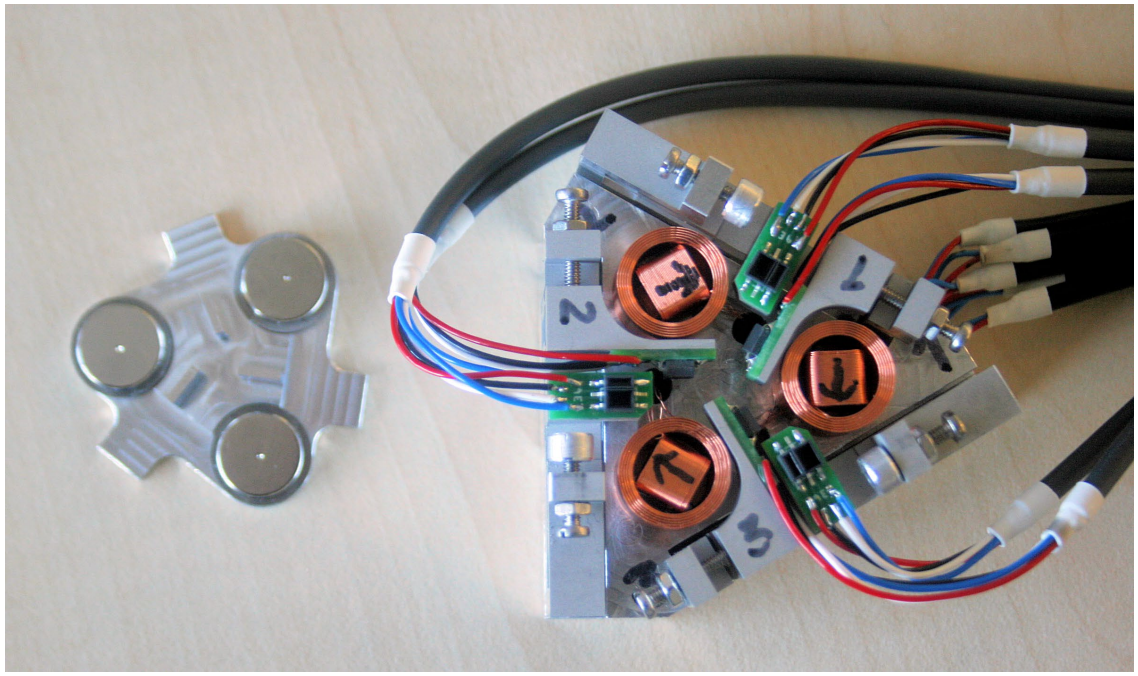
Design of a 6-DoF Miniature Maglev Positioning Stage

for Application in Haptic Micromanipulation



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Promotor:
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Outline

- Introduction: Framework
- Requirements and Concept
- Sensors
- Actuators
- System Modelling
- Mechanical design
- Conclusion
- Demonstration
- Debate

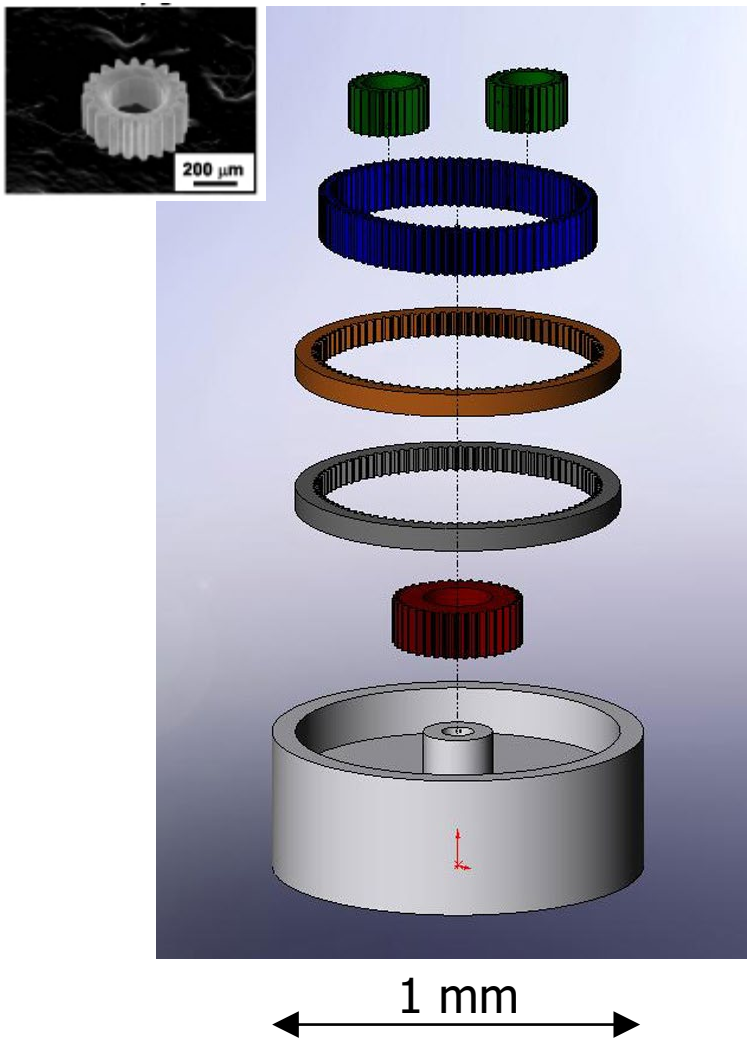
Introduction: Micromanipulation

Miniaturisation of mechanical and electronic systems

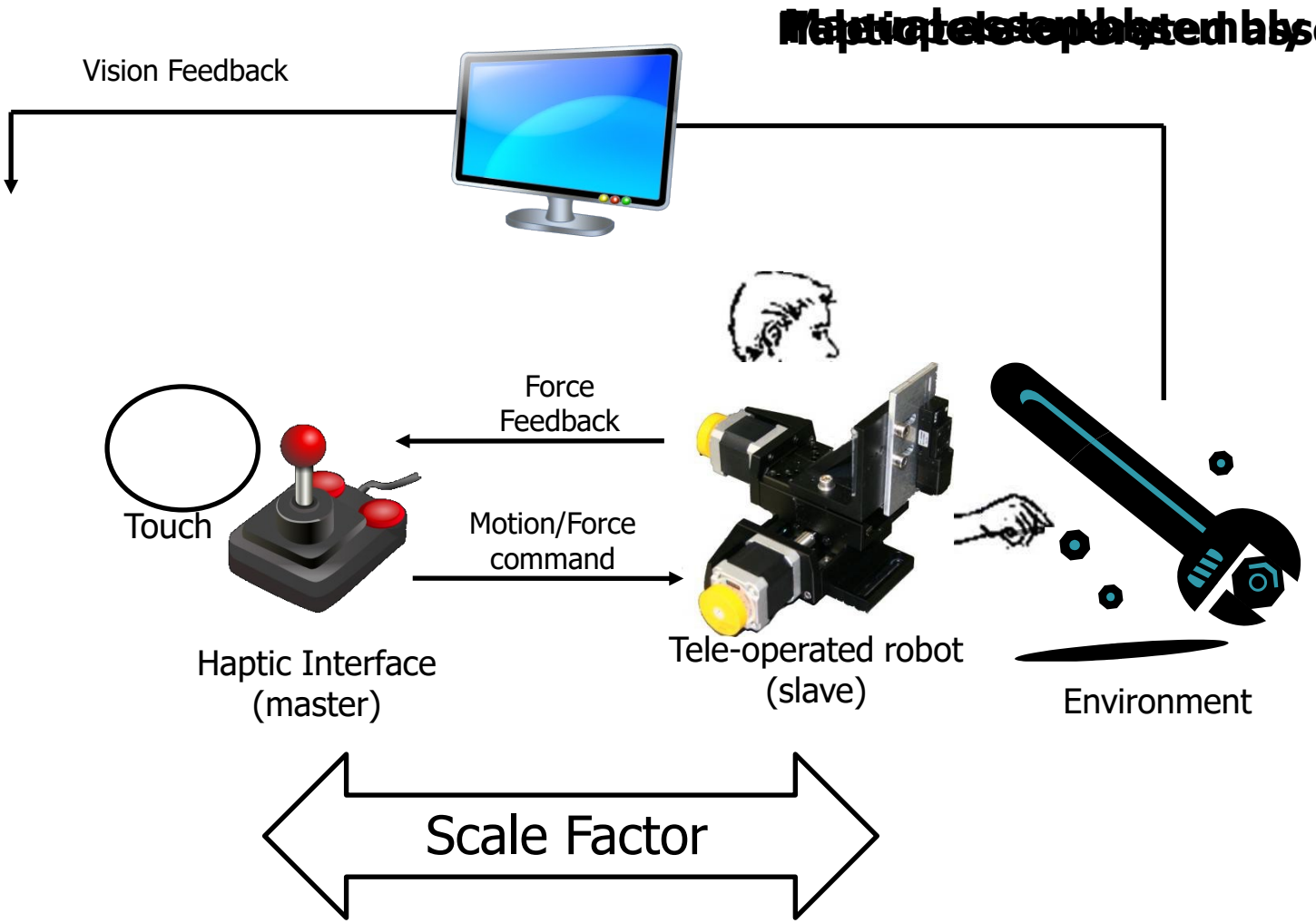
Requires manipulation and assembly of micro parts (sizes of 1 mm and smaller)

Required precision too great for unaided human operator (often less than 1 µm)

Varied and complex assembly tasks difficult for automatic systems



Introduction: Micromanipulation



Introduction: The slave robot

The positioner consists of two stages

- Coarse stage :

stepper motor stages,

20 mm range

- Fine stage :

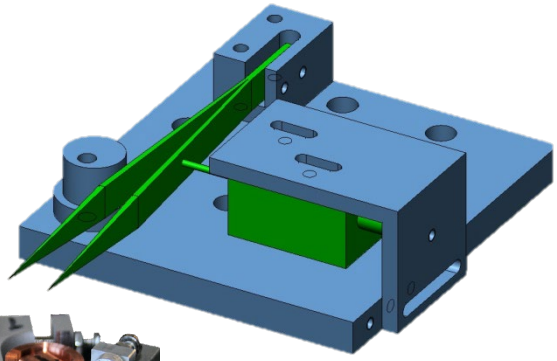
Maglev stage,

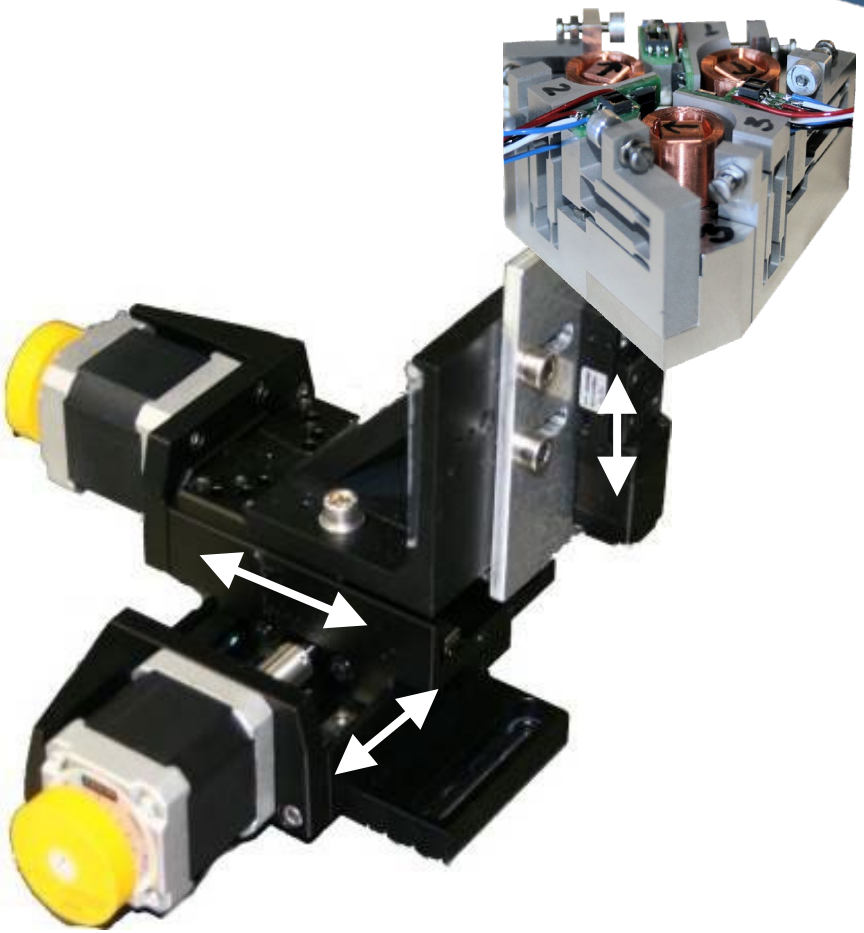
200 µm range

The slave robot positions micro parts relative to a gripper

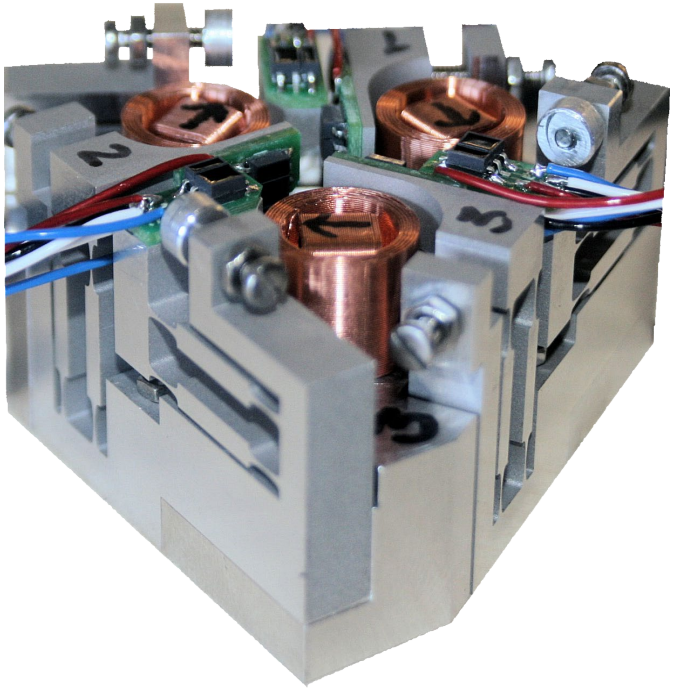
This thesis:

Design of fine stage





The fine stage



The fine stage: Considerations

- Compact and simple design
  → Affordable for small series assembly and prototyping

- Fragile parts → Fine force resolution :
  - Low stiffness
  - Contact-free
  - Low moving mass

- User in the loop :
  - No absolute positioning
  - No accuracy requirement
  - Limited command bandwidth

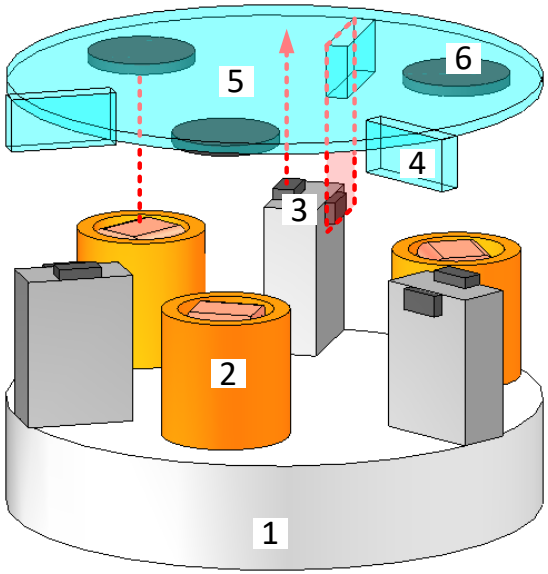
The fine stage: Specifications

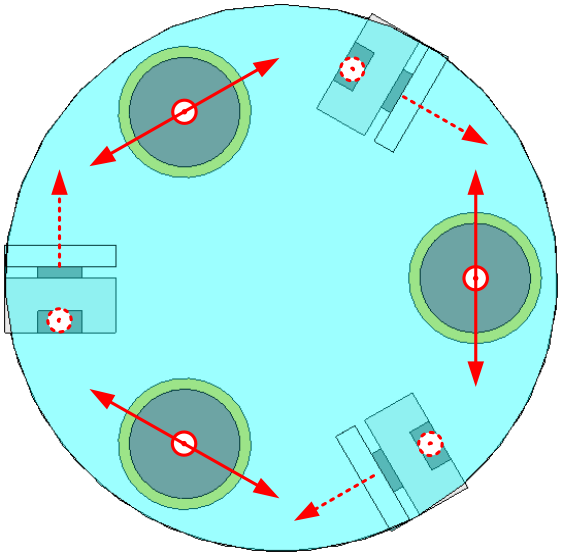
- Workspace : 200 µm x 200 µm x 200 µm
- Rotation : ± 1°, three axes
- Velocities : 1 mm/s
- Moving mass : 8 g

- Part tolerances : 1 µm – 200 nm
  → Position resolution : 40 – 100 nm

- Fragile parts handling
  → Force resolution : < 100 µN

The fine stage: Maglev concept





~ 5 cm

1. Base structure
2. Actuator coils
3. Sensor holders with sensors
4. Sensor targets
5. Floating disk
6. Actuator magnets

Sensors: Requirements and Principle

Required range : 200 µm

Maximum noise : 10 – 25 nm peak-peak

Bandwidth : 1 kHz

Contact-free

Small size, Low cost

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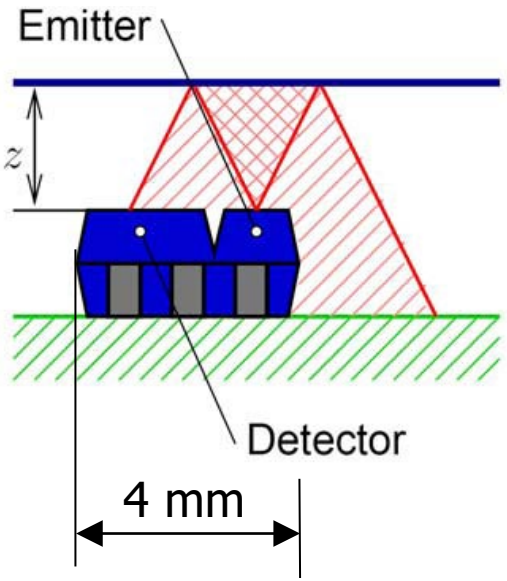
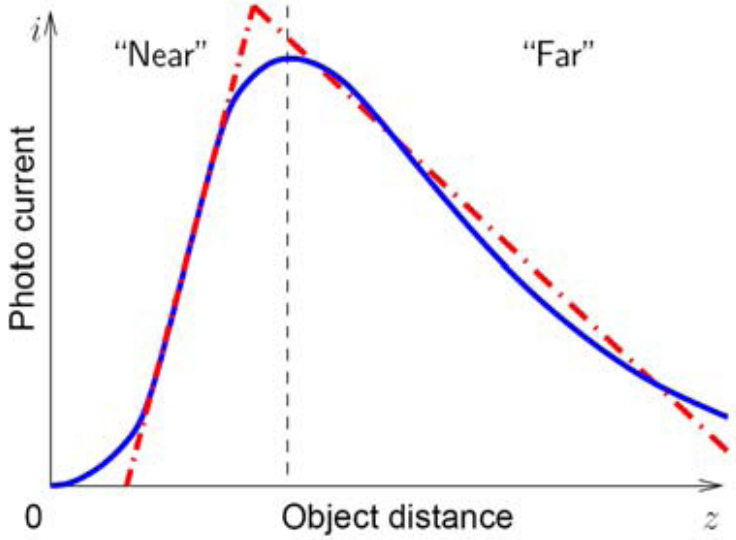


Infrared Reflective Position Sensor

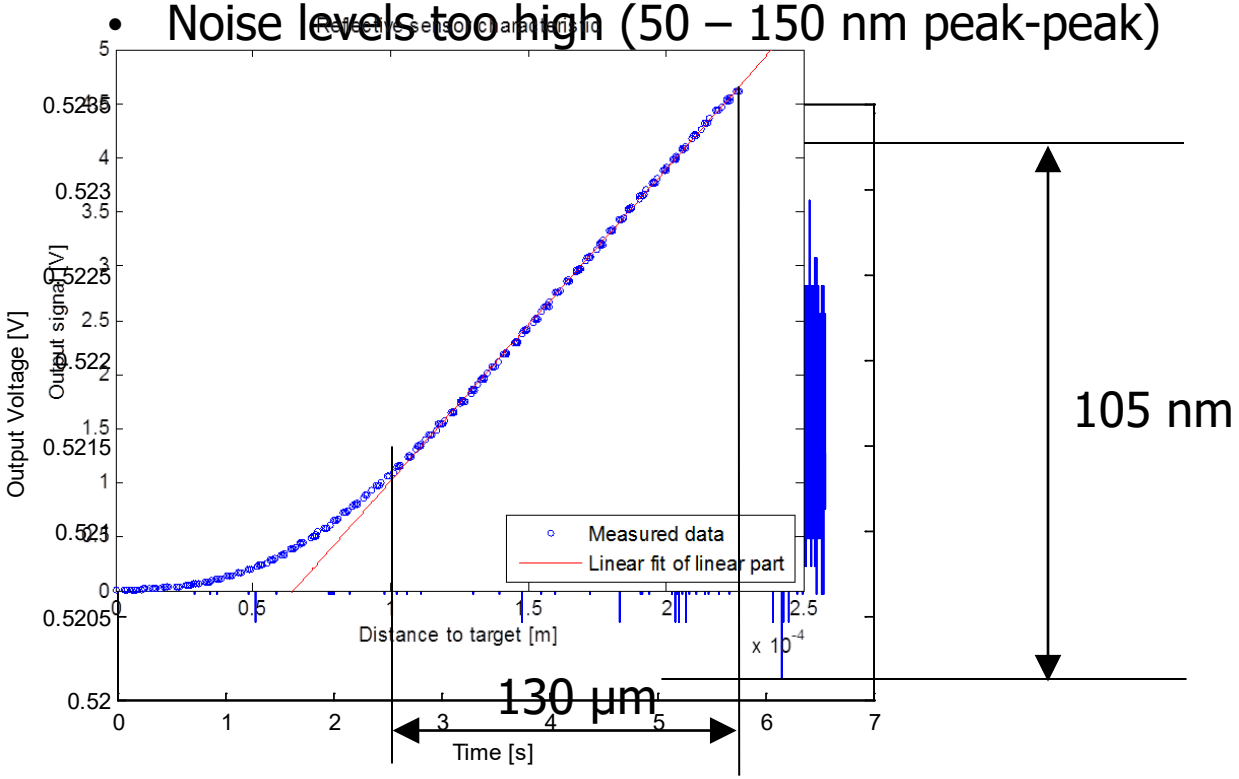


Position Sensor Characteristic

Linear "Near" range approx. 200 µm

Sensors: Problems

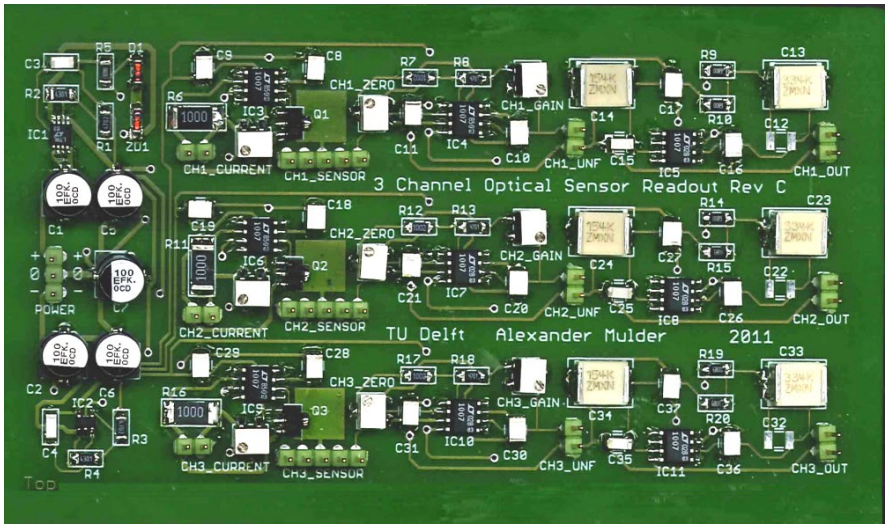
- Existing readout electronics not suitable for this application
  - Usable part of range too small (130 µm)
  - Noise levels too high (50 – 150 nm peak-peak)

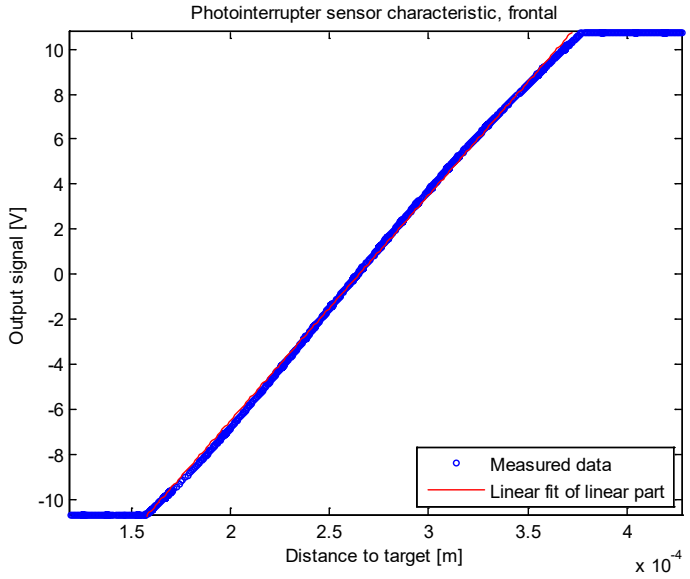


Sensors: Results

Fully redesigned readout electronics

Achieved range : 200 µm
Noise : 15 – 28 nm peak-peak

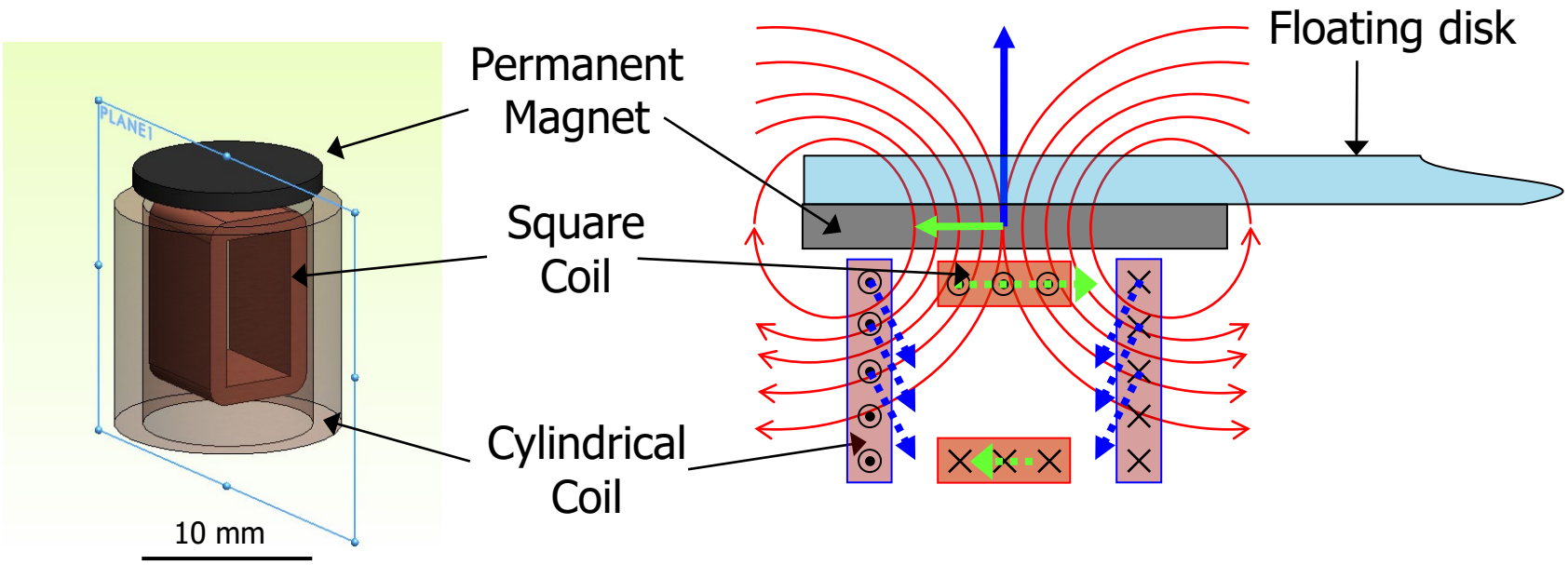




Sensor range equal to motion range → alignment needed

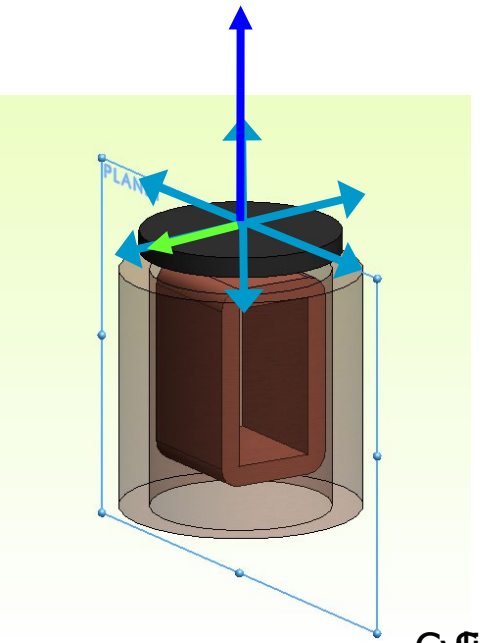
Drift

Actuators: Principle and Requirements



Peak force required:
- 40 mN vertical
- 20 mN horizontal

Actuators: Modelling

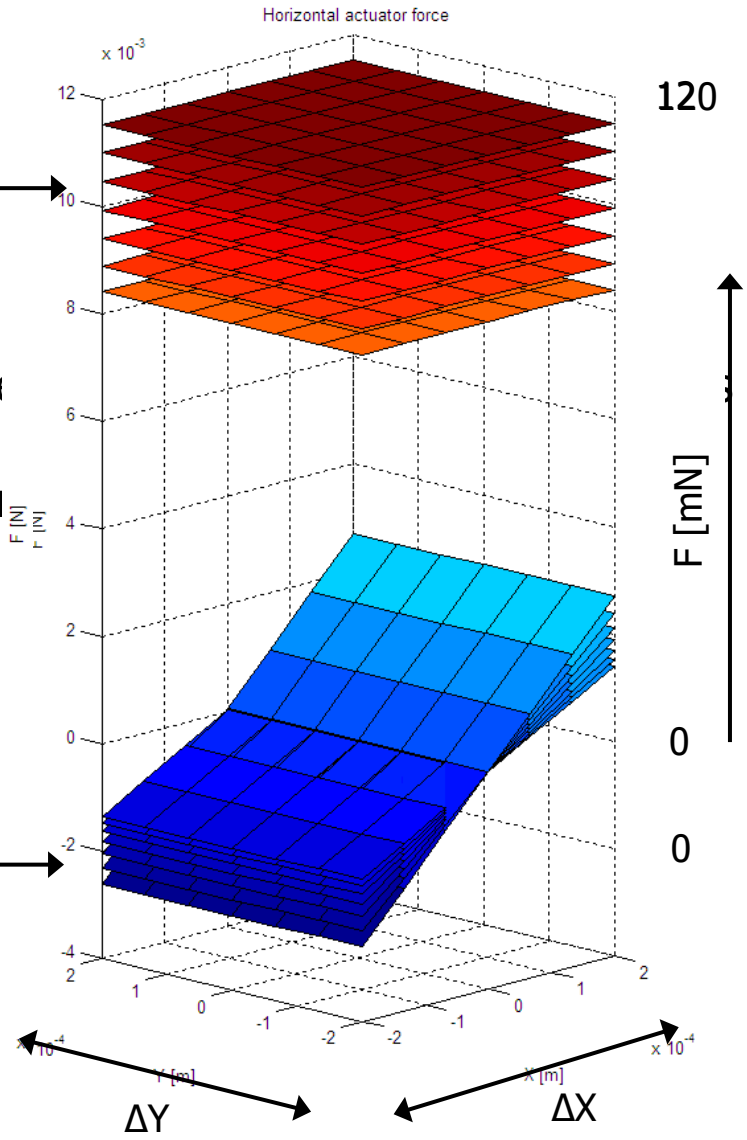


Cylindrical coil force

Finite El

displace

Cylindrical coil force (parasitic)



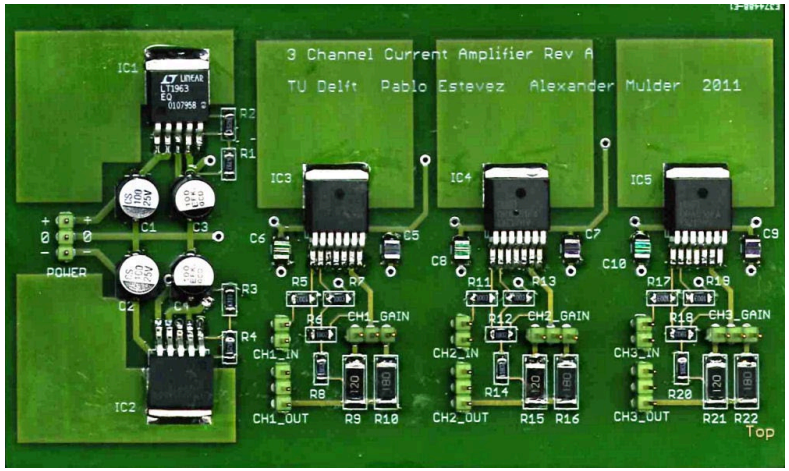
Actuators: Results

- Actuator force
  - Vertical: 80 mN continuous, 160 mN peak
  - Horizontal : 10 mN continuous, 20 mN peak

- Parasitic forces/torques appear at off centered positions

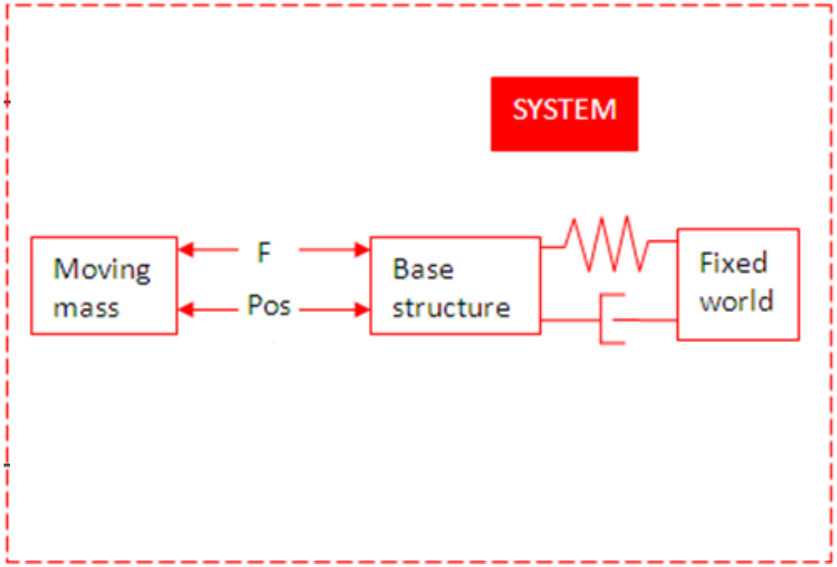
- But manageable with simple control schemes

- Designed current amplifier board



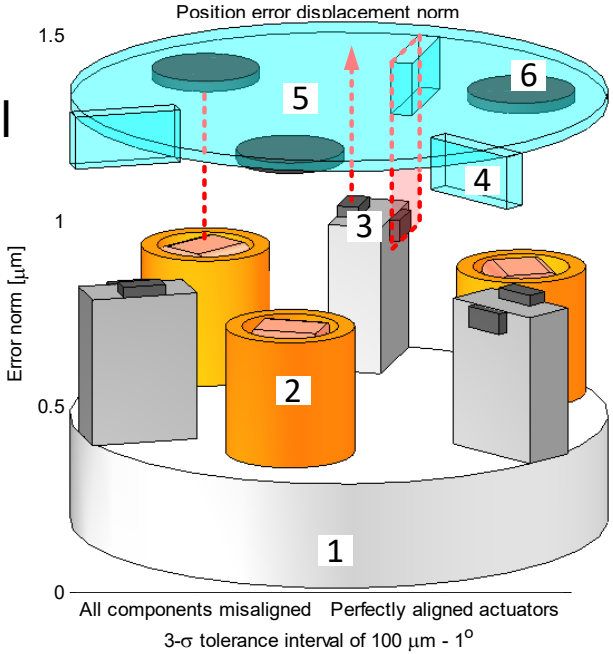
System modelling: Overview

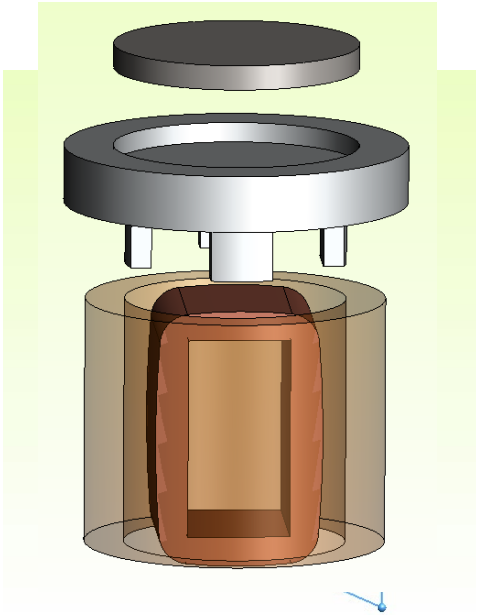
- Electro-mechanical model of fine stage
- Open-loop unstable → Controller



System modelling: Manufacturing tolerances

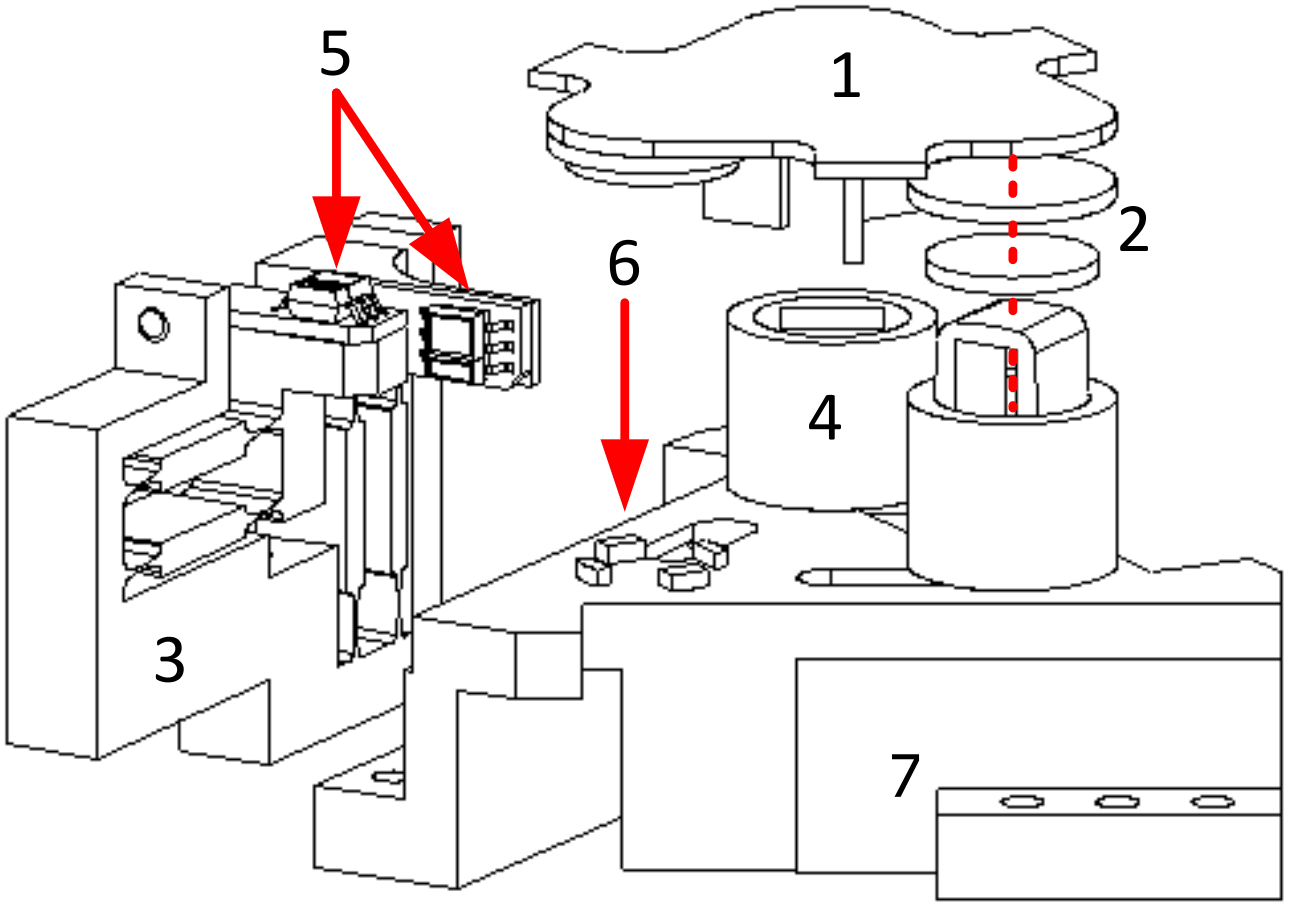
- Randomised tolerances added to stage components in model
- Results: Position errors manageable as long as magnets and coils are aligned
- Alignment tool



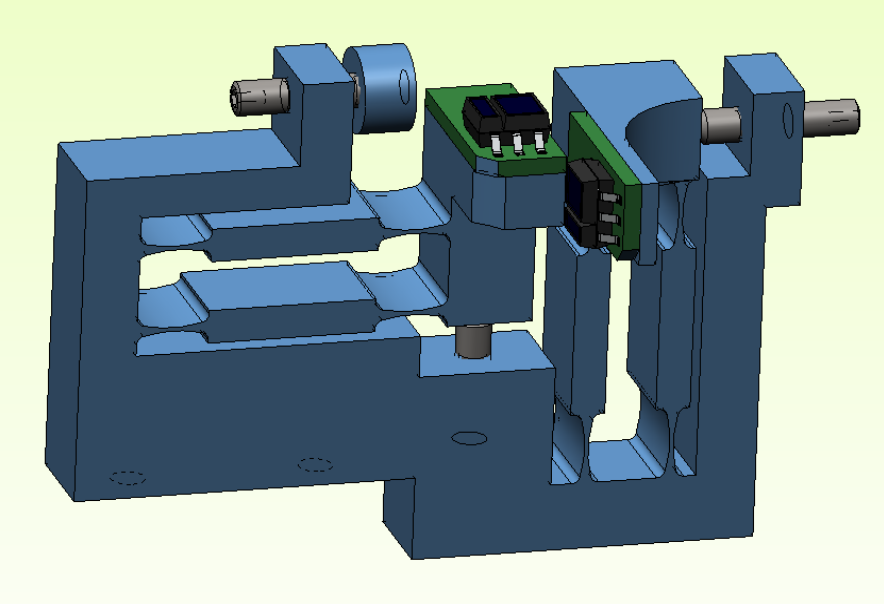


Mechanical design: Exploded view

1. Floating disk
2. Magnet and iron assembly
3. Adjustable sensor mount
4. Coils assembly
5. Horizontal and vertical position sensors
6. Coil alignment features
7. Base structure

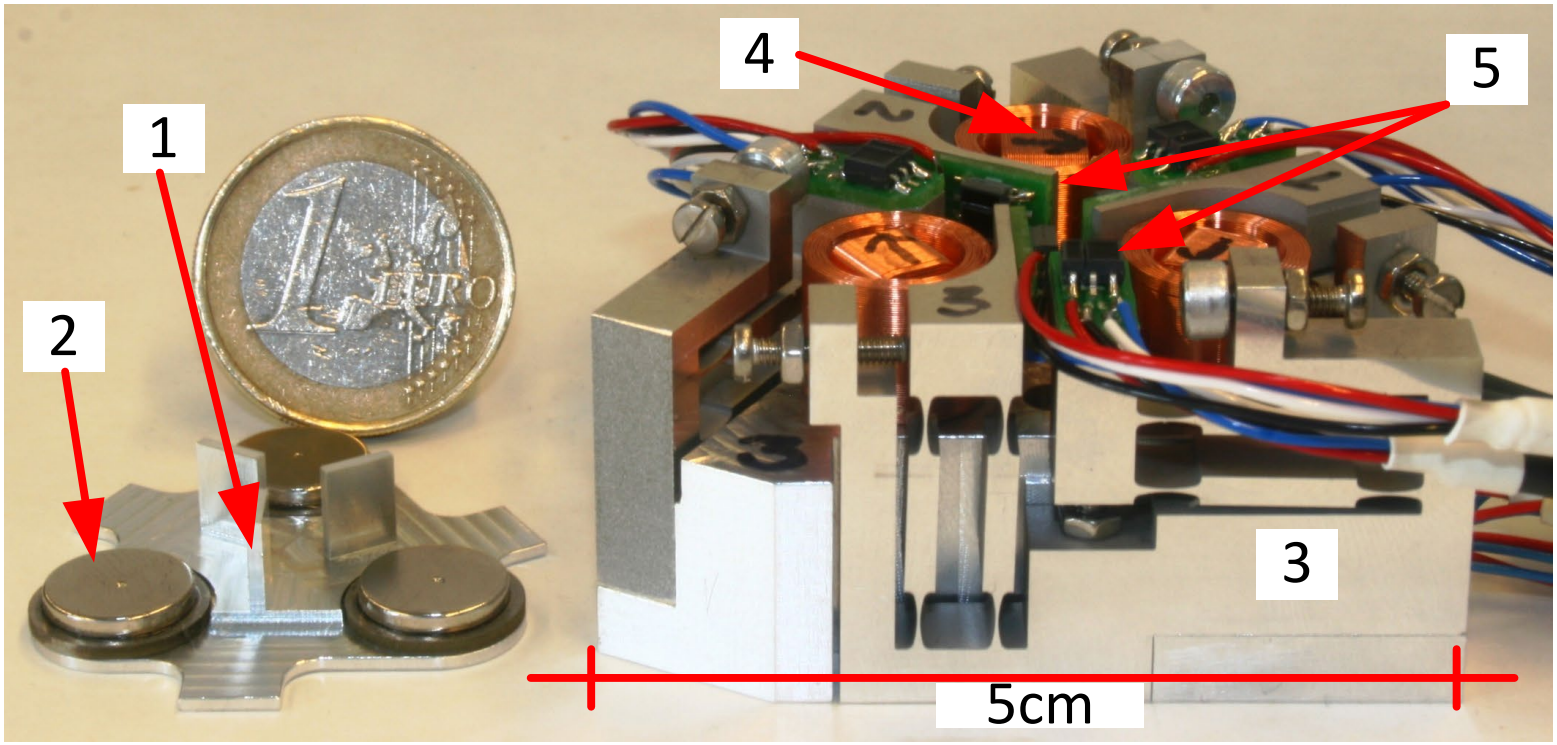


Mechanical design: Sensor adjustment



Limited sensor range → adjustable mounting

Mechanical design: Final design



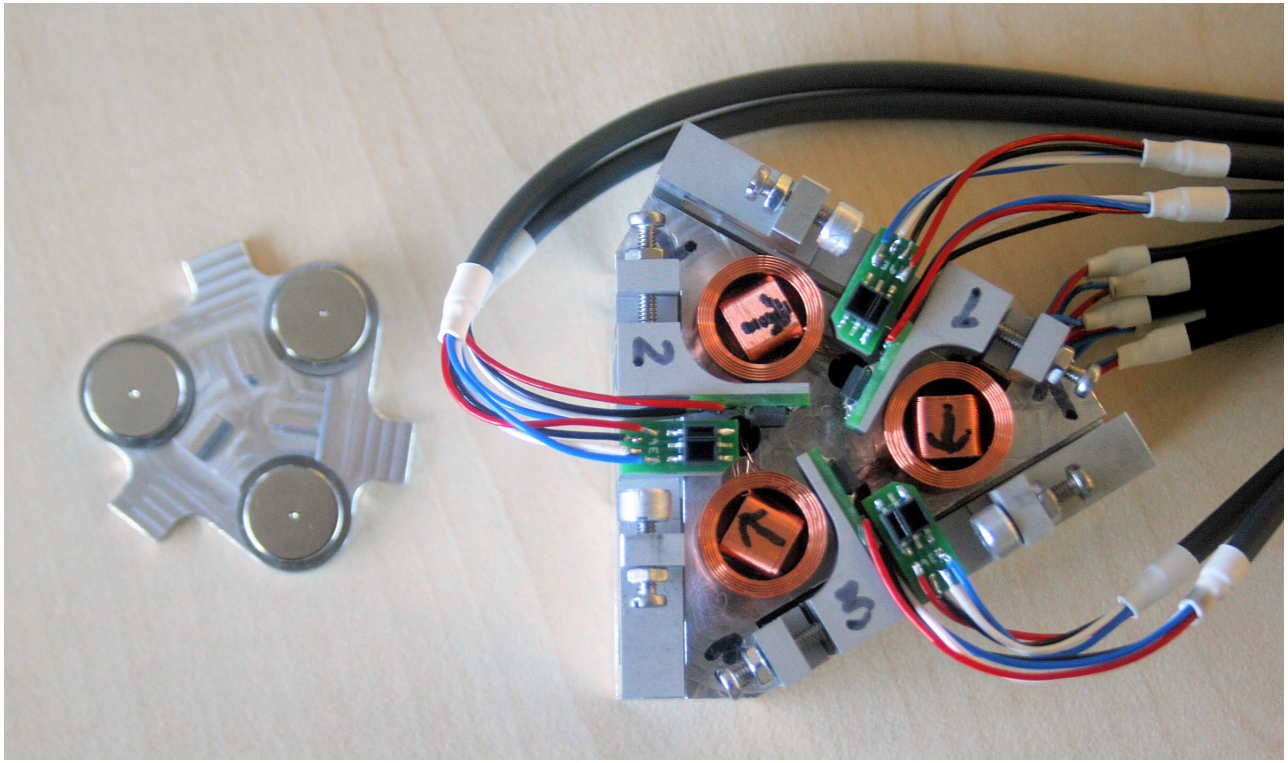
1. Floating disk
2. Magnet and iron assembly
3. Adjustable sensor mount
4. Coils assembly
5. Horizontal and vertical position sensors

Conclusion

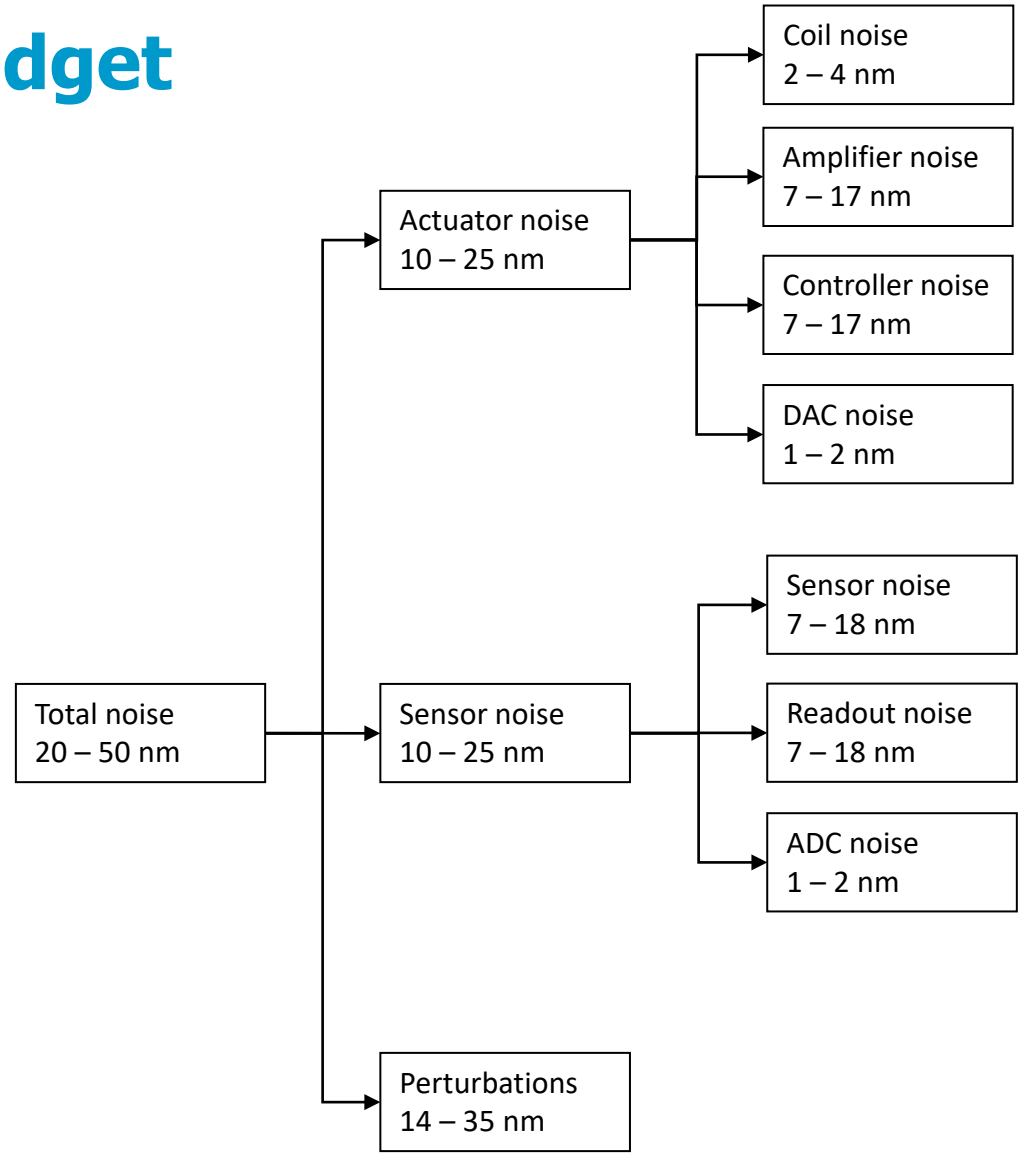
- Results
  - Designed and built 6-DoF maglev stage
  - Novel Lorentz actuator design
  - Low-noise optical position sensor
  - First closed-loop tests successful

- Recommendations
  - Further testing
  - Optimise actuator dimensions
  - Sensor with longer range
  - Design production prototype

Thank you for your attention!



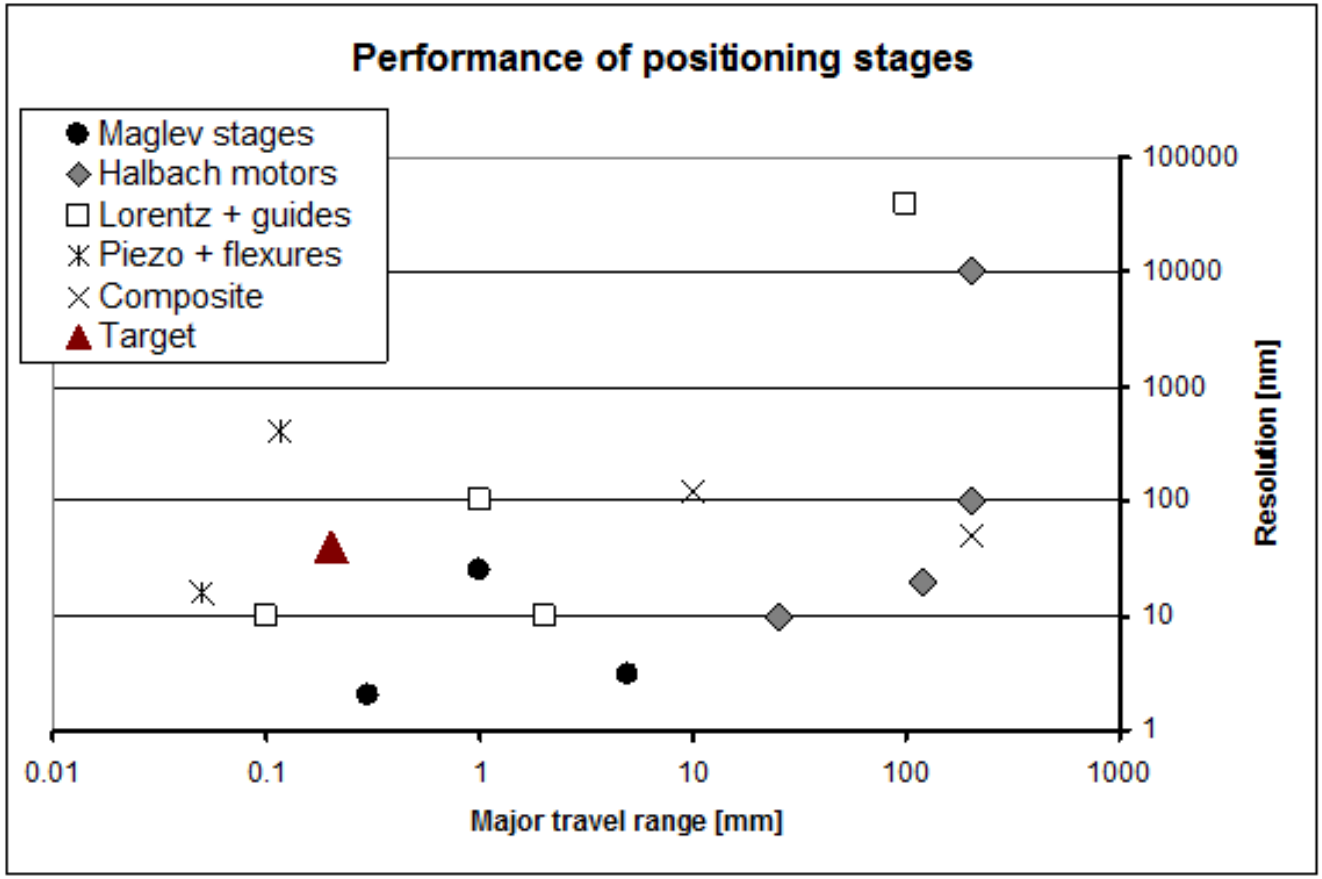
Error Budget



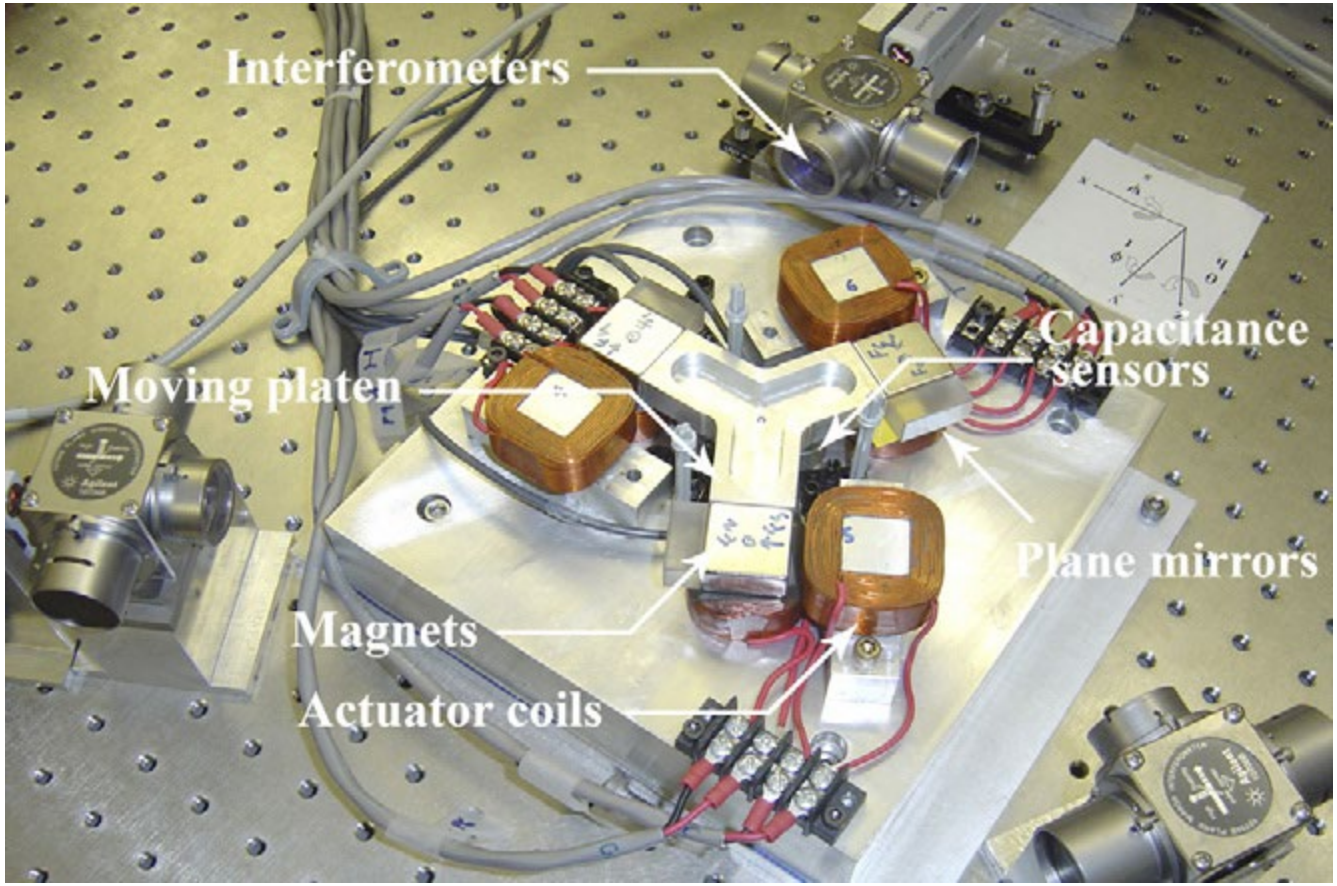
Requirement comparison

Requirement	Transport	Pre-alignment	Mount
Range, translation	20 x 20 x 10 mm	1 x 1 x 1 mm	200 x 200 x 200 µm
MIM, translation	< 100 µm	< 20 µm	40 – 100 nm
Range, rotation	360° (Θ_z)	360° (Θ_z)	2° x 2° x 2°
MIM, rotation	≤ 1°	≤ 1°	≤ 0.002°
Number of Degrees of Freedom	4	4	6
Velocity, translation	> 10 mm/s	> 3.5 mm/s	> 1 mm/s
Acceleration, translation	> 30 mm/s^2	> 20 mm/s^2	> 5 mm/s^2
Perturbation rejection, translation	< 50 µm	< 5 µm	≤ 7 – 35 nm
Perturbation rejection, rotation	< 0.5°	< 0.5°	≤ 0.0008° – 0.002°

State of the art: Micropositioning stages



Existing 6-dof stage
Kim et al.



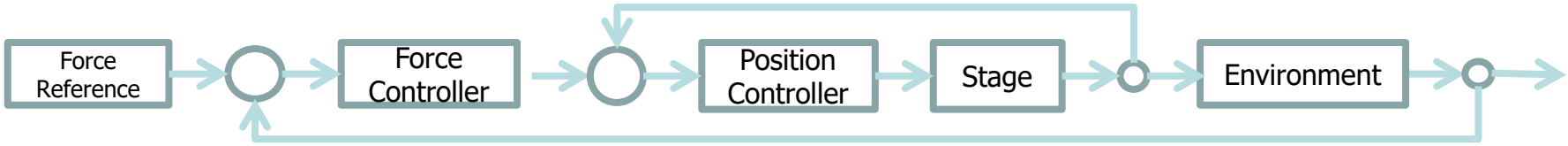
Stage technology comparison

Technology	Contact free	Open loop Stiffness	Linearity	Resolution	Range
Piezo	No	High	--	100 – 400 nm	50 – 100 µm
Lorentz	No	High / Zero	++	10 nm – 40 µm	100 µm – 100 mm
Maglev	Yes	Zero	+ / ++	2 – 20 nm	300 µm – 5 mm
Halbach	Yes	Zero	+	10 nm – 10 µm	20 – 200 mm
Required	Yes	Zero	++	40 – 100 nm	200 µm

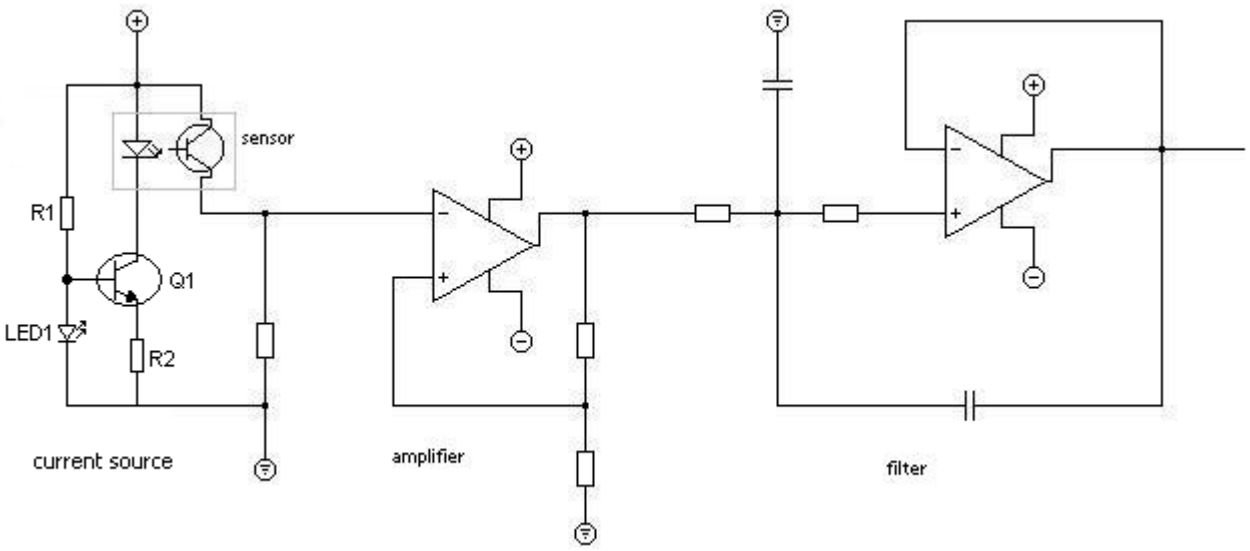
Technology	Complexity and cost	Control complexity	Suitable for miniature stage	Suitable for parallel stage
Piezo	+	+	+	-
Lorentz	+ / -	+	+	-
Maglev	+ / -	-	+	++
Halbach	--	--	-	+
Required	+	+	++	++

Stiff slave robot vs. force resolution

- Slave robots: Positioning stages → high stiffness "position actuators"
- Force sensitive tasks – fragile parts

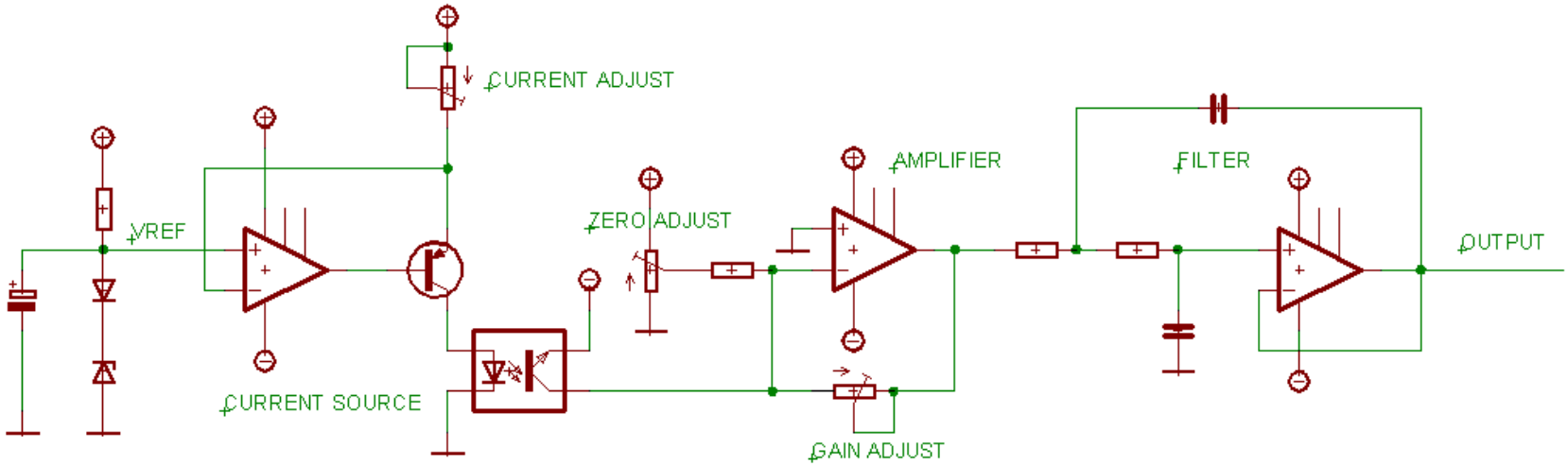


Sensor readout electronics

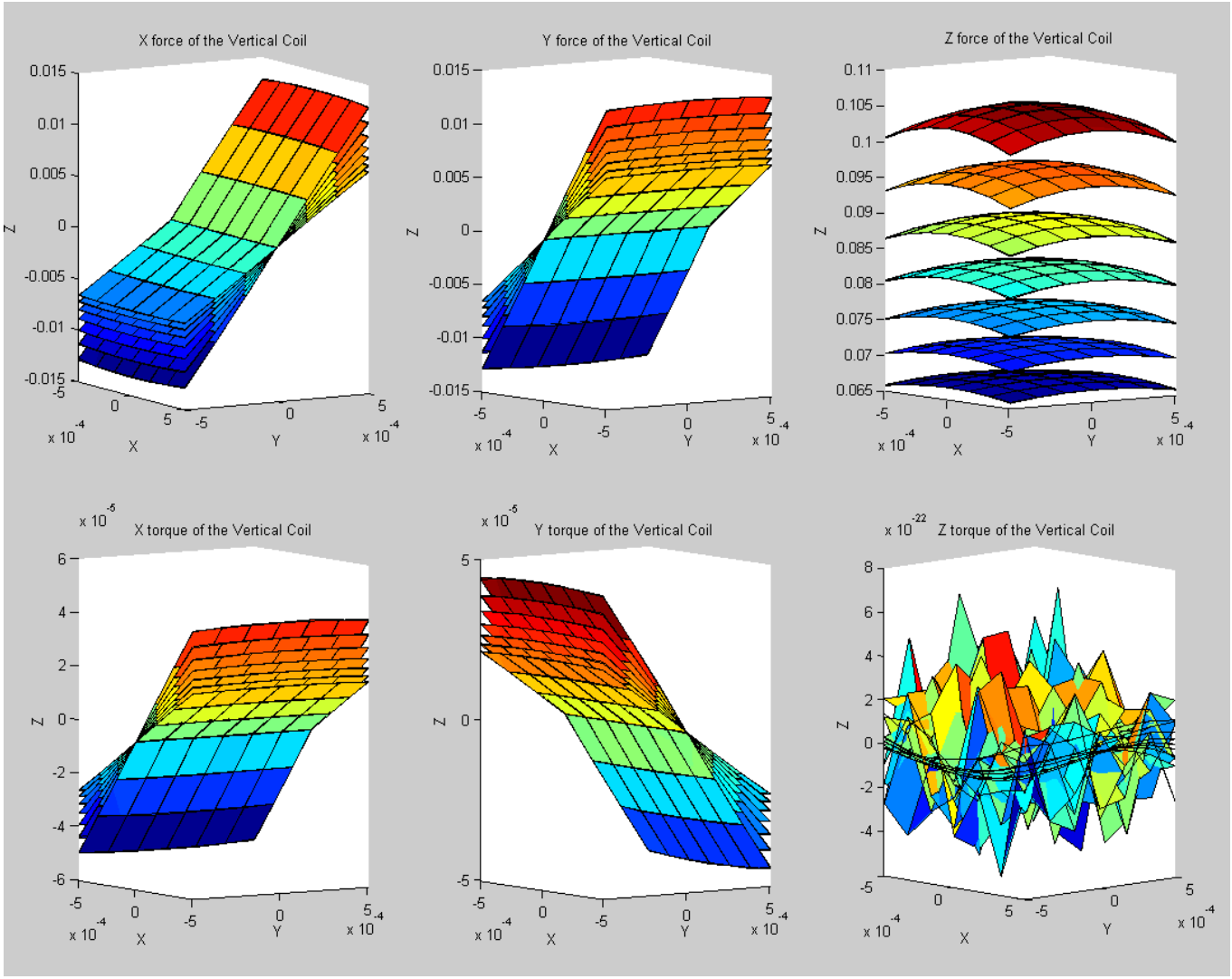


- Previously investigated by Rein Boshuisen and Ton de Boer
- Not optimized for this application:
  - 5V single supply
  - Range limited by saturation
- Improvements:
  - Redesign current source, amplifier
  - 15V symmetric supply
  - Low-noise components

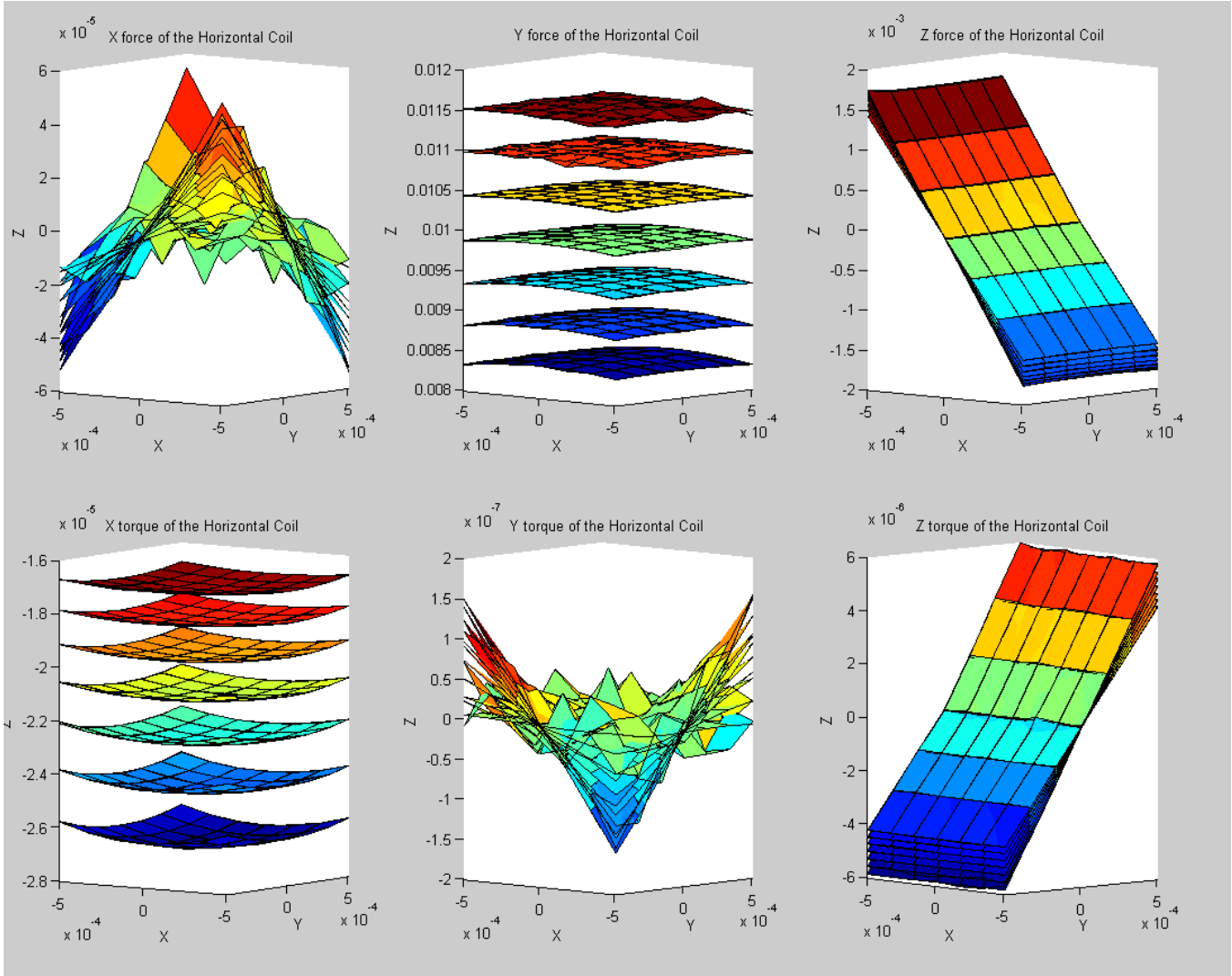
Improved sensor readout



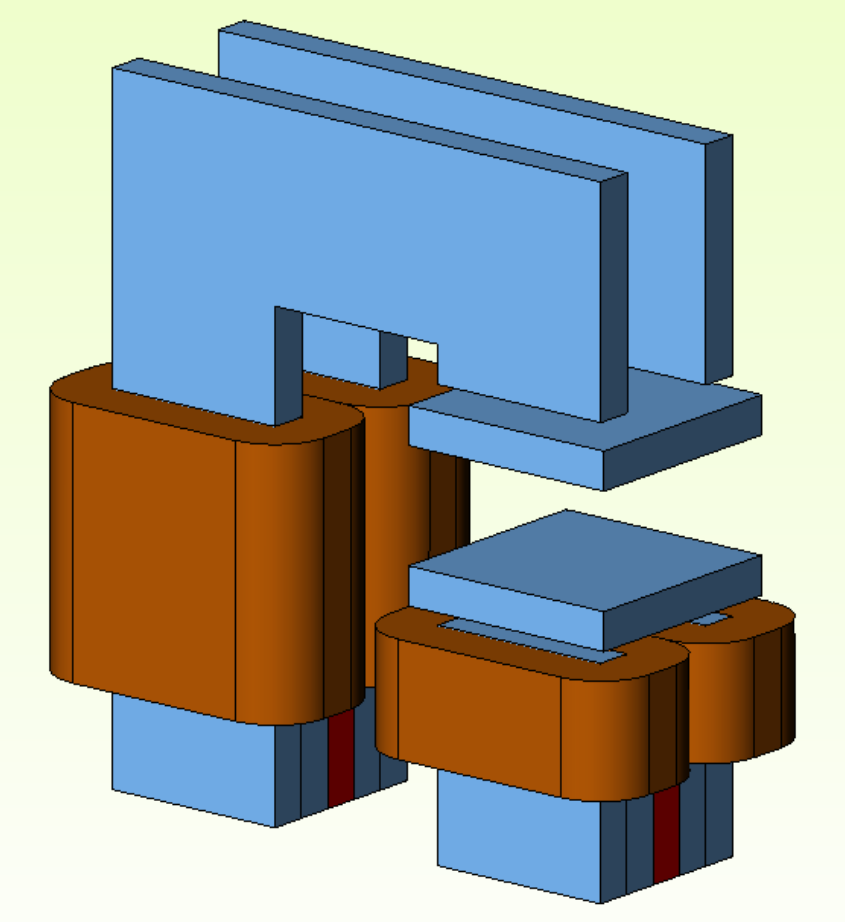
Vertical coil characteristics



Horizontal coil characteristics

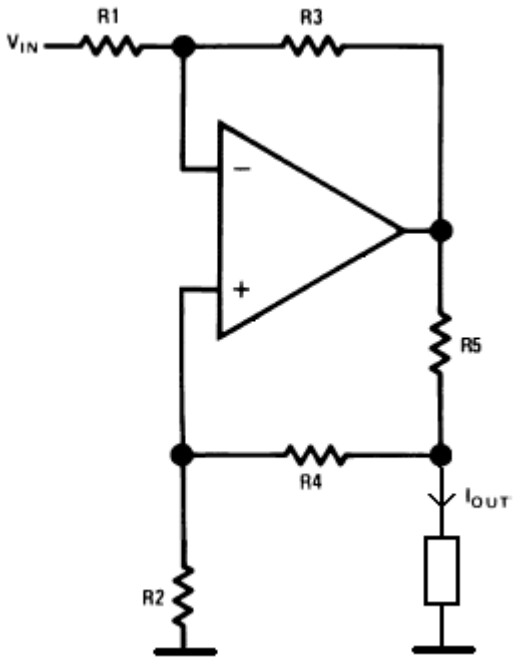


Reluctance Actuators



- Differential reluctance actuator
- 50 μN force range
- Target size 6 x 6 mm
- Designed, not tested

Current amplifiers



Widlar bilateral current source

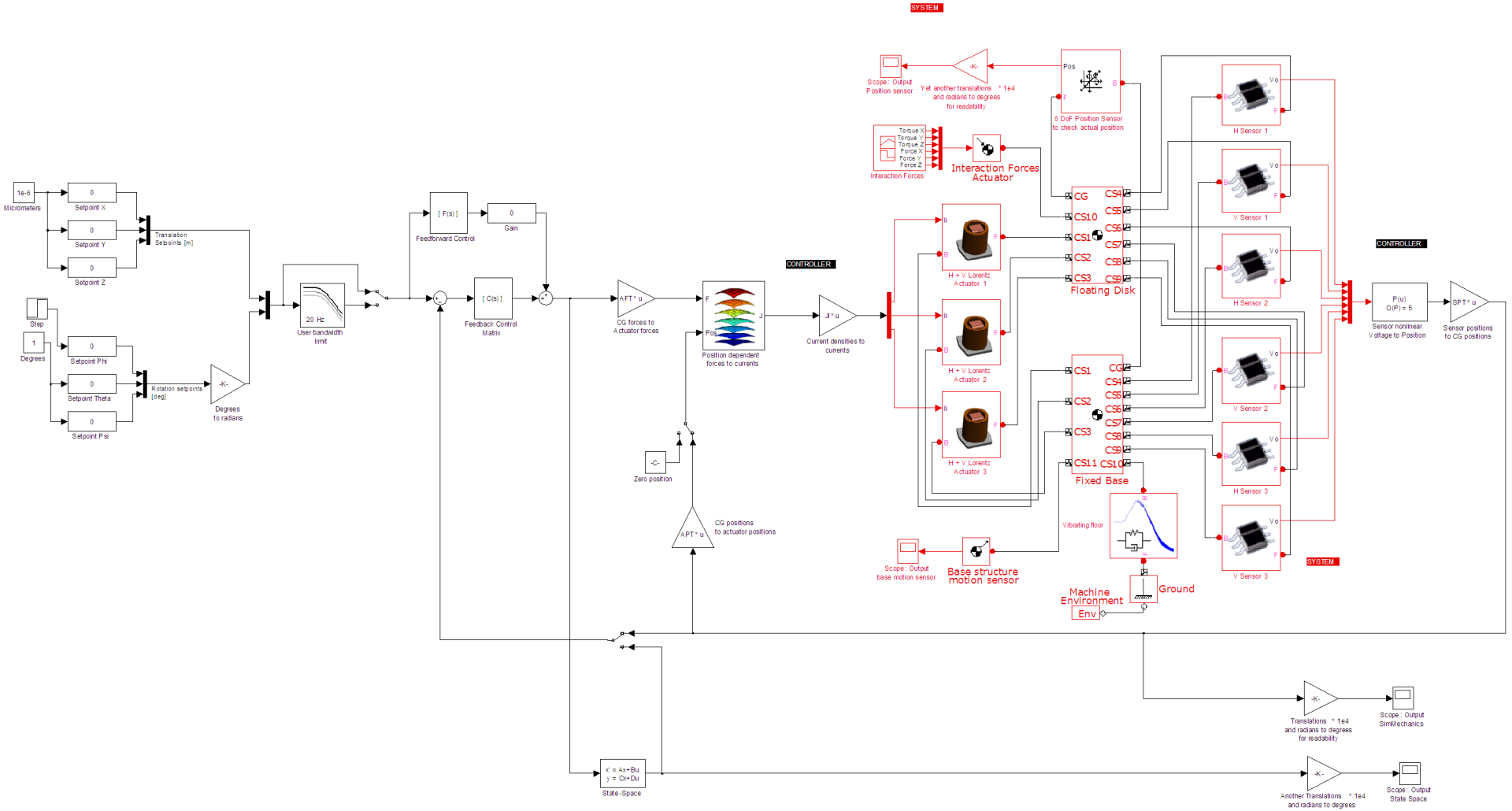
$$I_{out} = -V_{in}\left(\frac{R_3}{R_1 R_5}\right)$$

$$R_1 = R_2$$

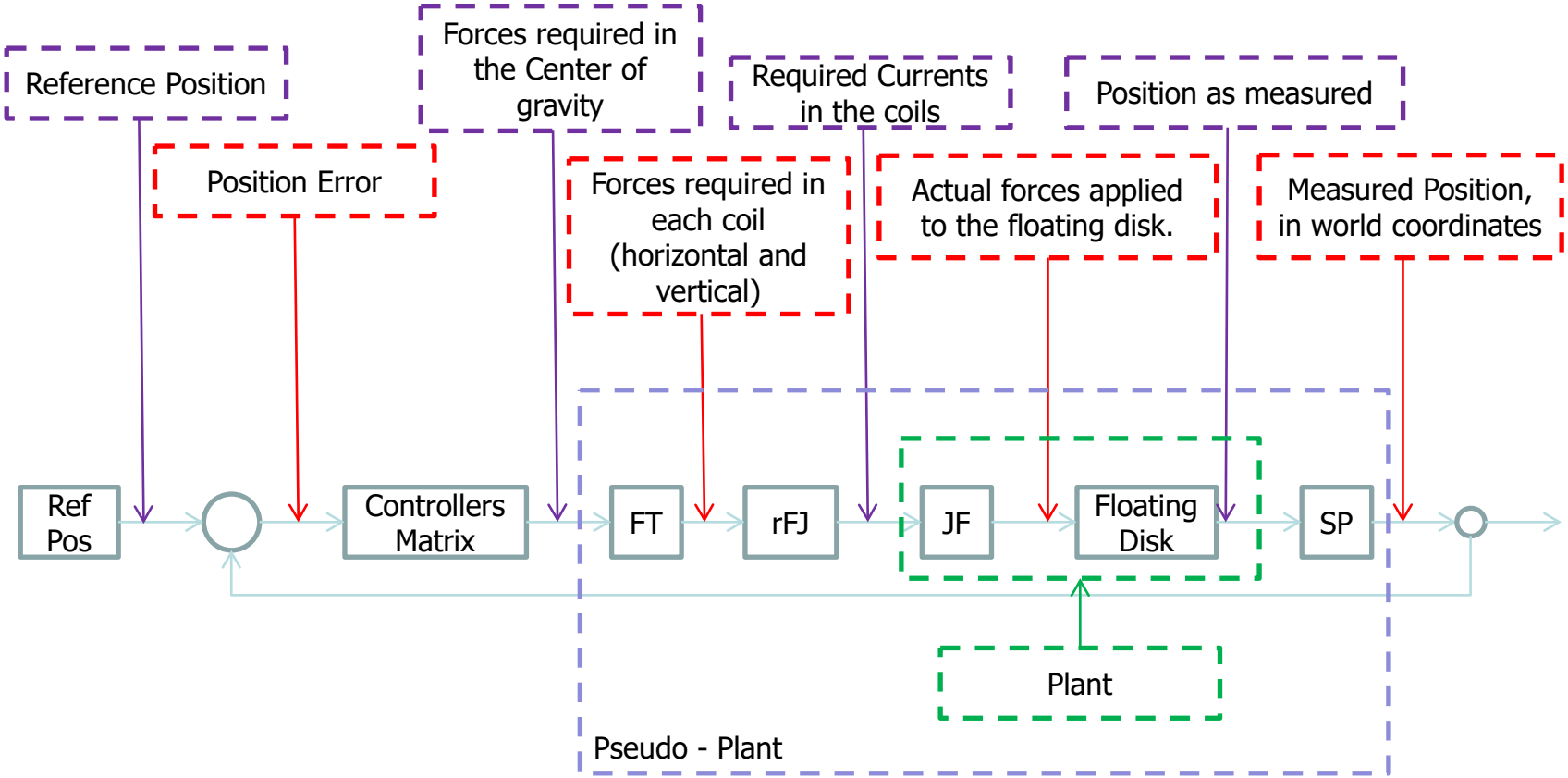
$$R_3 = R_4$$

$$R_1 + R_3 >> R_5$$

Simulation diagram



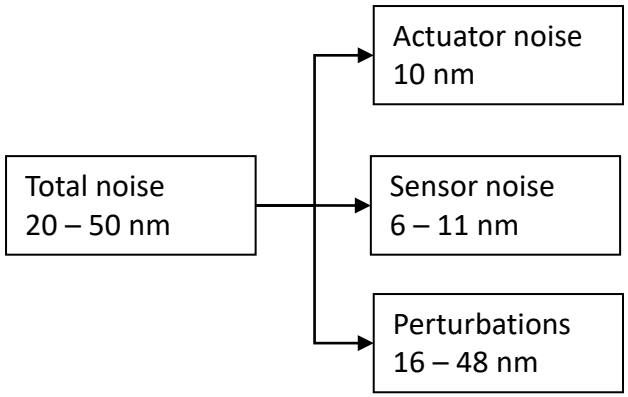
Control Layout

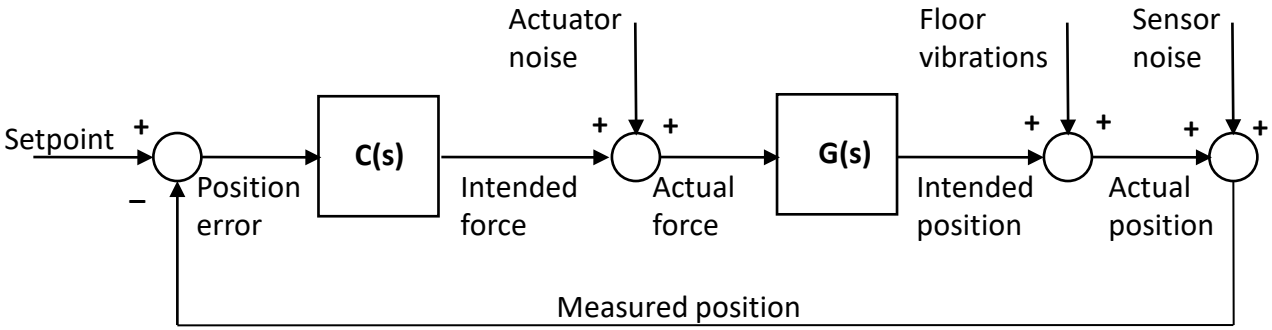


System modelling: Control loop

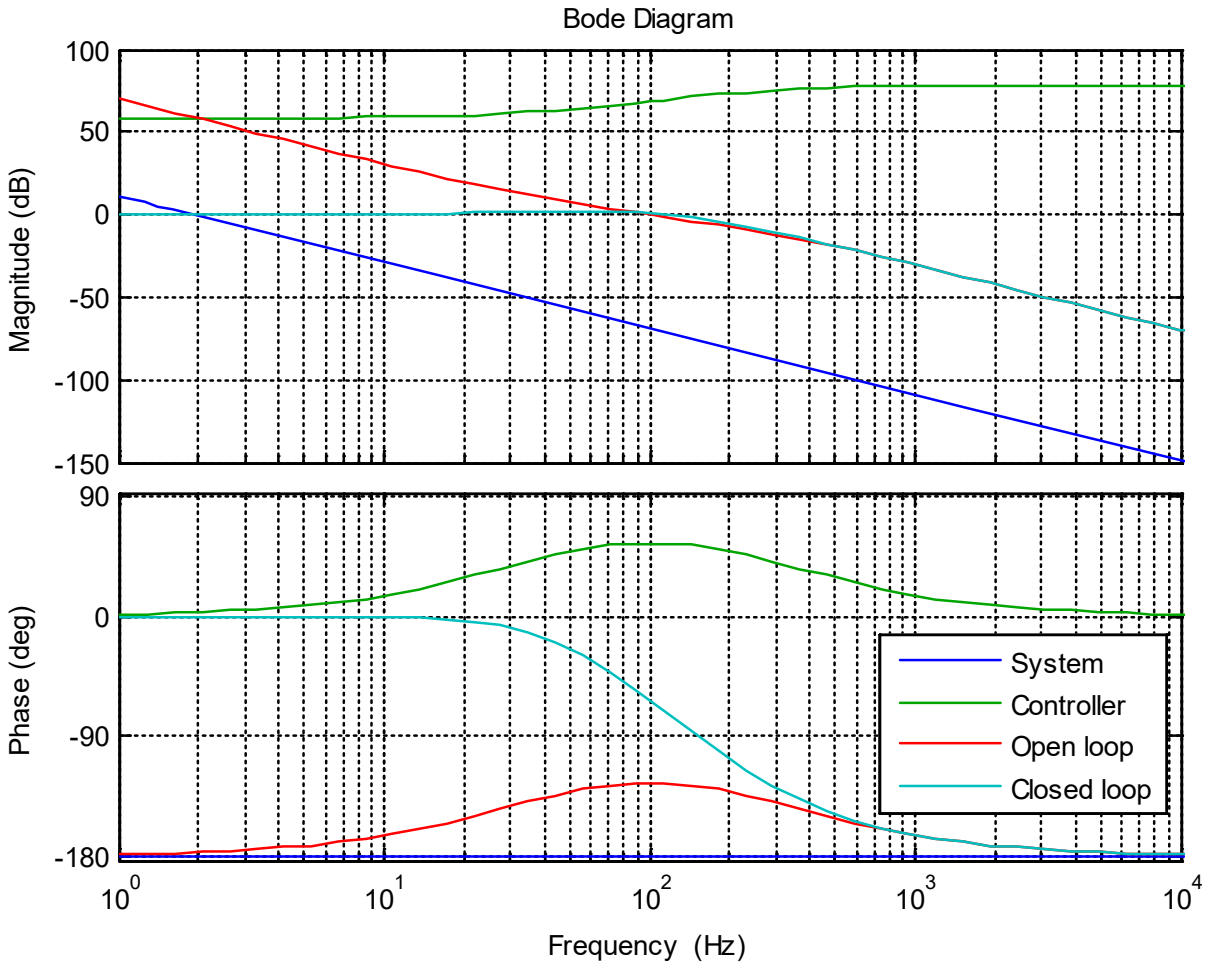
- Closed loop BW: 100 Hz

- Noise and vibrations
  → 40 – 100 nm resolution

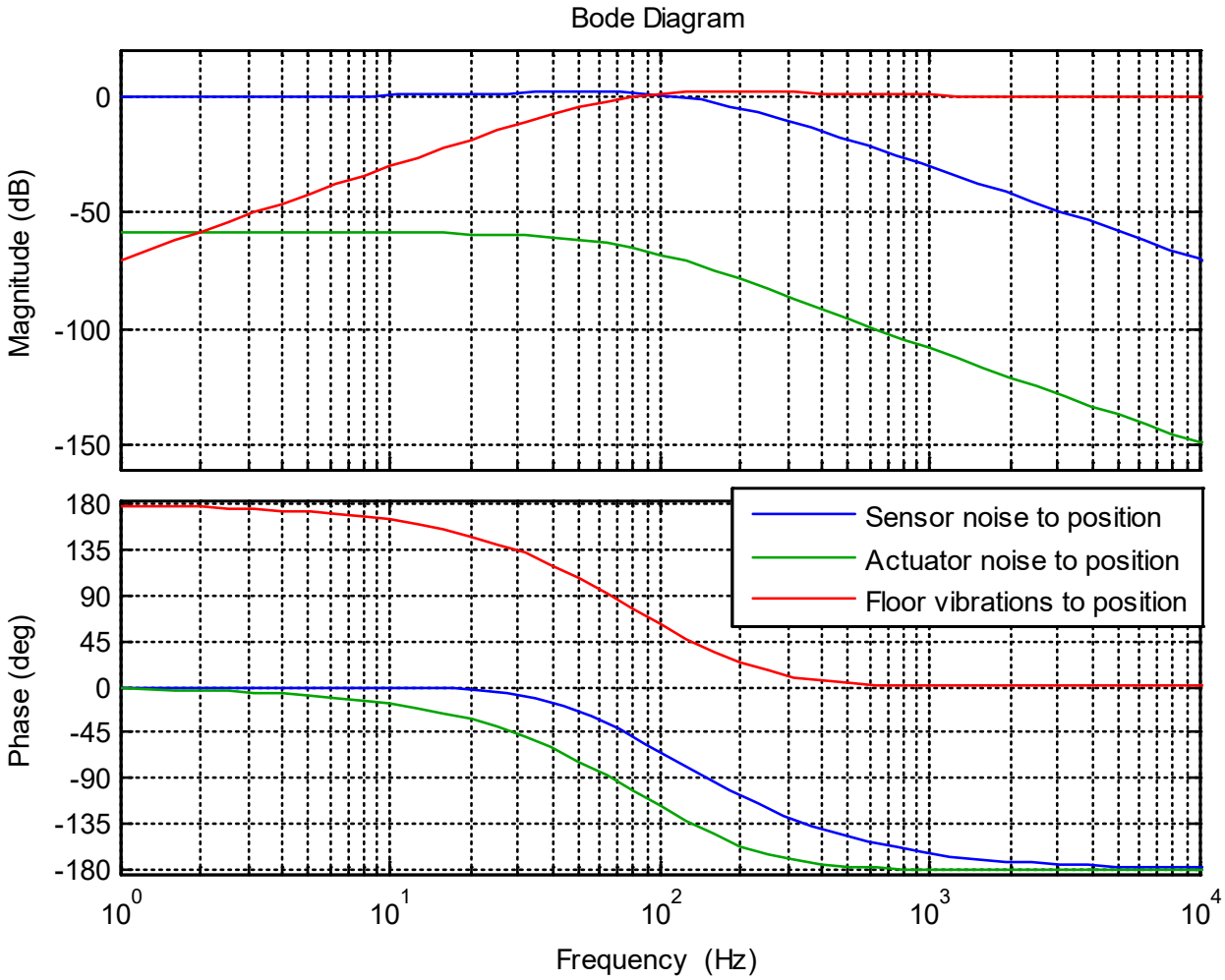




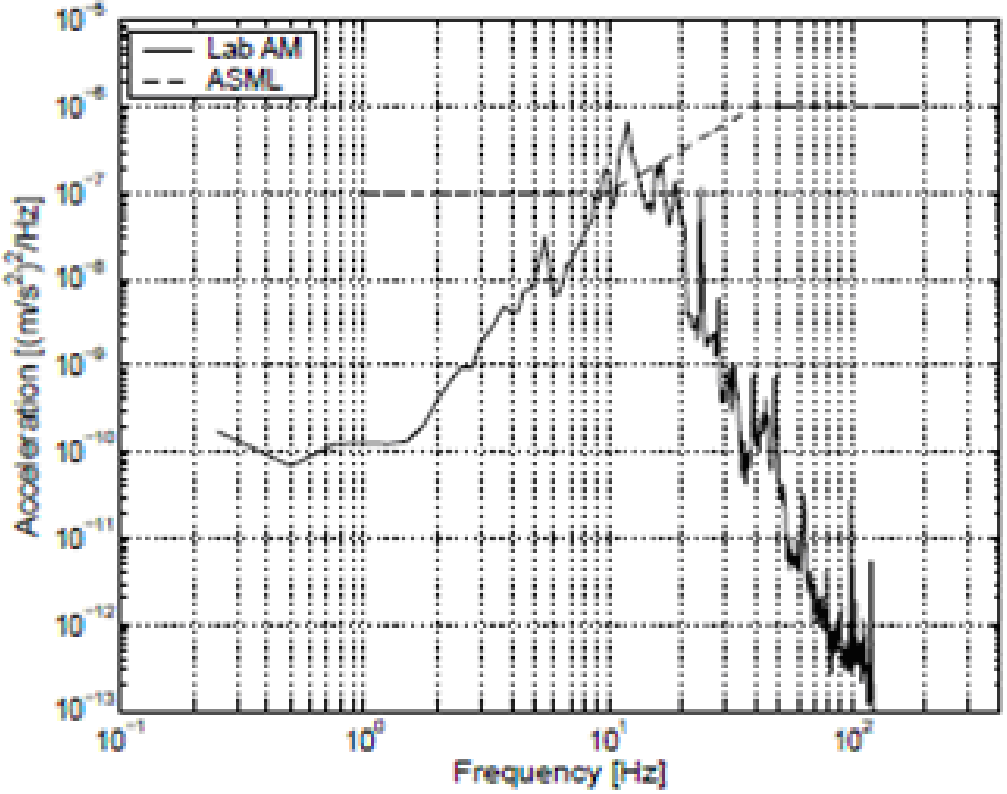
Frequency response: System and controller



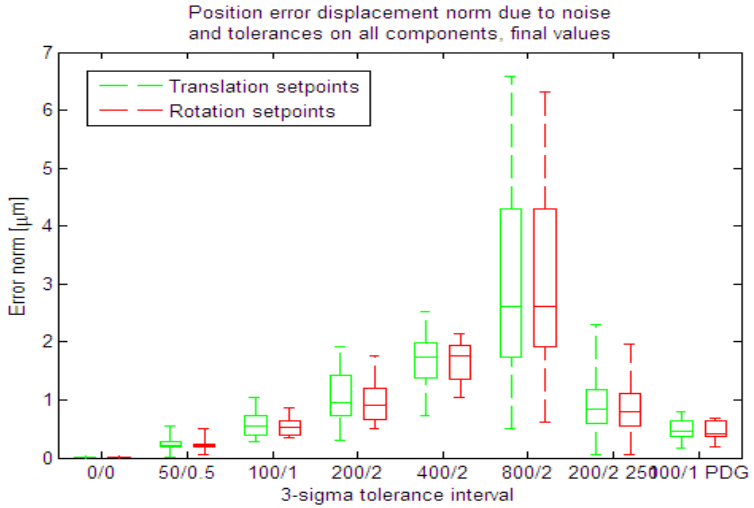
Frequency response: Sensitivity

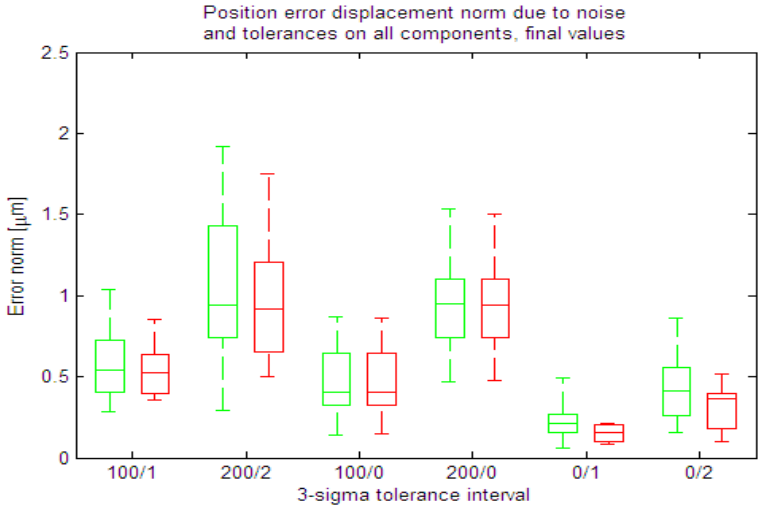


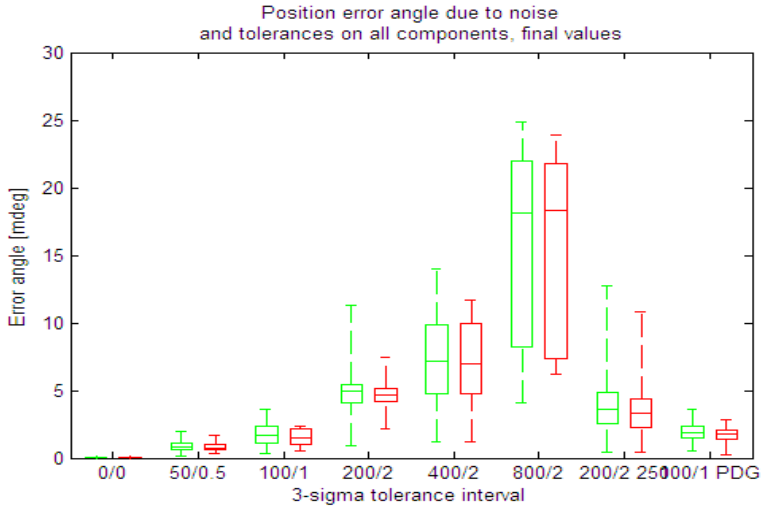
Floor vibrations (Mechatronics Lab)

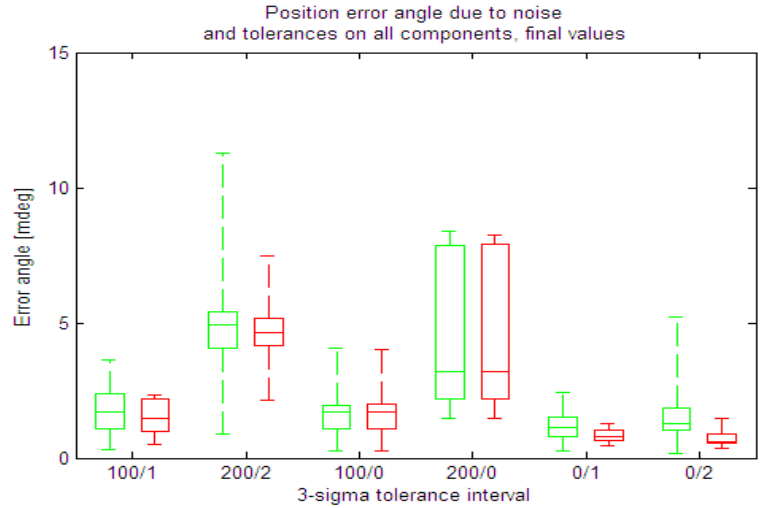


Tolerances: All components

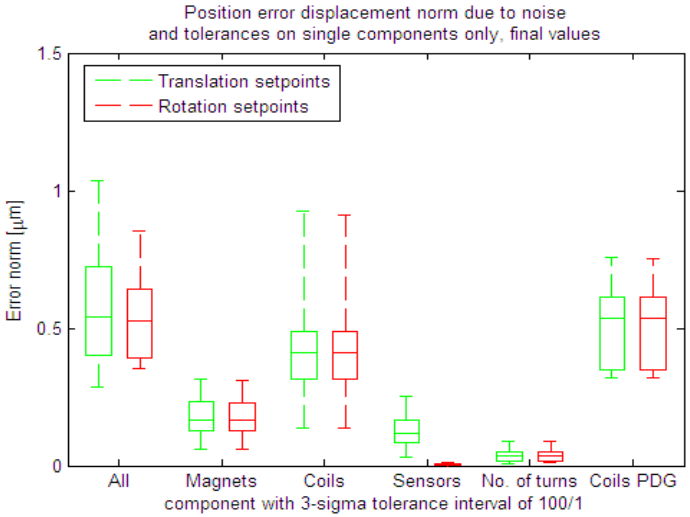


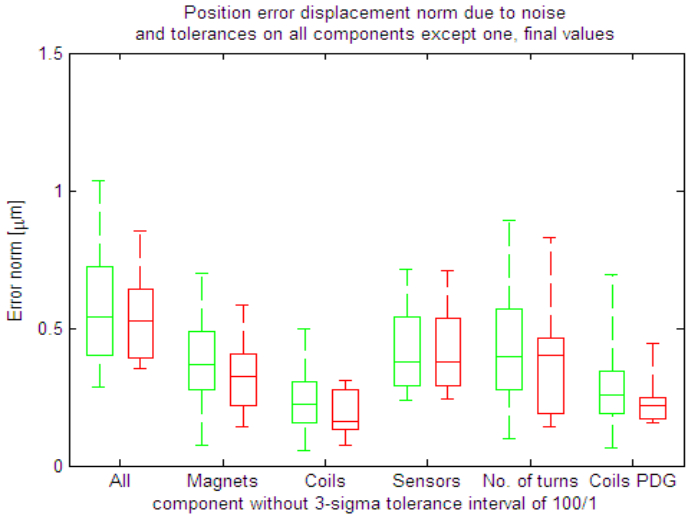


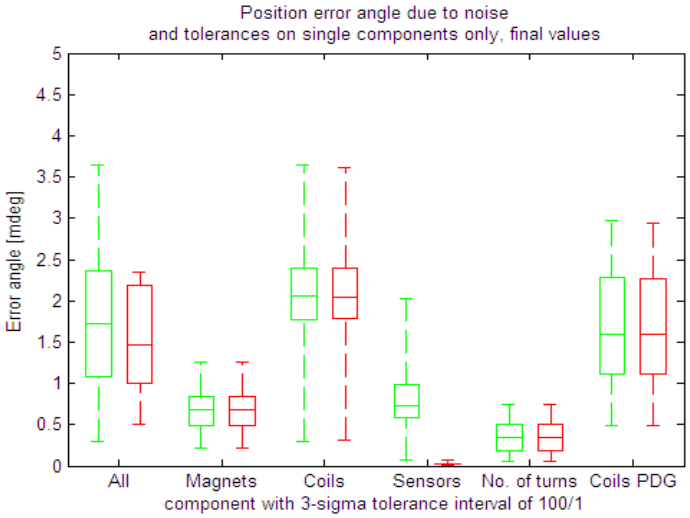


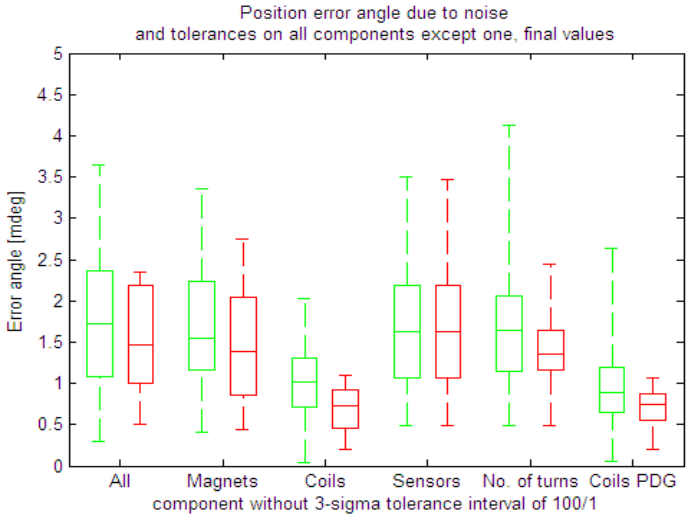


Tolerances: Selected components

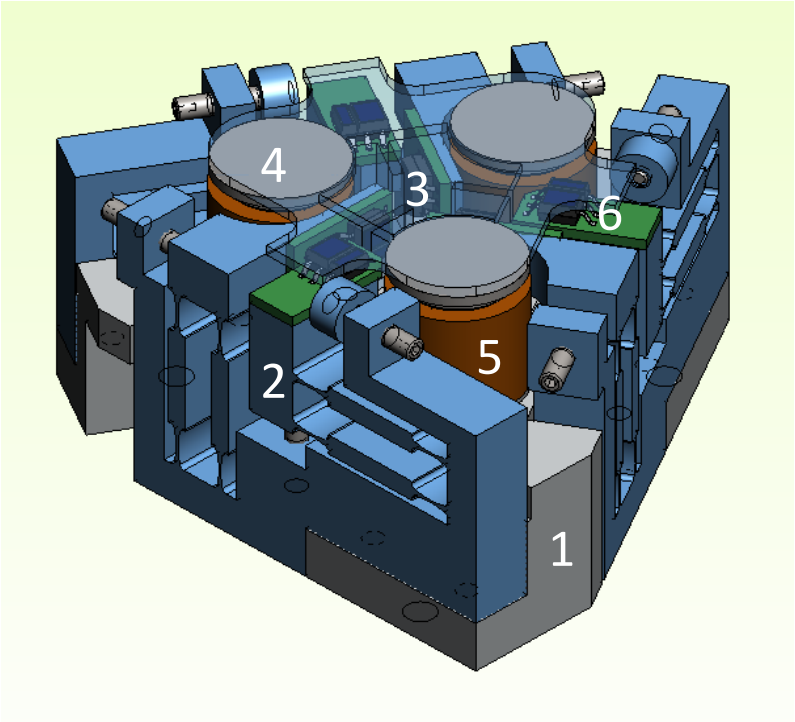






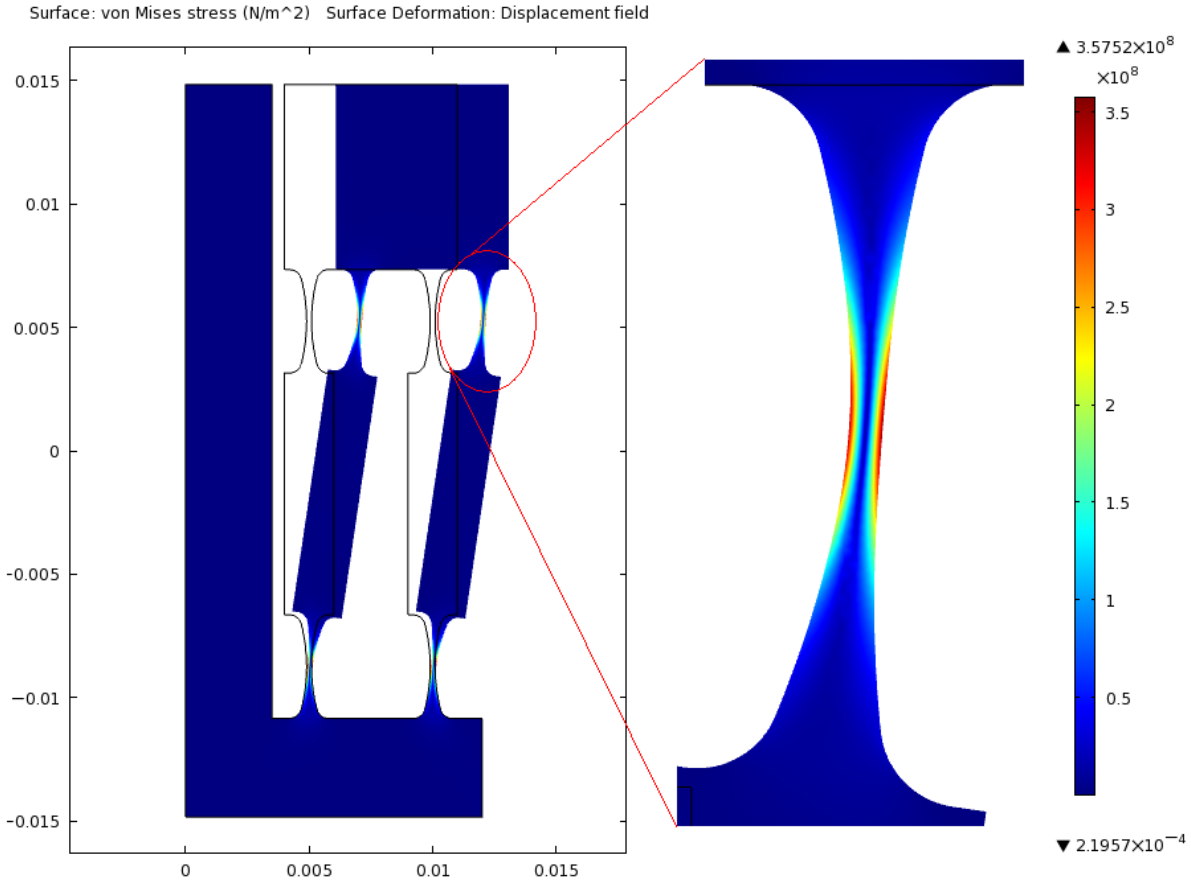


CAD Design



1. Base structure
2. Sensor alignment and support structure
3. Moving part
4. Actuator target
5. Actuator coil
6. Position sensor

Flexure mechanisms: FEM analysis



Floating disk: Modal analysis