Determination of volumetric machine tool errors by using a hole-bar material standard (Multi-Feature Bar – MFB)

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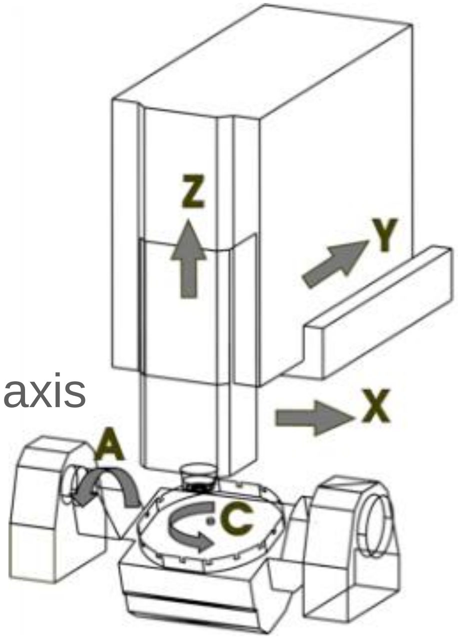
Automated Production Research Laboratory of ENS Cachan – Univ Paris Saclay

Introduction : Volumetric accuracy

5-axis machine tool

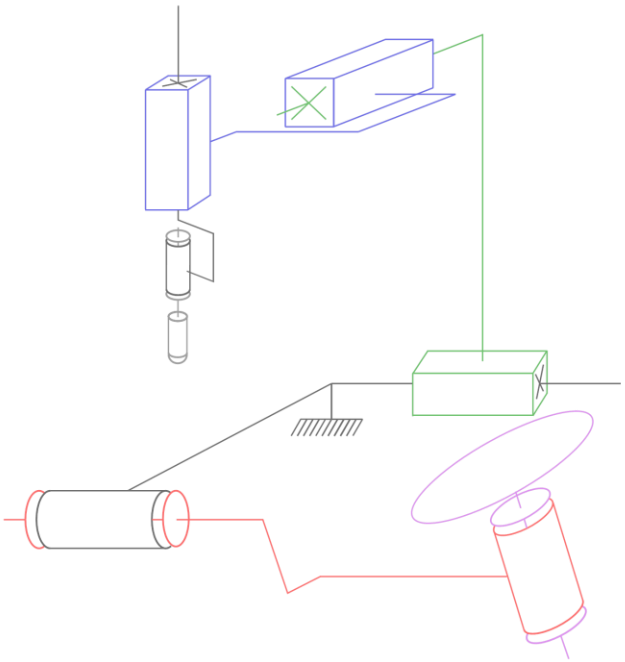
(Mikron UCP710 at LURPA)

Swiveling axis



Rotary Table

Kinematic Architecture



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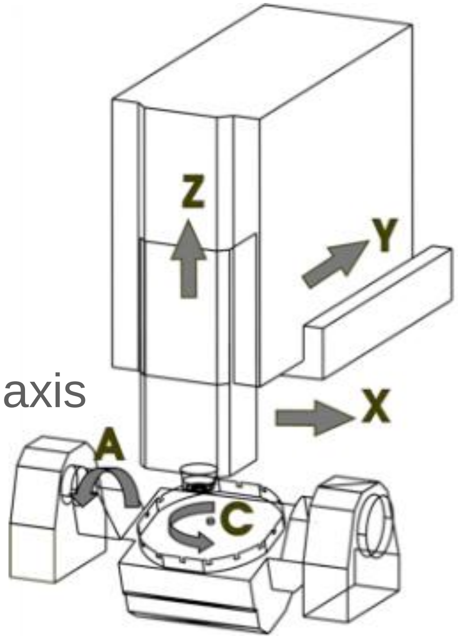

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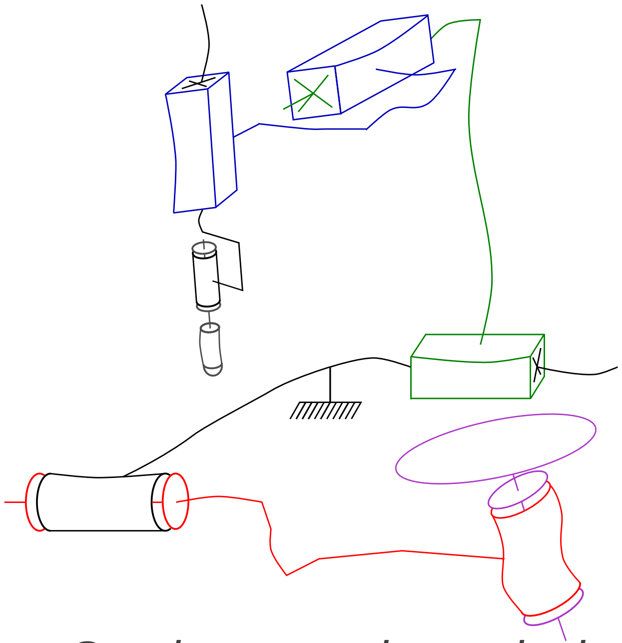

Gap between theoretical kinematic and real kinematic

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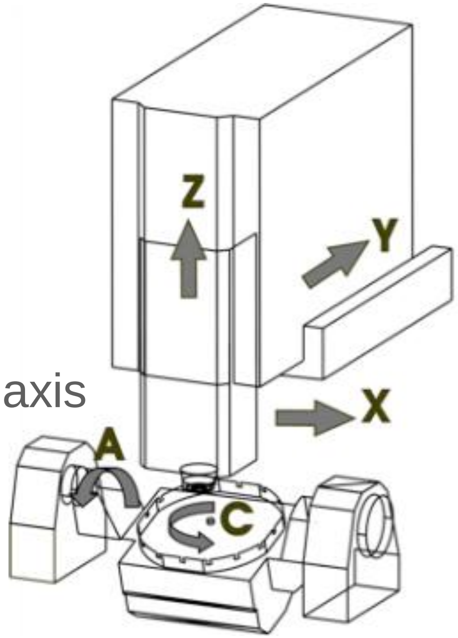

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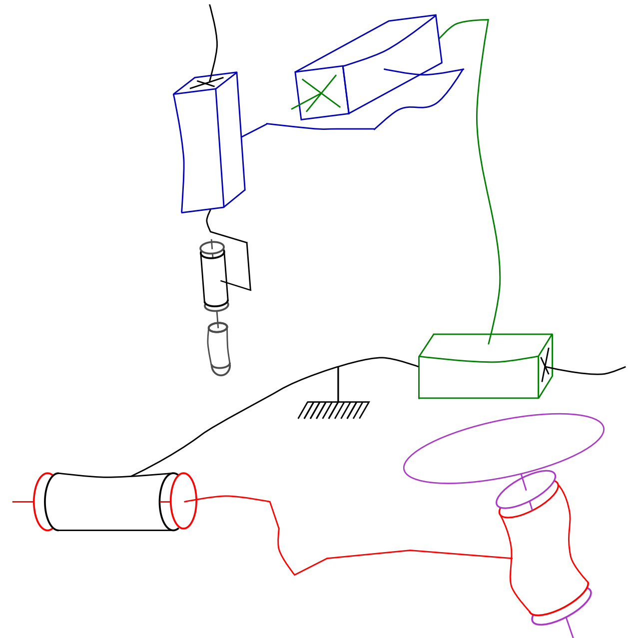
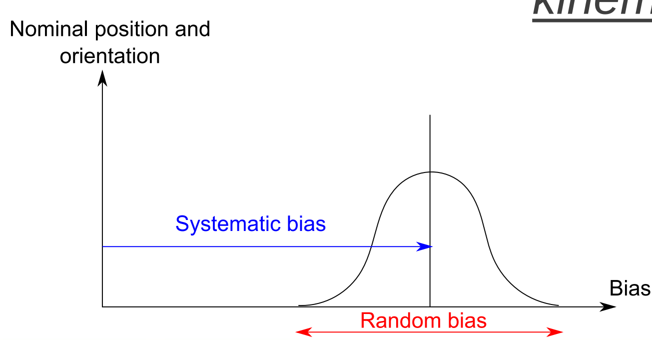


Gap between theoretical kinematic and real kinematic

Causes of this effect:



Geometric errors ➔ ~ 70% - 90%

Thermo-mechanical phenomena

Environmental hazards

Dynamic forces

Heats

CNC

Vibrations

…

[Mekid2012]
[Schwenke2008]

Introduction : Volumetric accuracy

Maximum range of relative deviations between actual and ideal position and maximum range of orientation deviations in the volume concerned, where the deviations are relative deviations between the tool side and the workpiece side of the machine tool [ISO230-1,2012]:

$$\begin{pmatrix} \vec{axis}_{eff} - \vec{axis}_{nom} \\ \\ \vec{C_{L_{eff}}} - \vec{C_{L_{nom}}} \end{pmatrix}_{6\times1} = \begin{pmatrix} \delta r \\ \\ \delta u \end{pmatrix}_{6\times1} = V_{xyz}$$

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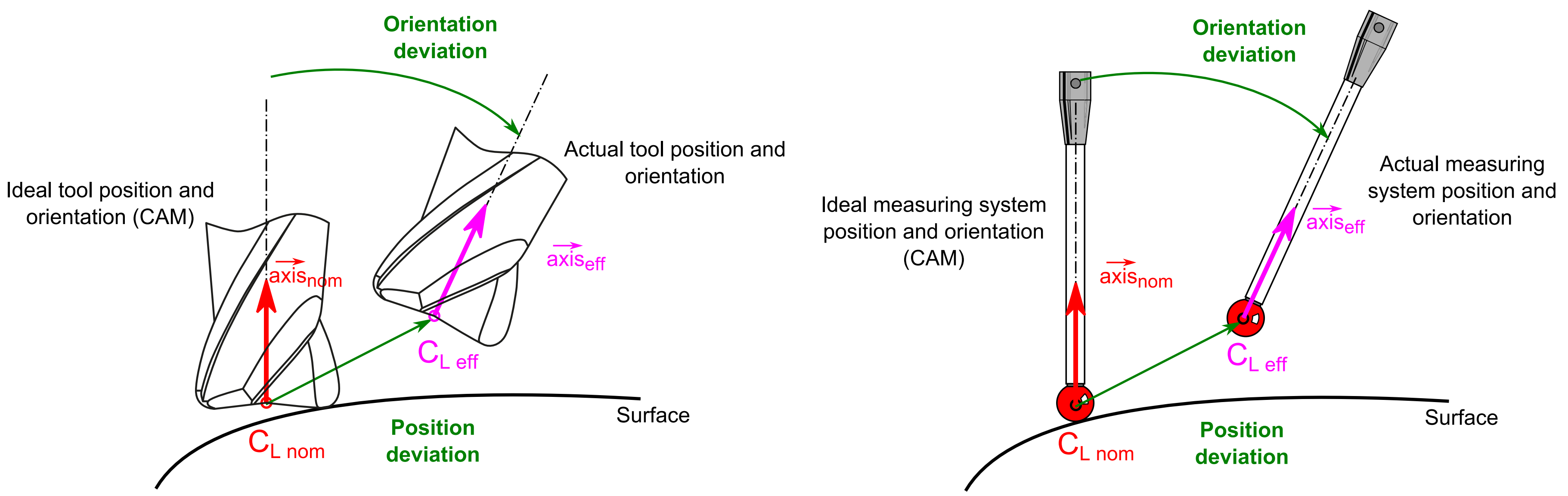

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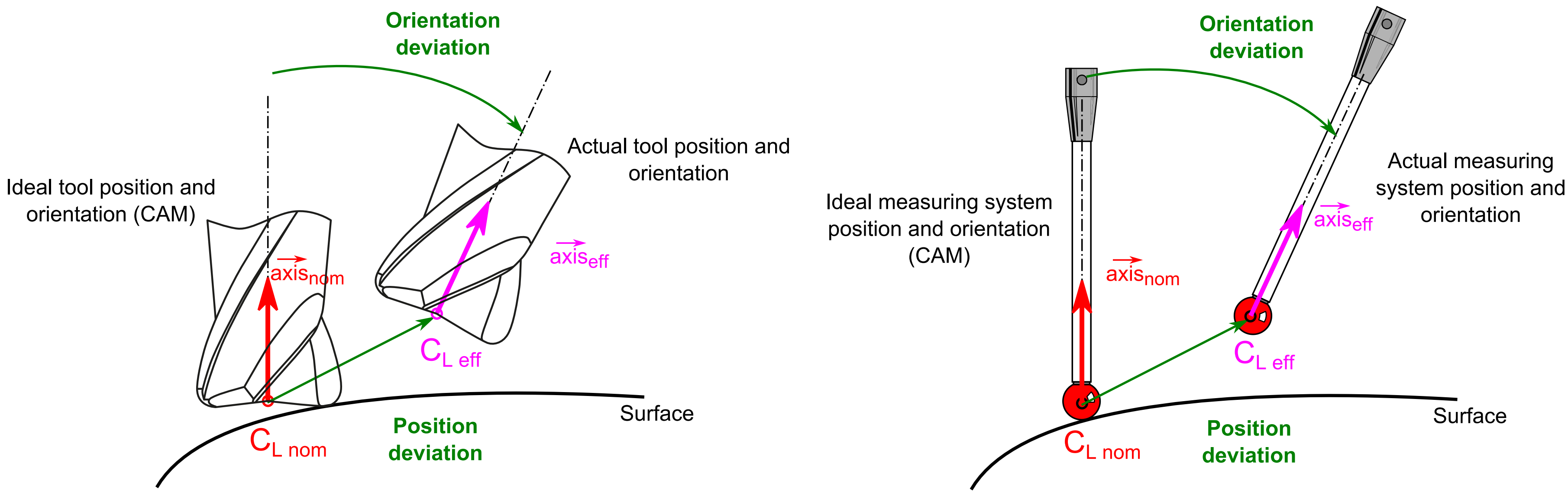
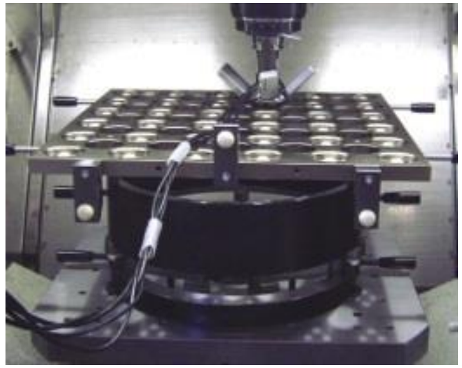


The aim of this study is to develop a novel material standard to identify motion errors:

- Usable on CMM, **3 or 5 machine tool**, by **on-line measurement,** to insure **traceable and accurate results**
- With large field of its application: **Metrology room** or **Manufacturing shop**

Introduction :
Literature review

Hole plate
[Trapet1991]



Ball plate
[Bringmann2009]

1

3

Hole Bar
[Lim2005]

Ball Bar
[Zhang1991]

2

4

Conventional method [ISO 230], [ISO 10360], [ISO 10791], [ISO 13041], [ISO 3070]

Laser Interferometry (On-line measurement)
[Schwenke2005], [Chen1999]

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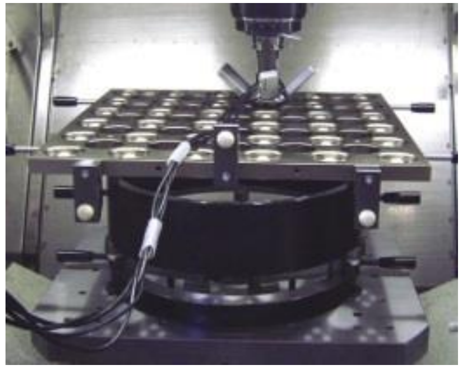
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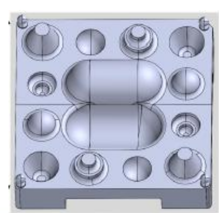
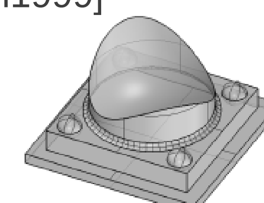
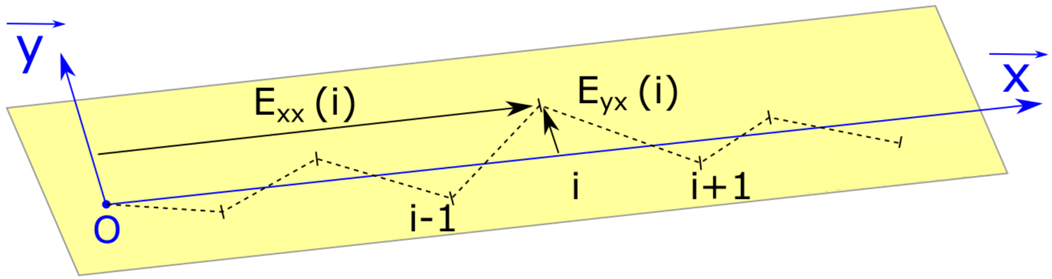


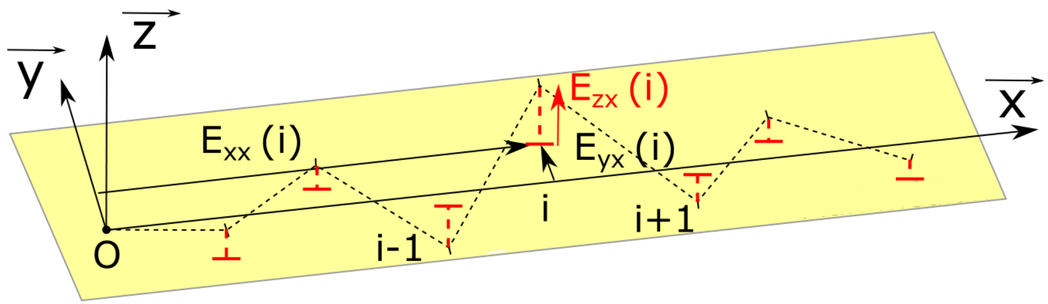
Hole-Bar

Actual Hole-Bar in litterature:

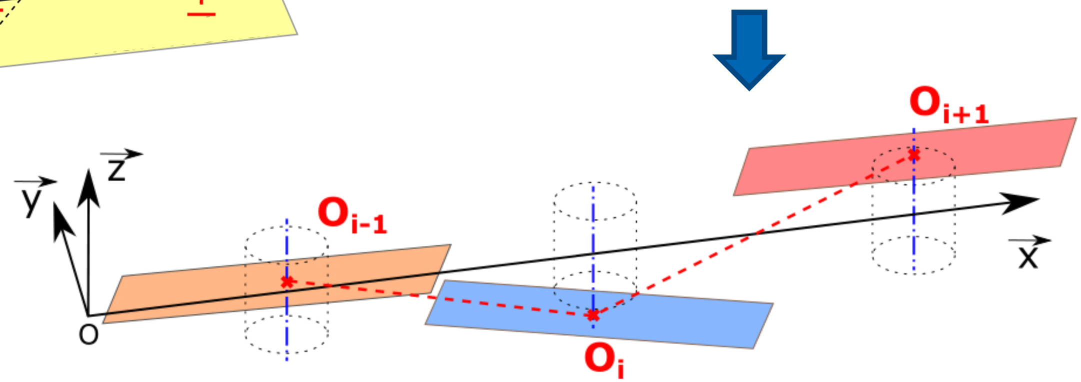


- ➔ One linear positioning error E_{xx}
- ➔ One linear positioning error E_{xx} and one horizontal straightness E_{yx}

Identification of an additional parameter:



- ➔ One linear positioning error E_{xx} and two straightnesses E_{yx} and E_{zx}



Development of a novel Hole-Bar with patterns
➔ maximization of the number of geometric errors to identify for each position of the Hole-Bar

Outline

- Development of the Novel Hole-Bar
  - Principle
  - Technical attributes
- Calibration
  - Reversal technique
  - Intercomparison
- Application on Machine tool
  - Measurement process
  - Geometric model
  - Results
- Conclusion

Principle of the new Hole-Bar

The design of the Hole-Bar consists in a repetition of a 3D pattern in one direction (Δ)

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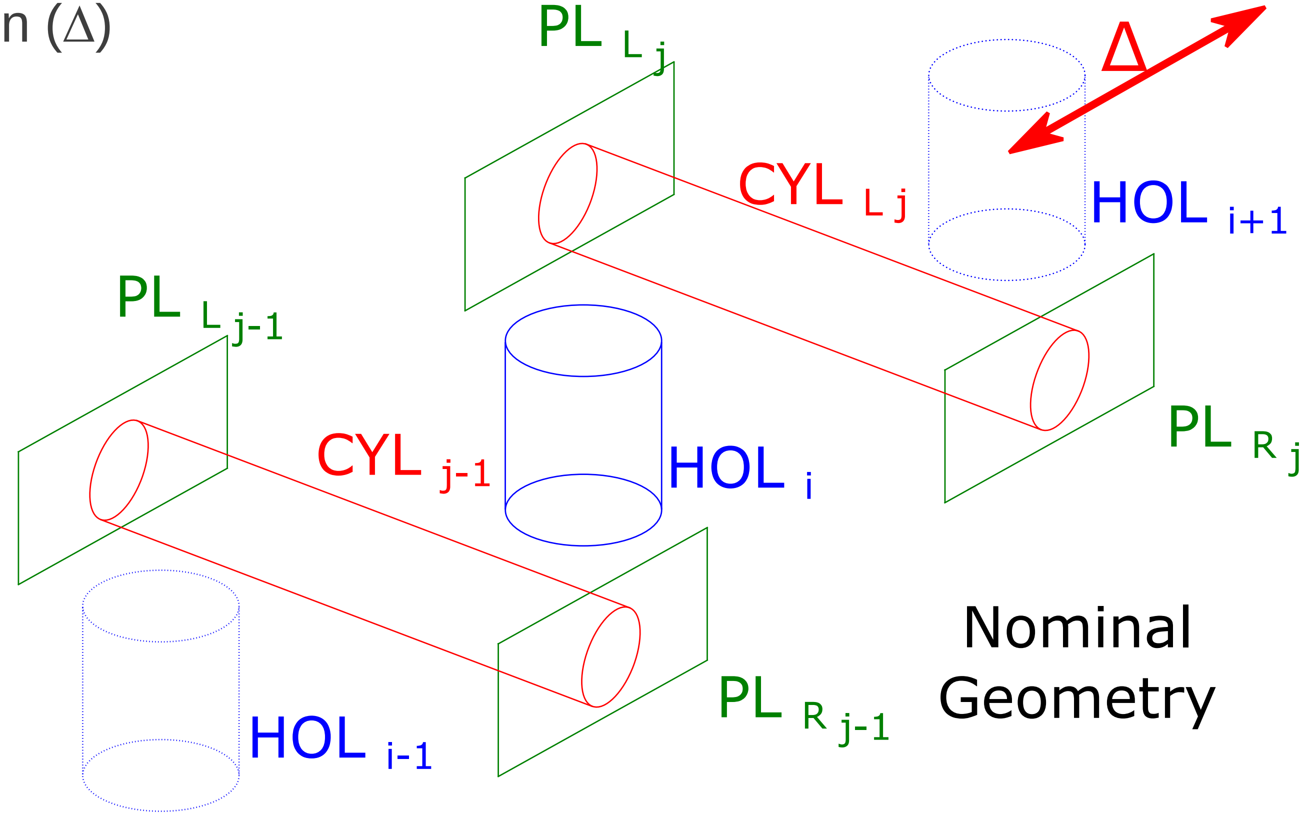

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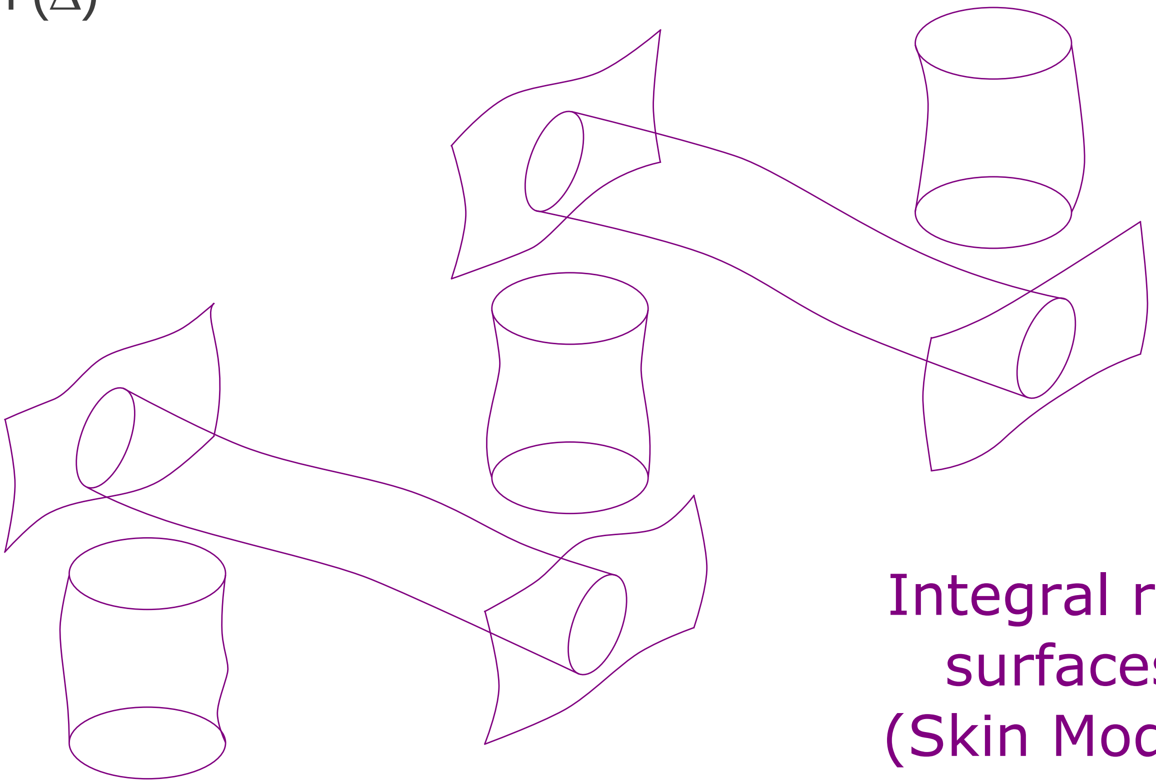
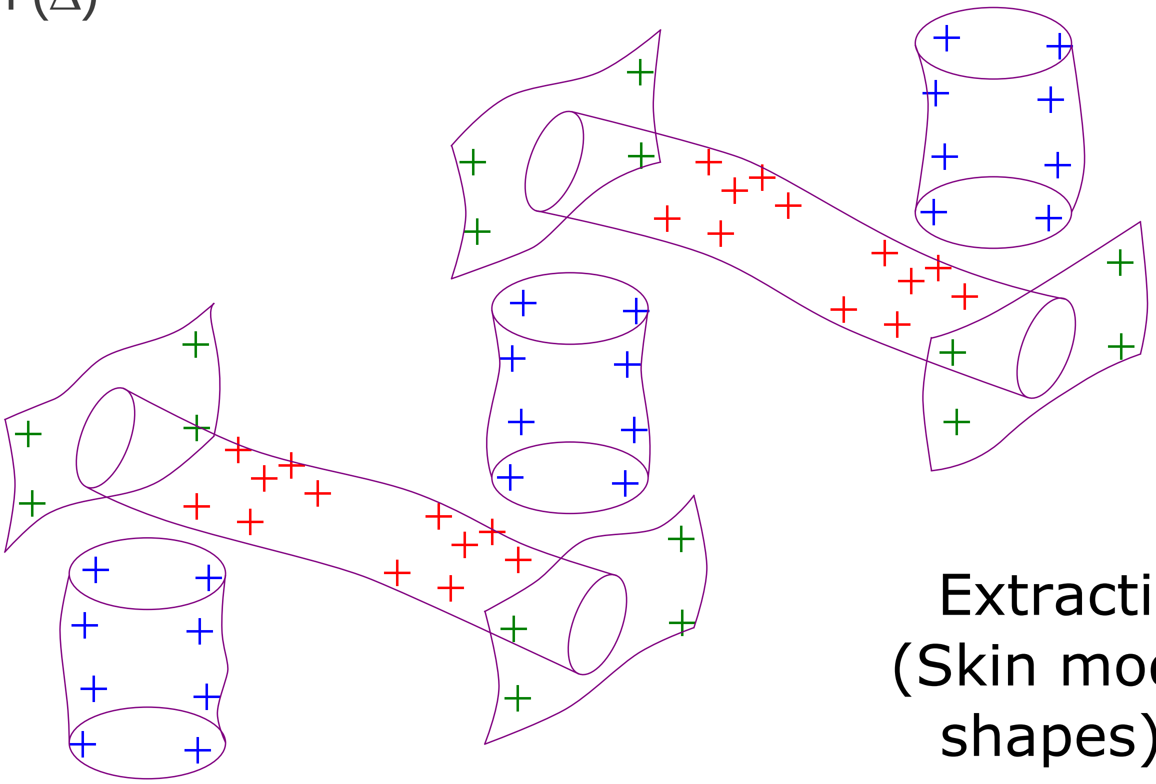


Integral real surfaces (Skin Model)

[ISO 5459:2011]

The design of the Hole-Bar consists in a repetition of a 3D pattern in one direction (Δ)



Extraction (Skin model shapes)

[ISO 5459:2011]

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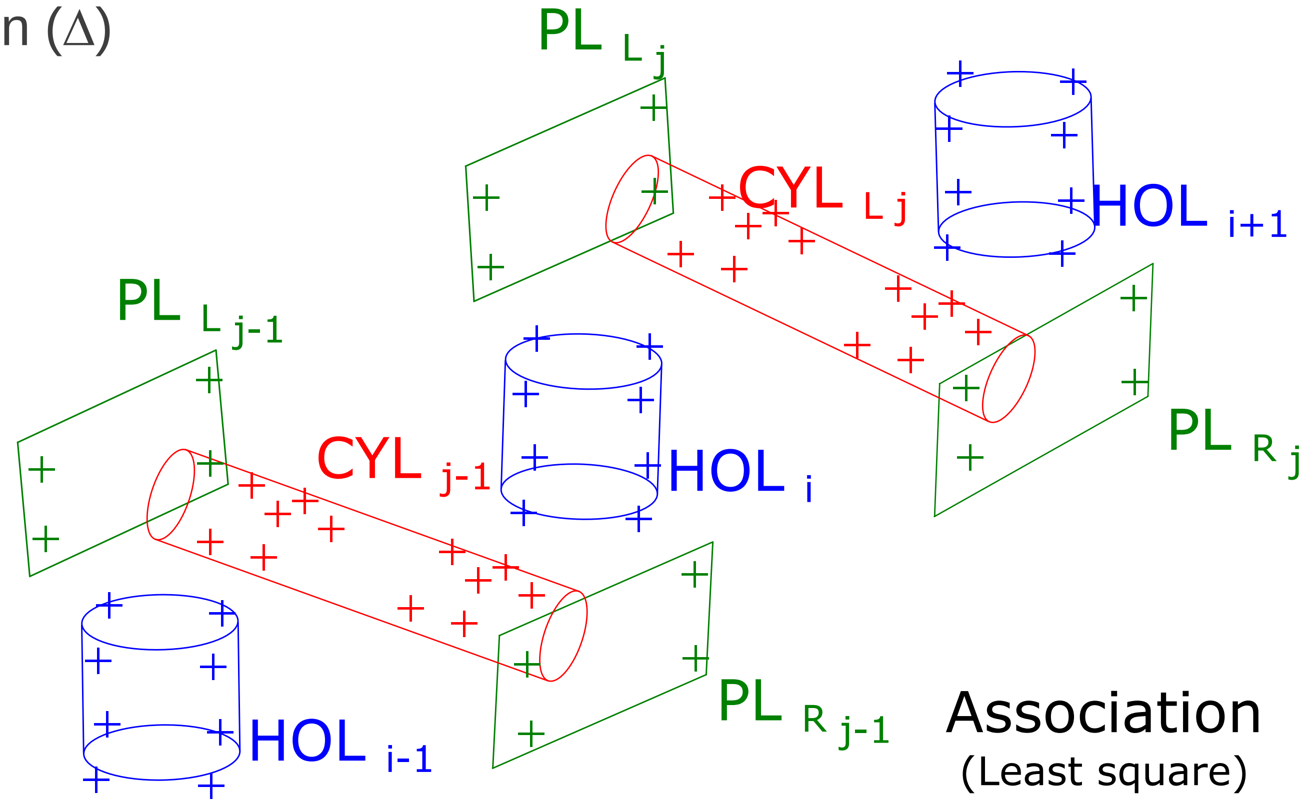
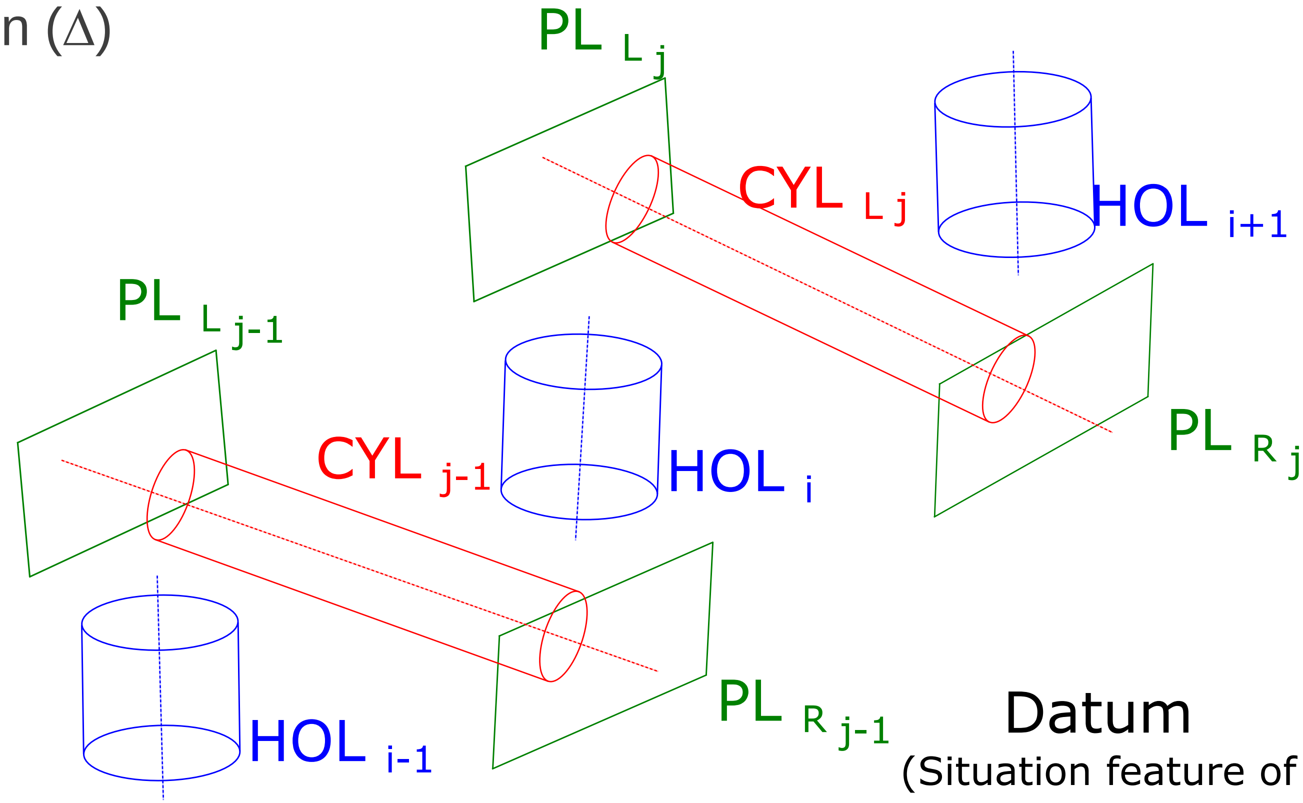


Association
(Least square)

[ISO 5459:2011]

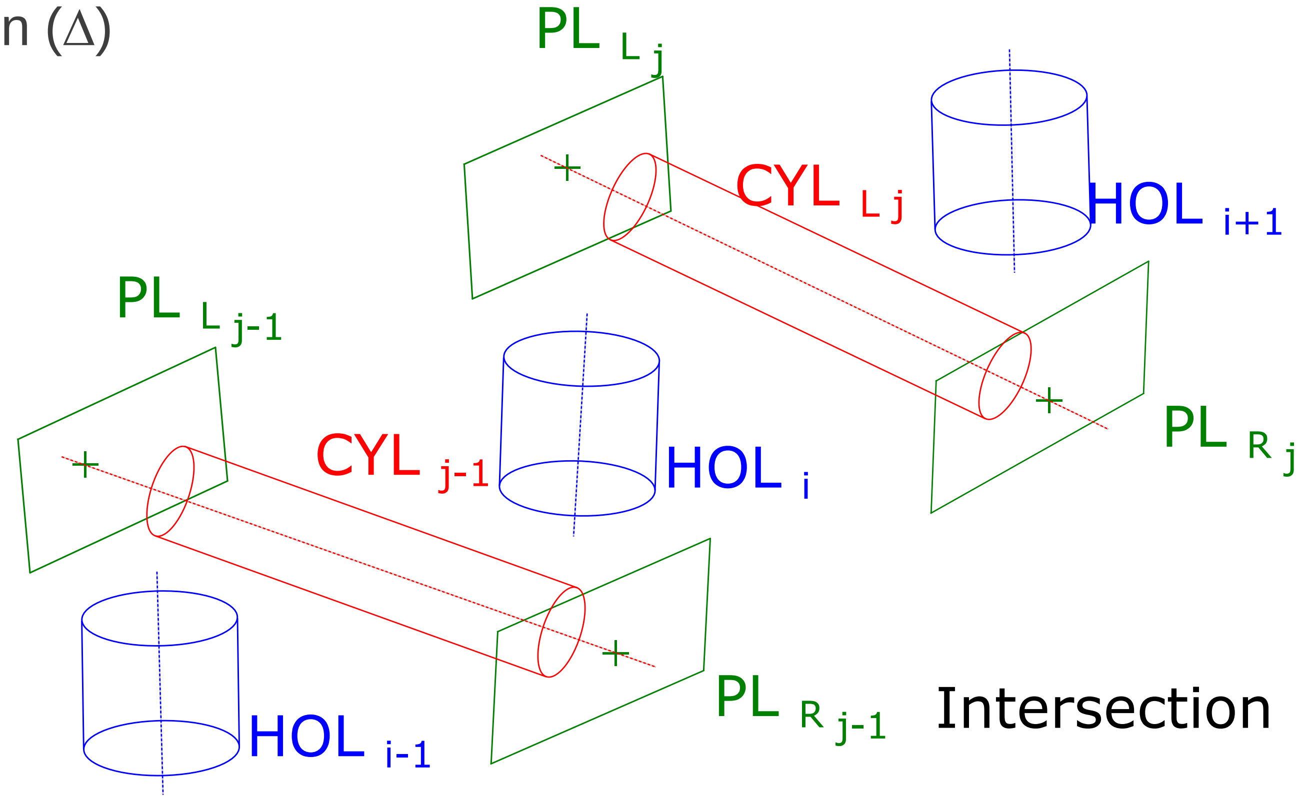
The design of the Hole-Bar consists in a repetition of a 3D pattern in one direction (Δ)



Datum
(Situation feature of the associated surface)

[ISO 5459:2011]

The design of the Hole-Bar consists in a repetition of a 3D pattern in one direction (Δ)



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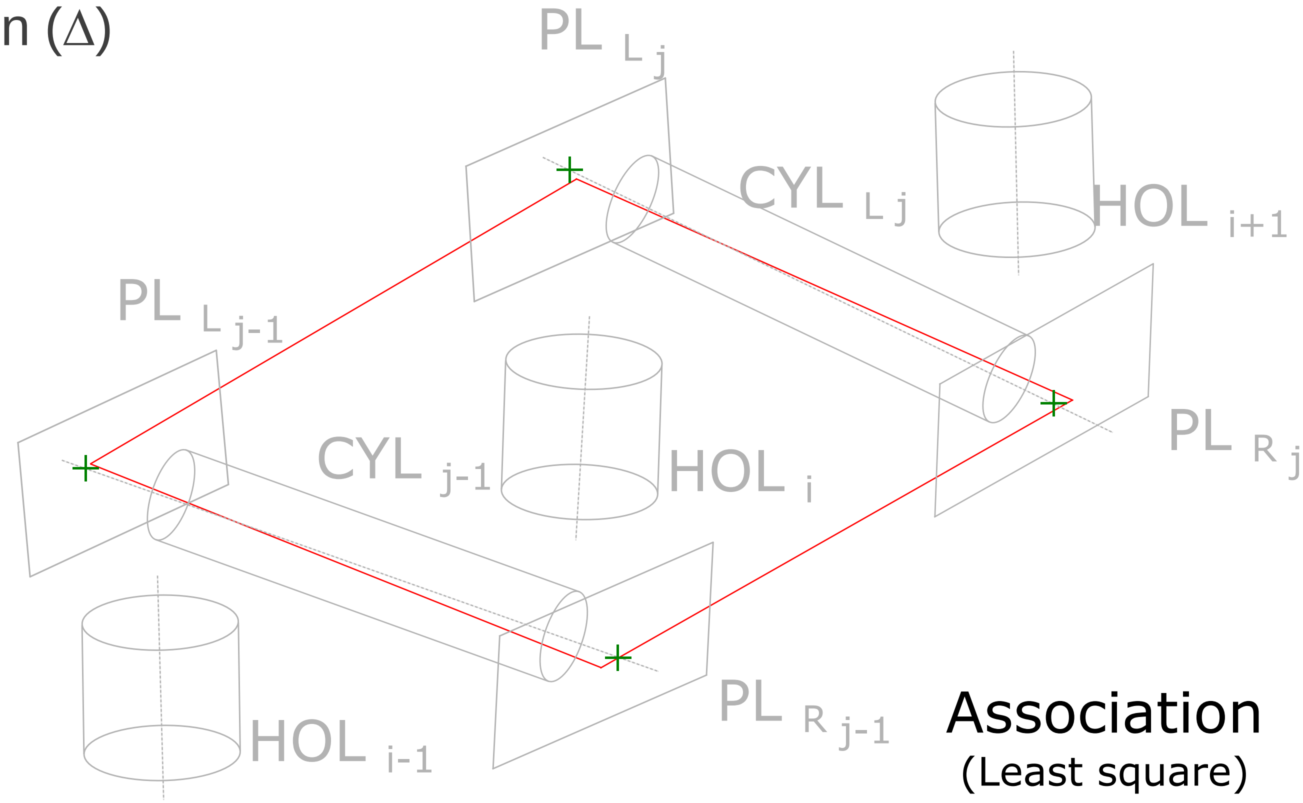

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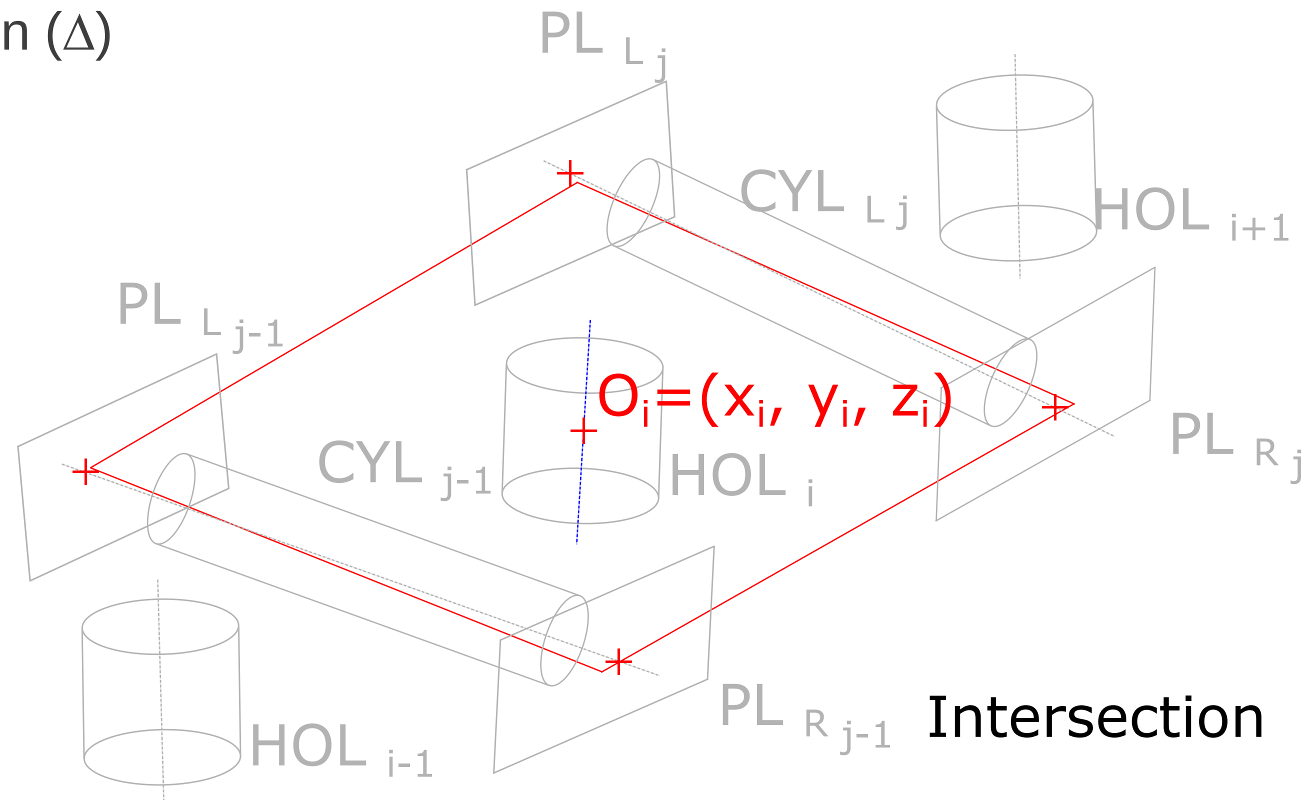

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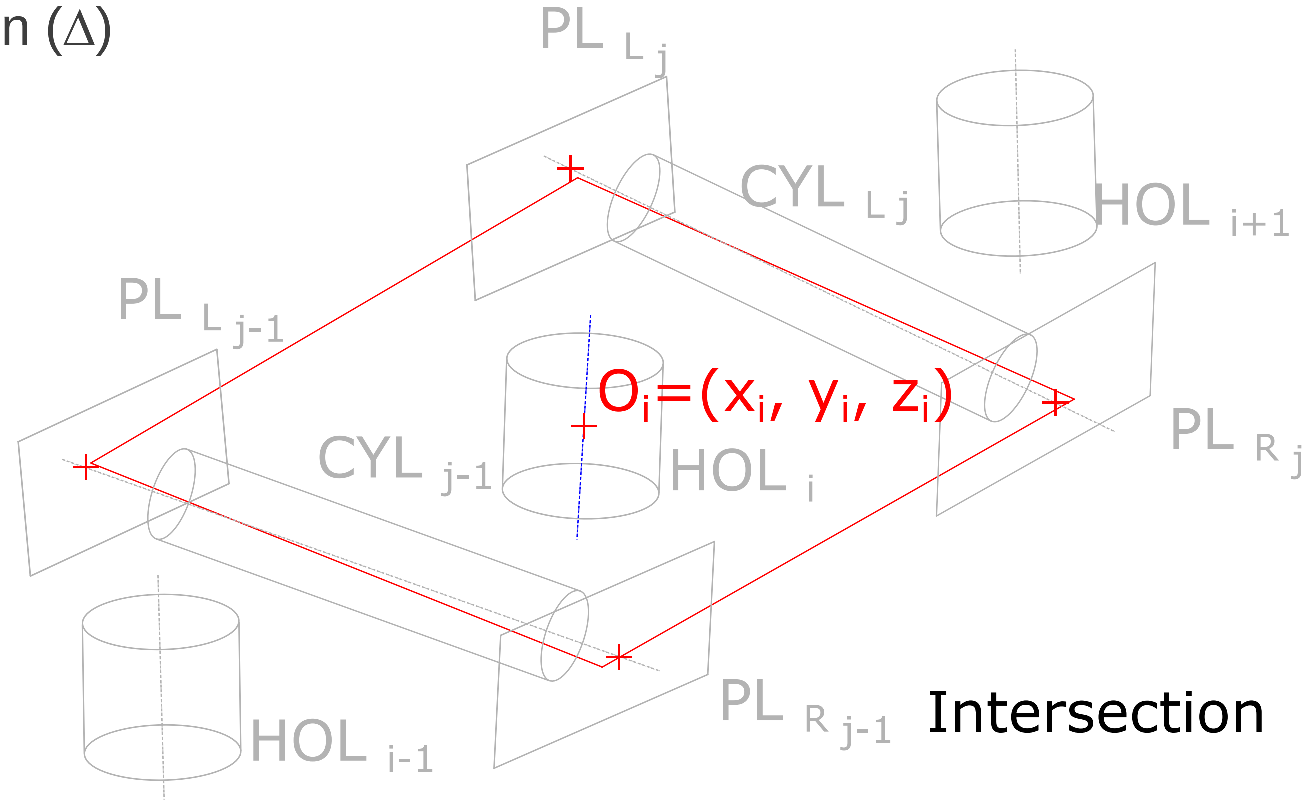
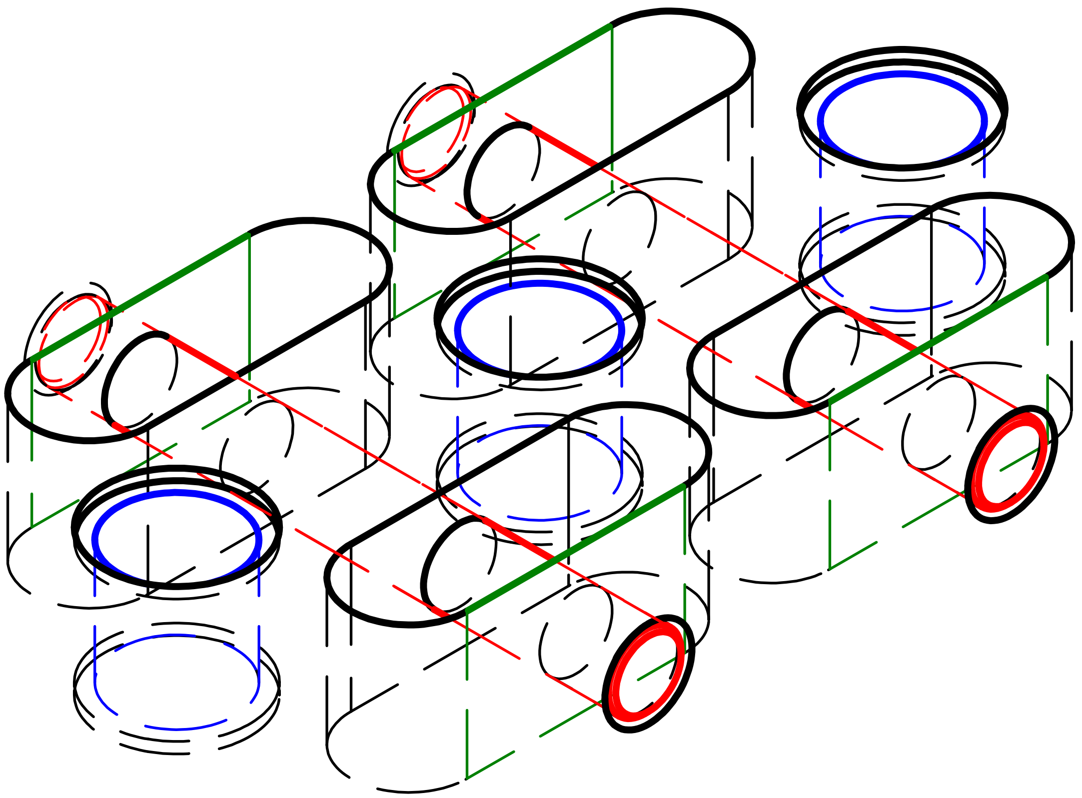
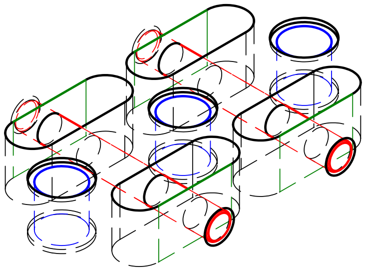


The identified points $O_i = (x_i ,y_i ,z_i)$ offers 3 intrinsic geometric parameters: 1 linear positioning and 2 straightnesses



Technical attributes of Hole-Bar (Invar)



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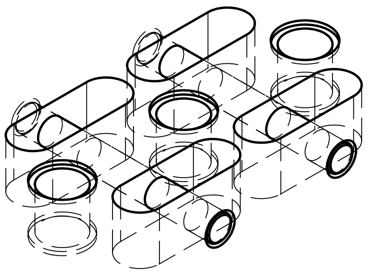

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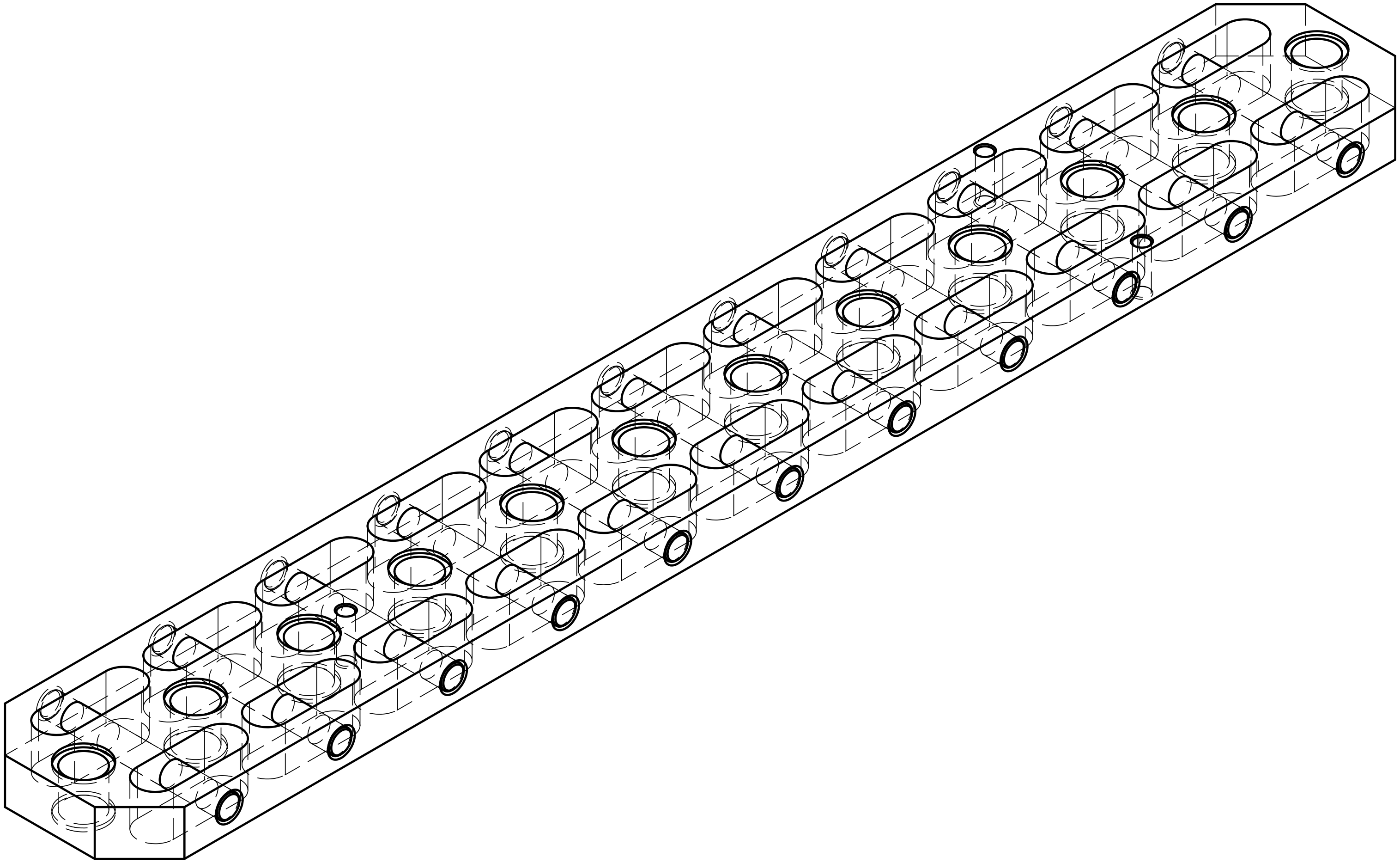

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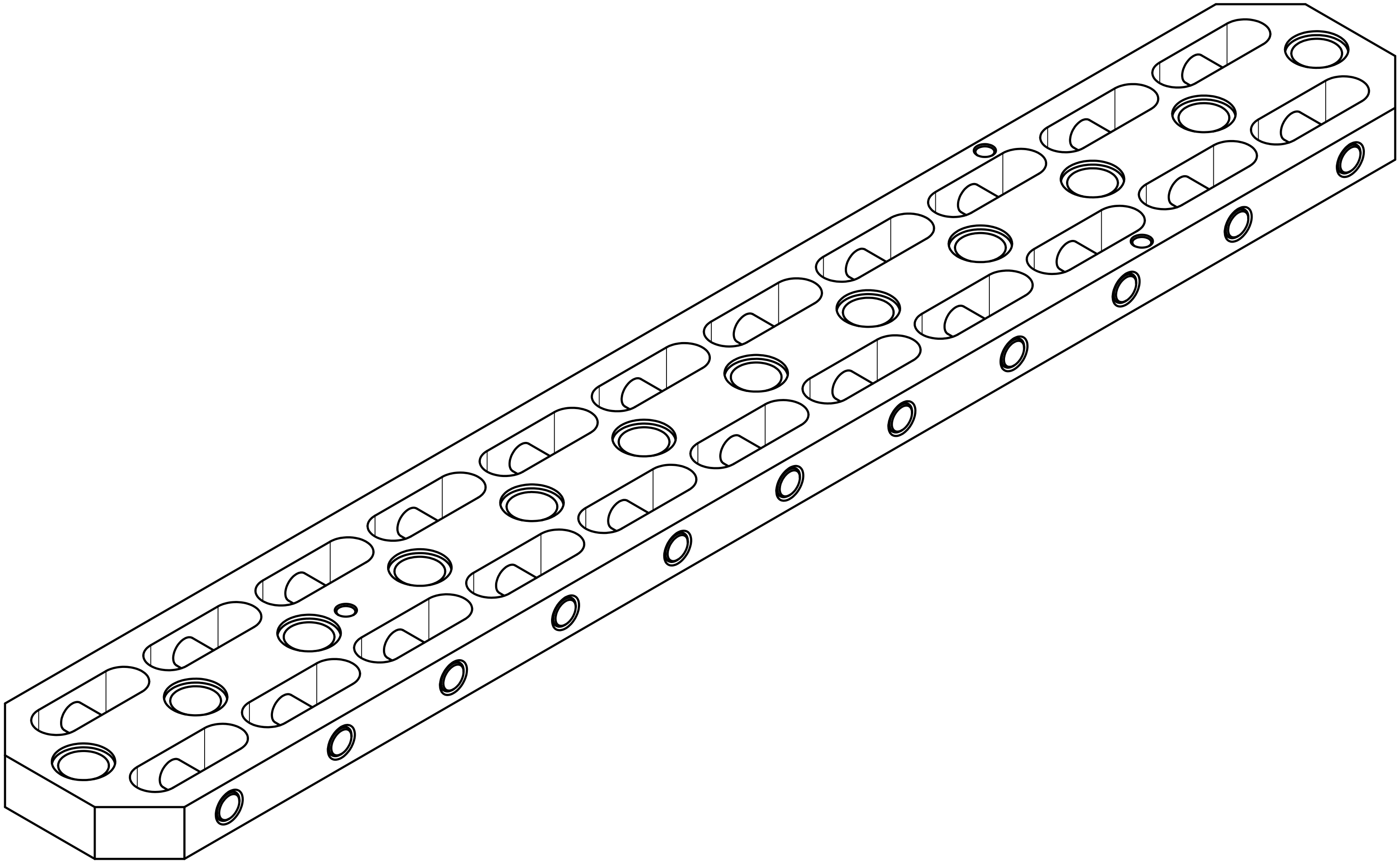

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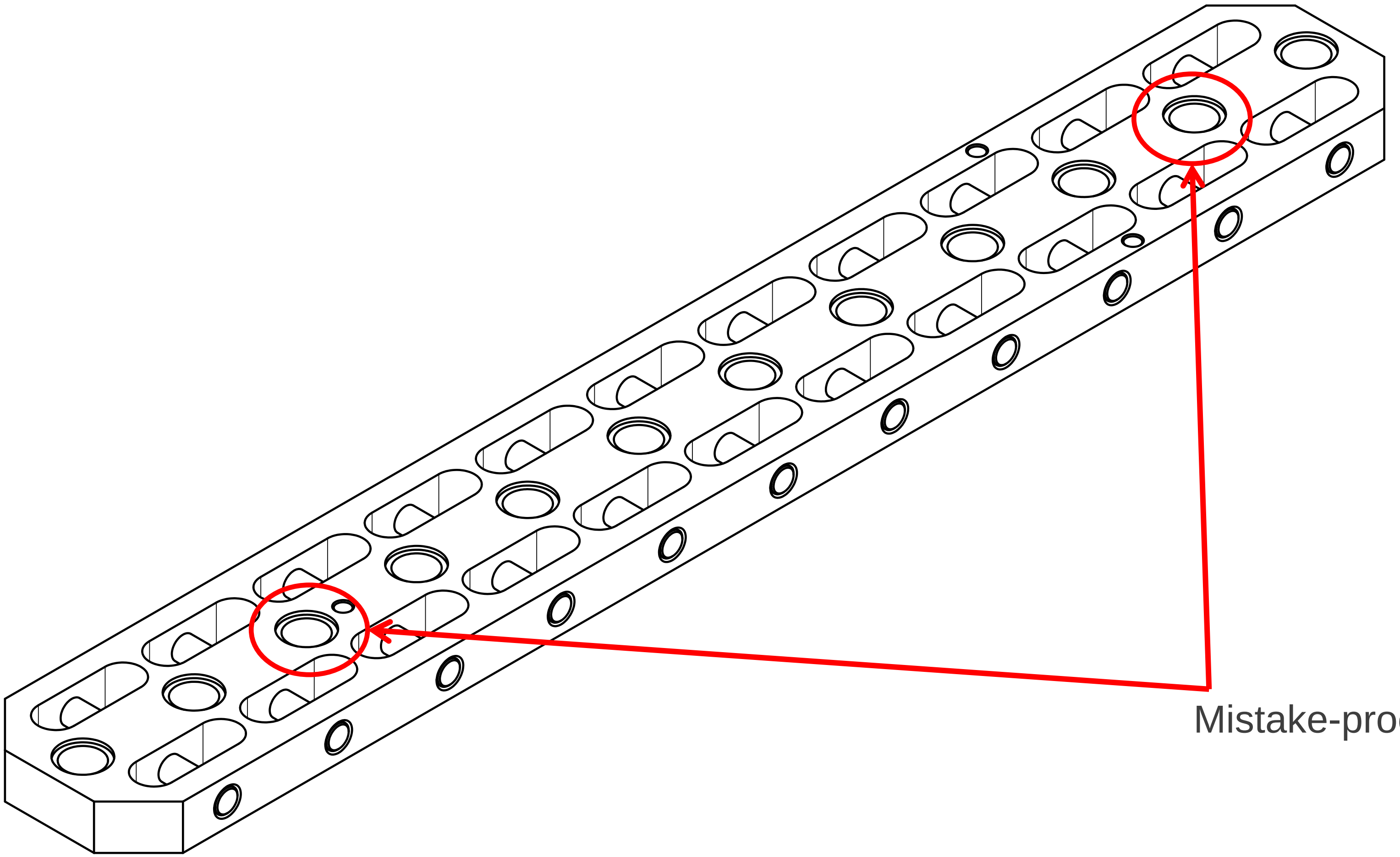

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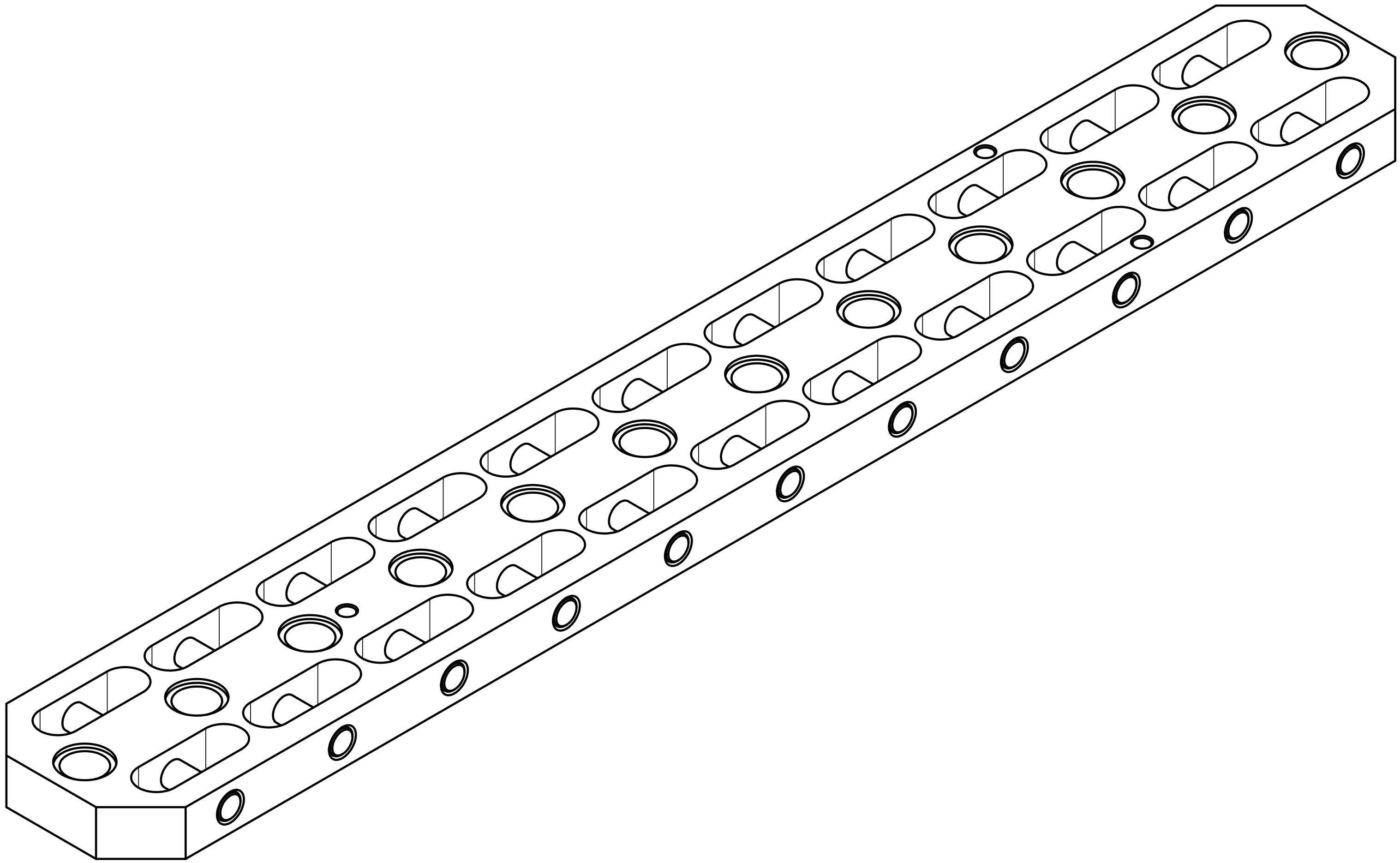

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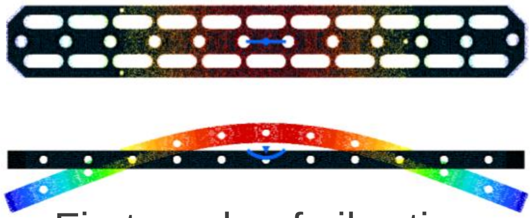
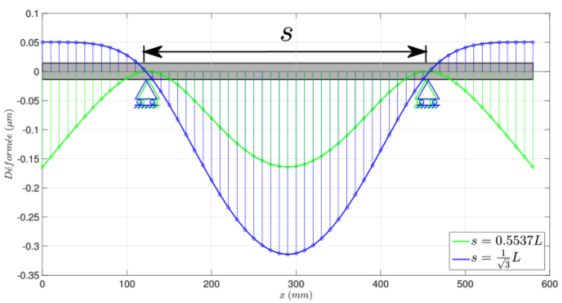
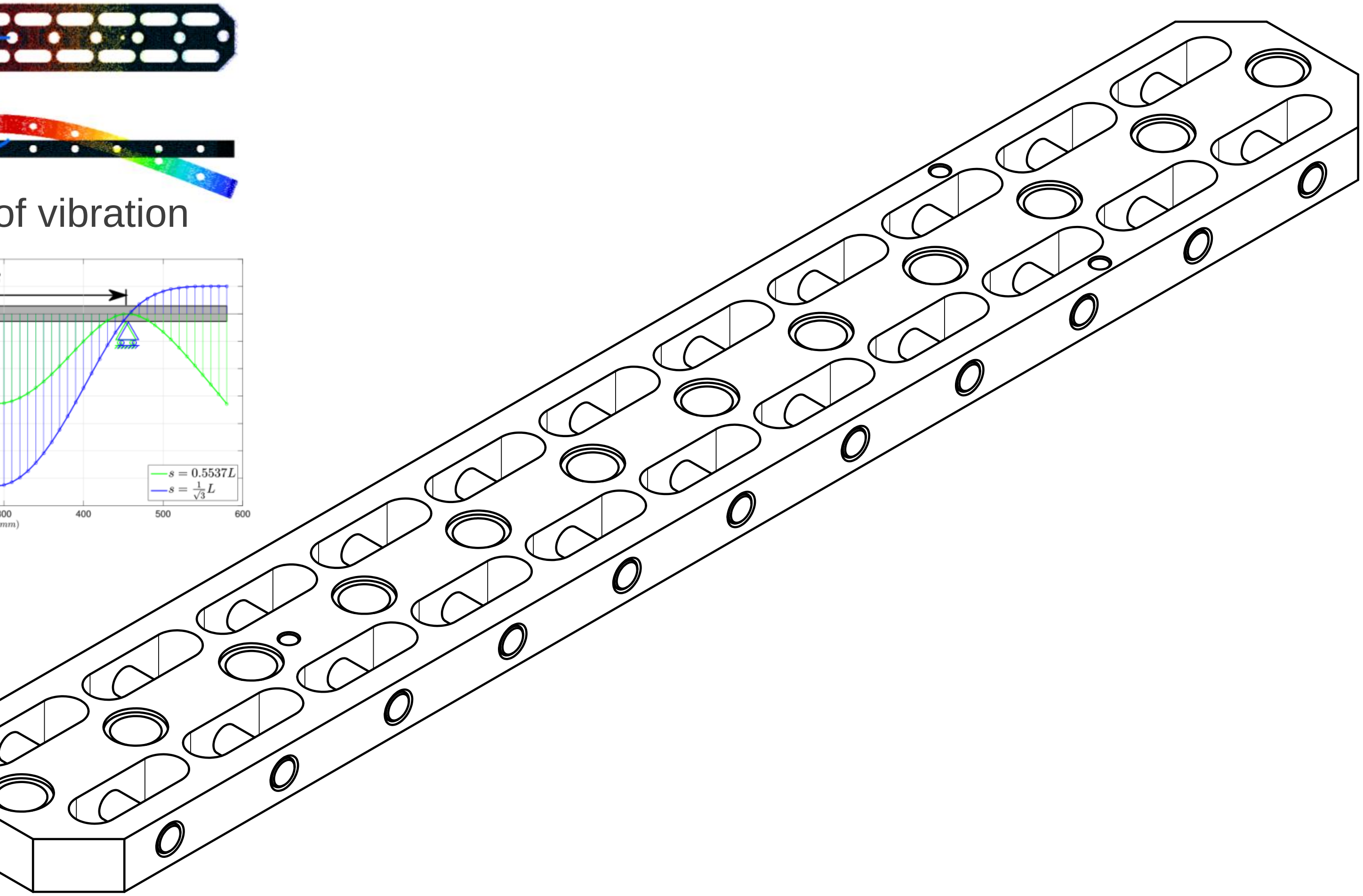


First mode of vibration





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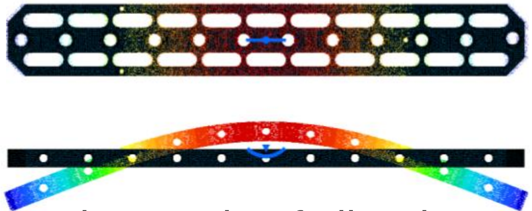

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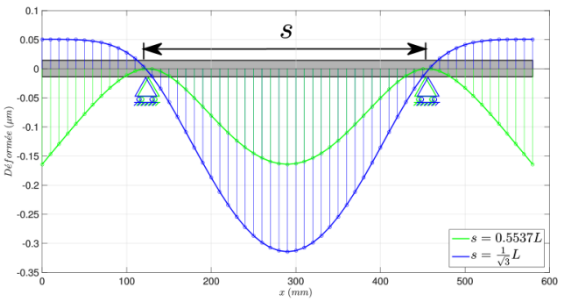
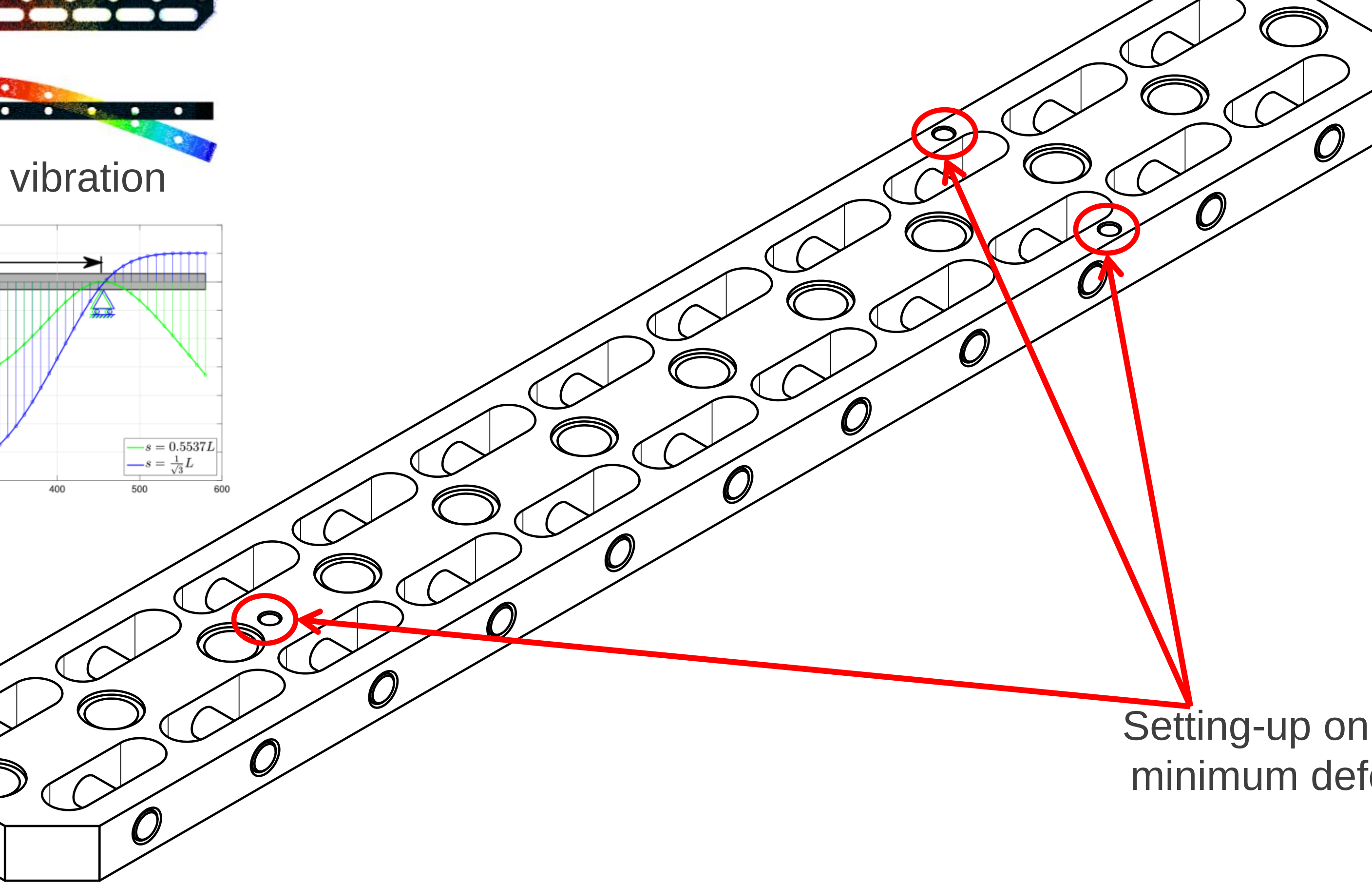
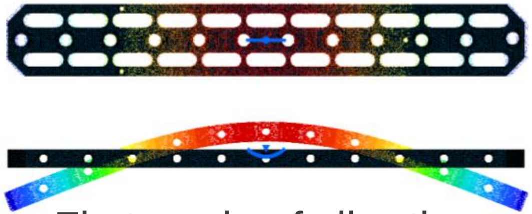




Setting-up on points of minimum deformation

Technical attributes of Hole-Bar (Invar)



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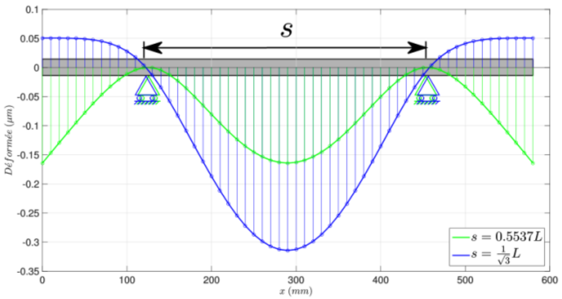

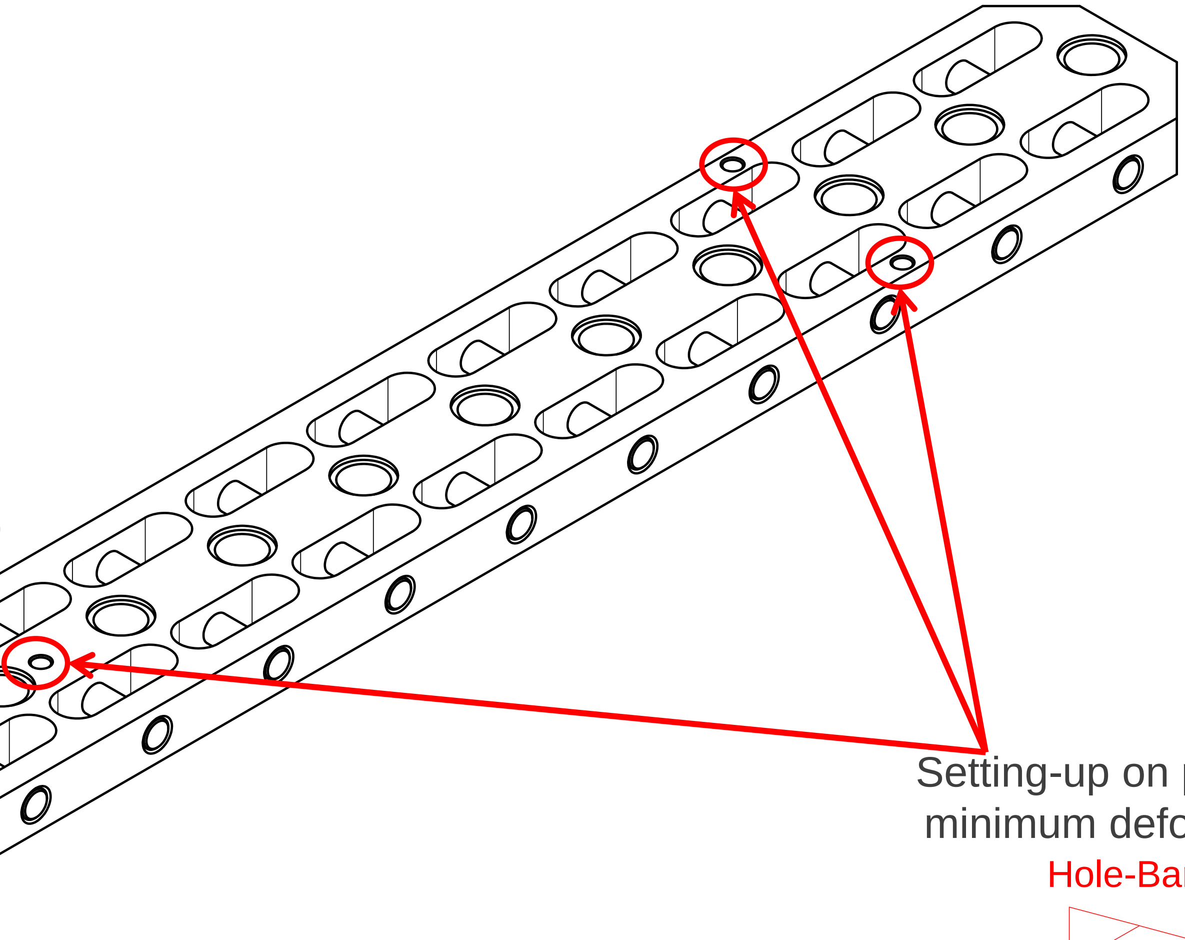

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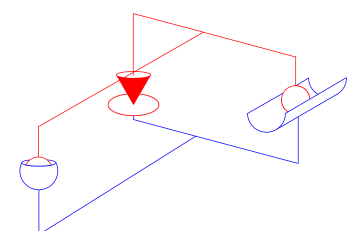

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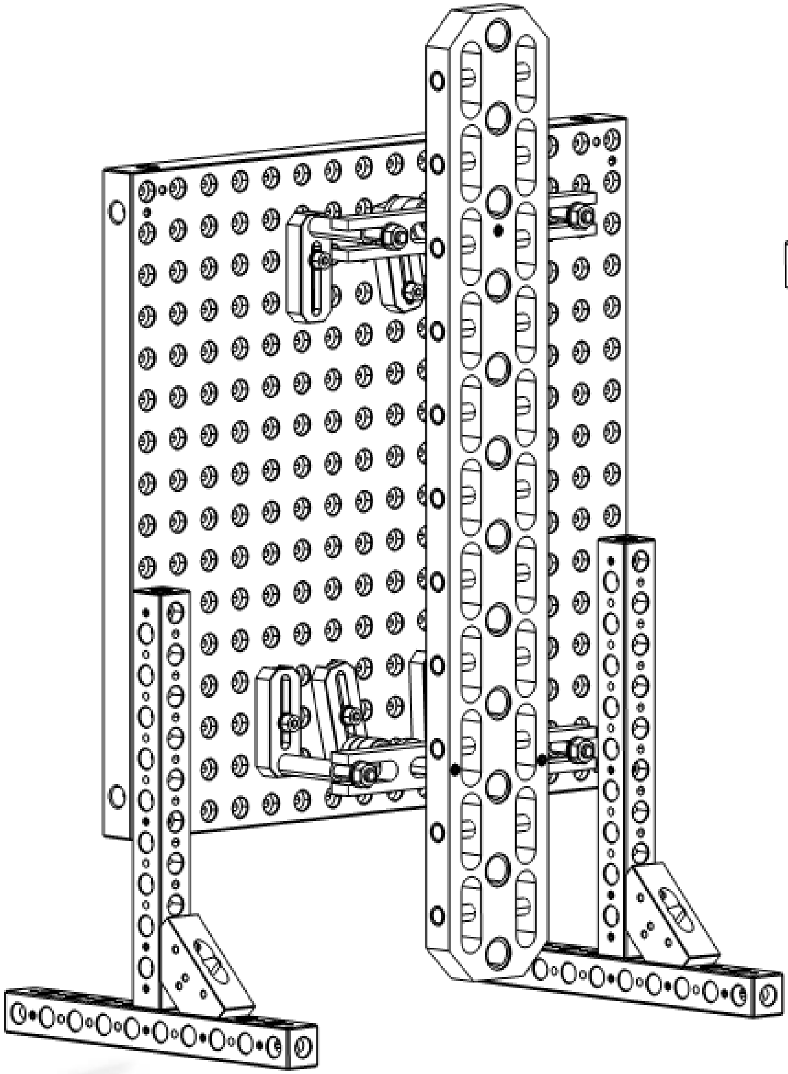
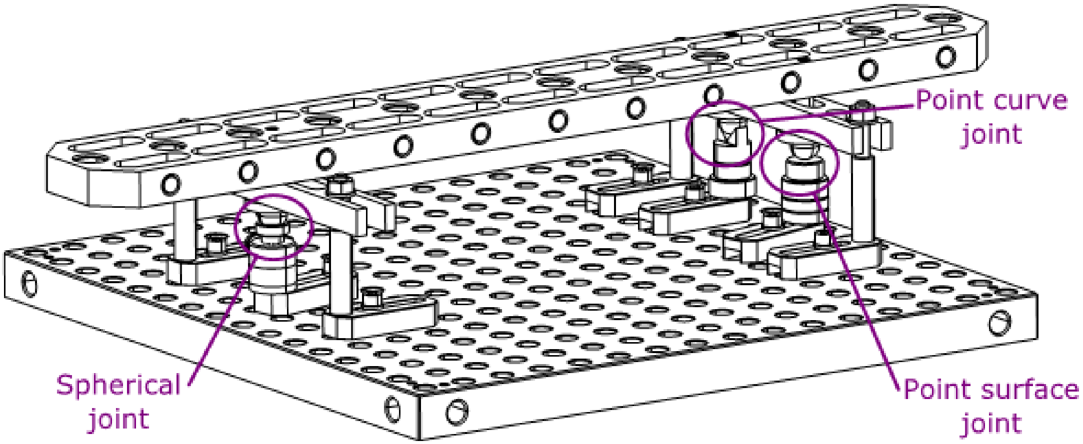
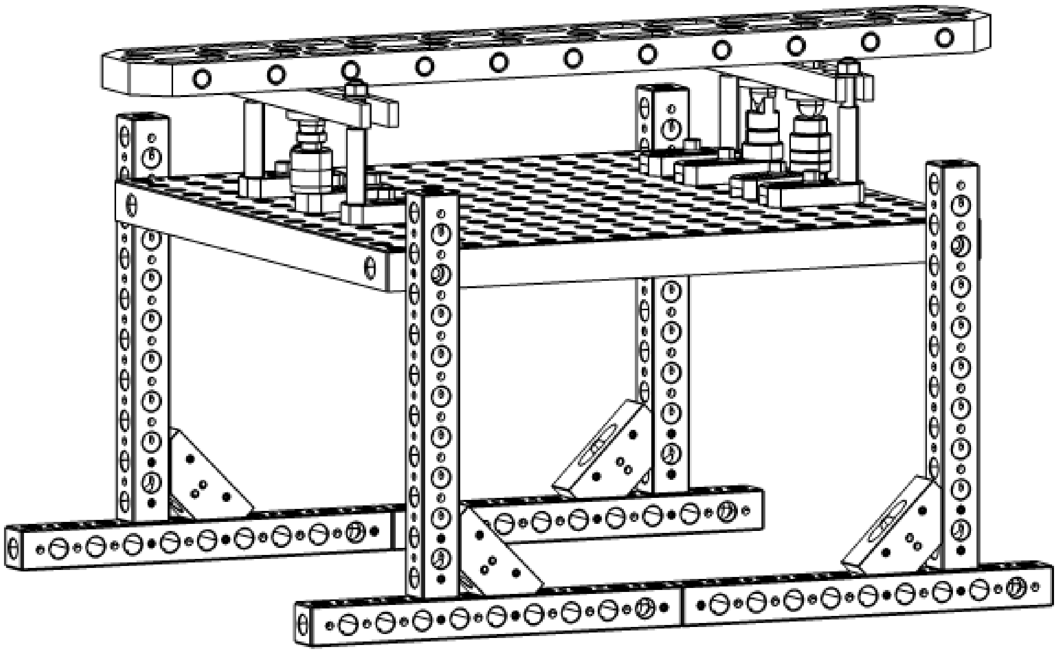


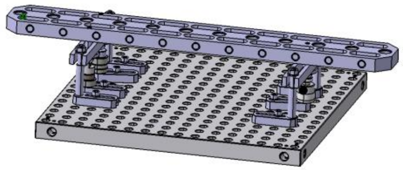




Coordinates of points of interest

Nominal coordinates (3D-CAD model)

$$\forall i \in [\![1\ ;\ N]\!],\quad \begin{pmatrix} x_i \\ y_i \\ z_i \end{pmatrix}_{R_{HB}} = \begin{pmatrix} (i-1) \times L \\ 0 \\ 0 \end{pmatrix}_{R_{HB}}$$



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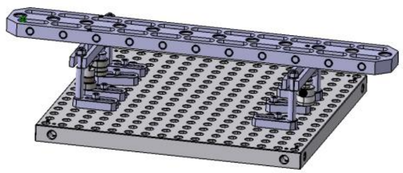
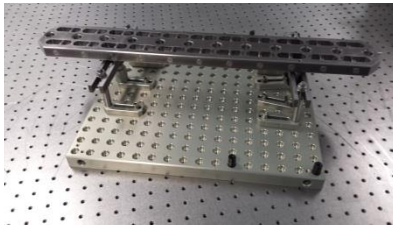


Real coordinates (real geometry)

$$\forall i \in [\![1\ ;\ N]\!],\quad \begin{pmatrix} x_i \\ y_i \\ z_i \end{pmatrix}_{R_{HB}} = \begin{pmatrix} (i-1) \times L & + E_{xx_{HB}}(i) \\ 0 & + E_{yx_{HB}}(i) \\ 0 & + E_{zx_{HB}}(i) \end{pmatrix}_{R_{HB}}$$



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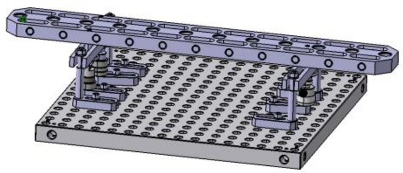

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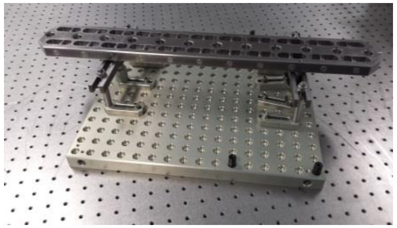

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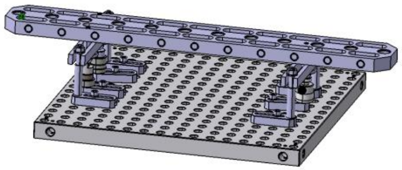

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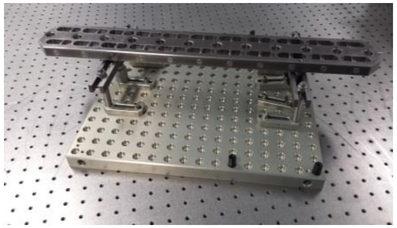

Calibration of the Hole-Bar on accurate CMM ➔ insures traceable measurements on machine tool

The reversal technique and substitution technique are applied to assess the calibration.

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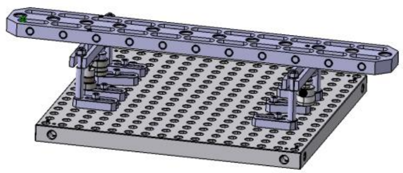
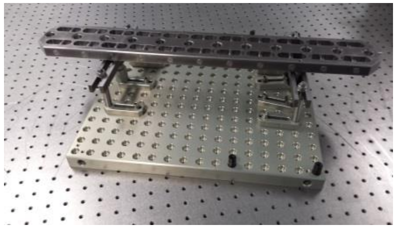


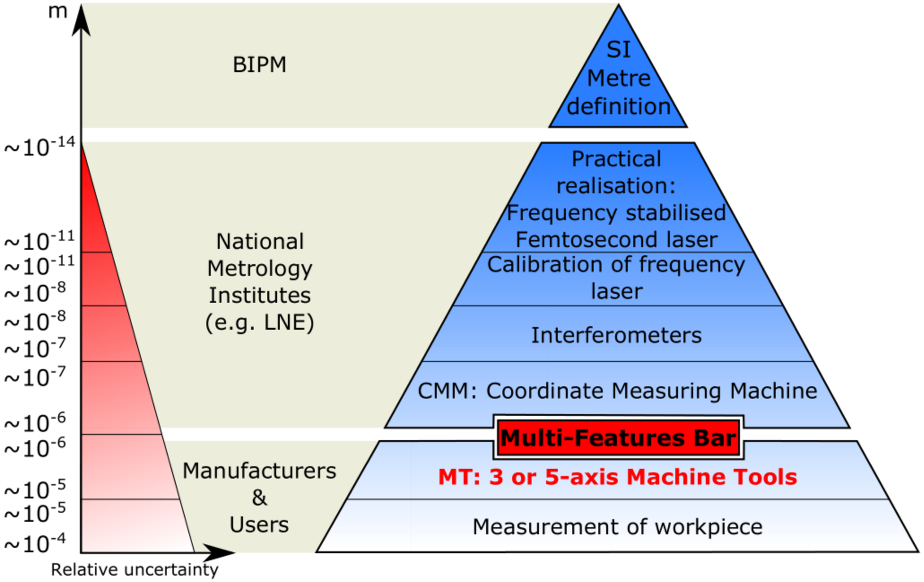
Real coordinates (real geometry)

$$\forall i \in [\![1\ ;\ N]\!],\quad \begin{pmatrix} x_i \\ y_i \\ z_i \end{pmatrix}_{R_{HB}} = \begin{pmatrix} (i-1)\times L & + \boxed{E_{xx_{HB}}(i)} \\ 0 & + \boxed{E_{yx_{HB}}(i)} \\ 0 & + \boxed{E_{zx_{HB}}(i)} \end{pmatrix}_{R_{HB}}$$

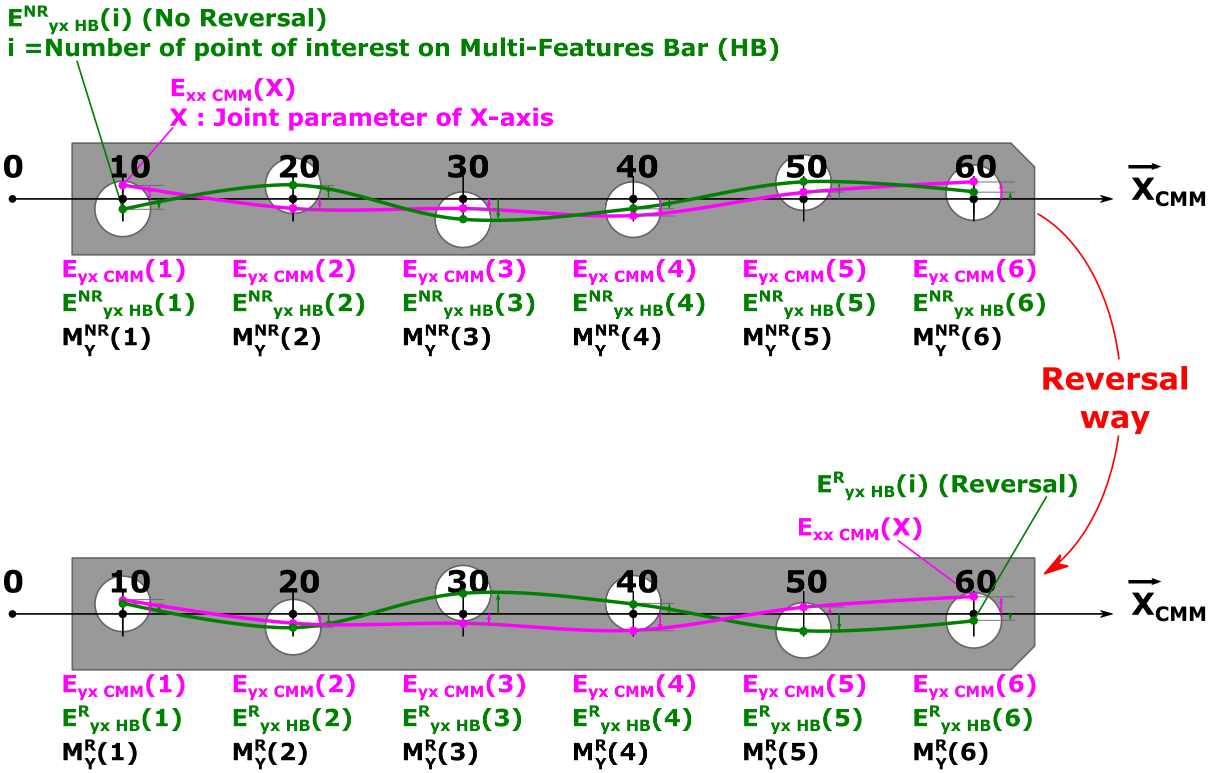


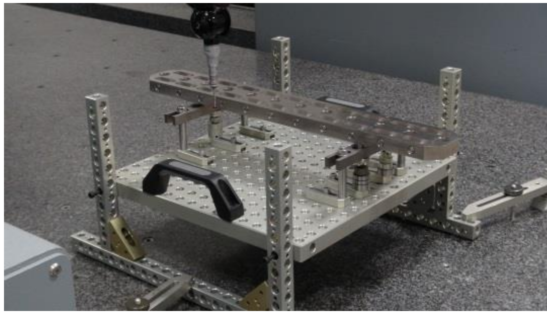
Calibration of the Hole-Bar on accurate CMM ➔ insures traceable measurements on machine tool

The reversal technique and substitution technique are applied to assess the calibration.

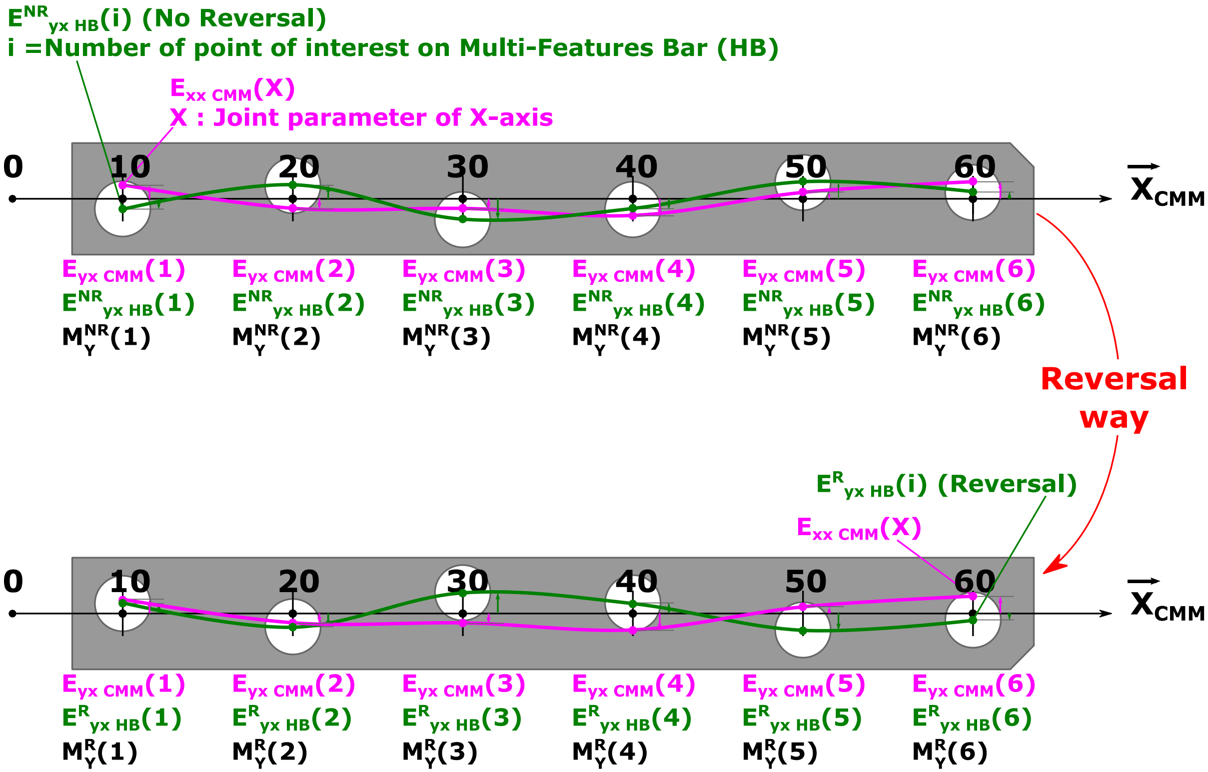


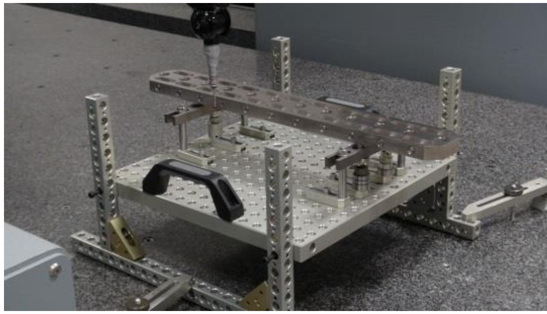
Calibration: Reversal technique





MFB calibration set-up on CMM at LNE



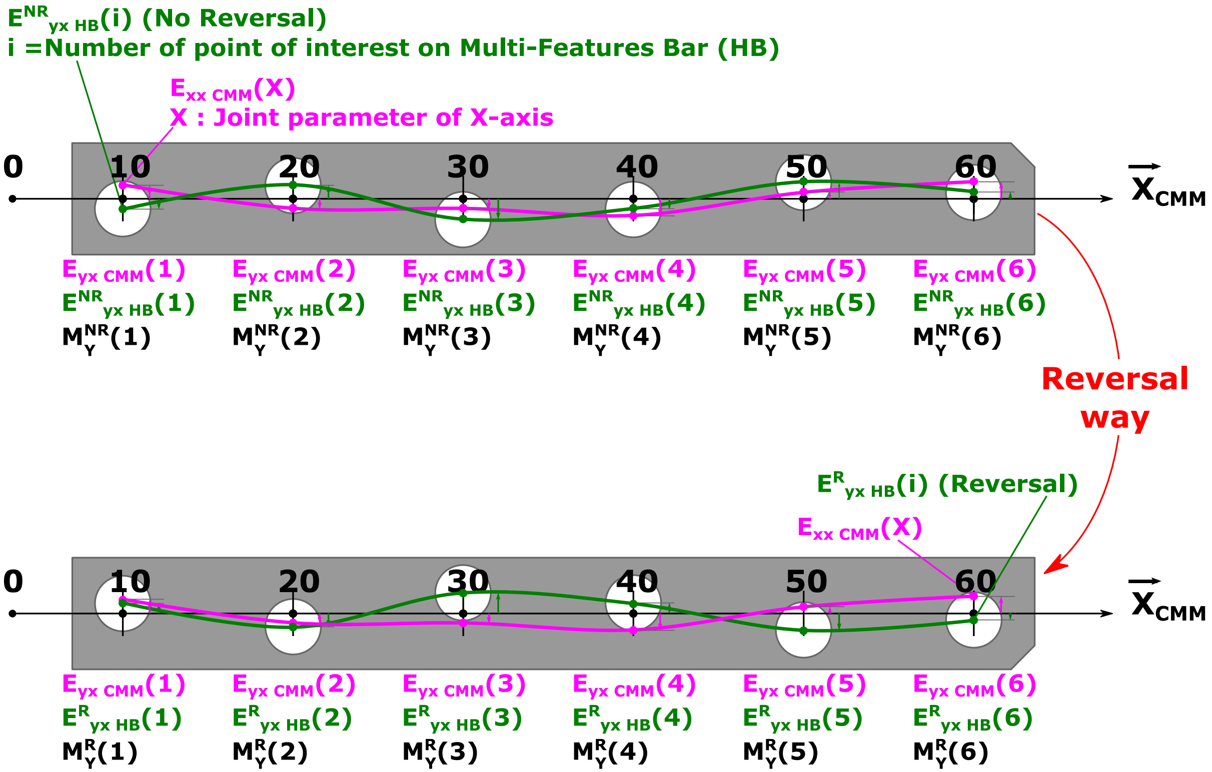


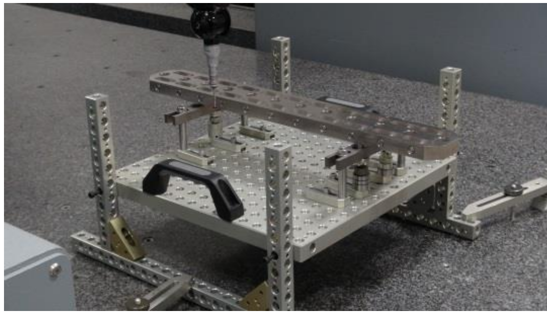
MFB calibration set-up on CMM at LNE

Linear positioning error along X_{HB}

$$E_{xx_{HB}}(i) = \frac{1}{2}\left[M_x^{NR}(i) + M_x^{R}(i)\right] - (i-1)\times L - E_{XX_{CMM}} - \epsilon_{ZZ_{CMM}}$$

Calibration: Reversal technique





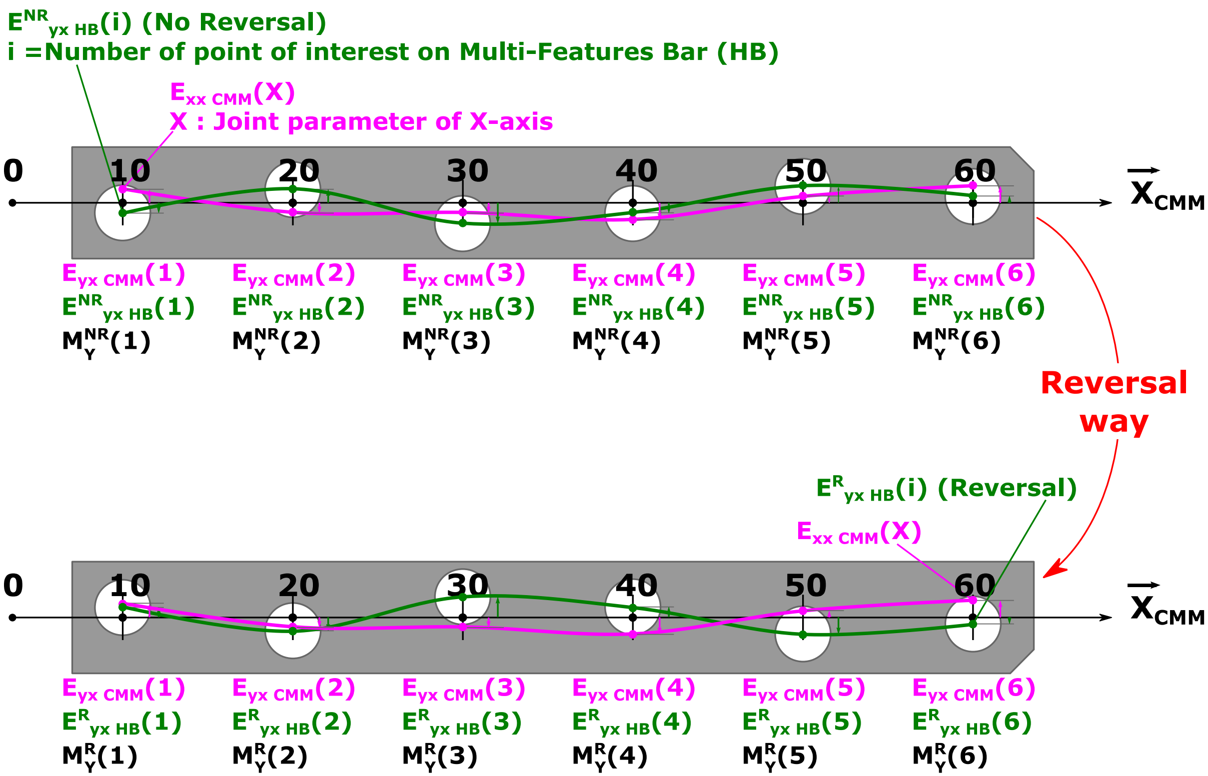
MFB calibration set-up on CMM at LNE

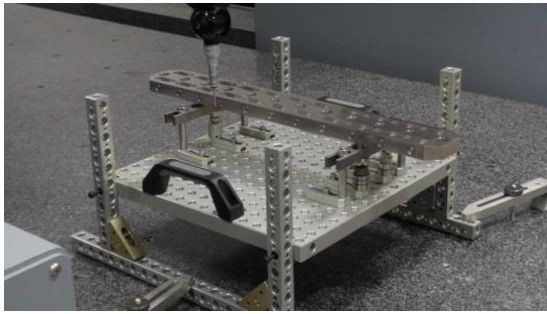
Linear positioning error along X_{HB}

Measurement — Nominal geometry — Linear positioning error along Z_{CMM} — Random error

$$E_{xx_{HB}}(i) = \frac{1}{2}\left[M_x^{NR}(i) + M_x^{R}(i)\right] - (i-1)\times L - E_{XX_{CMM}} - \epsilon_{ZZ_{CMM}}$$

Calibration: Reversal technique





MFB calibration set-up on CMM at LNE

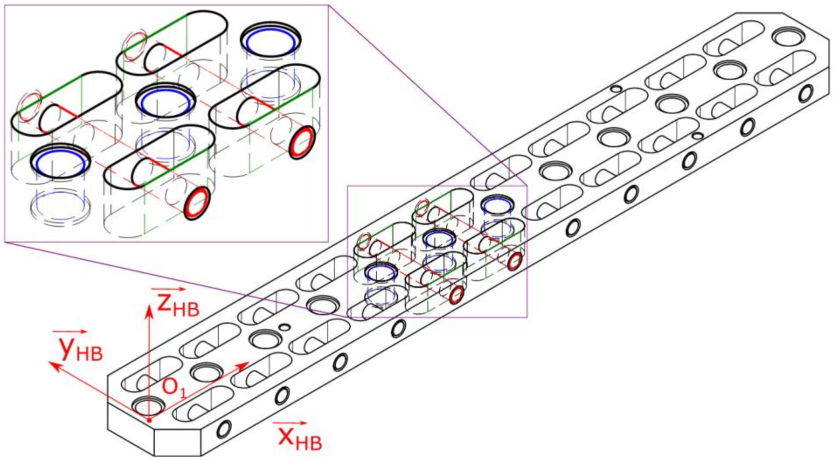
Measurement — Nominal geometry — Linear positioning error along Z_{CMM} — Random error

Linear positioning error along X_{HB}

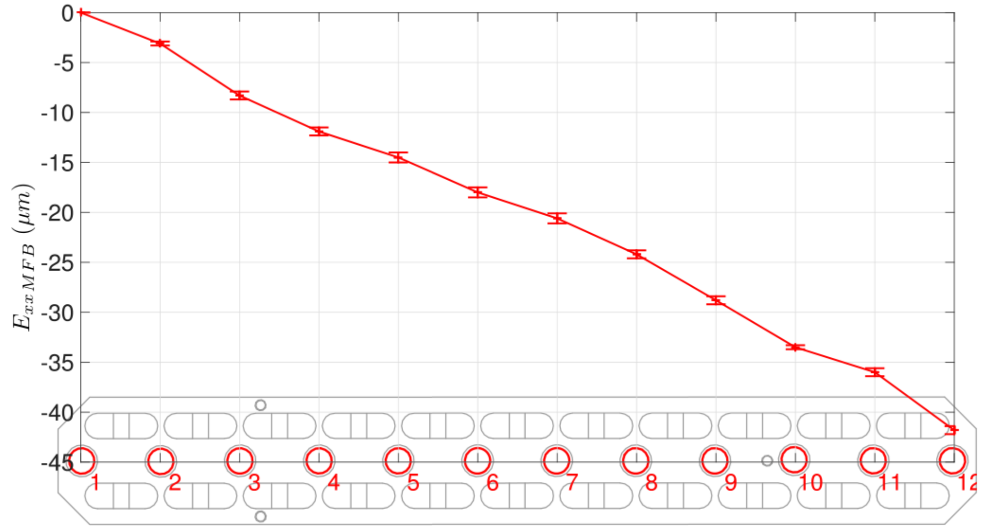
$$E_{xx_{HB}}(i) = \frac{1}{2}\left[M_x^{NR}(i) + M_x^{R}(i)\right] - (i-1)\times L - E_{XX_{CMM}} - \epsilon_{ZZ_{CMM}}$$

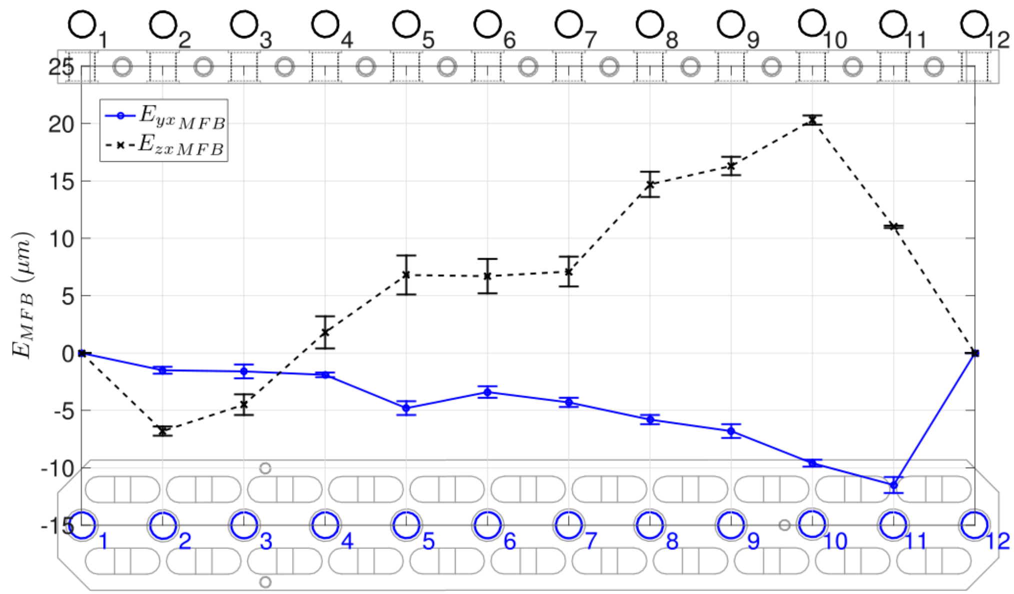
Straightness error along Y_{HB} and Z_{HB}

$$\begin{cases} E_{yx_{HB}}(i) = \frac{1}{2}\left[M_y^{NR}(i) - M_y^{R}(i)\right] - \epsilon_{YX_{CMM}} \\ E_{zx_{HB}}(i) = \frac{1}{2}\left[M_z^{NR}(i) - M_z^{R}(i)\right] - \epsilon_{ZX_{CMM}} \end{cases}$$

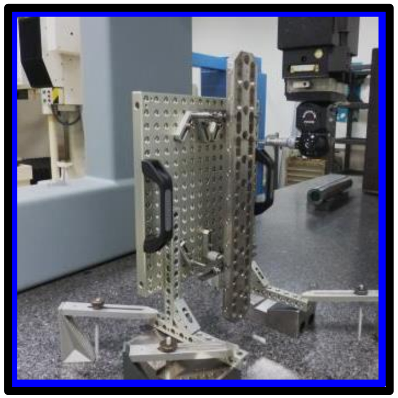


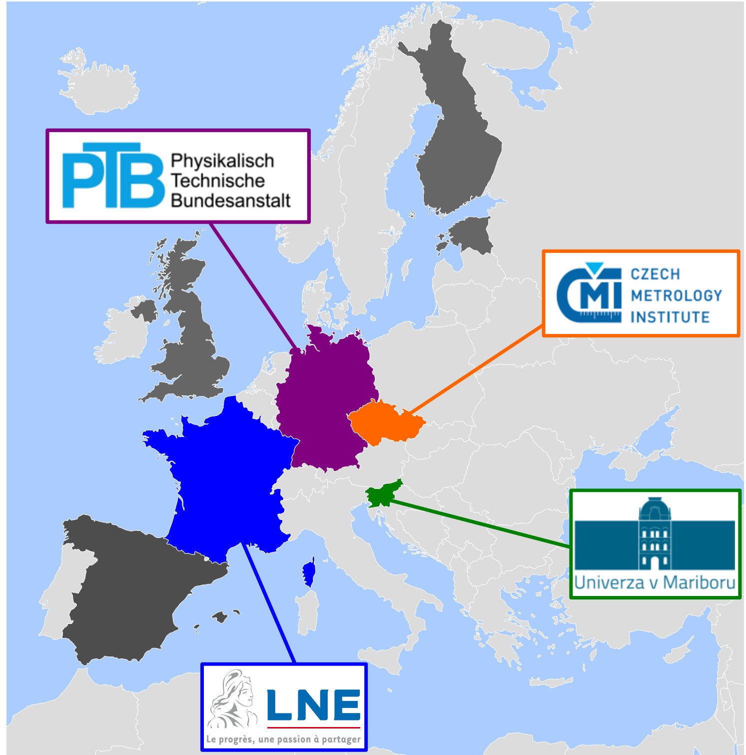
$$\forall i \in [\![1\ ;\ N]\!],\quad \begin{pmatrix} x_i \\ y_i \\ z_i \end{pmatrix}_{R_{HB}} = \begin{pmatrix} (i-1)\times L & +\ E_{xx_{HB}}(i) \\ 0 & +\ E_{yx_{HB}}(i) \\ 0 & +\ E_{zx_{HB}}(i) \end{pmatrix}_{R_{HB}}$$

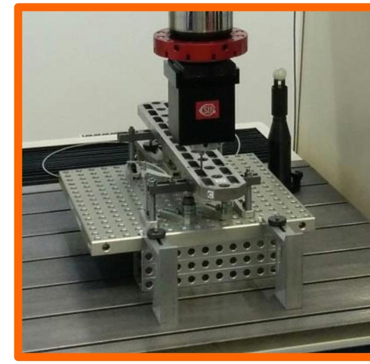


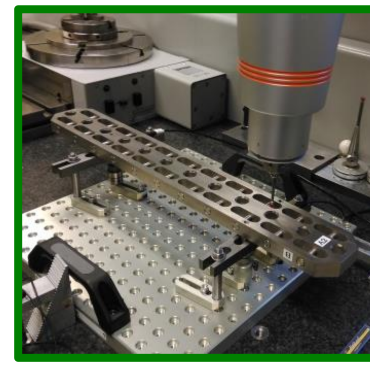


European Participants for intercomparison



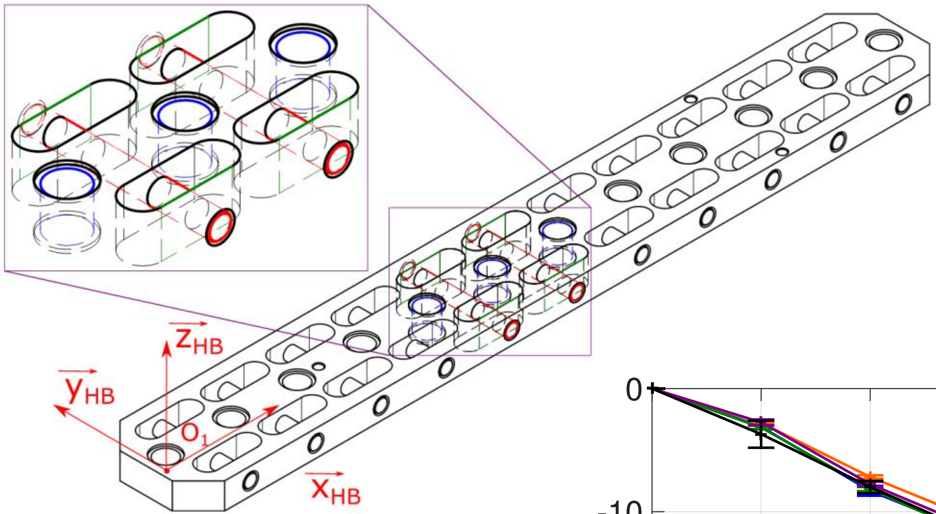




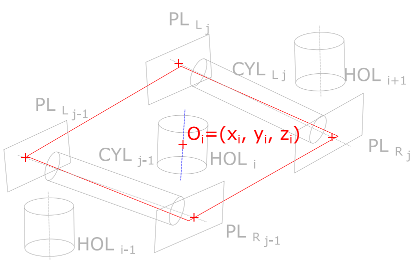


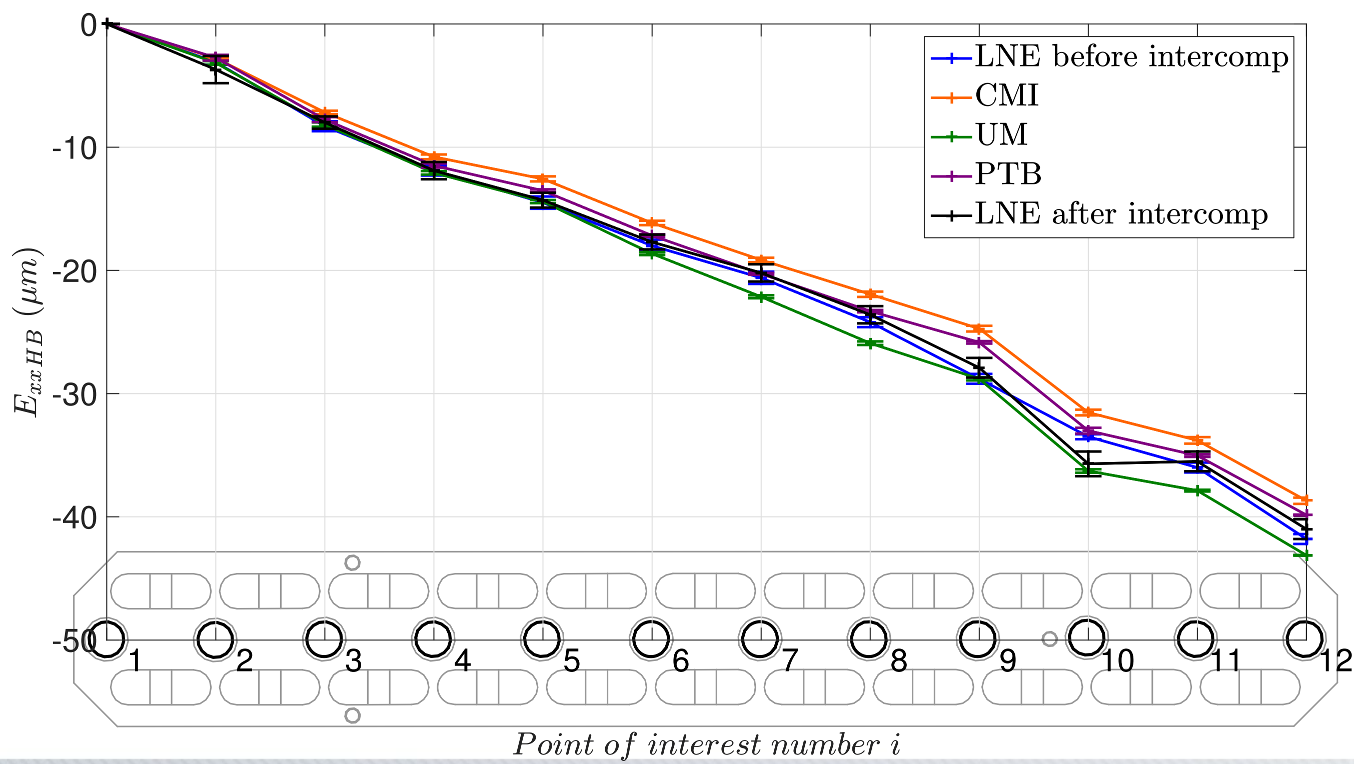
NMI	Type of CMM	Size of CMM (mm³)	U of CMM (µm+L(m)xµm)	T in metrology room (°C)	Along the CMM-axis	Operator	Signatory of CIPM MRA
LNE	Renault Automotion 251310	2500 x 1300 x 1000	4,5 + L x 4,0	20,26 ± 0,03	Z-axis	Fabien Viprey	Yes
CMI	SIP CMM5	710 x 710 x 550	0.8 + L x 1.3	19,73 ± 0,09	X-axis	Pavel Skalník	Yes
UM	Carl Zeiss UMC 850	1200 x 850 x 600	2,1 + L x 3,3	20,39 ± 0,03	Y-axis	Mitja Mlakar	Designated by MIRS
PTB	UPMC 850 CARAT	850 x 1200 x 600	0.8 + L x 3.5	20,18 ± 0,04	X-axis	Norbert Gerwien	Yes
LNE	Renault Automotion 251310	2500 x 1300 x 1000	4,5 + L x 4,0	20,04 ± 0,03	Z-axis	Fabien Viprey	Yes

Results: Linear positioning error along X_{HB}

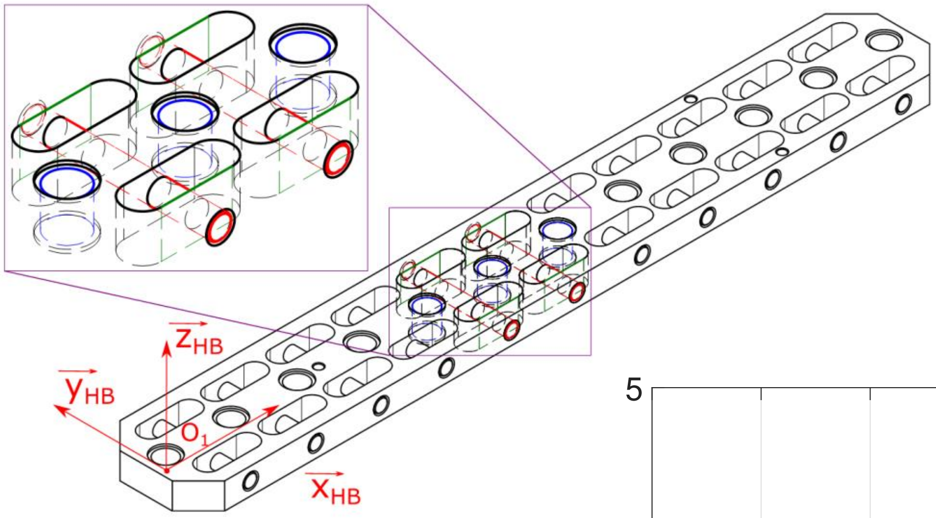


$$\forall i \in [\![1\ ;\ N]\!],\quad \begin{pmatrix} x_i \\ y_i \\ z_i \end{pmatrix}_{R_{HB}} = \begin{pmatrix} (i-1)\times L & + E_{xx_{HB}}(i) \\ 0 & + E_{yx_{HB}}(i) \\ 0 & + E_{zx_{HB}}(i) \end{pmatrix}_{R_{HB}}$$

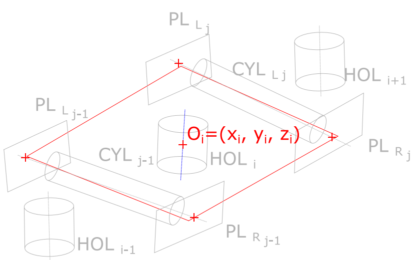


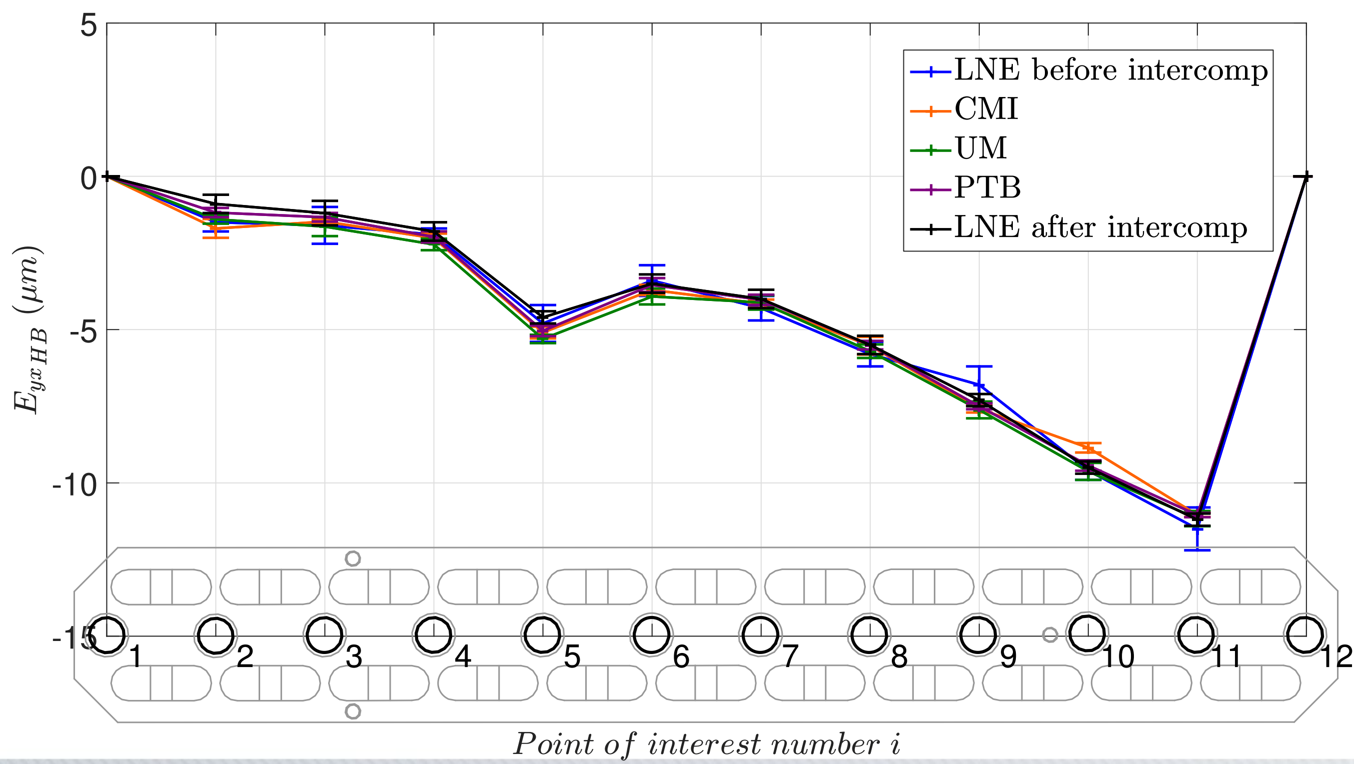


Results: Straightness error along Y_{HB}

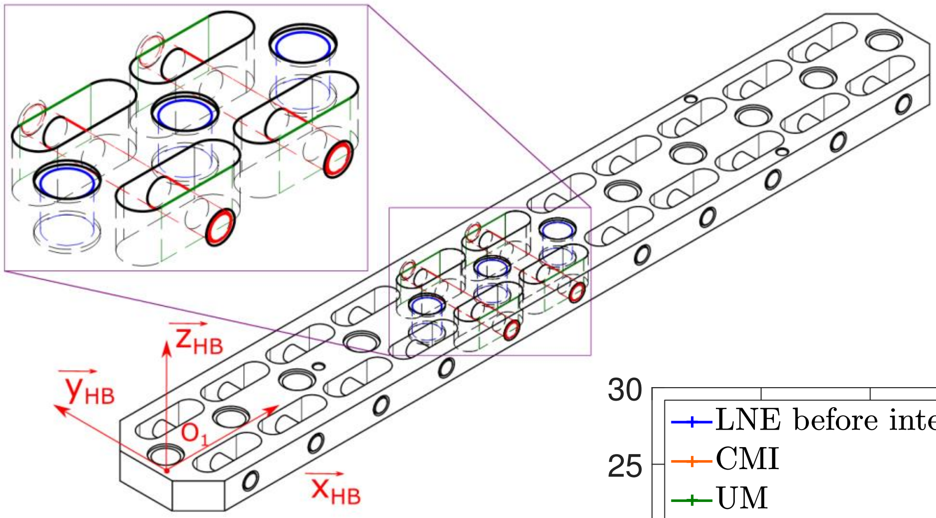


$$\forall i \in [\![1 \; ; \; N]\!], \quad \begin{pmatrix} x_i \\ y_i \\ z_i \end{pmatrix}_{R_{HB}} = \begin{pmatrix} (i-1)\times L & + E_{xx_{HB}}(i) \\ 0 & + E_{yx_{HB}}(i) \\ 0 & + E_{zx_{HB}}(i) \end{pmatrix}_{R_{HB}}$$

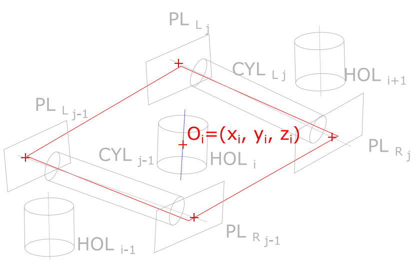


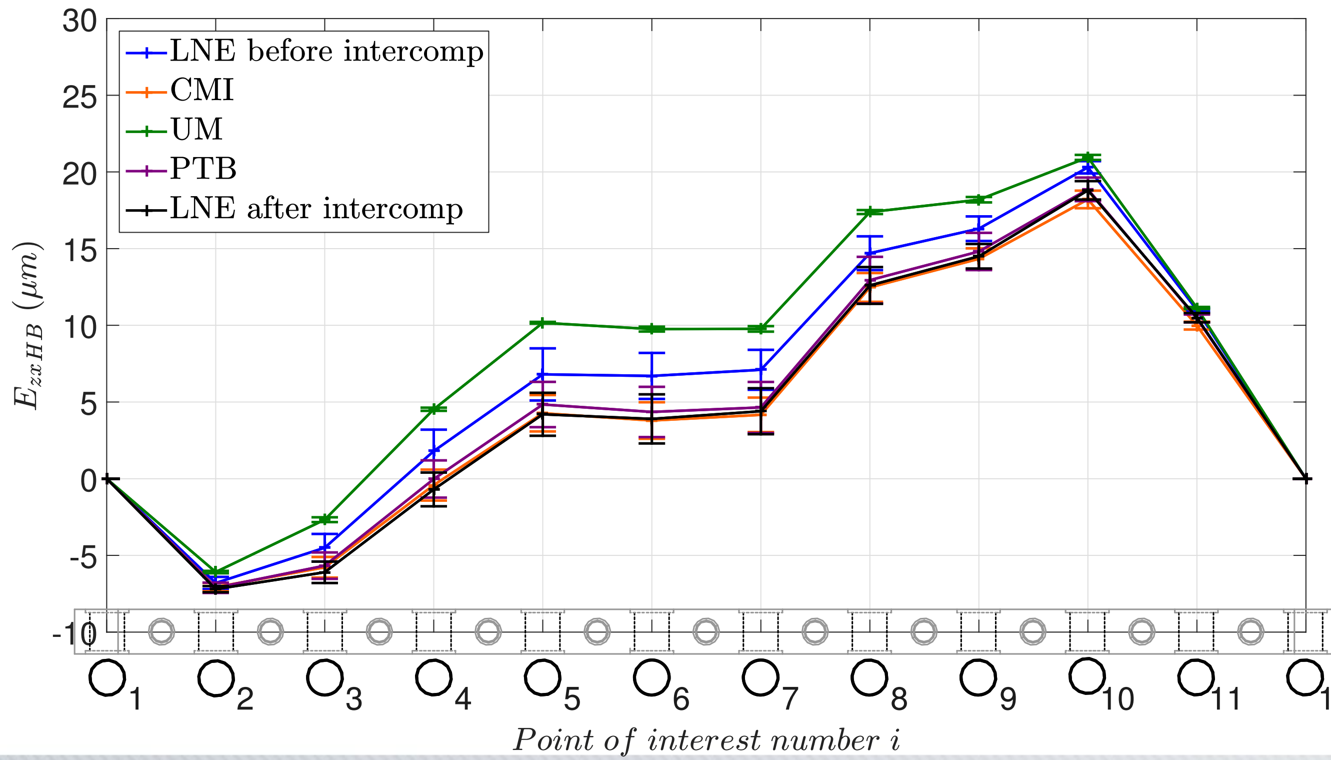


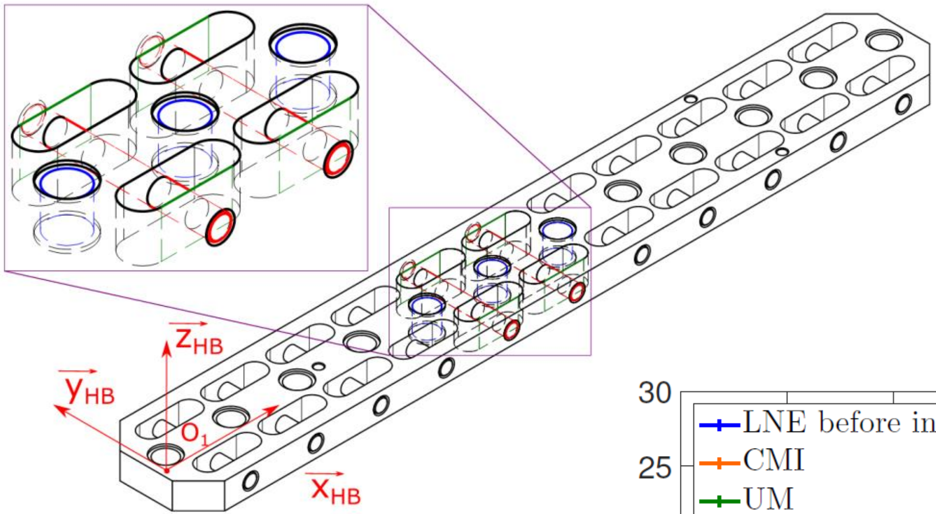
Results: Straightness error along Z_{HB}



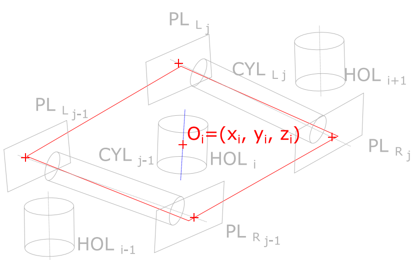
$$\forall i \in [\![1\ ;\ N]\!],\ \begin{pmatrix} x_i \\ y_i \\ z_i \end{pmatrix}_{R_{HB}} = \begin{pmatrix} (i-1)\times L & + E_{xx_{HB}}(i) \\ 0 & + E_{yx_{HB}}(i) \\ 0 & + E_{zx_{HB}}(i) \end{pmatrix}_{R_{HB}}$$

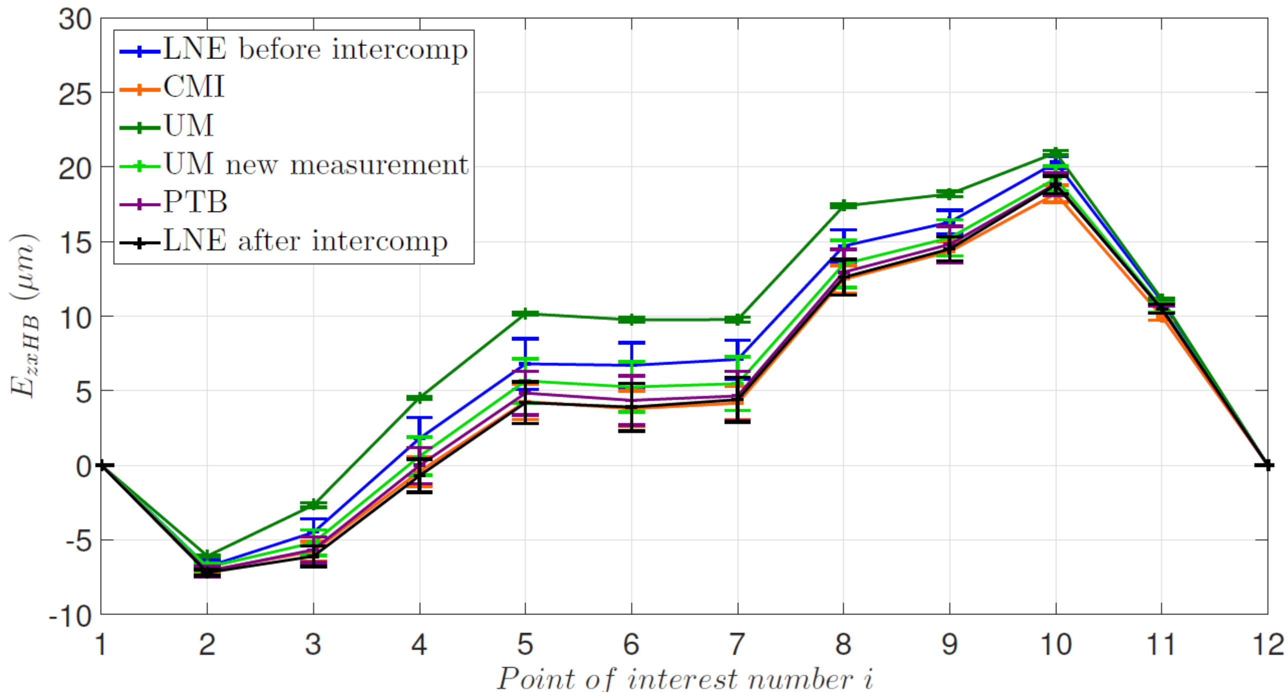






$$\forall i \in [\![1\ ;\ N]\!],\quad \begin{pmatrix} x_i \\ y_i \\ z_i \end{pmatrix}_{R_{HB}} = \begin{pmatrix} (i-1)\times L & +\ E_{xx_{HB}}(i) \\ 0 & +\ E_{yx_{HB}}(i) \\ 0 & +\ E_{zx_{HB}}(i) \end{pmatrix}_{R_{HB}}$$

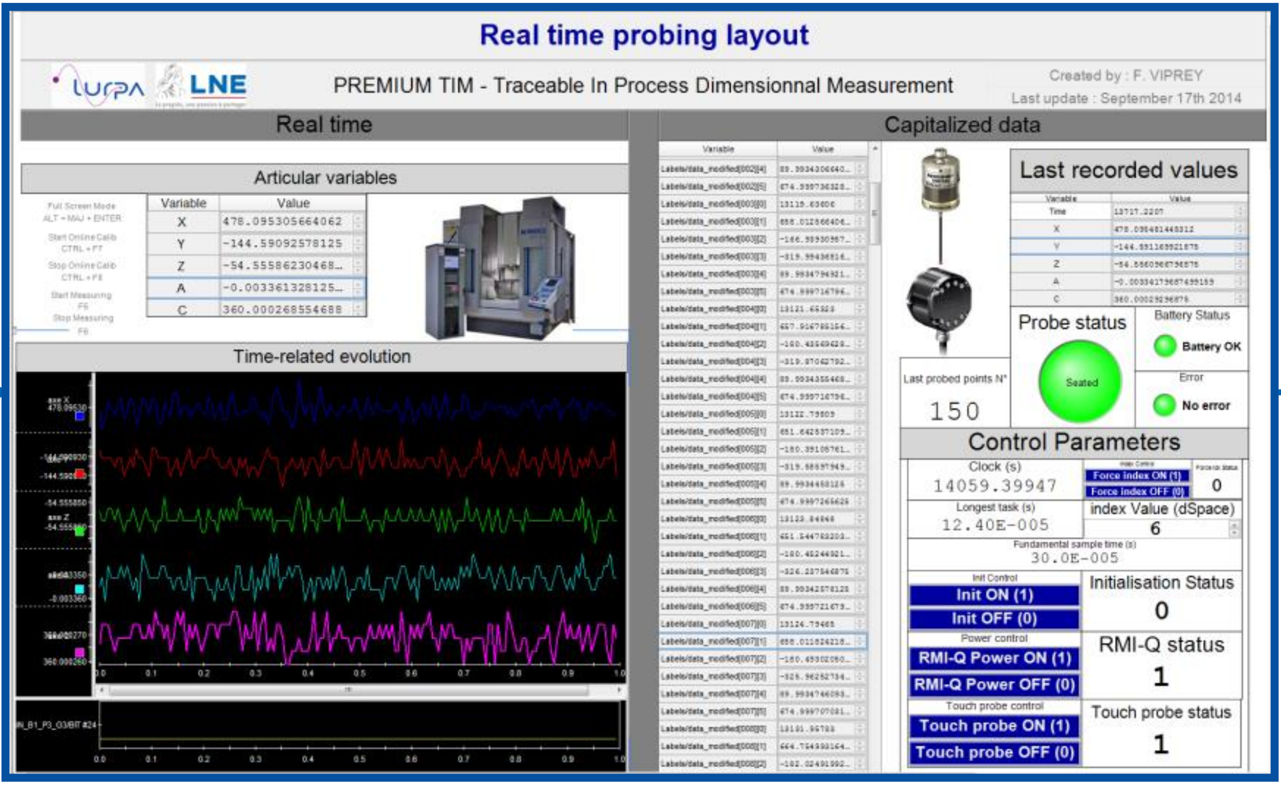




Real time plateform for Identification of geometric errors

Mikron UCP710

Probing trajectory →



→ Real time probing

Developed end user interface

F=33,33 kHz

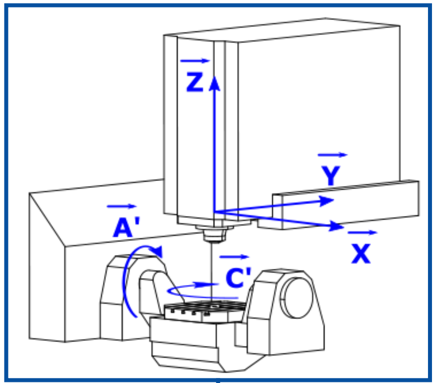
T=30 µs

Resolution = 10 nm

$U_{(k=2)\ RMP600}$ = 0,25 µm

$U_{delay\ max\ at\ 240mm/min}$ = 0,47µm

Geometric model of 3-axis chain of the investigated machine tools



$$
\underbrace{\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&1&0\\0&0&0&1\end{bmatrix}}_{^{R_f}\mathbb{T}_{R_{nom\,X}}}
\underbrace{\begin{bmatrix}1&0&0&X\\0&1&0&0\\0&0&1&0\\0&0&0&1\end{bmatrix}}_{^{R_{nom\,X}}\mathbb{T}_{R_{motion\,X}}}
\underbrace{\begin{bmatrix}1&-E_{CX}&E_{BX}&E_{XX}\\E_{CX}&1&-E_{AX}&E_{YX}\\-E_{BX}&E_{AX}&1&E_{ZX}\\0&0&0&1\end{bmatrix}}_{^{R_{motion\,X}}\mathbb{T}_{R_{nom\,Y}}}\times
$$

$$
\underbrace{\begin{bmatrix}1&-E_{C0Y}&0&0\\E_{C0Y}&1&0&0\\0&0&1&0\\0&0&0&1\end{bmatrix}}_{^{R_{nom\,Y}}\mathbb{T}_{R_{mean\,Y}}}
\underbrace{\begin{bmatrix}1&0&0&0\\0&1&0&Y\\0&0&1&0\\0&0&0&1\end{bmatrix}}_{^{R_{mean\,Y}}\mathbb{T}_{R_{motion\,Y}}}
\underbrace{\begin{bmatrix}1&-E_{CY}&E_{BY}&E_{XY}\\E_{CY}&1&-E_{AY}&E_{YY}\\-E_{BY}&E_{AY}&1&E_{ZY}\\0&0&0&1\end{bmatrix}}_{^{R_{motion\,Y}}\mathbb{T}_{R_{nom\,Z}}}\times
$$

$$
\underbrace{\begin{bmatrix}1&0&E_{B0Z}&0\\0&1&-E_{A0Z}&0\\-E_{B0Z}&E_{A0Z}&1&0\\0&0&0&1\end{bmatrix}}_{^{R_{nom\,Z}}\mathbb{T}_{R_{mean\,Z}}}
\underbrace{\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&1&Z\\0&0&0&1\end{bmatrix}}_{^{R_{mean\,Z}}\mathbb{T}_{R_{motion\,Z}}}\times
$$

$$
\underbrace{\begin{bmatrix}1&-E_{CZ}&E_{BZ}&E_{XZ}\\E_{CZ}&1&-E_{AZ}&E_{YZ}\\-E_{BZ}&E_{AZ}&1&E_{ZZ}\\0&0&0&1\end{bmatrix}}_{^{R_{motion\,Z}}\mathbb{T}_{R_{nom\,T}}}
\underbrace{\begin{bmatrix}1&0&0&-J_X\\0&1&0&-J_Y\\0&0&1&-J_Z\\0&0&0&1\end{bmatrix}}_{^{R_{nom\,T}}\mathbb{T}_{R_T}}\times
\underbrace{\begin{bmatrix}0\\0\\0\\1\end{bmatrix}}_{\mathbf{p}_{t/R_T}} =
$$

$$
\underbrace{\begin{bmatrix}a&d&g&p_x\\b&e&h&p_y\\c&f&i&p_z\\0&0&0&1\end{bmatrix}}_{^{R_f}\mathbb{T}_{R_W}}\times
\underbrace{\begin{bmatrix}x\\y\\z\\1\end{bmatrix}}_{\mathbf{p}_{w/R_w}}
$$

Differential analysis

$$
\begin{aligned}
\delta X = &-E_{XX}(X) - E_{XY}(Y) - E_{XZ}(Z)\\
&-(E_{B0Z} + E_{BX}(X) + E_{BY}(Y)) \times G(x, y, z)\\
&+(E_{C0Y} + E_{CX}(X)) \times F(x, y, z)\\
&+E_{BZ}(Z) \times J_Z\\
&-(E_{CY}(Y) + E_{CZ}(Z)) \times J_Y
\end{aligned}
$$

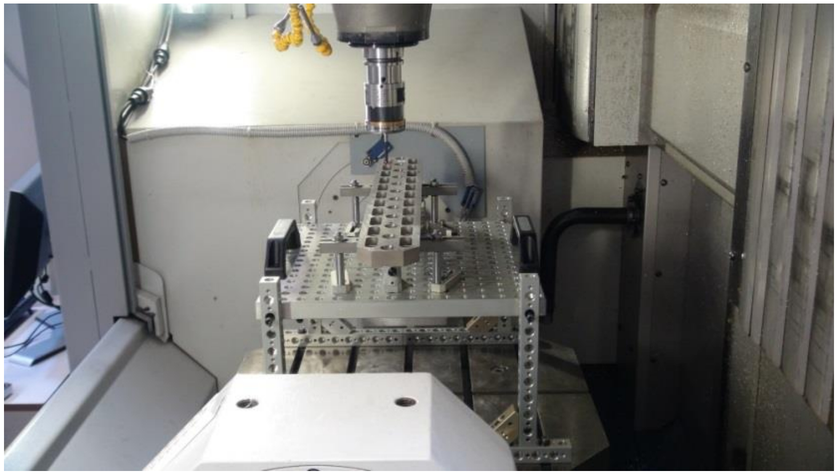
$$
\begin{aligned}
\delta Y = &-E_{YX}(X) - E_{YY}(Y) - E_{YZ}(Z)\\
&+(E_{A0Z} + E_{AX}(X) + E_{AY}(Y)) \times G(x, y, z)\\
&-E_{AZ}(Z) \times J_Z\\
&+(E_{C0Y} + E_{CX}(X) + E_{CY}(Y) + E_{CZ}(Z)) \times J_X
\end{aligned}
$$

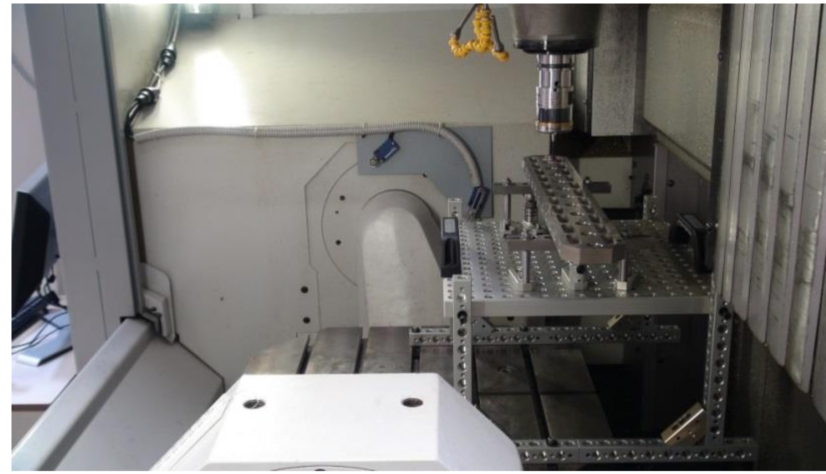
$$
\begin{aligned}
\delta Z = &-E_{ZX}(X) - E_{ZY}(Y) - E_{ZZ}(Z)\\
&-E_{AX}(X) \times F(x, y, z)\\
&+(E_{A0Z} + E_{AY}(Y) + E_{AZ}(Z)) \times J_Y\\
&-(E_{B0Z} + E_{BX}(X) + E_{BY}(Y) + E_{BZ}(Z)) \times J_X
\end{aligned}
$$

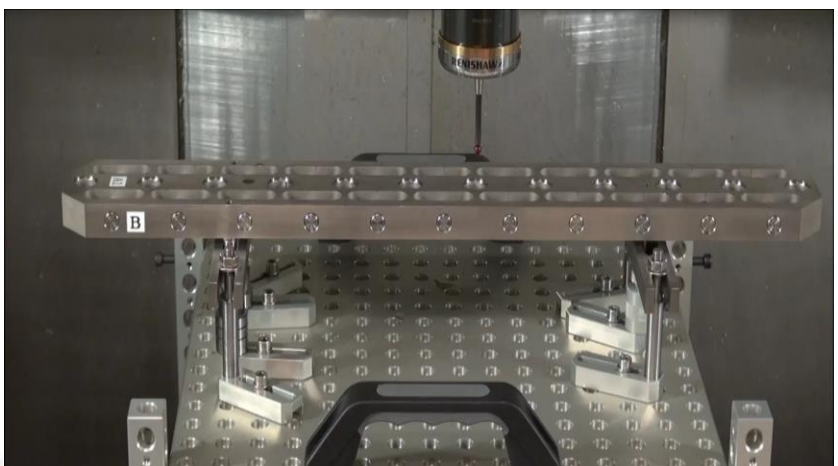
Geometric errors effects on the joint parameters

Application on Mikron UCP710 5-axis machine tool:

E_{XX} , E_{YX} , E_{ZX} , E_{AX} , E_{BX} and E_{CX} along the X-axis identified on the points of interest O_i of the Hole-Bar:



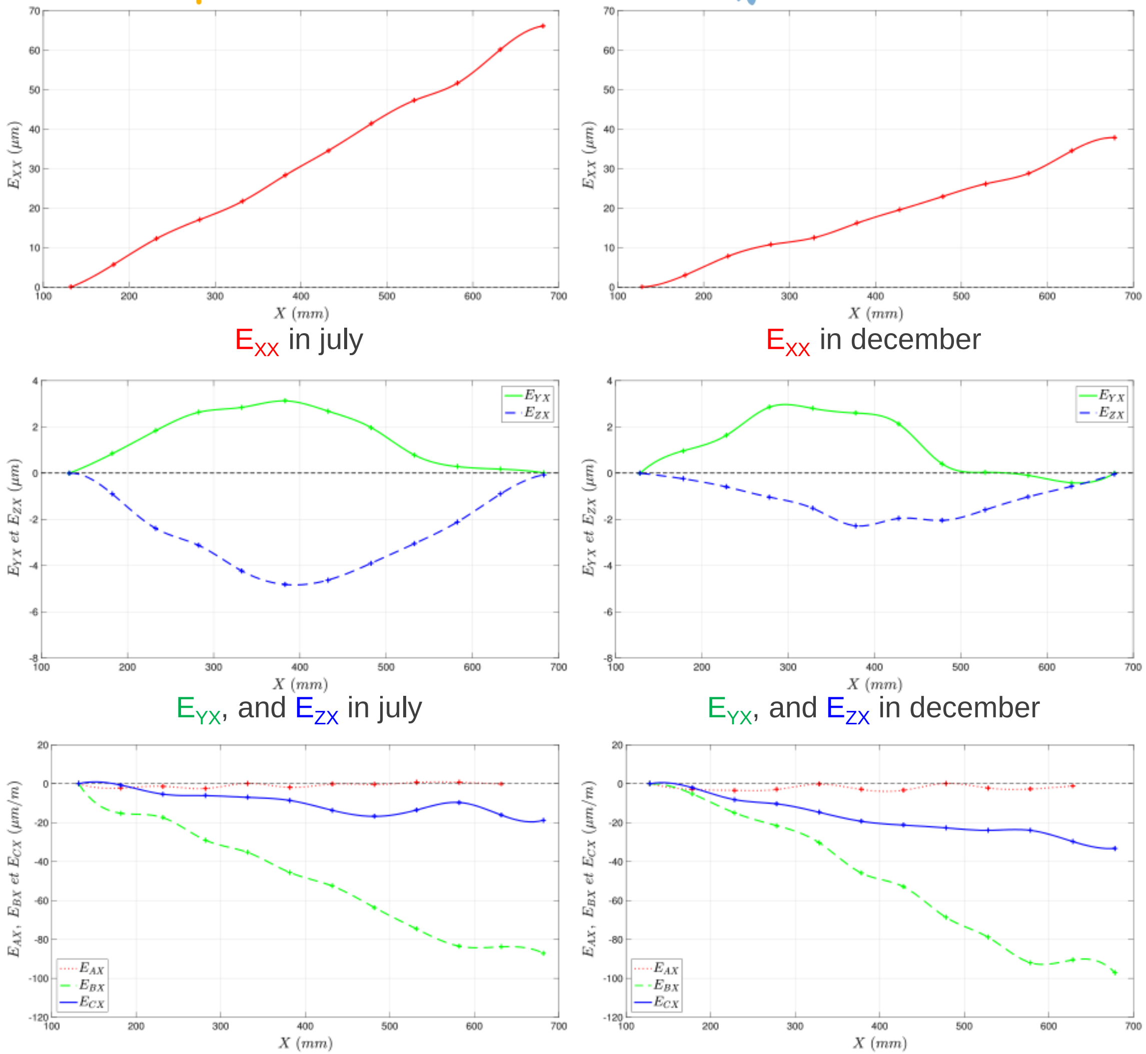




Results of identification in the shop floor

T=27±1°C

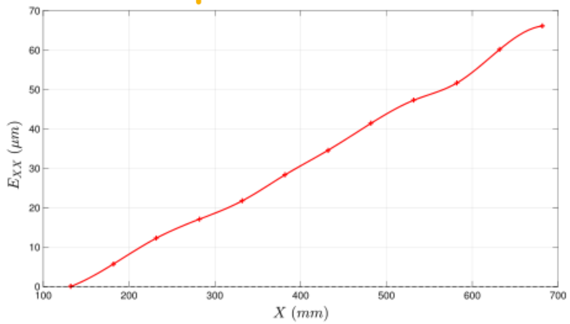
T=20±1°C



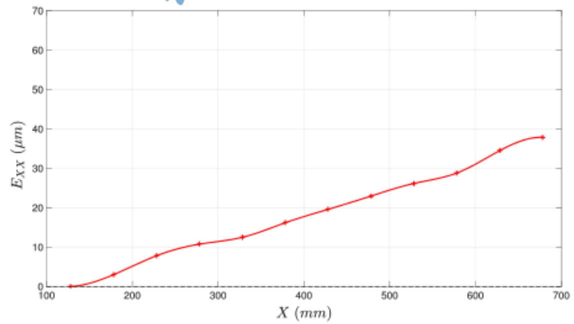
Results of identification in the shop floor

T=27±1°C

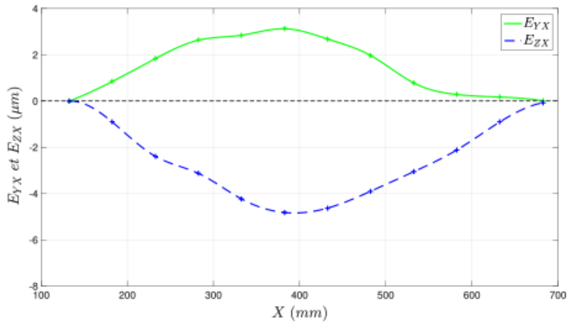
T=20±1°C



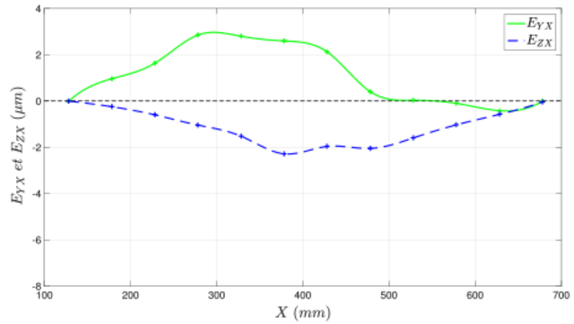
E_{XX} in july



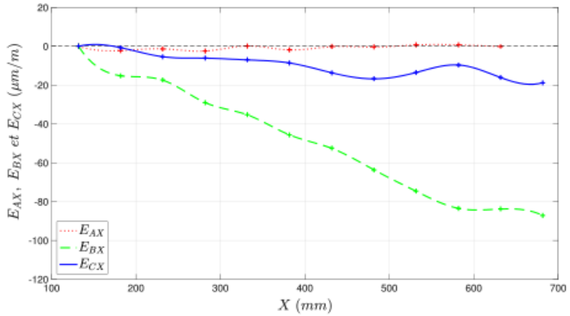
E_{XX} in december



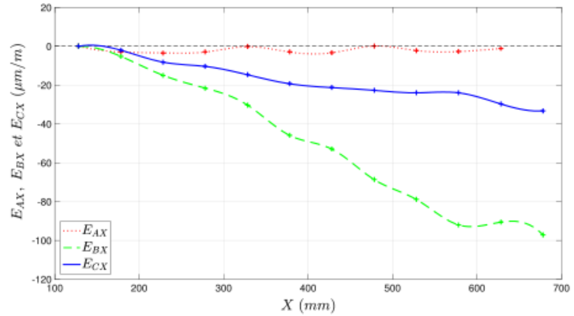
E_{YX}, and E_{ZX} in july



E_{YX}, and E_{ZX} in december



E_{AX}, E_{BX}, and E_{CX} in july



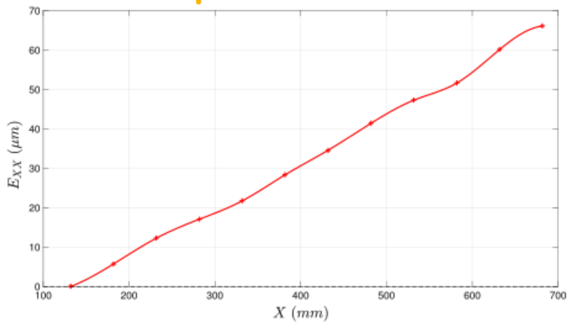
E_{AX}, E_{BX}, and E_{CX} in december

Identified geometric errors depend on the environmental conditions

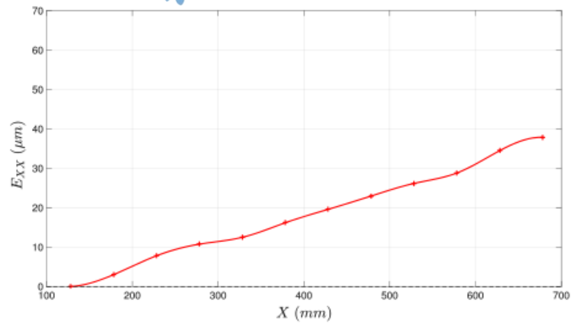
Results of identification in the shop floor

T=27±1°C

T=20±1°C

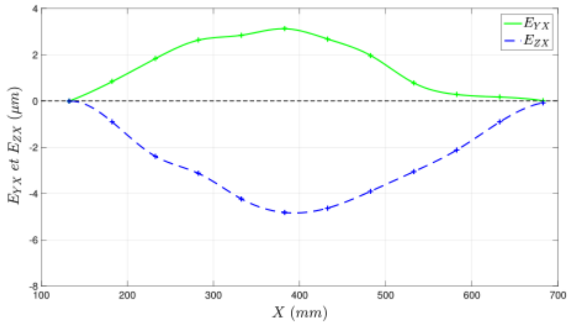


E_{XX} in july

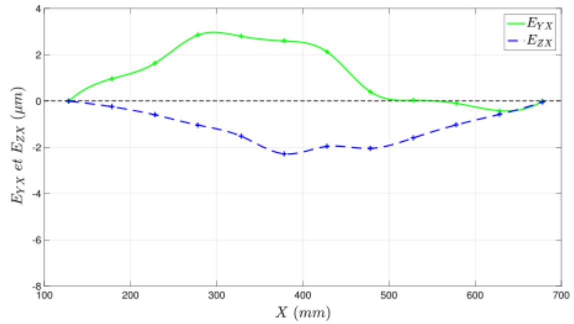


E_{XX} in december

Identified geometric errors depend on the environmental conditions



E_{YX}, and E_{ZX} in july

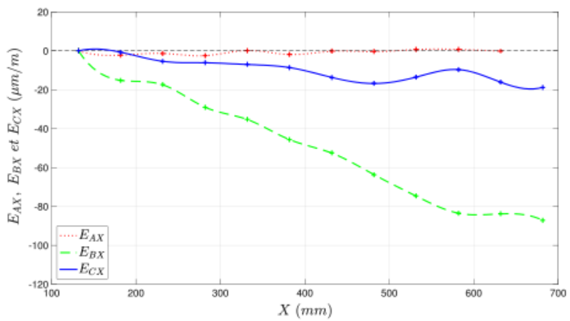


E_{YX}, and E_{ZX} in december

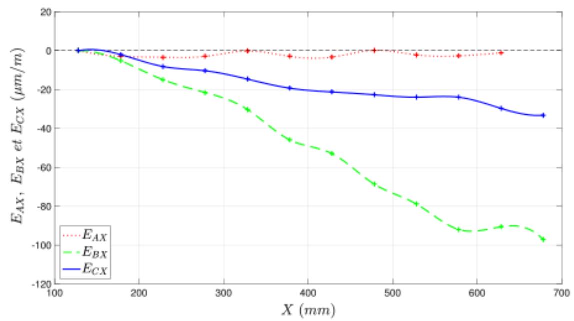
Solutions:

➔ use of climate chamber

➔ compensation of boundary conditions: several geometric models which depend on boundary conditions

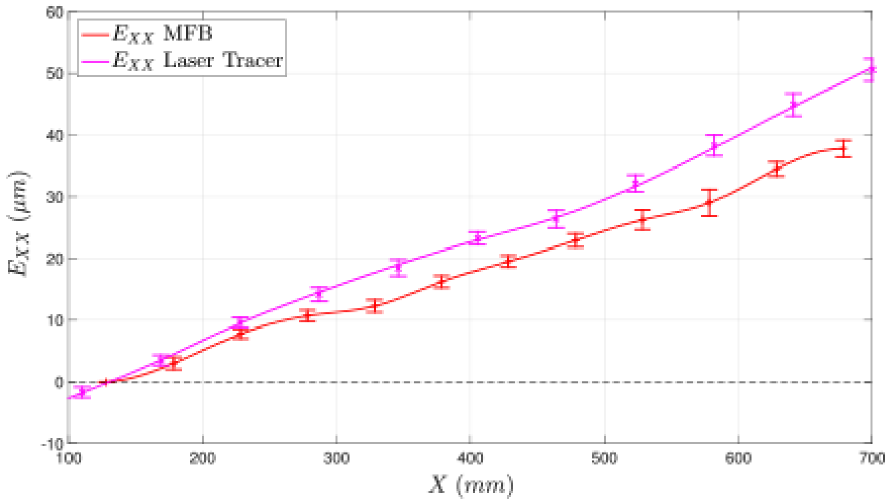


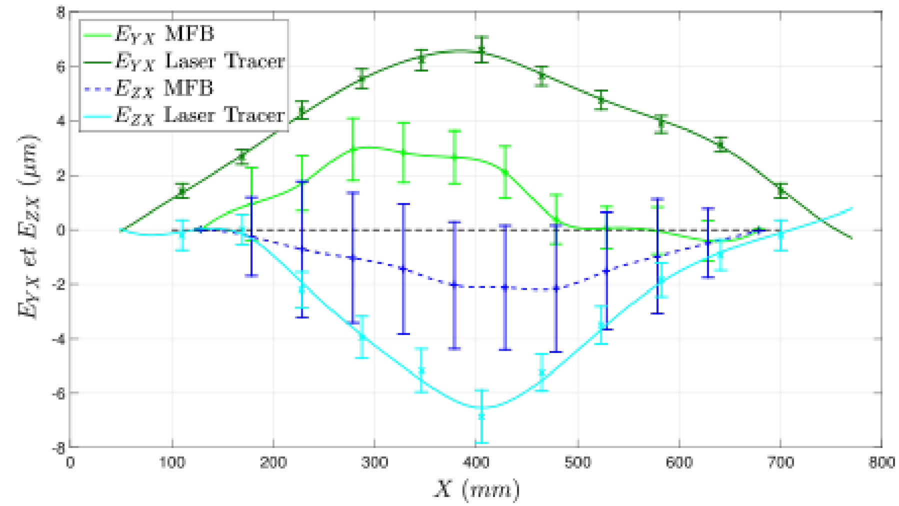
E_{AX}, E_{BX}, and E_{CX} in july

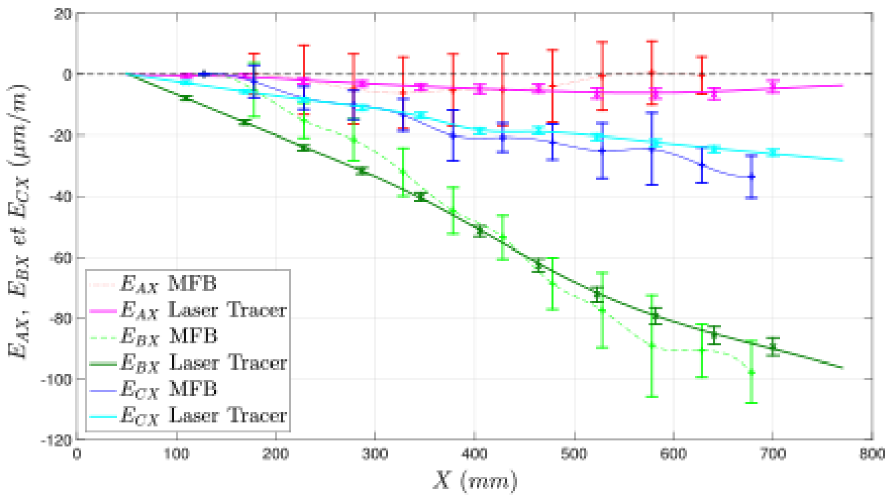


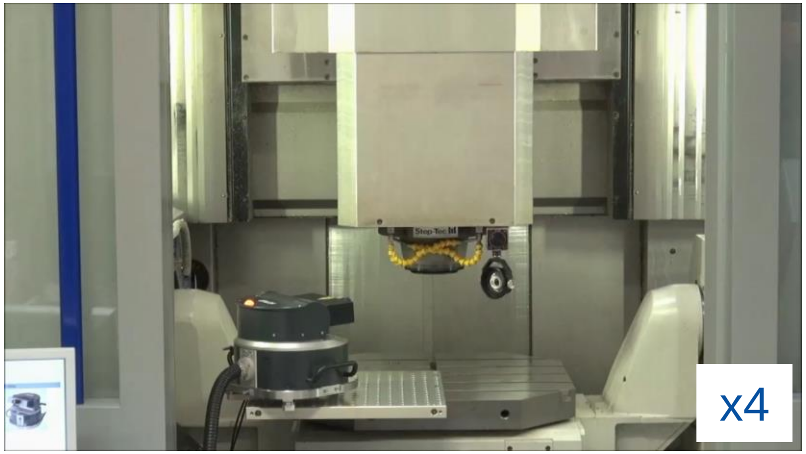
E_{AX}, E_{BX}, and E_{CX} in december

Calibration using a Laser Tracer

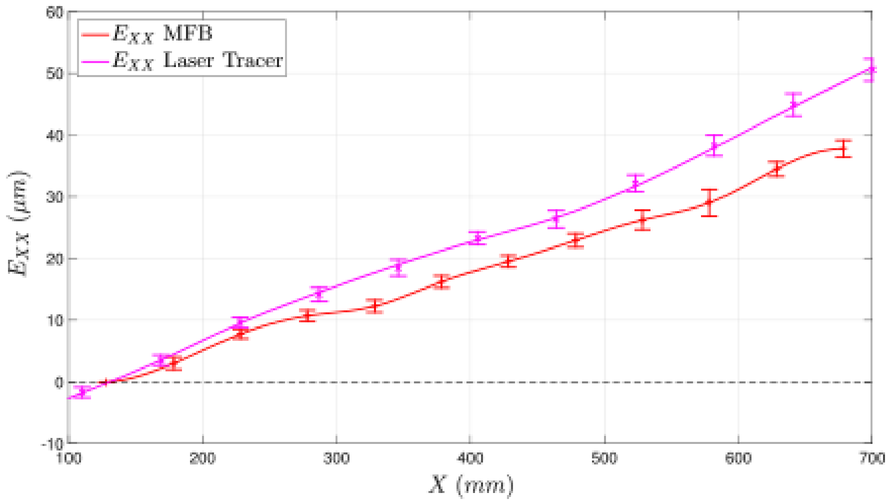


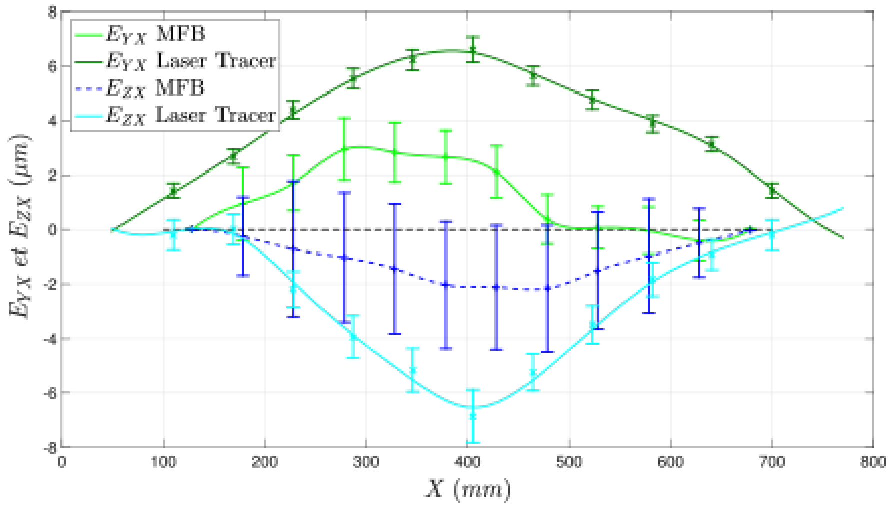


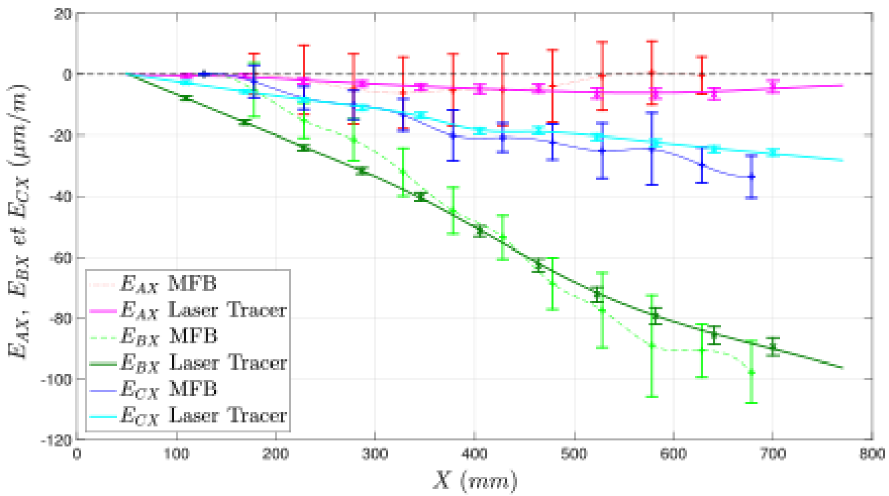


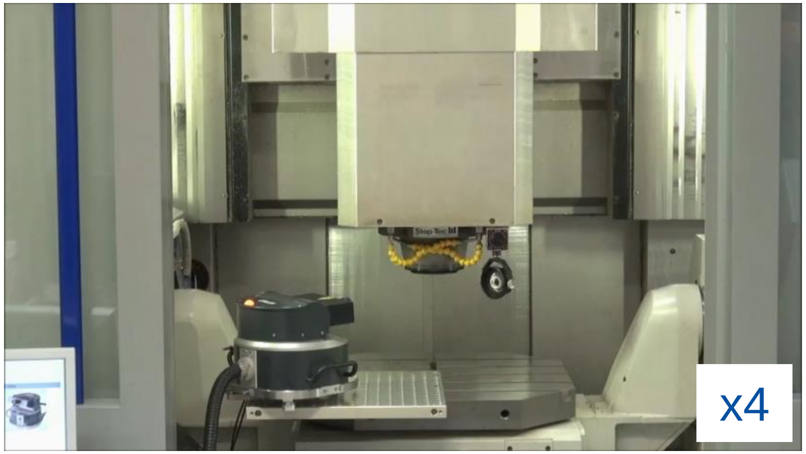


Calibration using a Laser Tracer







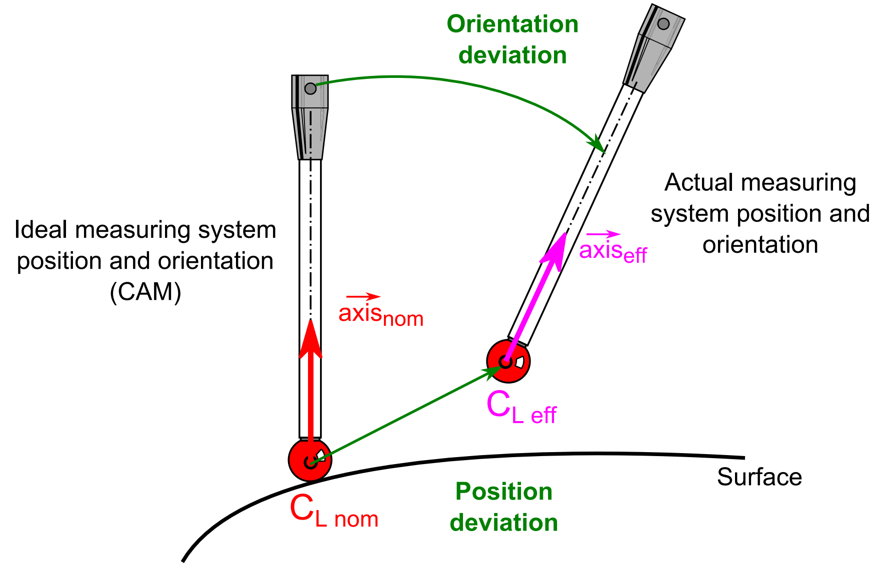


A variation between the results can be observed ➔ definition of end-point reference straight line (end-points), effects of the angular errors and boundary conditions

Conclusion

- Novel Hole-Bar made of thermo-invariant material (Invar) was defined and developed to calibrate machine tool
- The design of the Hole-Bar involves several patterns, including cylindrical and plane geometric entities, useful to extract 12 points of interests ➔ providing 3 geometric errors (linear positioning error and 2 straightnesses) for each selected position
- The developed Hole-Bar was carefully calibrated on an accurate CMM, traceable to the SI meter definition at LNE
- The reversal technique was applied to calibrate the Hole-Bar in order to separate the motion errors of the CMM and the true intrinsic parameters of the Hole-Bar
- An intercomparison was shuttled between 4 european NMIs (PTB, CMI, UM, LNE)
- The Hole-Bar was used for the calibration of the Mikron UCP710 machine tool to evaluate the efficiency

- Submission of a journal paper about the intercomparison
- Identification of the motion errors of the rotary axes using the Hole-Bar
- Application of a compensation



Dissemination

- 2nd MacroScale International Conference, Wien (Austria), October 2014
- Article submitted for publication in the journal: Precision Engineering

Novel multi-feature bar design for machine tools geometric errors identification

Thank you for your attention!

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