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Frame deformation control based on reduced order thermo-elastic models

Towards industrial application

13-01-2024

Walter Aarden

Public DSPE lunch v1.0

Introduction

- Walter Aarden
- Mechatronic System Architect
- 15+ years experience high tech industry. >6 years at MI-partners
- Background: MSc. Applied Physics & Mechanical engineering

Background

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- Internal Advanced Competence Development project.
- Refresh and secure knowledge about thermal error correction models.
- Integrate with our Model Reduction (Matlab/ANSYS) toolbox + internal WoW.
- Starting point for further research in collaboration with universities / industrial partners

Motivation & Context

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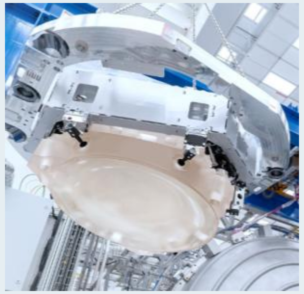
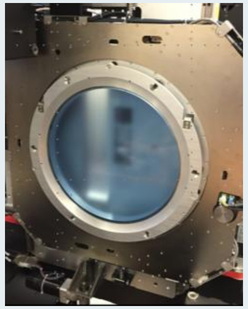
Challenge: Thermal induced deformations impacts positioning accuracy.
Markets: Accuracy requirements getting smaller → thermal induced deformations larger impact
Solutions: Upgrading to complex, accurate, but expensive metrology systems not always possible, i.e. limitation budgets / volume / controller hardware capability
Alternative: Use relative inexpensive/ less complex solution based upon temperature measurements & model-based position estimation icm lower costs mechanical parts/modules

Semiconductor Front-end

Accuracy	sub nm – μm
Environment	UHV
Thermal stability	~1 mK

Semiconductor Back-end

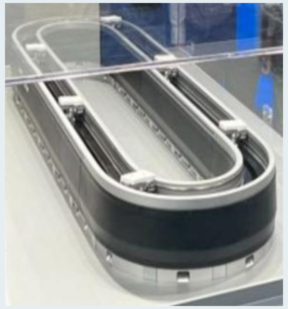



Accuracy	sub μm – μm
Environment	ISO1-7 Clean
Thermal stability	~100 mK

Scientific instrumentation


Accuracy	nm – sub μm
Environment	UHV, Cryogenic, X-ray
Thermal stability	~1 - 100 mK

Handling equipment




Accuracy	sub μm – μm
Environment	UHV, HV, etc.
Thermal stability	~0.1 - 1 K

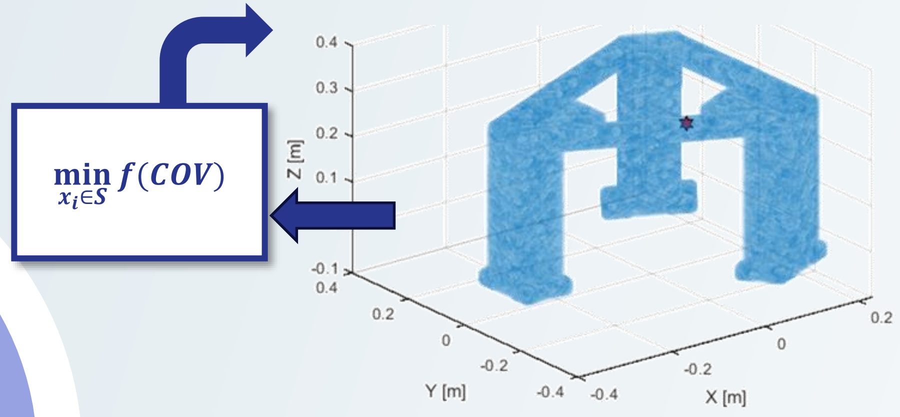
Overview

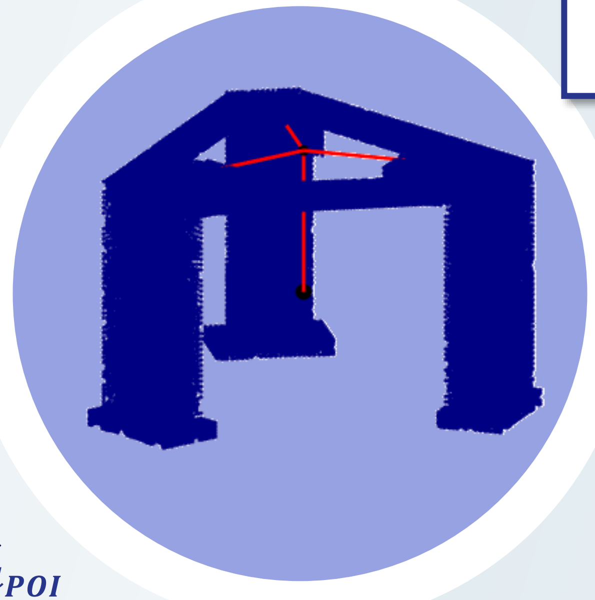
Reduced Order Modelling

$$E\,\dot{T} = A\,T + B\begin{bmatrix} Q \\ T_\infty \end{bmatrix}$$

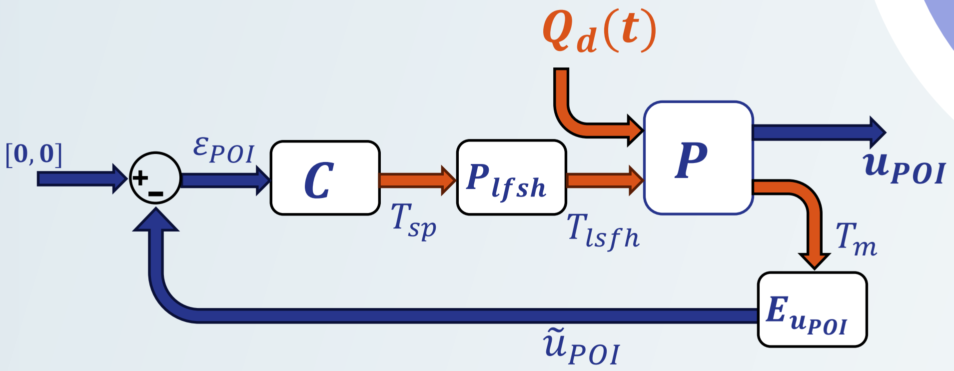
$$\hat{E}\,\dot{z} = \hat{A}\,z + \hat{B}\begin{bmatrix} Q \\ T_\infty \end{bmatrix}$$

Sequential sensor placement

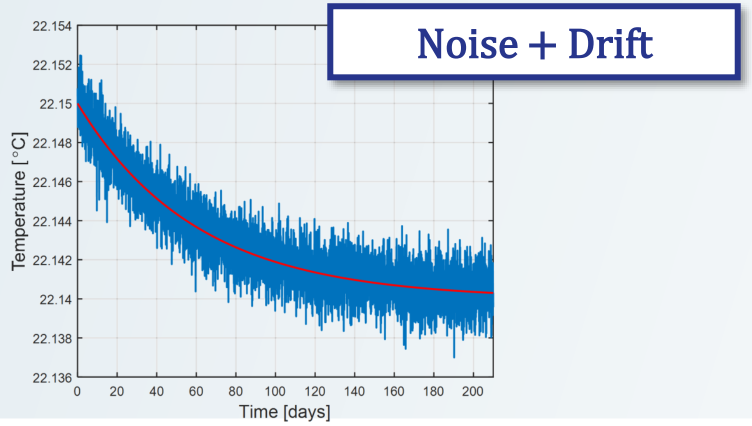




Real-time compensation / control



Constraints



Problem

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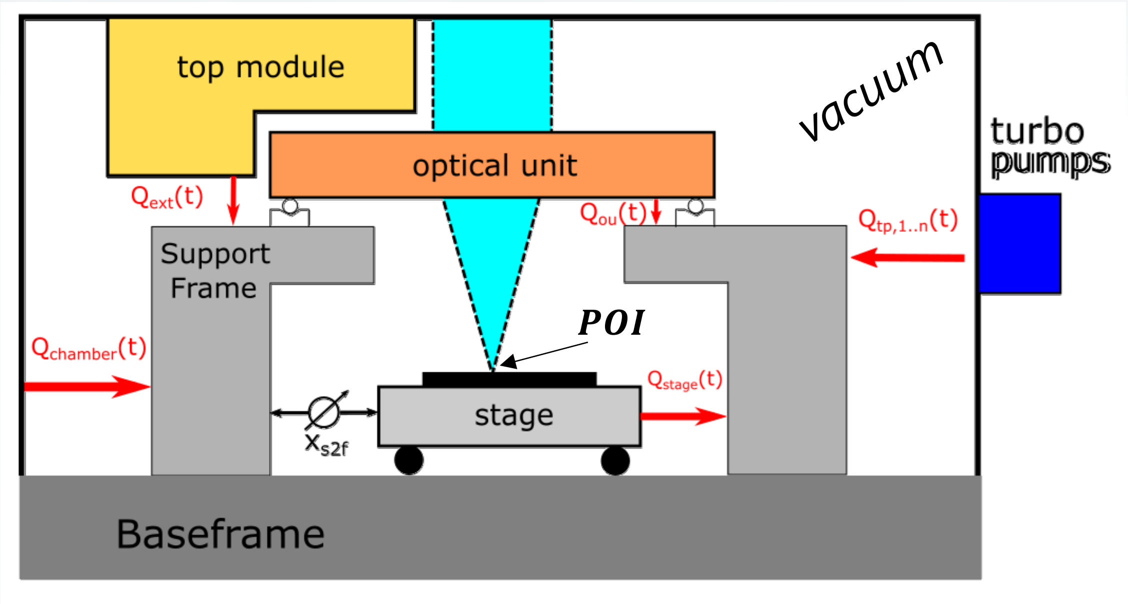

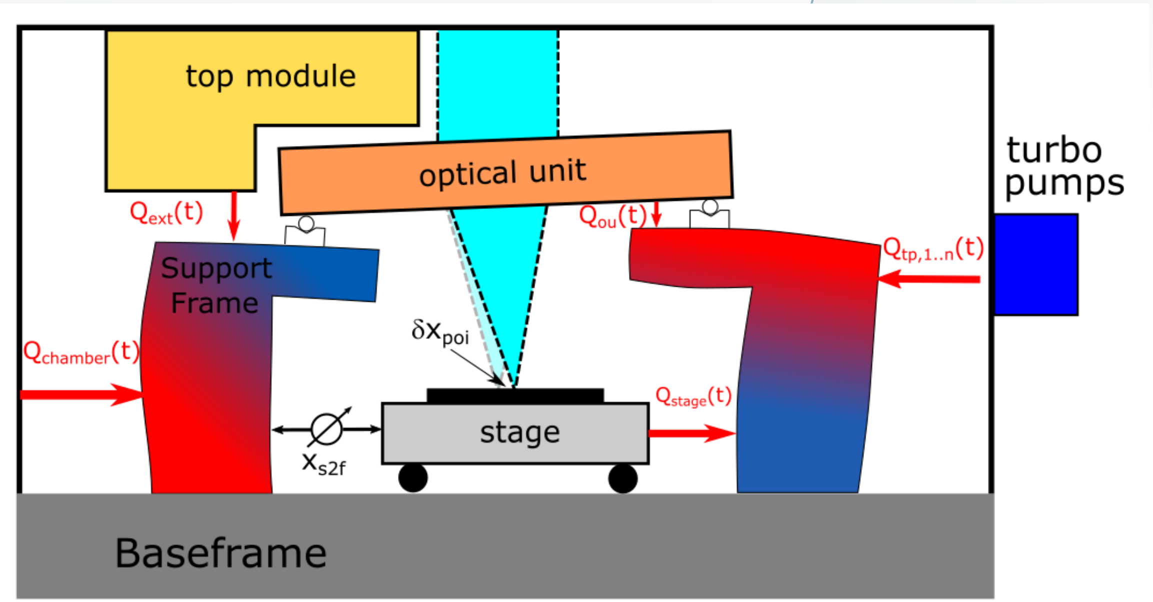

- Stage positioning in 2 DoF using a metrology system with respect to the support frame $\boldsymbol{x_{s2f}}$
- Performance defined at Point of Interest (**POI**).
- System in vacuum → radiative transient heat loads $\boldsymbol{Q_{xx}(t)}$
- Thermal induced frame deformations → Tilt of optical unit → **unobservable errors** at POI, $\boldsymbol{\delta x_{poi}}$

Thermo-Mechanical Model

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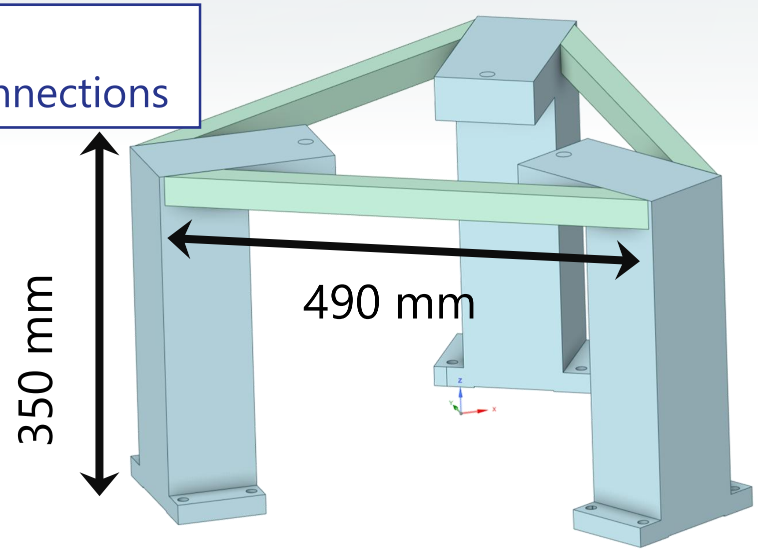
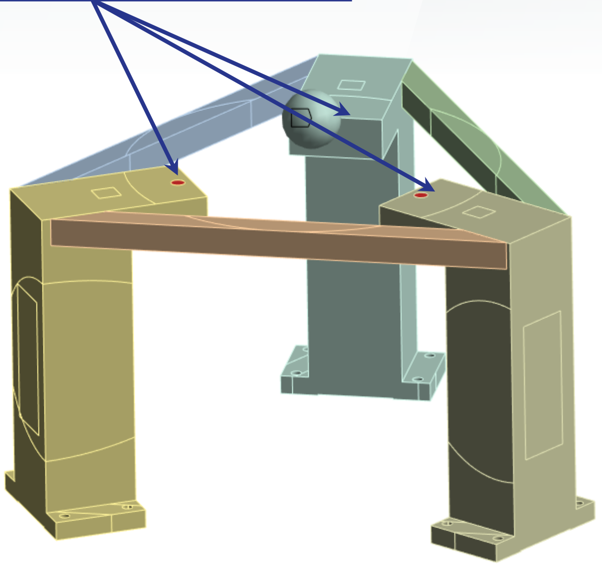
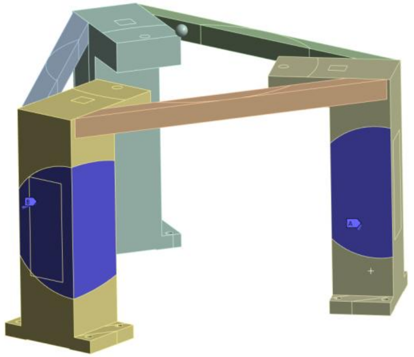
Al parts
Bolted connections

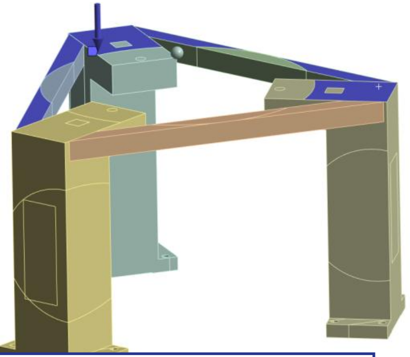


3x kinematic mounts
Interface to rigid body
(optical unit)

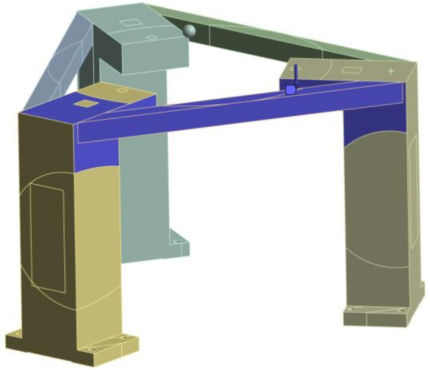




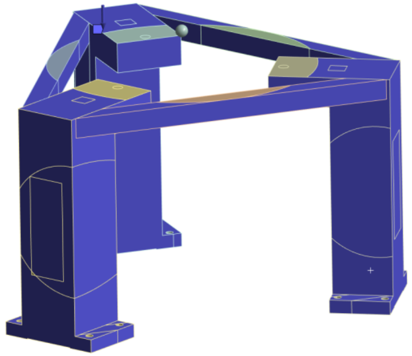
Turbo pumps
$Q_{tp} = 1.3W$



Top module
(static)
$Q_{tm} = 0.9W$



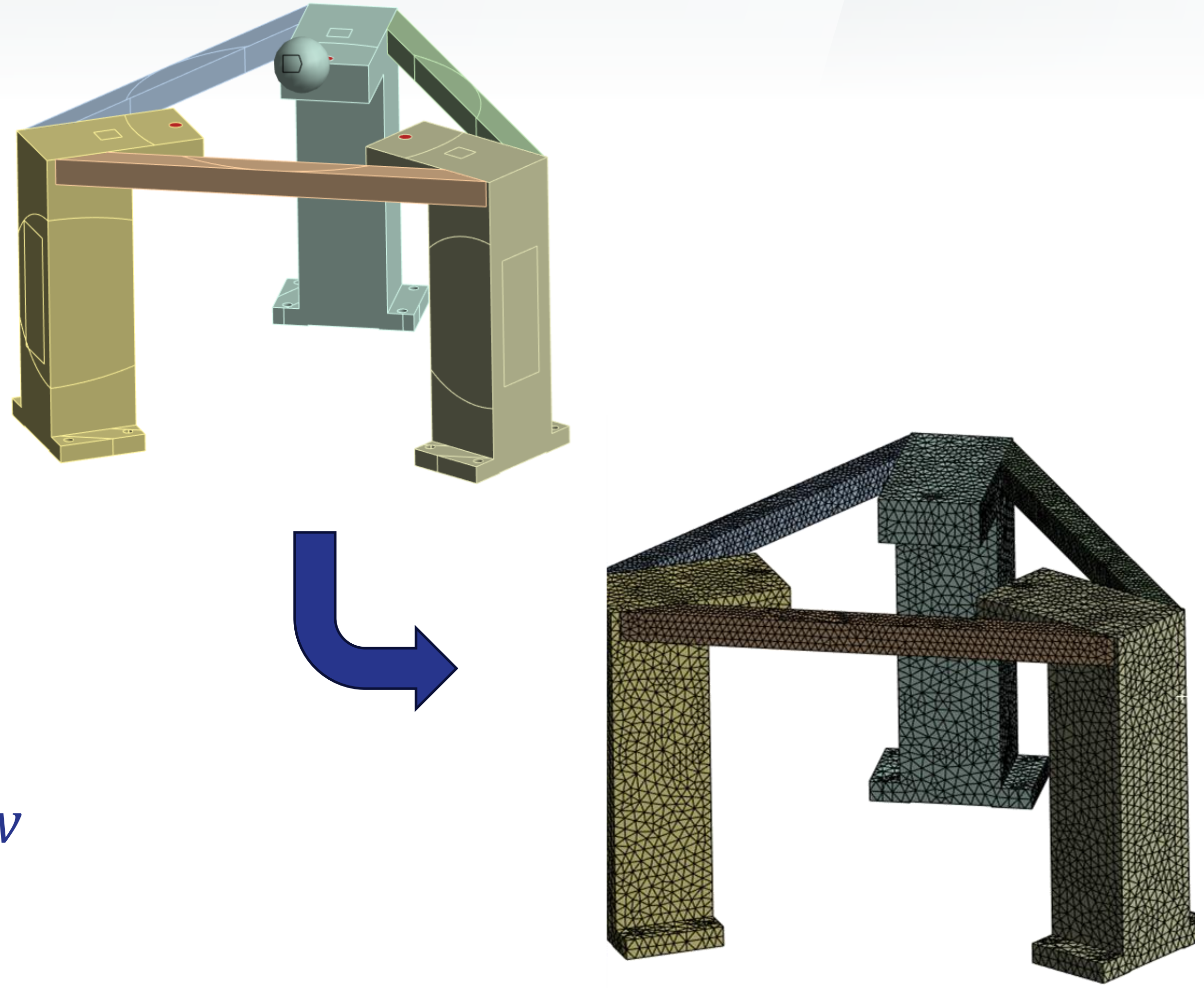
Top module (varying)
$Q_{tp_{side}} = 0.75W$



Vacuum chamber
$Q_{vc} = 0.83W$

Thermo-Mechanical Model

- Generate a coupled physics FE model
- Custom made ANSYS to Matlab toolbox extract all relevant system matrices.
- $K_{TT} = K_0 + \Sigma h_i K_{h,i}$ parametric as is B_T



Stiffness matrix

Thermo-elastic coupling

$$\begin{bmatrix} 0 & 0 \\ 0 & C_T \end{bmatrix} \begin{bmatrix} \dot{u} \\ \dot{T} \end{bmatrix} = \begin{bmatrix} -K_{uu} & K_{uT} \\ 0 & -K_{TT} \end{bmatrix} \begin{bmatrix} u \\ T \end{bmatrix} + \begin{bmatrix} 0 \\ B_T \end{bmatrix} w$$

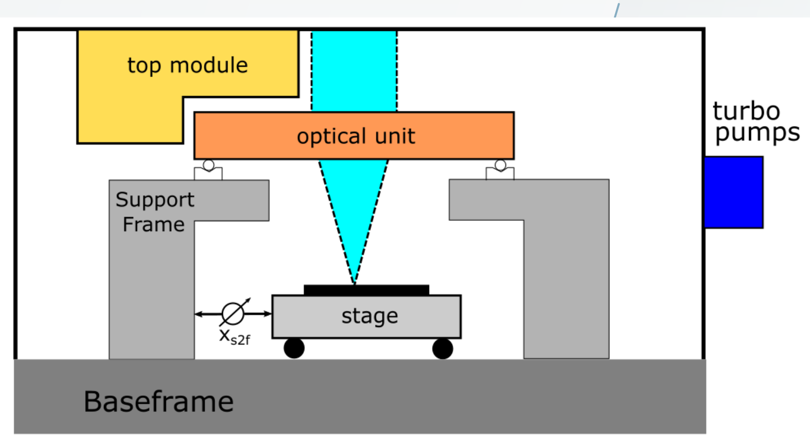
Thermal capacitance matrix

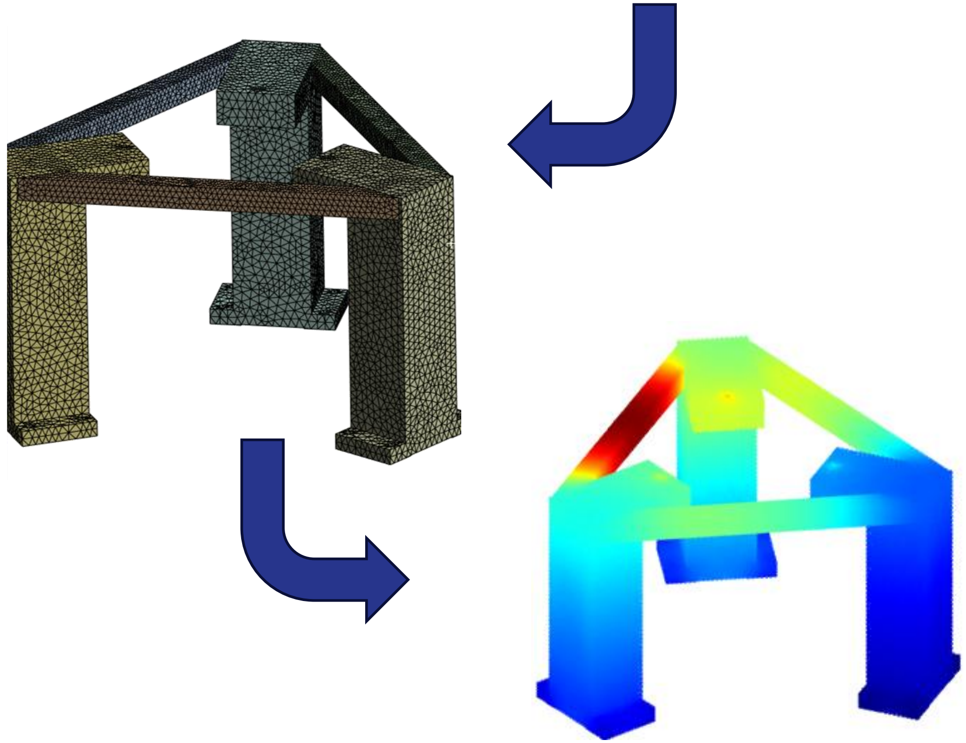
Thermal conductivity matrix

Model Reduction

motivation

- Analysis: **accurate predictive modelling,** i.e. Finite Element Models
- Simulate system response for **different loads, initial conditions and boundary conditions**
- Use in **optimization problems**, e.g. sensor and/or actuator placement
- **Very long simulation times** or even not feasible to compute
- Acceleration required while maintaining **accuracy** → **Model reduction**





Model Order Reduction

General concept: thermal shapes

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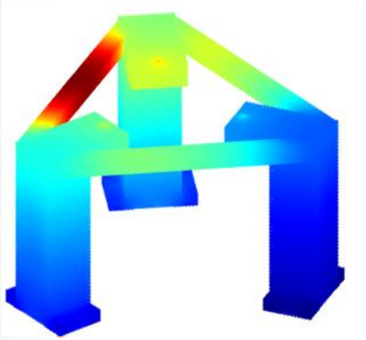


$\approx \quad \times \tilde{T}_1(t) + \quad \times \tilde{T}_2(t) + \ \ldots + \quad \times \tilde{T}_k(t)$

$$\boldsymbol{T(t)} \approx V_{T1}\tilde{T}_1(t) + V_{T2}\tilde{T}_2(t) + V_{Tk}\tilde{T}_k(t)$$

FEM: N states
$N \sim \mathcal{O}(10^5)$

$$E\,\dot{T} = A\,T + B\begin{bmatrix} Q \\ T_\infty \end{bmatrix}$$

ROM: $k \ll N$ states

$$\hat{E}\,\dot{\tilde{T}} = \hat{A}\,\tilde{T} + \hat{B}\begin{bmatrix} Q \\ T_\infty \end{bmatrix}$$

Reduce model using projection with $\boldsymbol{V_T}$

How to obtain these shapes:

- Model decomposition
- Moment matching
- Balanced Truncation
- POD

Toolbox ANSYS → Matlab with automatic order selection

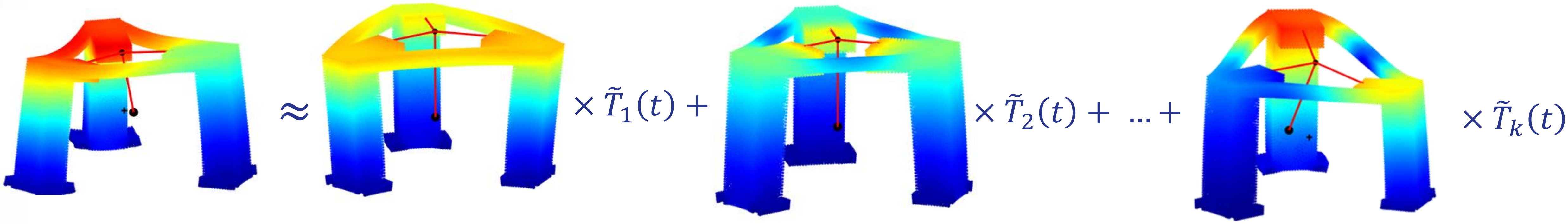
Model Order Reduction

To deformations

Frame Deformation

$$U = K_{uu}^{-1} K_{uT} T$$

$$U \approx K_{uu}^{-1} K_{uT} \left(V_k \tilde{T} \right)$$



Deformation estimation using temperature sensors

basic idea

Using $\tilde{\boldsymbol{T}}$ and shapes $\boldsymbol{V_k}$ → accurate temperature estimation $\boldsymbol{E_T}$ using a small set of temperature measurements $\boldsymbol{T_m}$ at locations $\boldsymbol{x_i}$

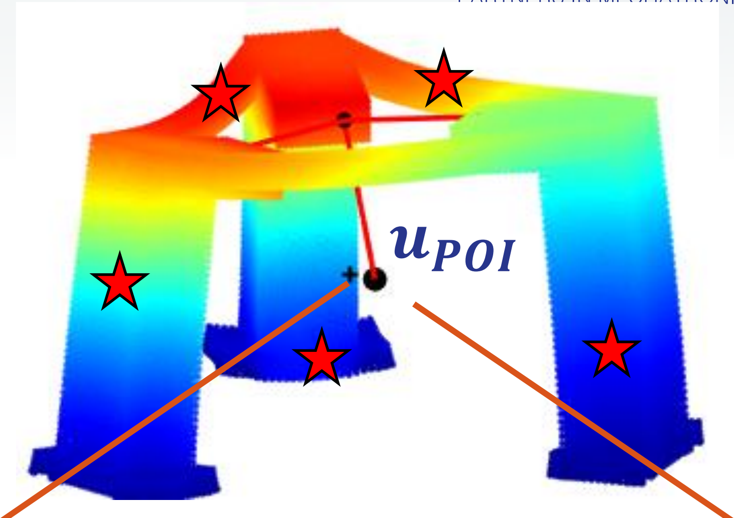
Estimator $\boldsymbol{E_T}$ solution to least-square problem:

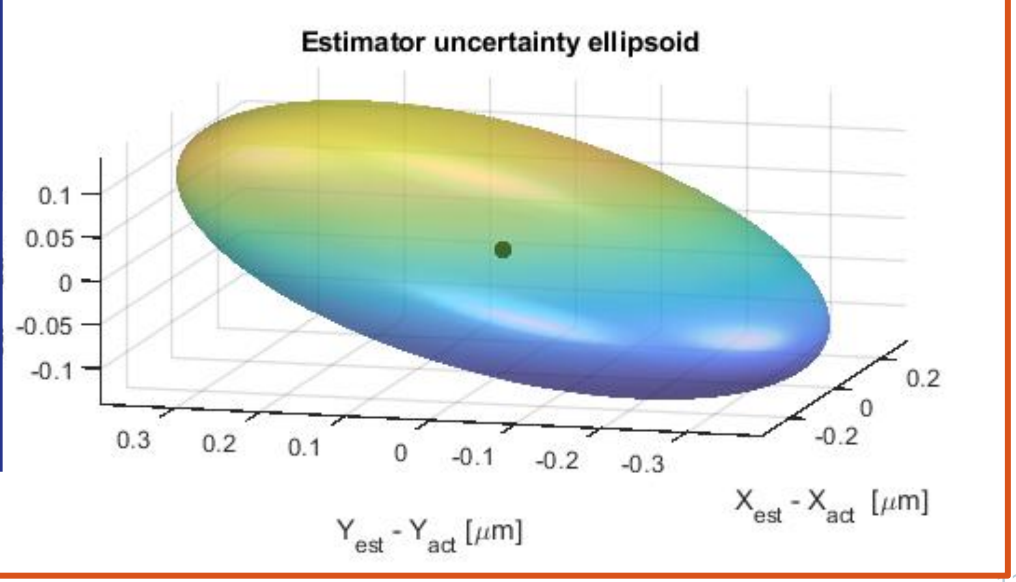
$$\min_{\tilde{T}\in\mathbb{R}^k} \frac{1}{2}\sum_{i=1}^{n_s}\left(V(x_i)\tilde{T} - T_{m,i}\right)^2$$

$$\tilde{\boldsymbol{T}} = \boldsymbol{E_T T_m}$$

The deformation estimator $\boldsymbol{E_u}$ can easily calculated using

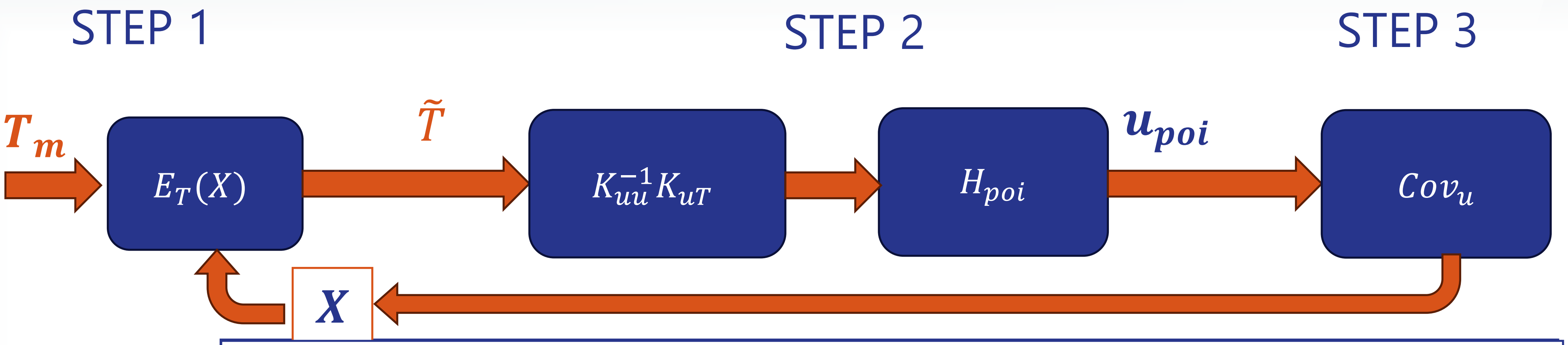
$$\boldsymbol{E_u} = \boldsymbol{K_{uu}^{-1} K_{uT} E_T}$$





Sequential sensor placement

algorithm



Step 4 : Update temperature field estimator E_T

Solve least square problem given the previous sensor locations X and start with a new possible location x_i:

$$[V_T(x_1, 1{:}2); V_T(x_i, 1{:}2)]\,\tilde{T} = T_m$$

$$\rightarrow$$

$$\tilde{T} = E_T(x_1; x_i)T_m$$

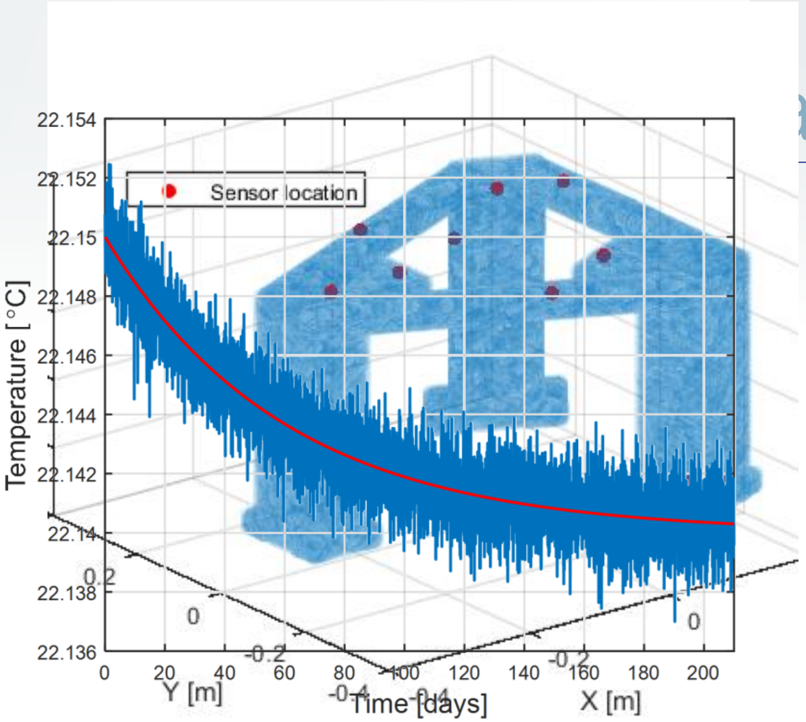
Sequential sensor placement

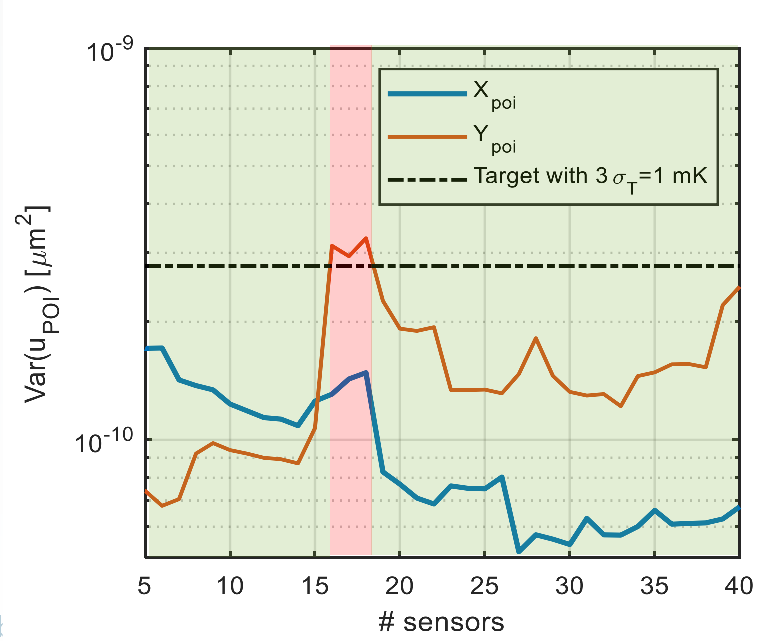
Constraints and results

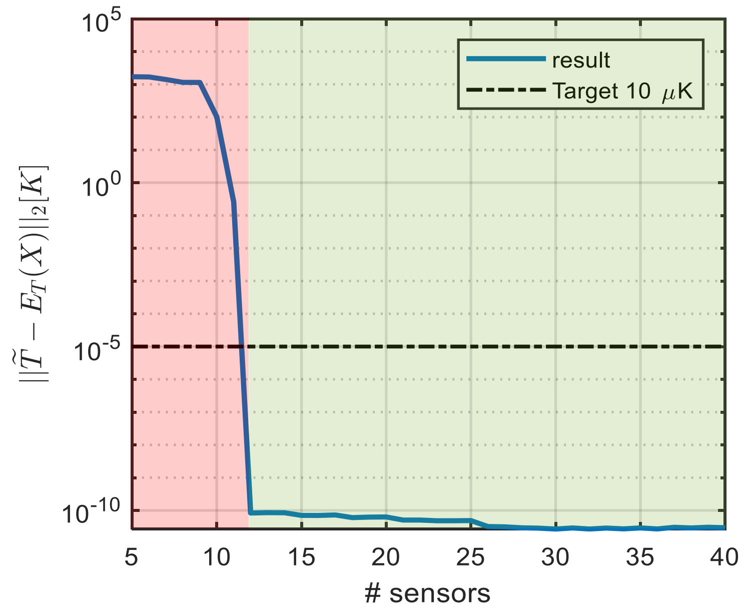
Constraints:

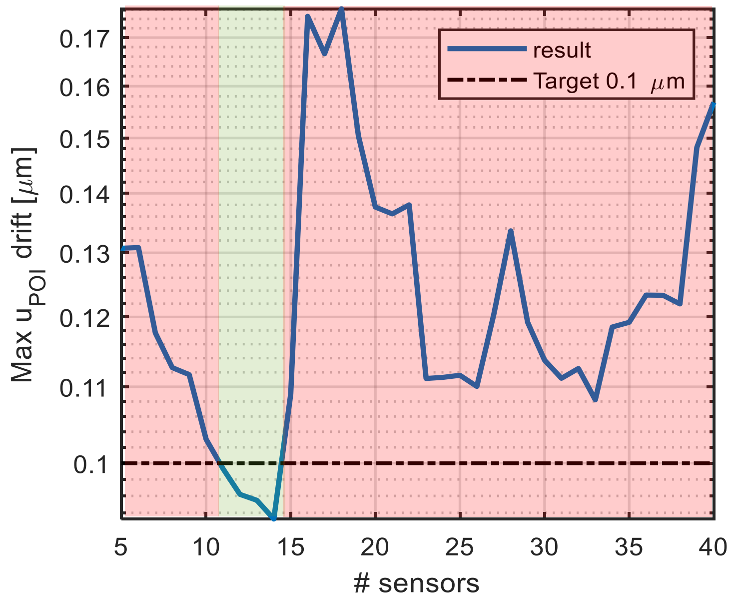
- Limit the search space, i.e. only at <u>certain surfaces</u>
- Budget POI noise: $3\sigma_{u_{poi}} < 0.05\ \mu m$, with $3\sigma_T = 1\ mK$
- Temperature estimation $< 10\ \mu K$
- Max drift sensors +/-10 mK → drift $|u_{poi}| < 0.1\mu m$

#sensors = 12 ... 14



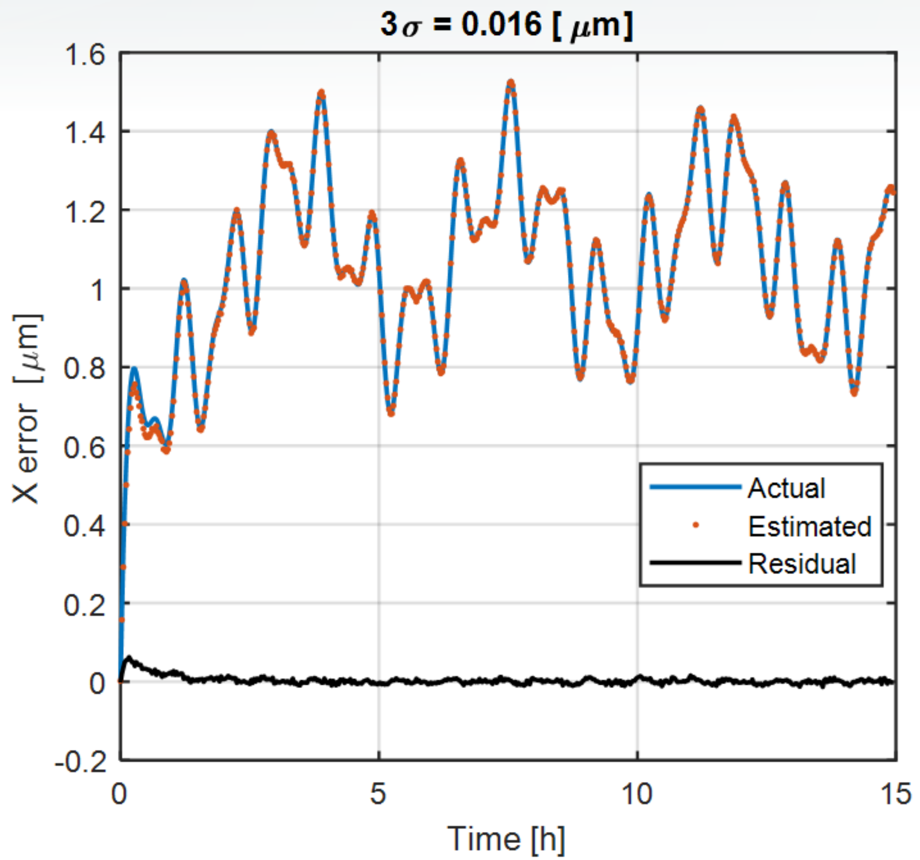


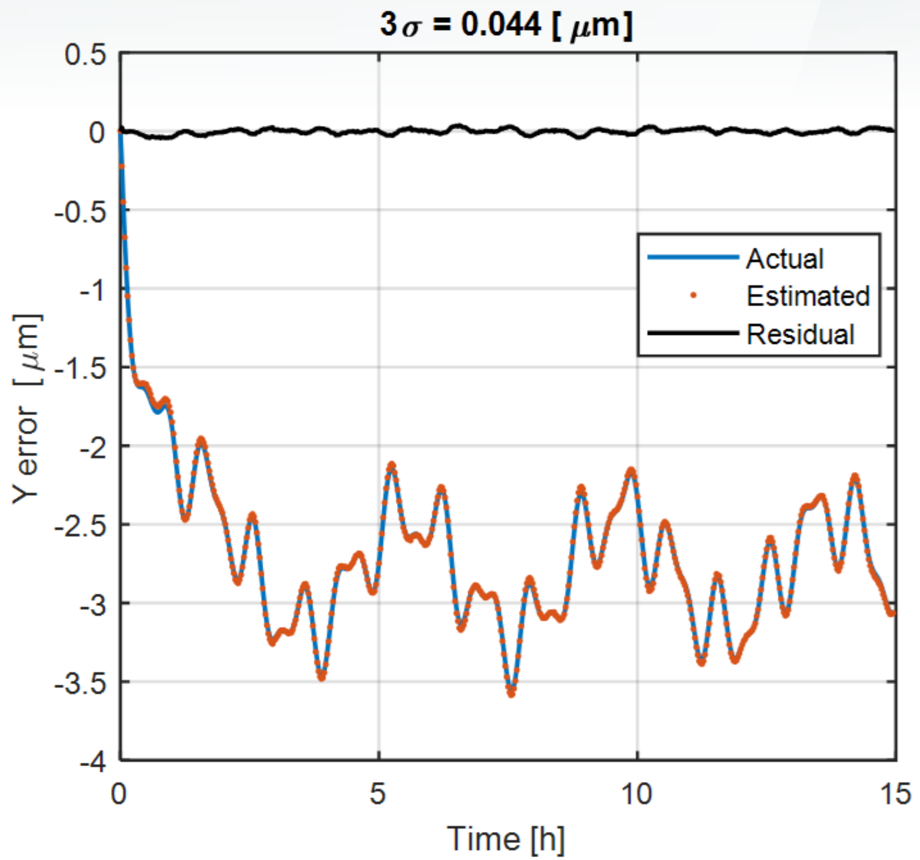




Sequential sensor placement

results





Estimator of POI displacements can now be used for **compensation**, i.e. offset the X/Y setpoints in the position control loop.
With a maximum update rate 100 s

Sensitivity

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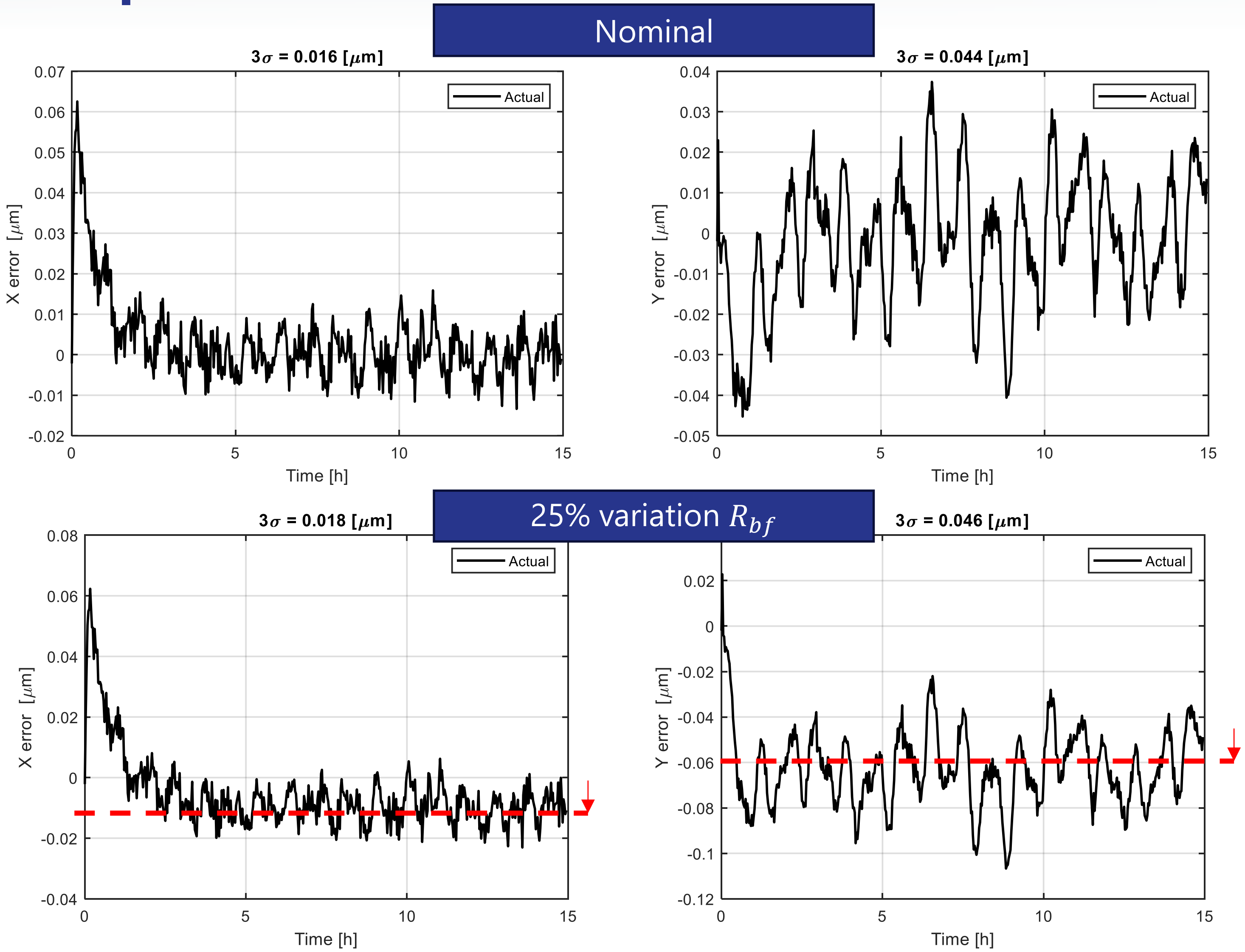
Example: Influence of 25% contact resistance variation to baseframe.



$$\Delta x_{mean} = -0.01\ \mu m$$

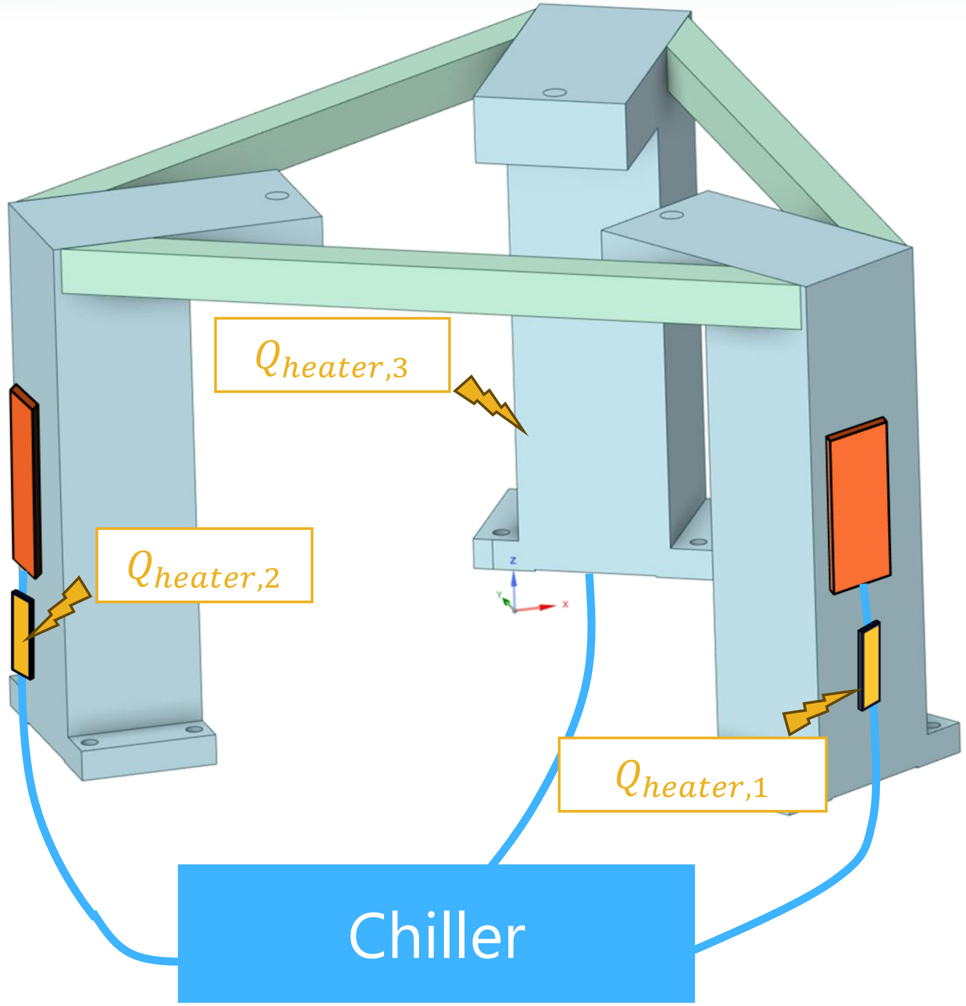
$$\Delta y_{mean} = -0.06\ \mu m$$

$$\Delta(3\sigma_x) = \Delta(3\sigma_y) = 0.002\ \mu m$$

More work to be done

Control Implementation

Summary

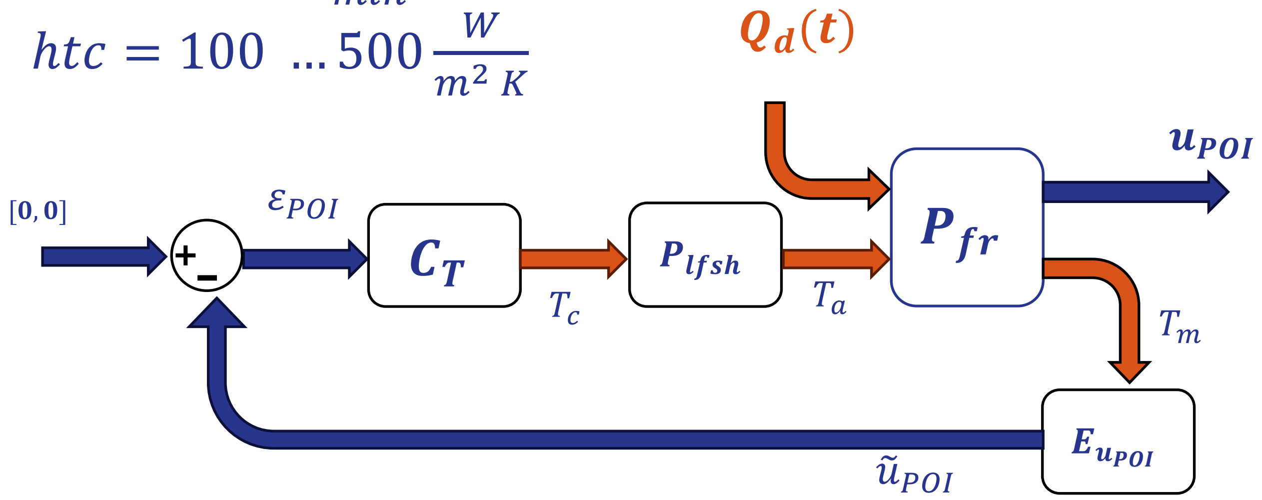


Add thermal control to limit avg heat up of frame

- 3x cooling plates
- 3x local fluid stream heaters
  - Q_{heater} max ~1.0 kW
- External water chiller, at a fixed T offset < T_{amb}

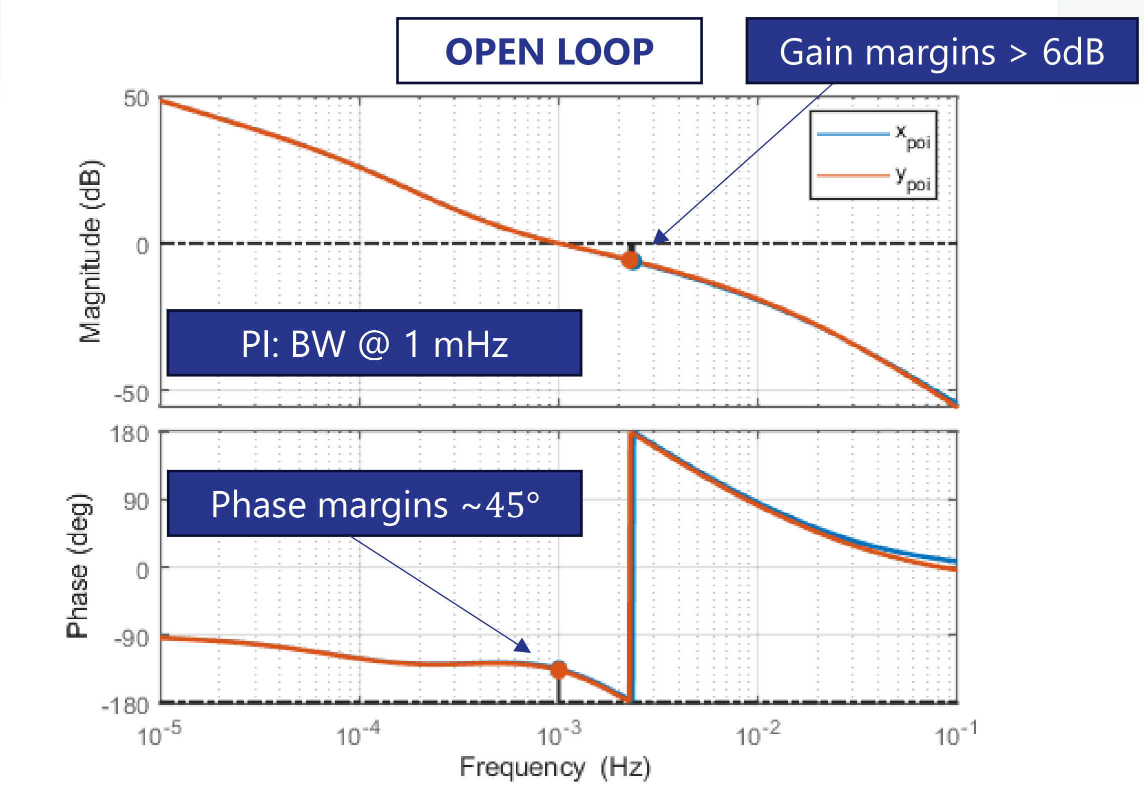
Resulting controller parameters:

- $\phi = 0.5 \ \ldots 5 \ \frac{l}{min}, \Delta T = \pm 20 \ \ldots \pm 2°C$
- $htc = 100 \ \ldots 500 \ \frac{W}{m^2\ K}$

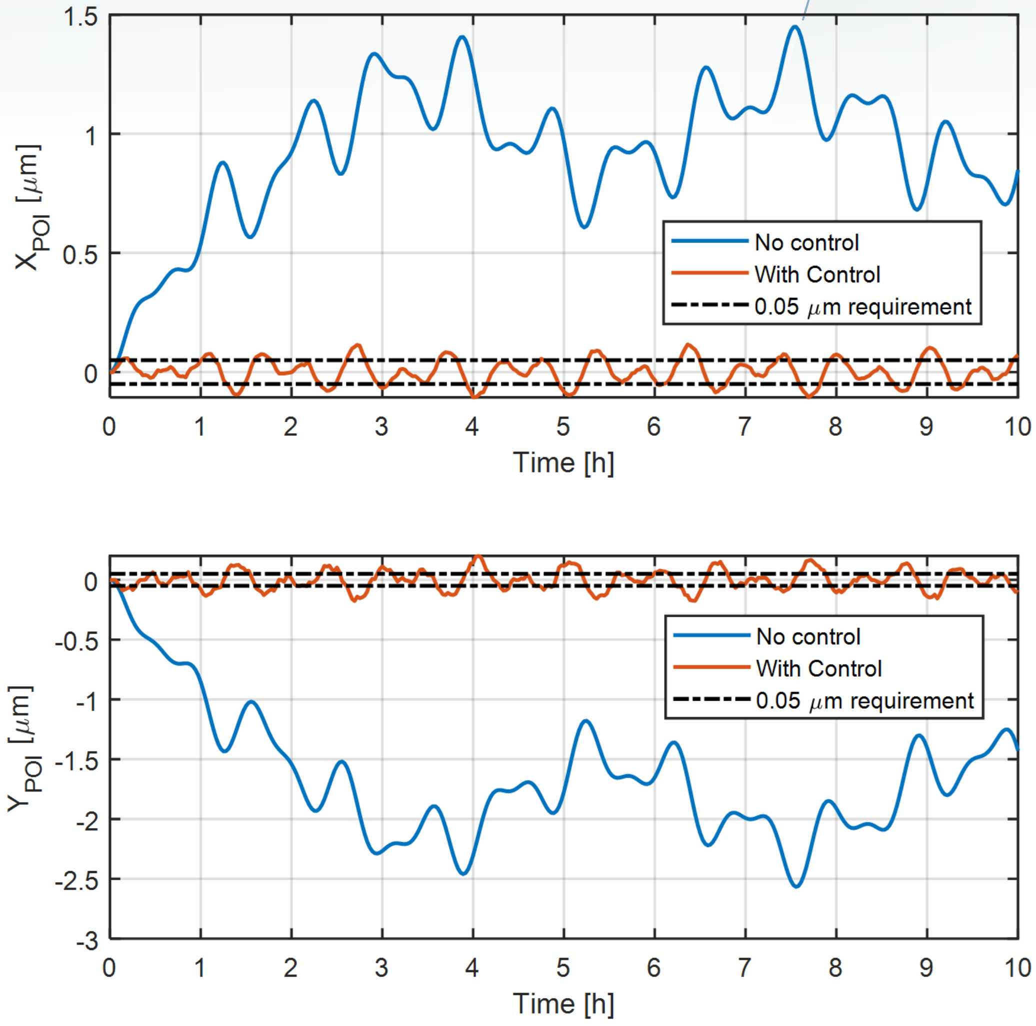


Control Implementation

results



Locations and # cooling plates are limiting the bandwidth



Residual position error **<0.2μm**

Conclusion and main findings

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Conclusion

- Way of working developed to generate a thermal induced deformation estimator
- Efficient and accurate reduced order model generation
- Sequential sensor placement algorithm tested and validated with models
- First thermal control problem implemented and validated.

Main findings

Compensation method:

Achieved **0.05μm (3σ)** position estimation accuracy with a minimum of **12 "optimally" placed sensors**

Correction method:

Achieved ~**0.2μm (3σ)** position accuracy by using the **position estimation** and **thermal control**

Future work

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- More detailed investigation on additional use cases and limitations.
- Investigate sensor fusion, e.g. using position information already available in the system.
- Investigate improvements for better performing thermal controller(s).
- Thermal system identification methods to calibrate reduced order model with measurement data of real system.
- Build test setup and validate all steps.

Questions?

Thanks for your attention

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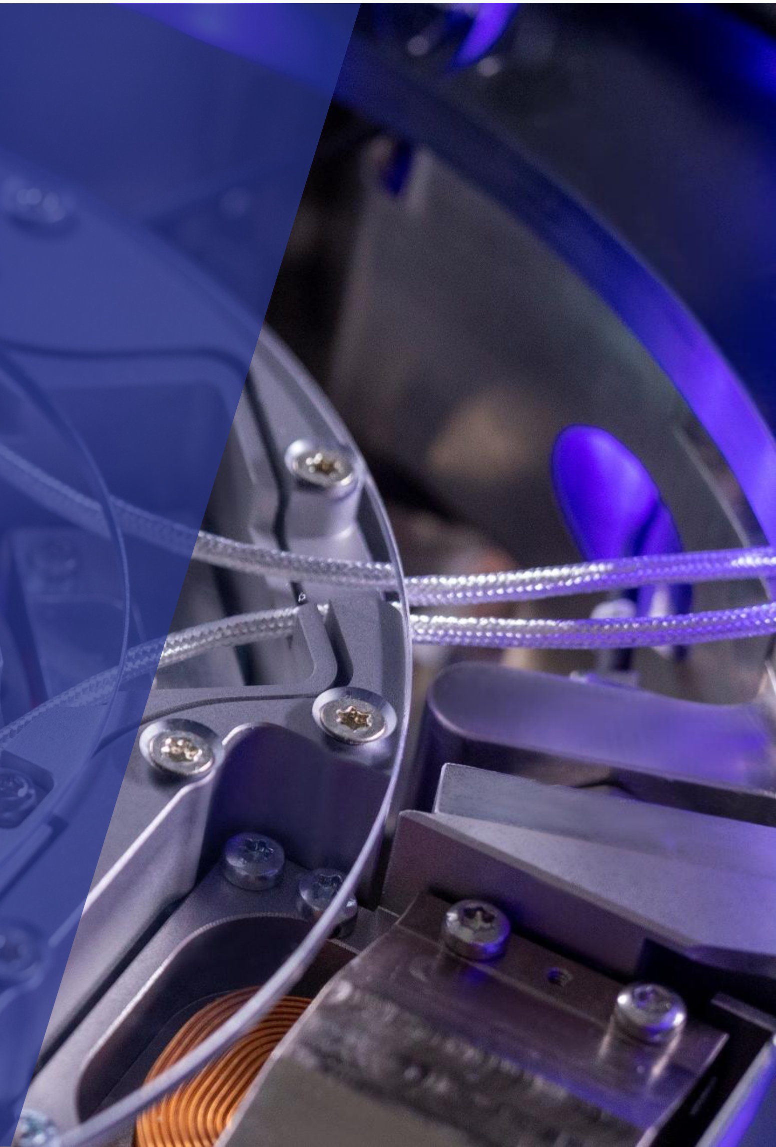

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ROM accuracy wrt reduction order

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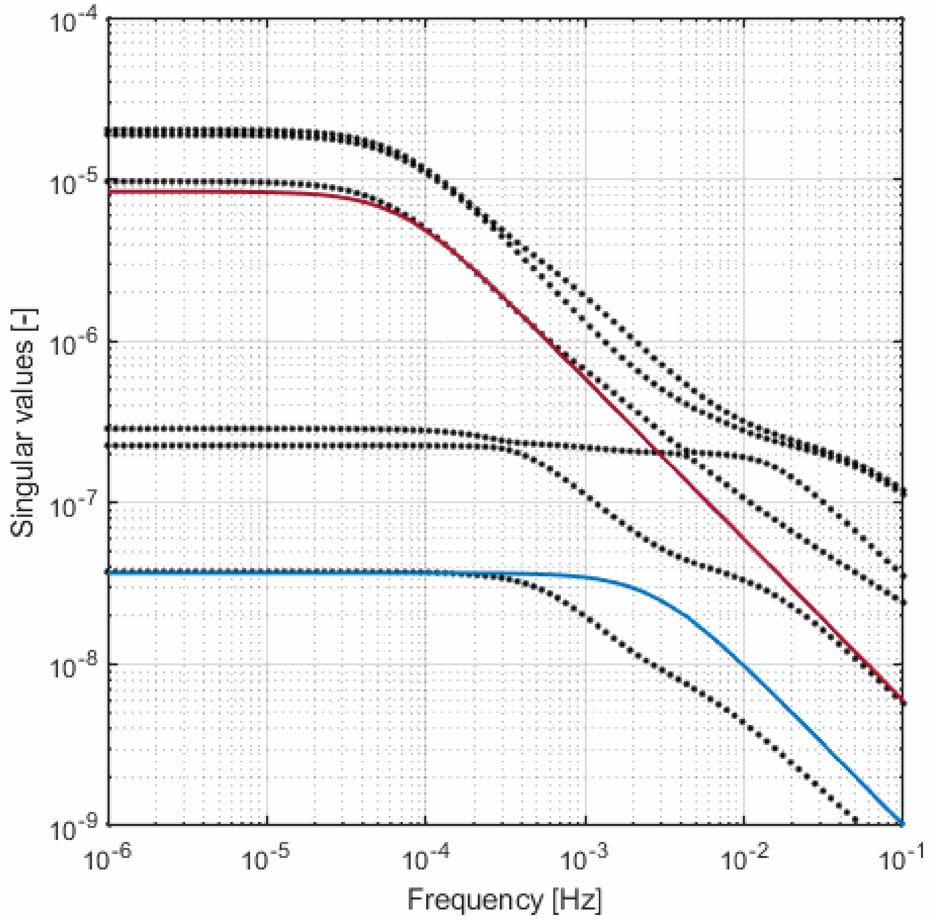
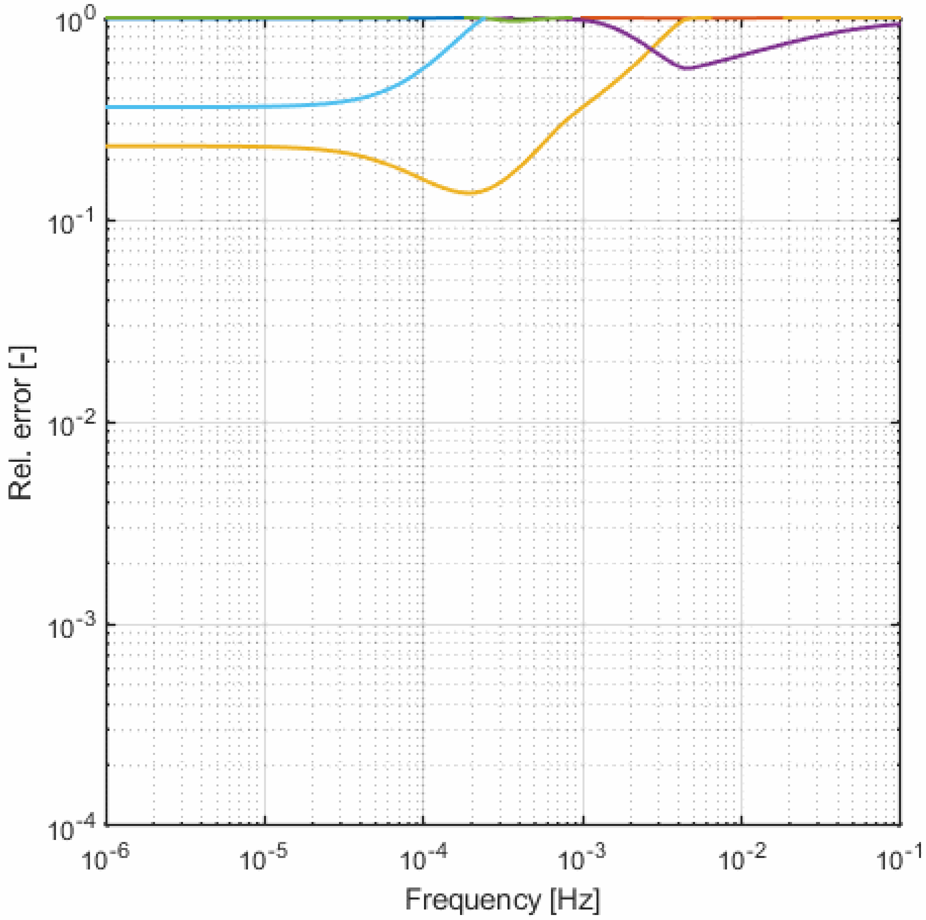
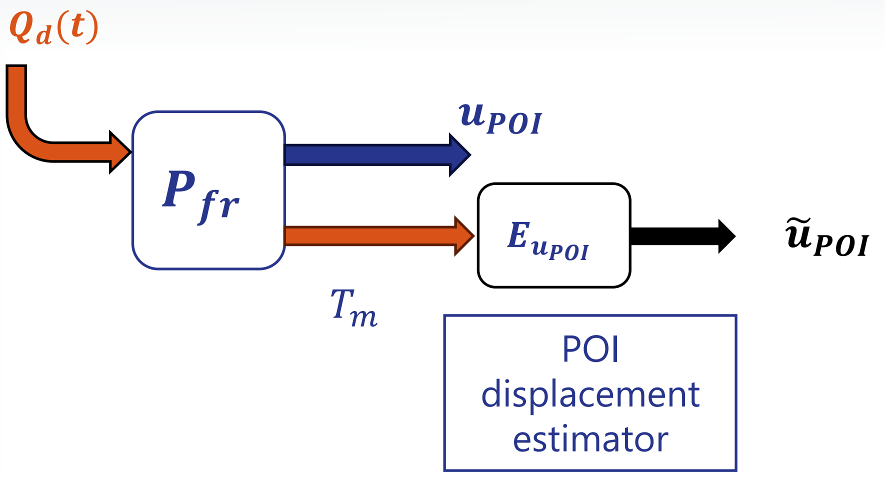
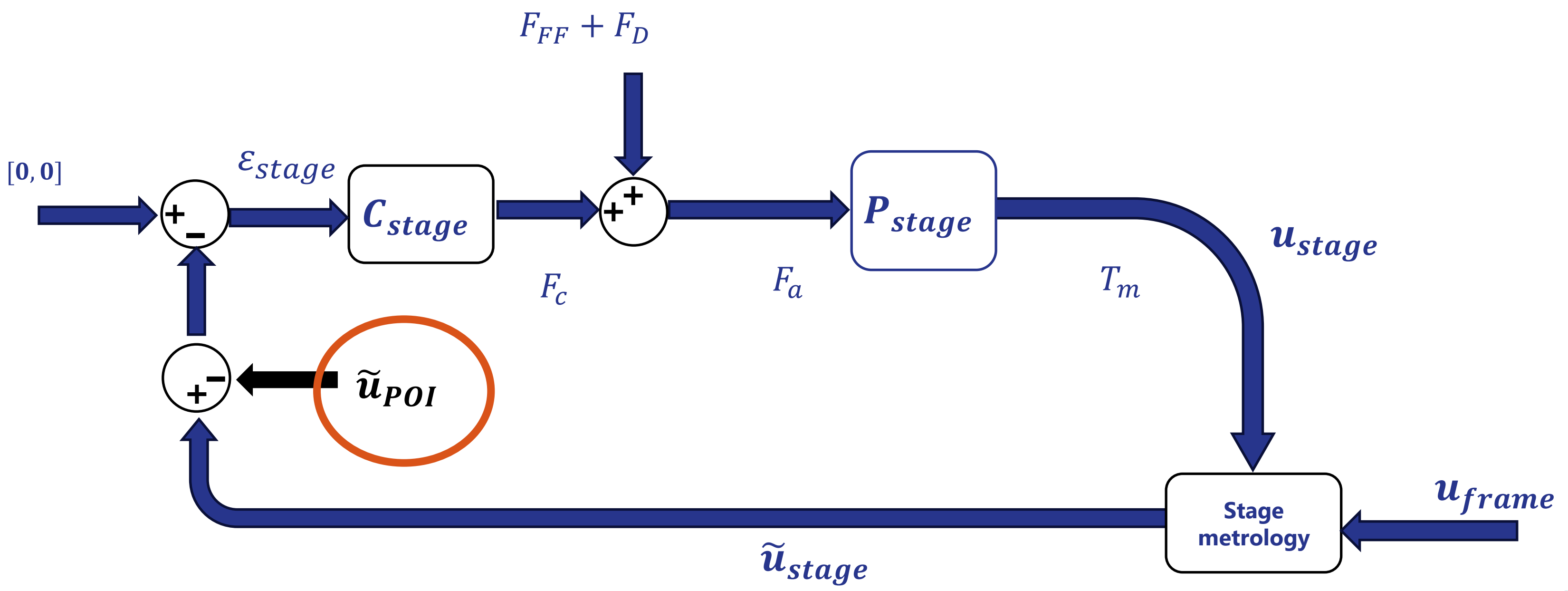




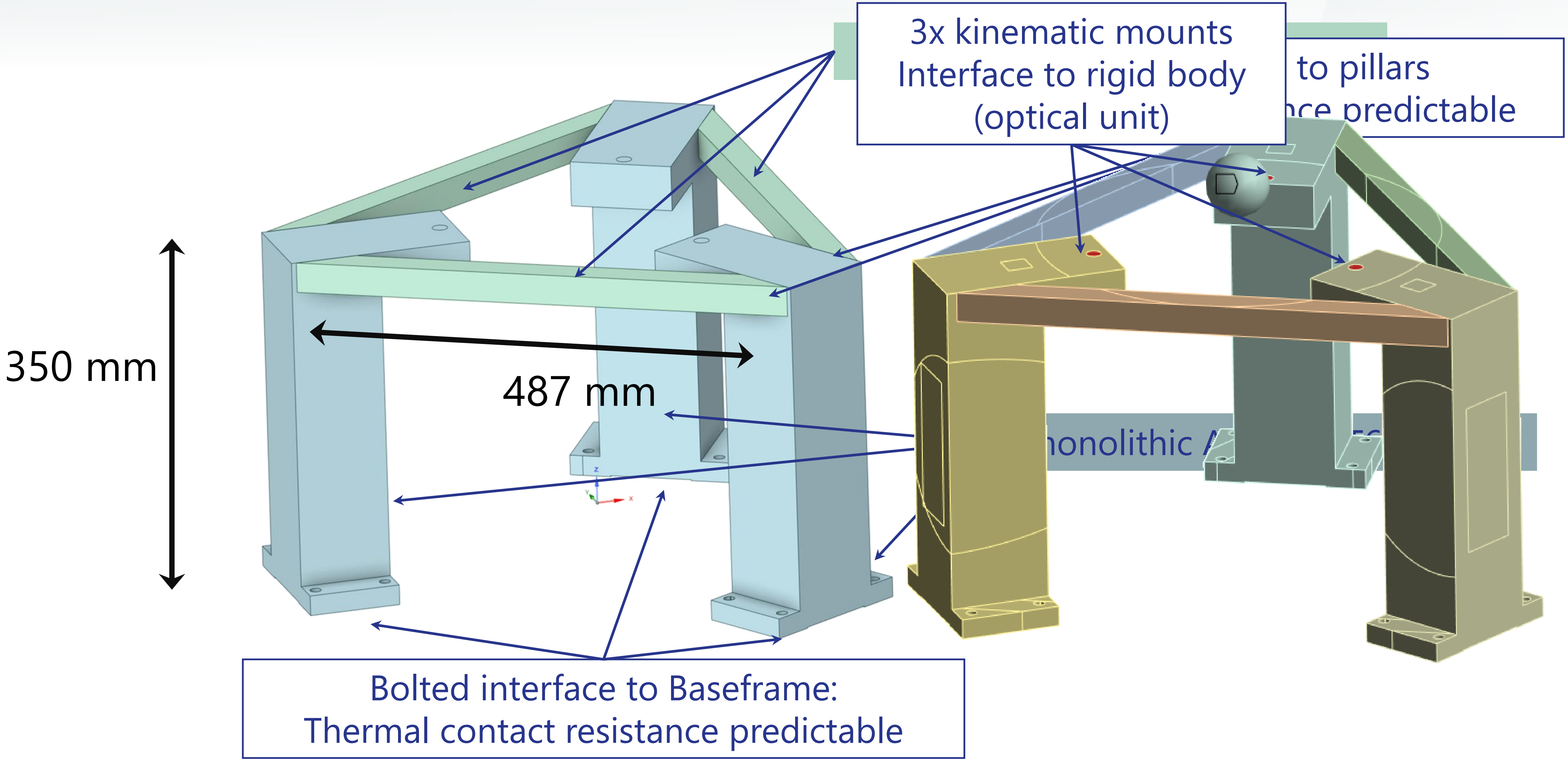
Compensation



Main position control loop



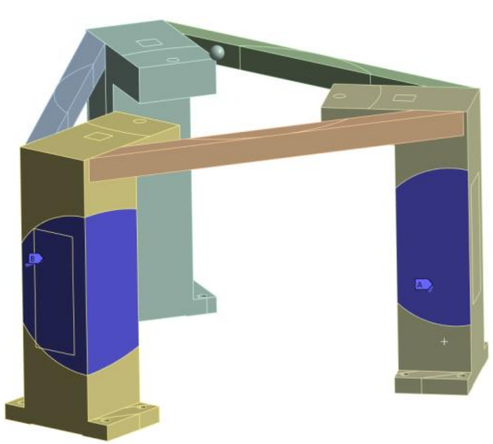
Thermo-Mechanical Model



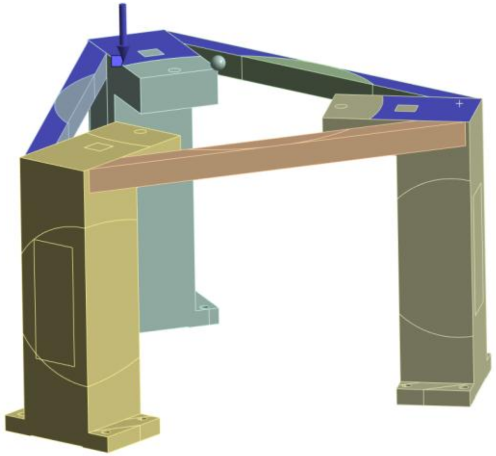
Thermo-Mechanical Model

Several identified radiative heat loads:

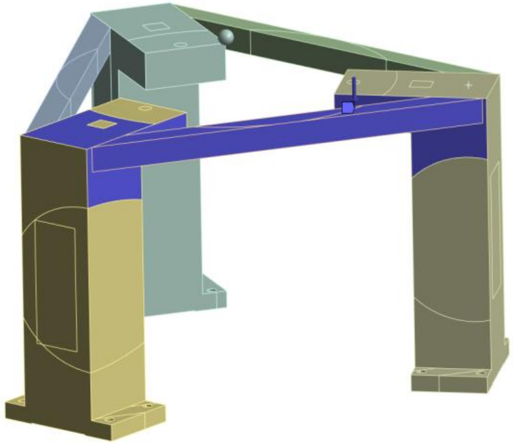
- view factors estimated using additional simulations
- simplified were necessary



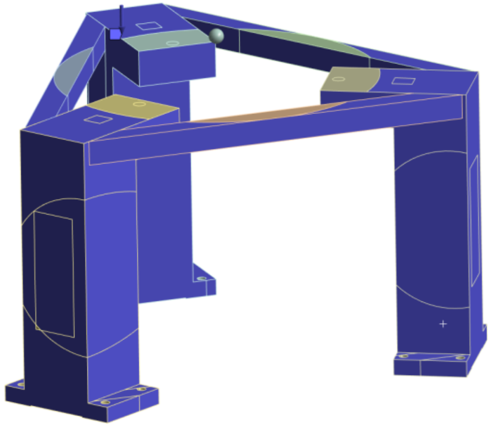
Turbo pumps
$Q_{tp} = 1.3W$



Top module (static)
$Q_{tm} = 0.9W$



Top module (varying)
$Q_{tp_{side}} = 0.75 \pm 0.65W$



Vacuum chamber
$Q_{vc} = 0.83W$

Introduction

Objective & main finding

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Objective

- Thermal induced deformation **compensation / correction** methods, for
- **high-precision systems** using
- **reduced-order modelling** in combination with
- **optimal sensor placement** to allow for
- Stage setpoint **compensation** or apply direct **correction** using thermal control

Main findings

Compensation method:

Achieved **0.05µm (3σ)** position estimation accuracy with a minimum of **12 "optimally" placed sensors**

Correction method:

Achieved ~**0.2µm (3σ)** position accuracy by using the **position estimation** and **thermal control**