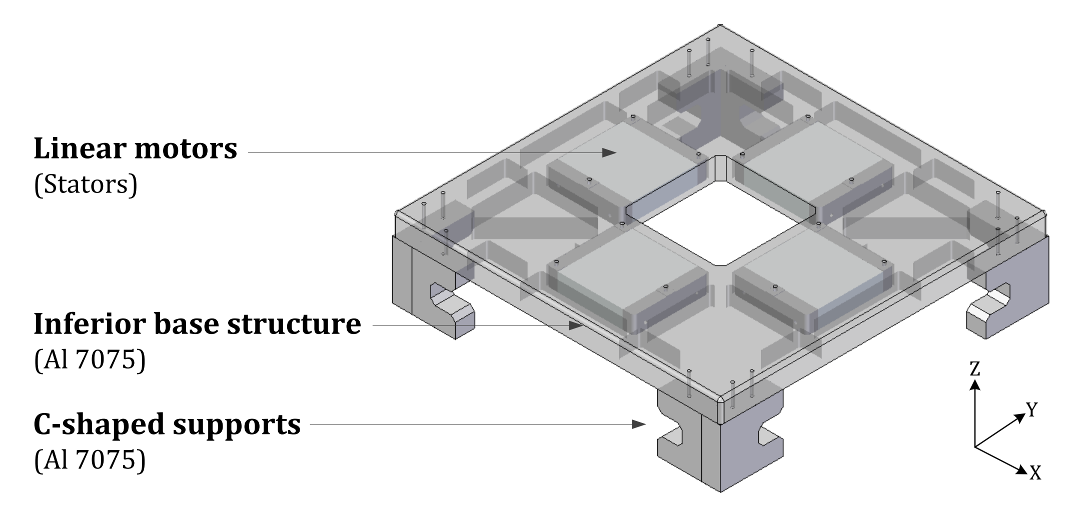


Error reduction & compensation

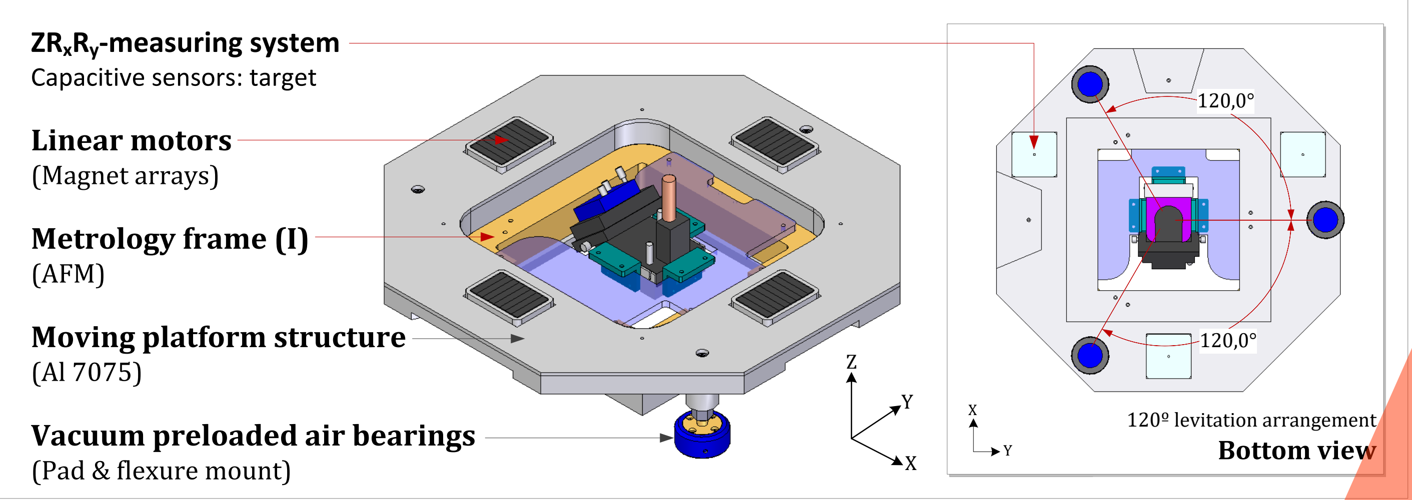
- Error budget study
- SPM calibration techniques
- Self-calibration methodology

Small range: NanoPla

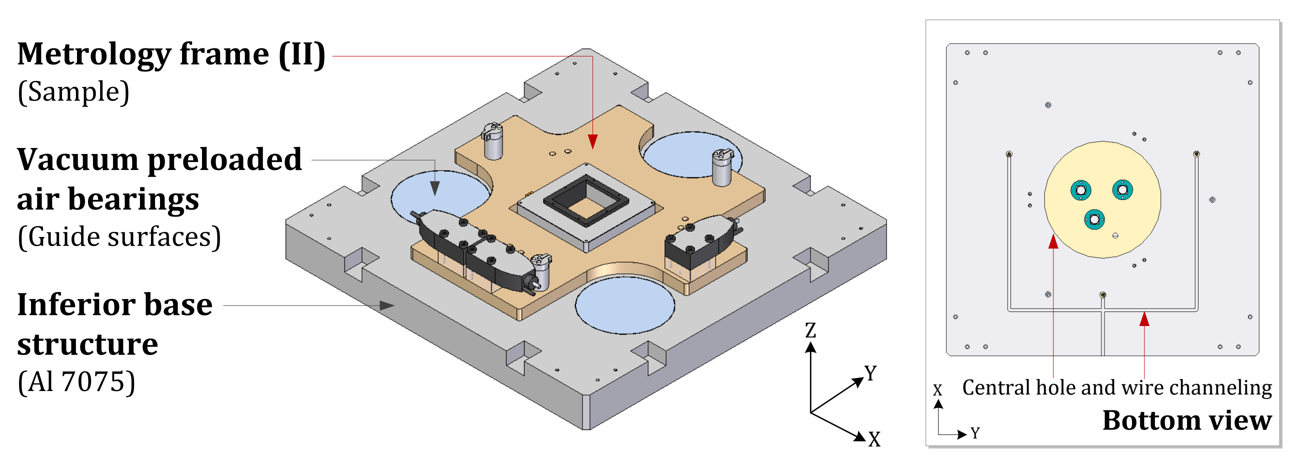
Structure and alignment principles / Small range systems

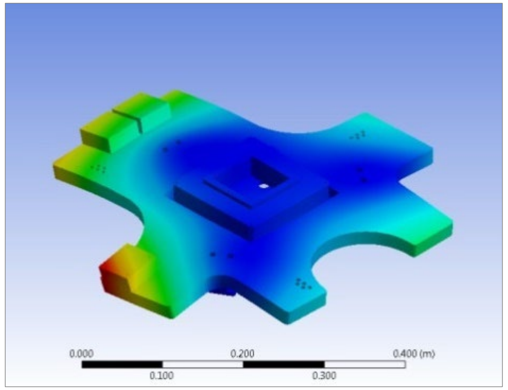


Superior base



Moving platform





Inferior base

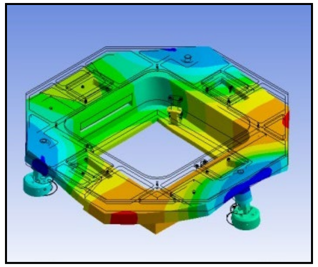
Small range: NanoPla

Nanopositioning stage development

Structure and alignment principles

Motion measurement and control principles

Error mitigation principles



System design

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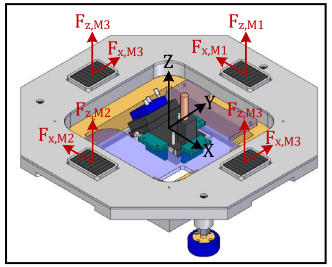

Drive & control system

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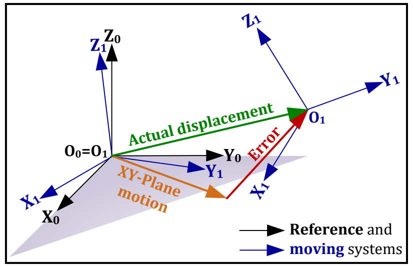


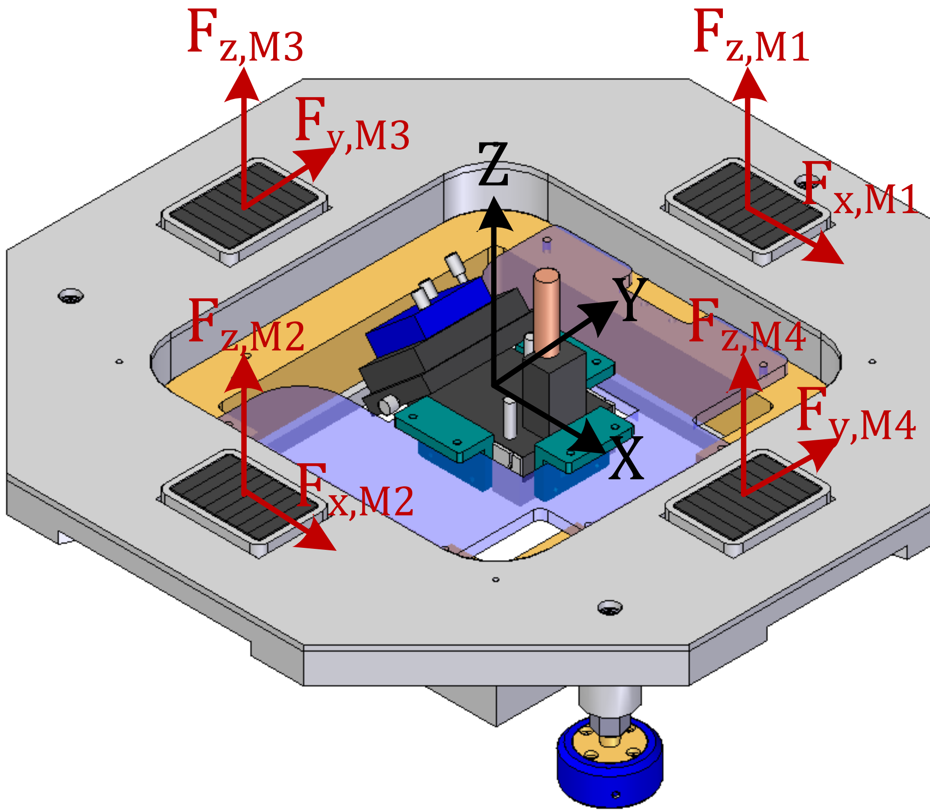
Error reduction & compensation

- Error budget study
- SPM calibration techniques
- Self-calibration methodology

Small range: NanoPla

Motion measurement & control / Small to medium range (1 mm - 5 m)

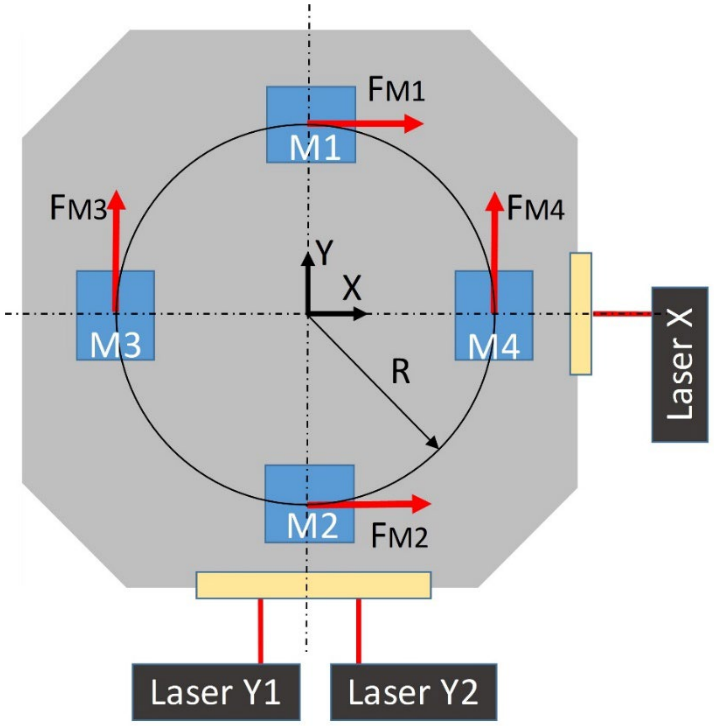
Forces on the moving platform



$$F_x = F_{M1} + F_{M2}$$

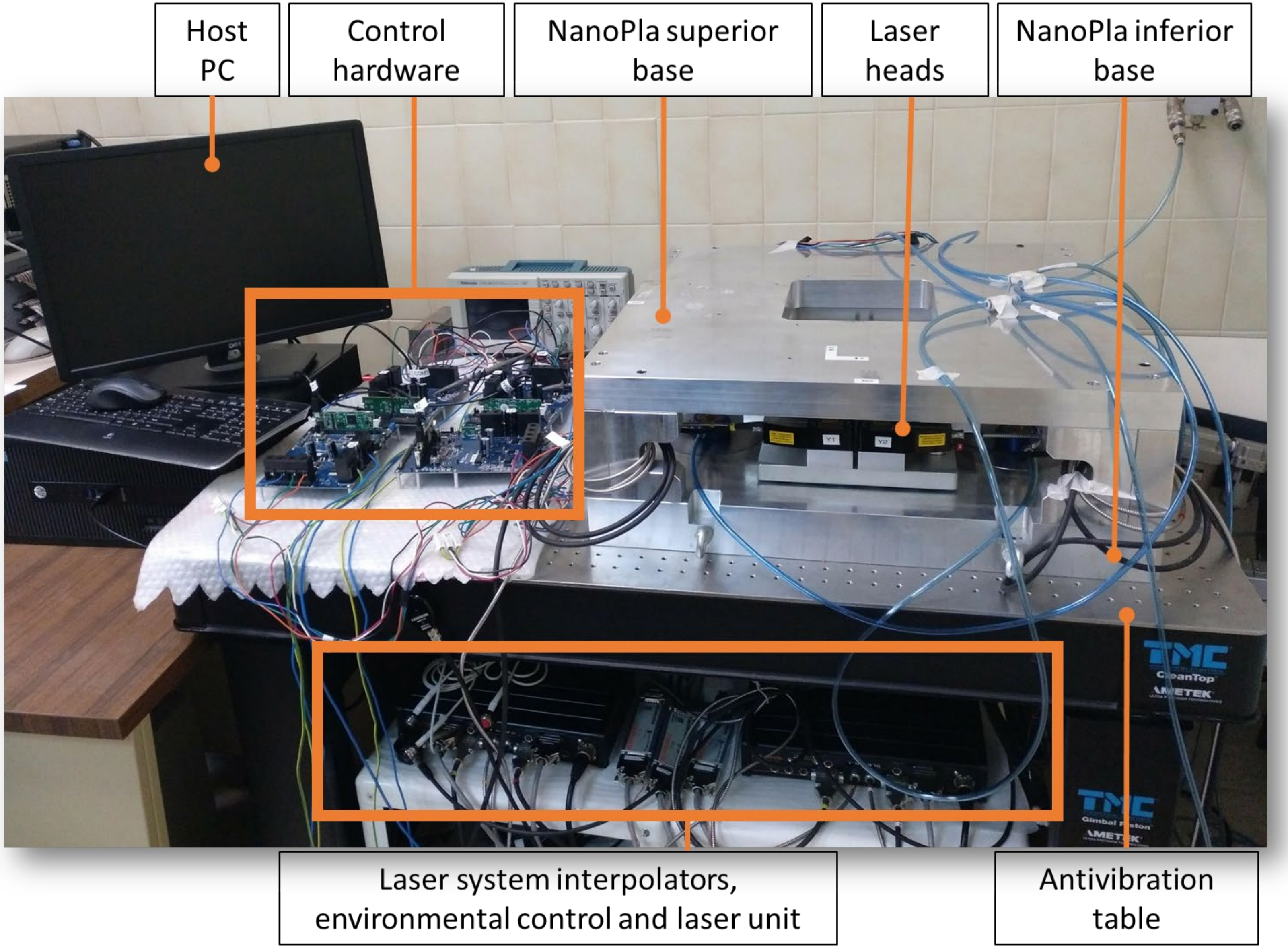
$$F_y = F_{M3} + F_{M4}$$

$$T_z = -F_{M1} \cdot R + F_{M2} \cdot R - F_{M3} \cdot R + F_{M4} \cdot R$$



Small range: NanoPla

Motion measurement & control / Small to medium range (1 mm - 5 m)

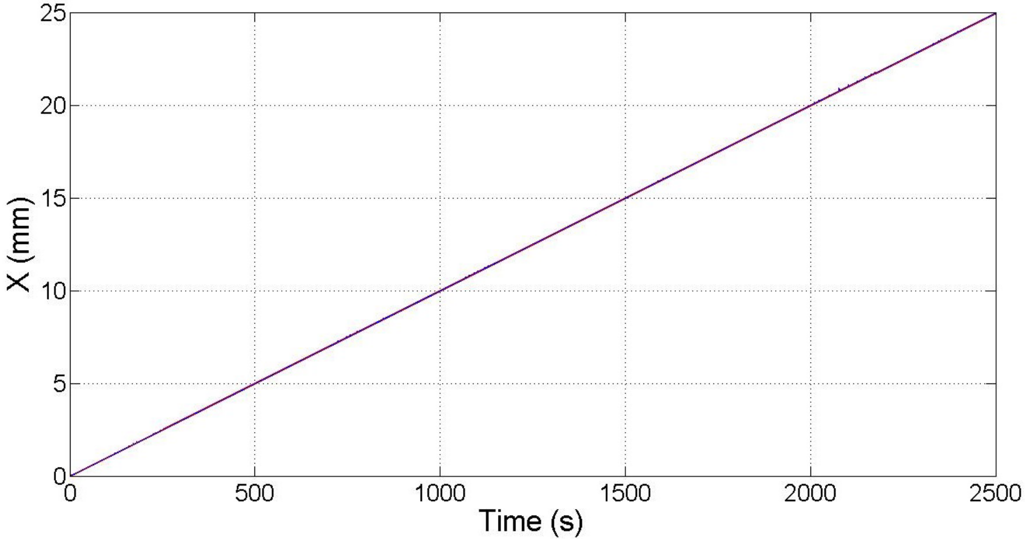


Small range: NanoPla

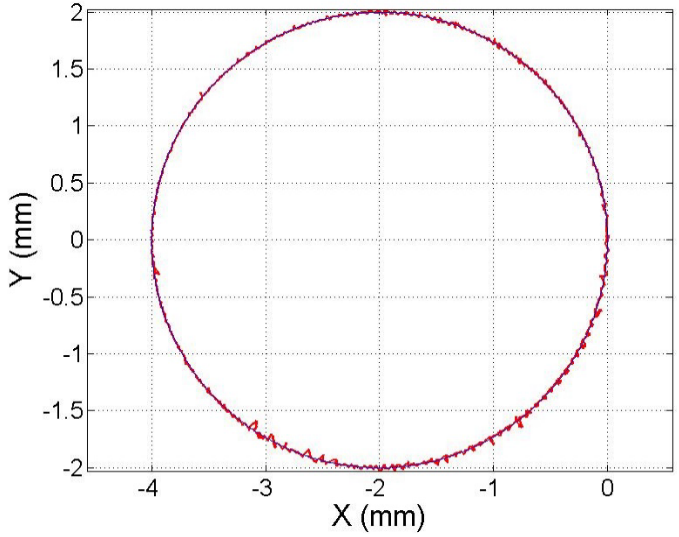
Motion measurement & control / Small to medium range (1 mm - 5 m)

Experimental validation: Planar scanning motion

25-mm displacement at constant speed

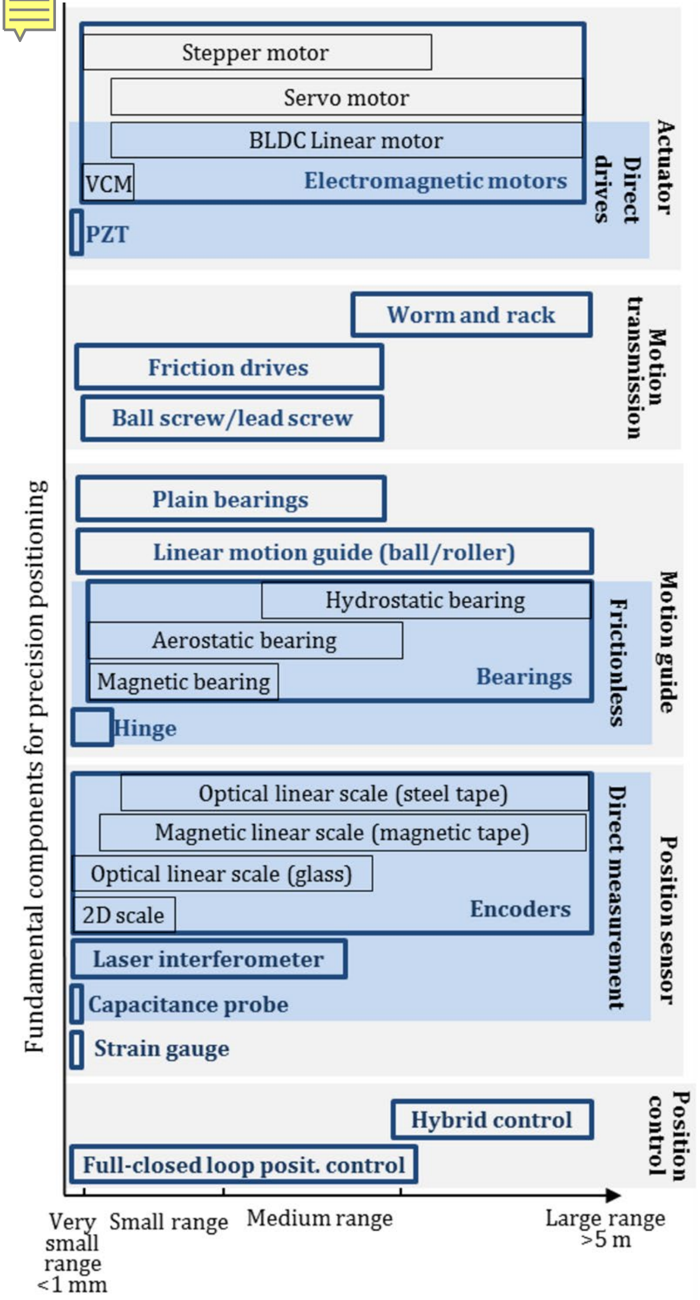


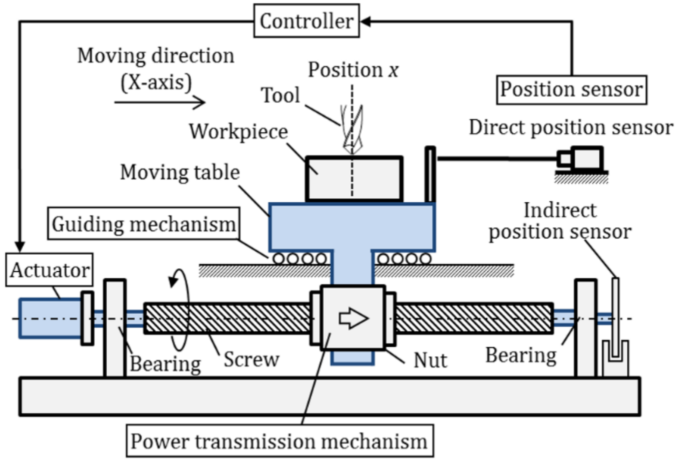
Simultaneous motion in X and Y-axes



Small range: NanoPla

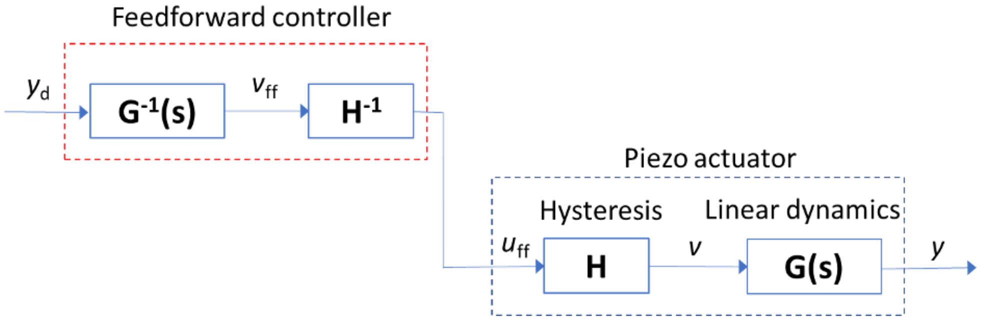
5. Motion measurement and control principles





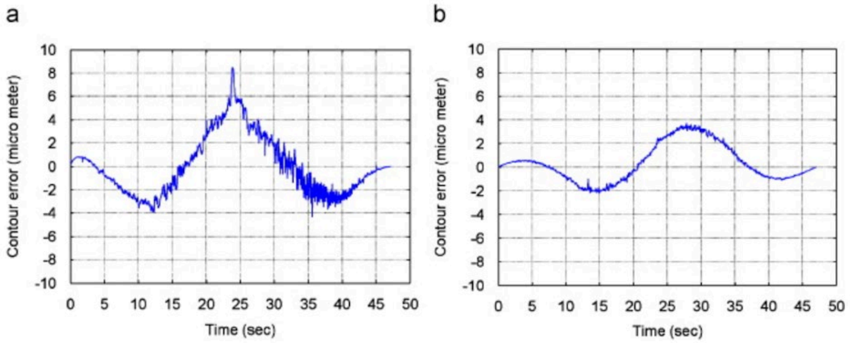
- Main components for precision positioning in different travel ranges. Blue boxes indicate typical range of application.
- Relationship between the components in a precision positioning system
- Feedforward control

Feedforward control of piezo actuator



Leang, K.K., et al., 2009, Feedforward control of piezoactuators in atomic force microscope systems, IEEE Control Systems Magazine, 29/1

(a) PI vs (b) PI with additional feedforward control with disturbance observer



Yang, C., et al., 2008, Research on the Structure of High-speed Large-scale Ultra-precision Positioning System, in 2008 3rd IEEE International Conference on Nano/Micro Engineered and Molecular Systems

Motion measurement & control / Very small range (≤ ± 1 mm)

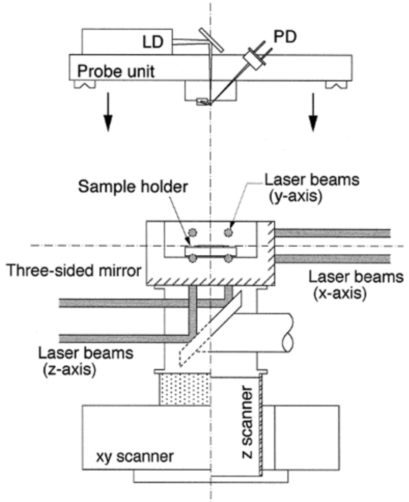
- PZTs: position resolutions of < 1 nm, extremely high accelerations, frictionless and backlash free.
- Used in many nanopositioning stages based on elastic hinges that allow planar motion. PZTs moving stroke can be extended.
- Increasing the bandwidth of precision machining applications by additional sensor/actuator by fast tool servo (FTS) technology.
- Laser interferometers, optical linear scales, capacitance probes, strain gauges, …

PZT
\+
Hinge
\+

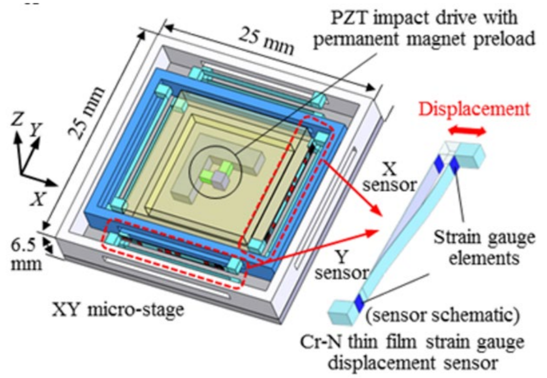
Position sensor	
Capacitance probe	• Standard combination • Trade off between range and resolution
Laser interferometer	• For ultra precision systems • High resolution in extended range • Easy for 2D/3D Abbe error free design
Strain gauge	• For low-cost systems • Trade off between range and resolution
Optical scale	• For robust systems • High resolution in extended range

Components for precision positioning in very small range

A metrological AFM [1]



XY micro-stage with strain gauges [2]



[1] Gonda, S., et al., 1999, Accurate topographic images using a measuring atomic force microscope, Applied Surface Science, 144–145

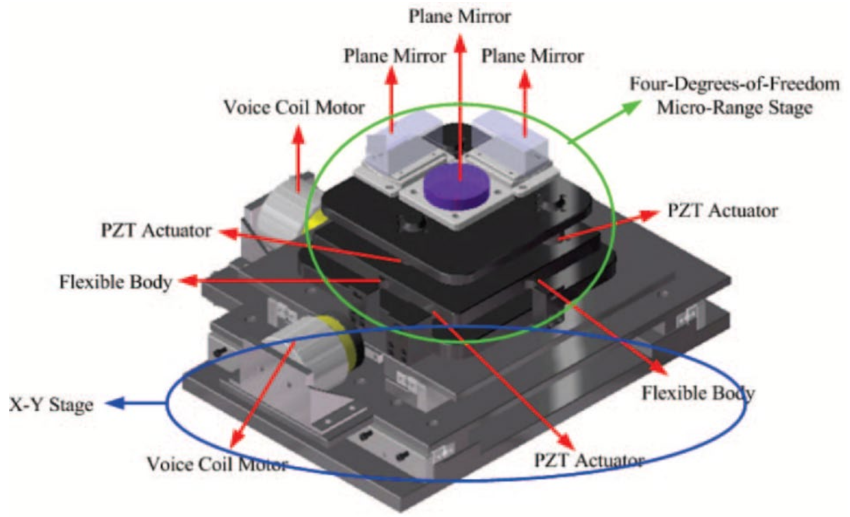
[2] Courtesy of Wei Gao

Motion measurement & control / Small to medium range (1 mm - 5 m)

Standard combination	Other components for precise applications	
Actuator		
Servo motor	Linear motor	• For high-speed systems of medium thrust force
+		
Motion transmission and motion guide		
Ball screw + Bearings + Linear guide	Linear guide	
	Aerostatic bearing	• For measuring instrument and machine tools of high speed and moderate load
	Hydrostatic bearing	• For machine tools of moderate speed and high load
	Magnetic bearing	• For 2D photolithography equipment of high speed and low load. Vacuum environment compatible.
+		
Position sensor		
Linear scale	2D scale	• For 2D photolithography equipment of high speed and low load. Vacuum environment compatible.
	Laser interferometer	• For ultra-precision measuring instrument with Abbe error free design
+		
Full-closed loop position controller		

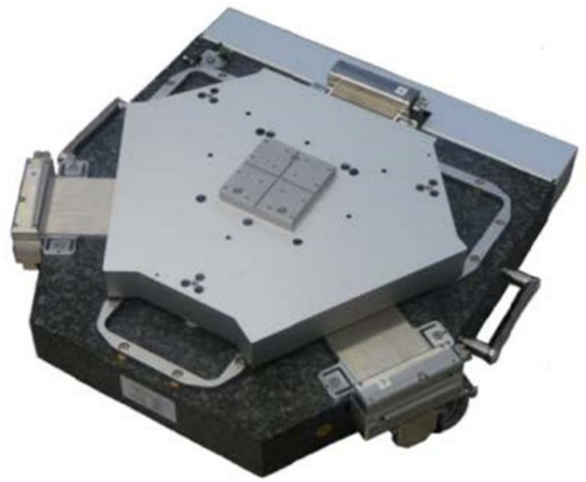
- Linear drives (stacked vs planar), VCM, BLDC motors, …
- Frictionless guiding systems: flexures, and aerostatic, hydrostatic, or magnetic levitation bearings.

Middle-range 6-dof system using VCM



Jywe, W., et al., 2009, Development of a middle-range six-degrees-of-freedom system, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 224/4

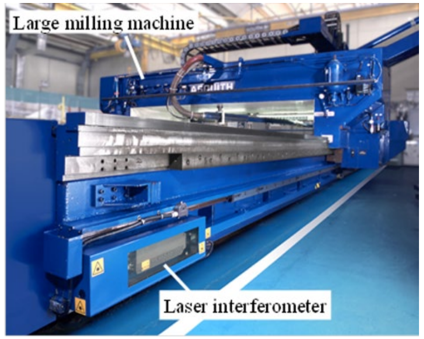
PIMag 6-dof planar magnetic levitation with Halbach arrays



Schaeffel, C., Katzschmann, M., Mohr, H.-U., Gloess, R., Rudolf, C., et al., 2016, 6D planar magnetic levitation system - PIMag 6D, Mechanical Engineering Journal, 3/1

Motion measurement & control / Large range (> 5 m)

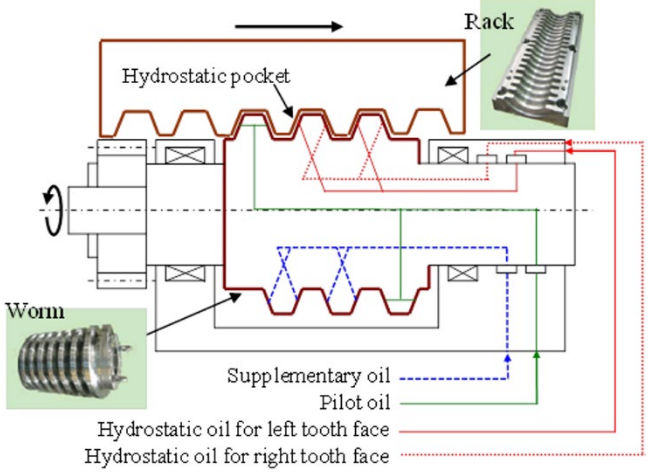
Standard combination	Other components for precise applications	
Actuator		
Servo motor	Linear motor	• For moderate speed systems of medium thrust force
+		
Motion transmission and motion guide		
Worm/rack + Hydrostatic bearing	Linear motion guide	• For measuring instrument with low speed and light load
+		
Position sensor		
Linear scale	Laser interferometer	
+		
Controller		
Hybrid position controller	Full-closed loop position controller	• For ultra-precision systems



Laser interferometer in large MT (Renishaw)

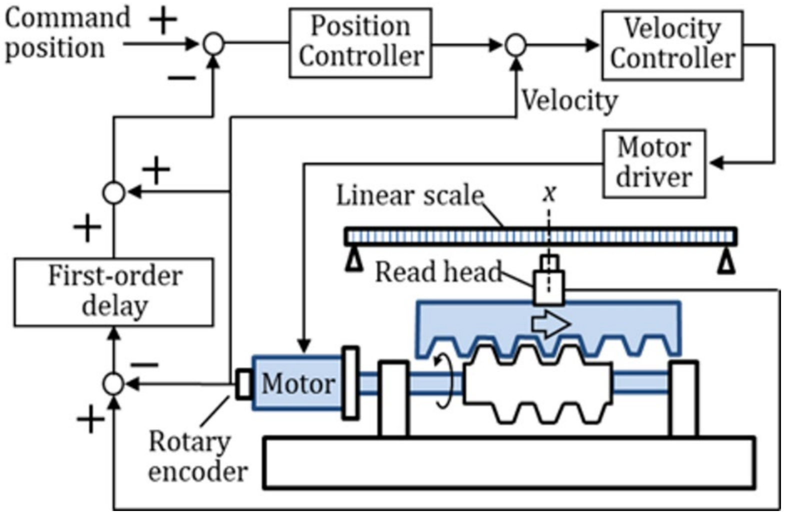
- Large masses → large friction → positioning errors due to stick-slip conditions. Feedforward control is used to minimize this effect.
- Friction reduction by a hydrostatic worm and rack mechanism. Hydrostatic bearings.
- Linear encoders. Linear interferometers.
- Hybrid position controller.

Hydrostatic worm and rack mechanism for a large MT



Sagara, M., 2017, Challenges and solutions for large and giant machine tools, Machines and Tools, 4:1–12

Hybrid position controller for a large MT of heavy load



Motion measurement & control / Discussion

Application of motion measurement and control precision design principles:

Precision Design Principles	Very small range systems	Small to medium systems	Large range systems
Direct (linear) drives	●	◑	◔
Frictionless motion/bearings	●	◑	◔
Planar motion	●	◔	○
Direct position sensor	●	●	◕
Non-contact position sensor	◕	●	●
Full-closed loop position control	●	●	●
Hybrid position control	○	◔	◔

Legend: the blacker the circle is the more often the principle is applied in the indicated range

- Advances in high precision optical sensors make the use of non contact direct sensors a completely scalable principle. In very small machines capacitive sensors are commonly used, while in larger ranges, laser systems and optical scales are the most common solution.
- It facilitates the full-closed loop position control, which is also a scalable principle which is implemented in machines of every range. In large machines full-closed loop control combined with semi-closed control in a hybrid controller → rapid control over a wide frequency bandwidth.

6. Error mitigation principles

Error mitigation strategies:

Mitigation strategy	Principal methods	Examples
Error avoidance	Architecture modification	Replacement of over-constrained structure with kinematic support
Error reduction	Component-wise improvement	Lapping of an axis to improve straightness
Error correction	Steady-state offsets of known, stable errors	Measurement of straightness errors of an axis, with subsequent correction
Error compensation	Real time, model-based computation of offsets	Estimation of scale growth due to temperature, with subsequent compensation based on the measured temperature(s)

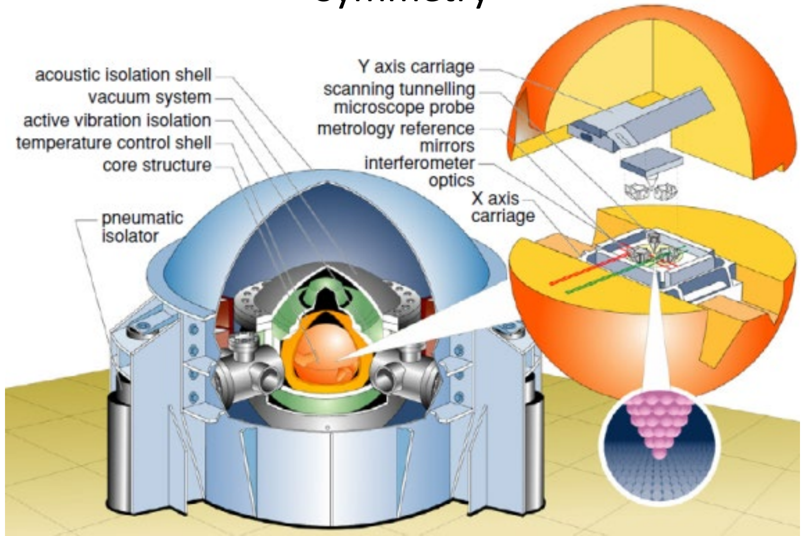
- The error of either the tool tip, stylus tip, retro-reflector, … measurement location is the measurand

- Error avoidance: at the conceptual design stage / Kinematic couplings, materials, isolation, …
- Error reduction: during the detail design where final component selection is performed / Additional processing, control, …
- Error correction: is based on the machine model and errors measured when the system is operating in its final placement / stability of errors, reversal, …
- Error compensation: addresses errors from real-time sources, such as a changing thermal environment / errors changing in time, model, …

Error mitigation principles / Small range systems

- Small range machines relatively massive when compared to the workpieces produced or measured
- The movement of the tool or sensor must be accomplished with precision
- Main focus: Design and control stages → Error avoidance & Error reduction
- Symmetry, damping, …

Symmetry



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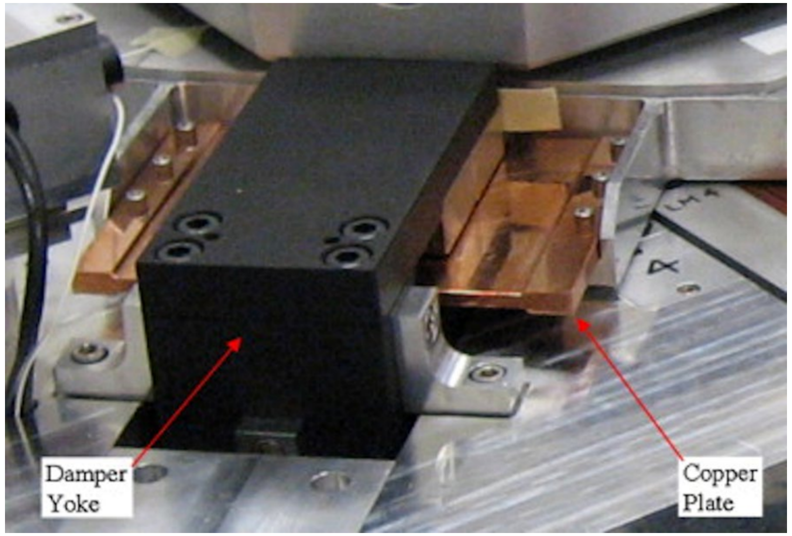
Eddy current damper



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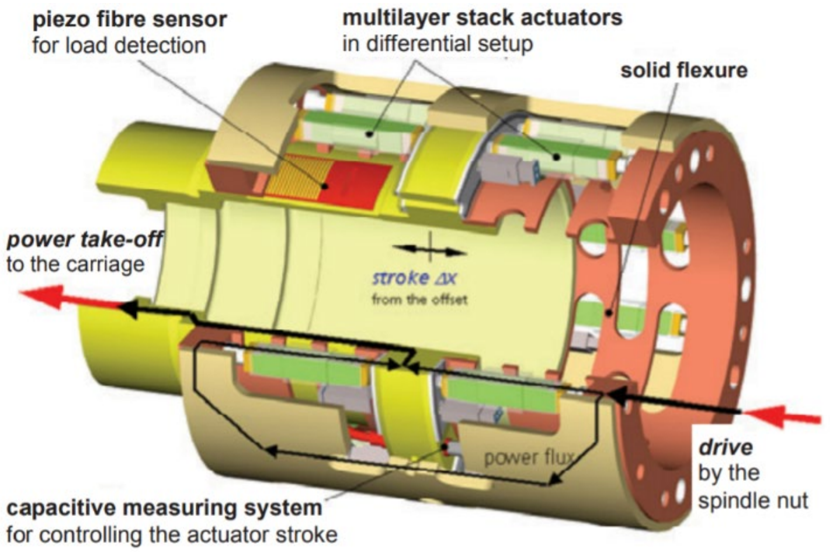
Error mitigation principles / Medium range systems

- Most of industrial manufacturing and measuring equipment
- All aspects of error mitigation are utilized
- Active error reduction: PZT as compensation devices
- Error reduction: control of environment

Axial vibration compensation unit



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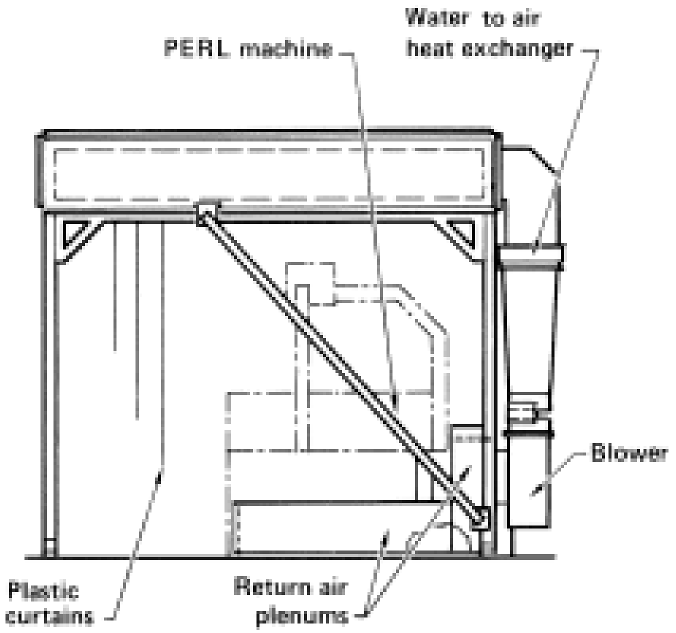
Environmental enclosure



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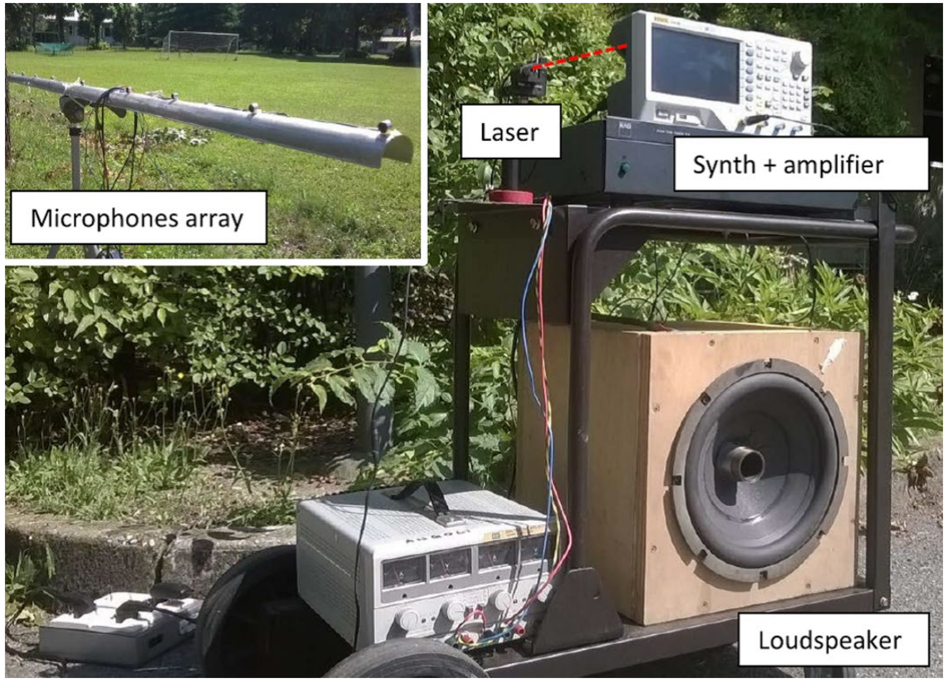
Error mitigation principles / Large range systems

- Experience errors that cannot be "designed out" or reduced by traditional methods
- Only occasional examples of vibration isolation of precise components used for large scale applications can be found (LIGO)
- Errors due to gradients in the environmental conditions, and the self-weighing (gravitational) effects of large system structures and the workpieces themselves
- Error compensation: Determining the refractive index of air to compensate the laser-based measurements (foundation of many large-scale systems)

Large-scale index of air estimation



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Error correction / Large range systems

- Simultaneous multilateration approach: Interferometric or absolute displacement measurements between tracking interferometers that are fixed to the machine base and a reflector, fixed to the machine spindle, near to the tool centre point (TCP)

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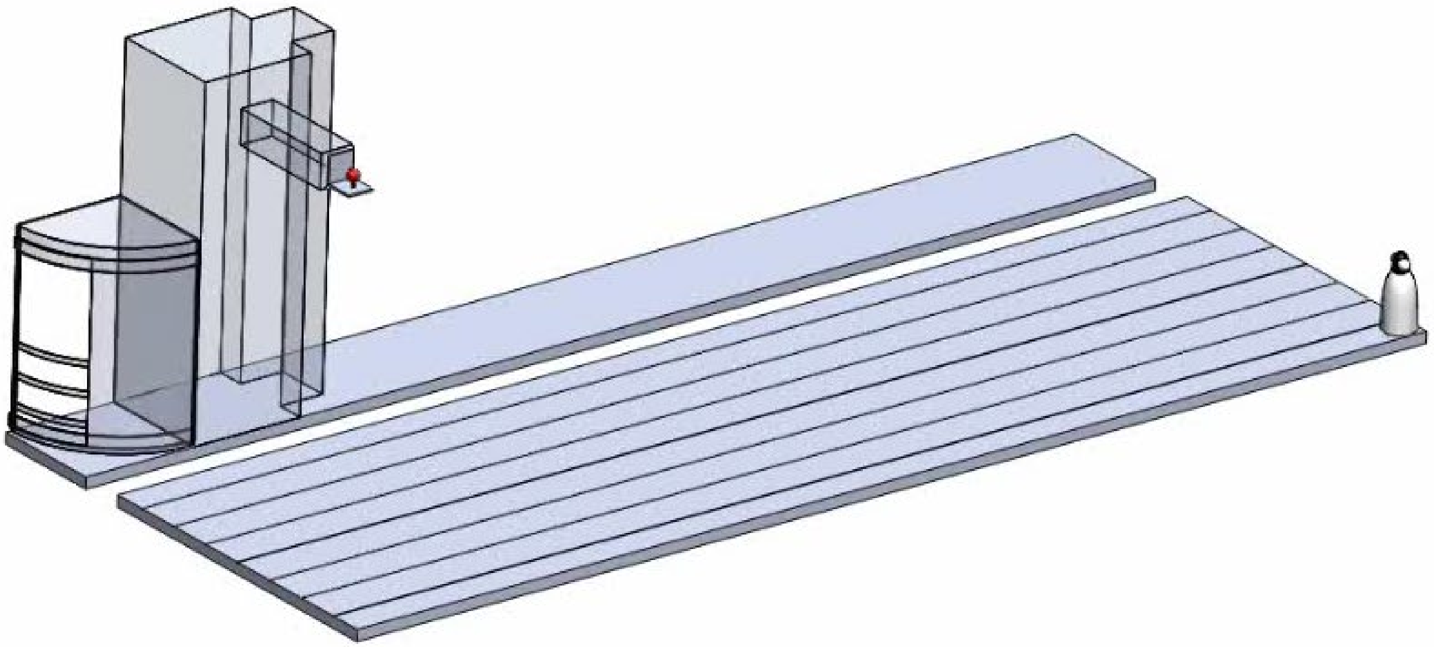
Large range

Error correction / Large range systems

- Sequential multilateration approach:



Large range

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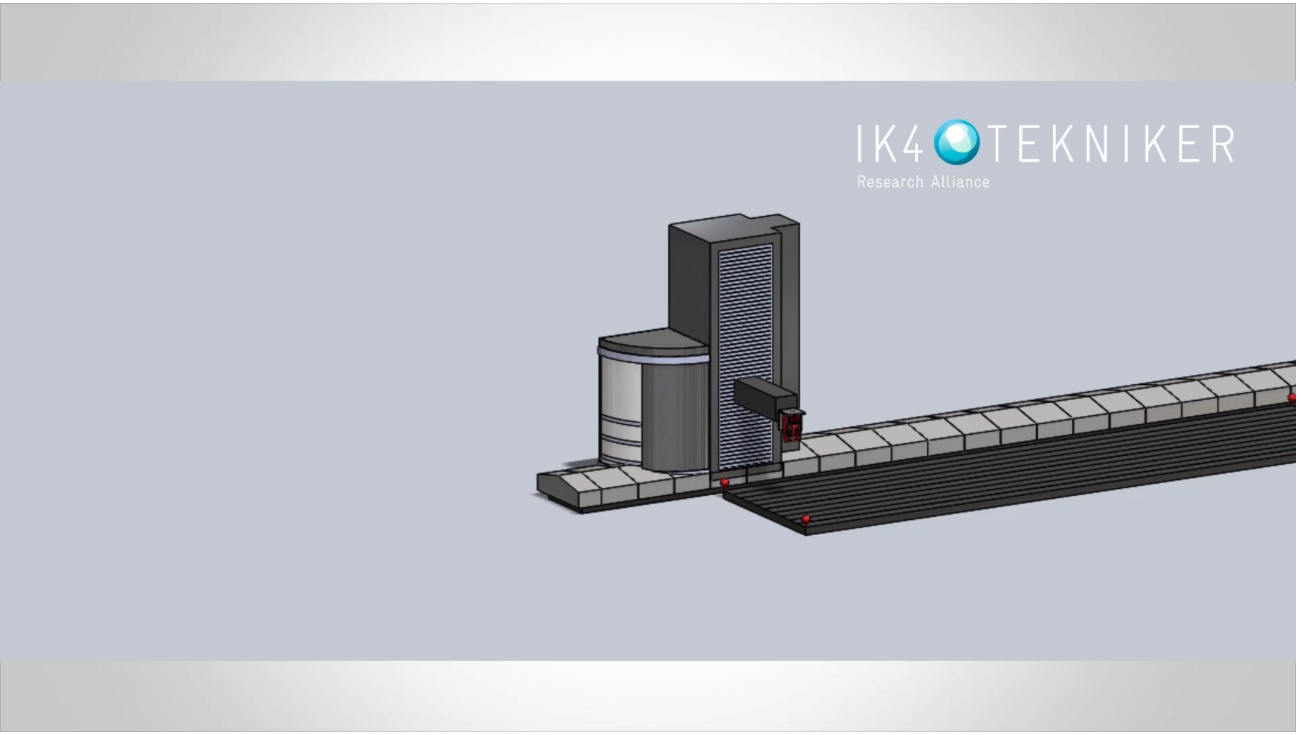
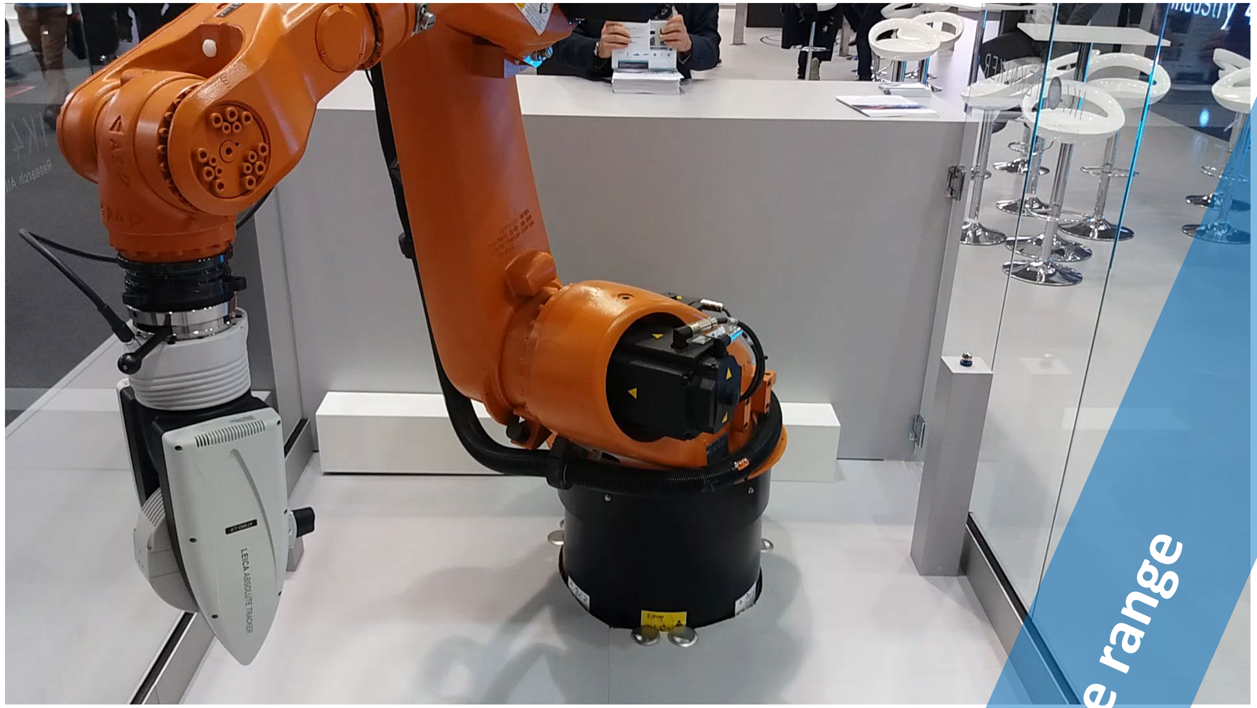
Error correction / Large range systems

Integrated multilateration for machine tool automatic verification





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Large range

Error mitigation principles / Discussion

Application and effectiveness of error mitigation strategies:

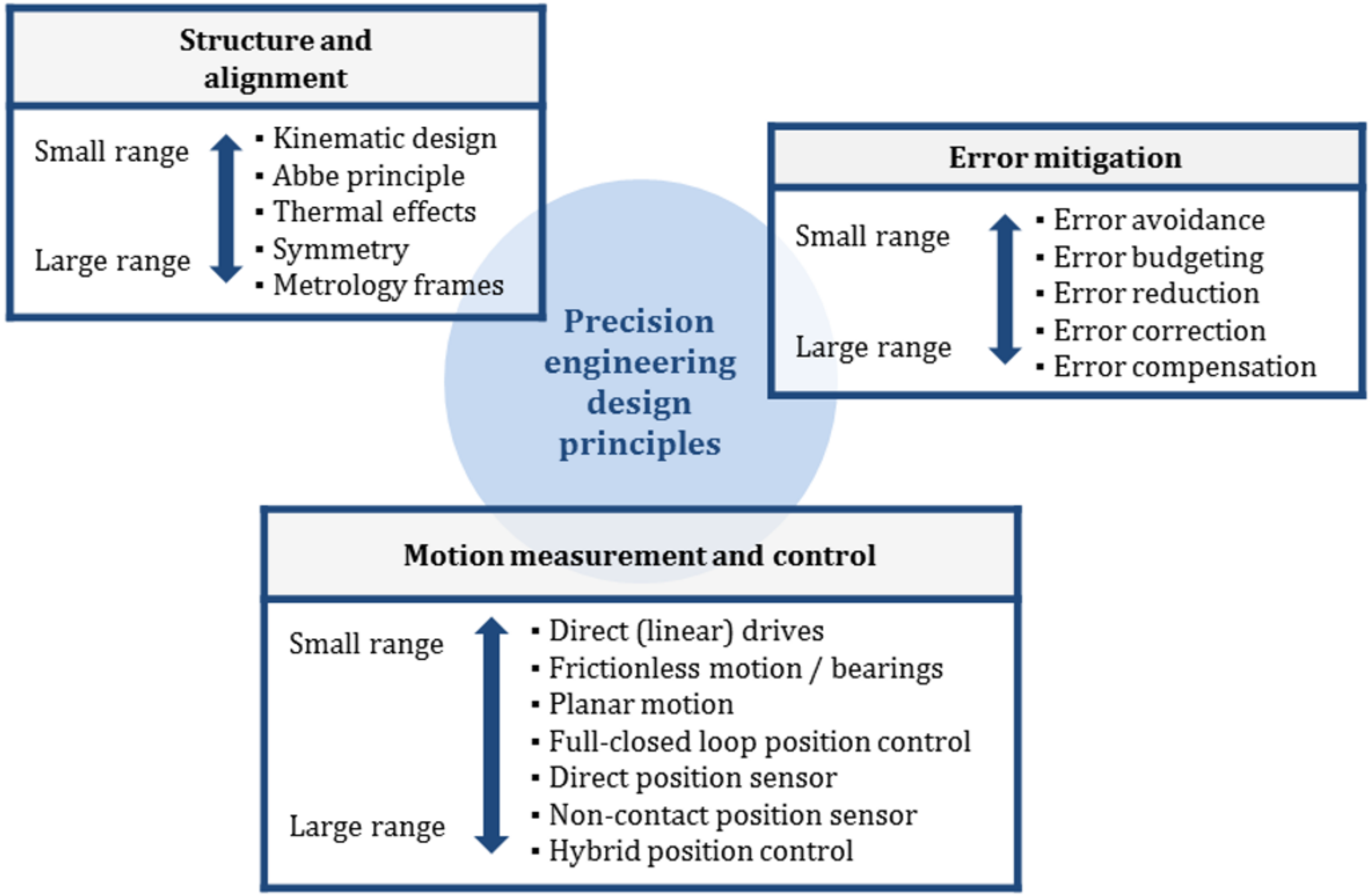
Error mitigation strategy	Small range systems	Medium range systems	Large range systems
Error Avoidance	●	◕	◔
Error Reduction	◕	●	◑
Error Correction	◑	●	◕
Error Compensation	◔	◑	●

Legend: the blacker the circle is the more applied the principle is in the indicated range

- High-precision systems rely on all of the mitigation techniques
- Small-range systems tend toward pure determinism
- Large-range systems rely more on error correction and compensation
- Medium-range systems rely heavily on all of the error avoidance and correction techniques
- ML or AI + big data collected during the process. Promise complex models. Risks → many ML methods are purely data-driven → How to ensure that accuracy is maintained in all machine states?

7. Conclusions

- The classical 11 precision engineering design principles keep being valid
- They are scalable, although at different levels



Conclusions / Future trends

- Structure and alignment principles remain the basis of a precise system design
- Digital twins → Proper validation
- Networks, 5G → Speed up the analysis time
- Correction or compensation with ML or AI (when they gain reliability)
- Inline / Integrated metrology → Thermal variations
- Improvements in resolution accuracy and speed of sensors; (e.g. optical frequency comb-based sensor technologies)
- More and more advanced control systems: learning / adaptive controls

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Precision Design Principles. Does the size matter? A methodological approach

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