Reduction of a five axis machine tool kinematic model by combinatorial analysis to improve volumetric accuracy

PhD Student **Fabien VIPREY** LNE – LURPA

fabien.viprey@lne.fr

Dr. Ing. Hichem NOUIRA LNE

Dr. Ass Prof Sylvain LAVERNHE LURPA

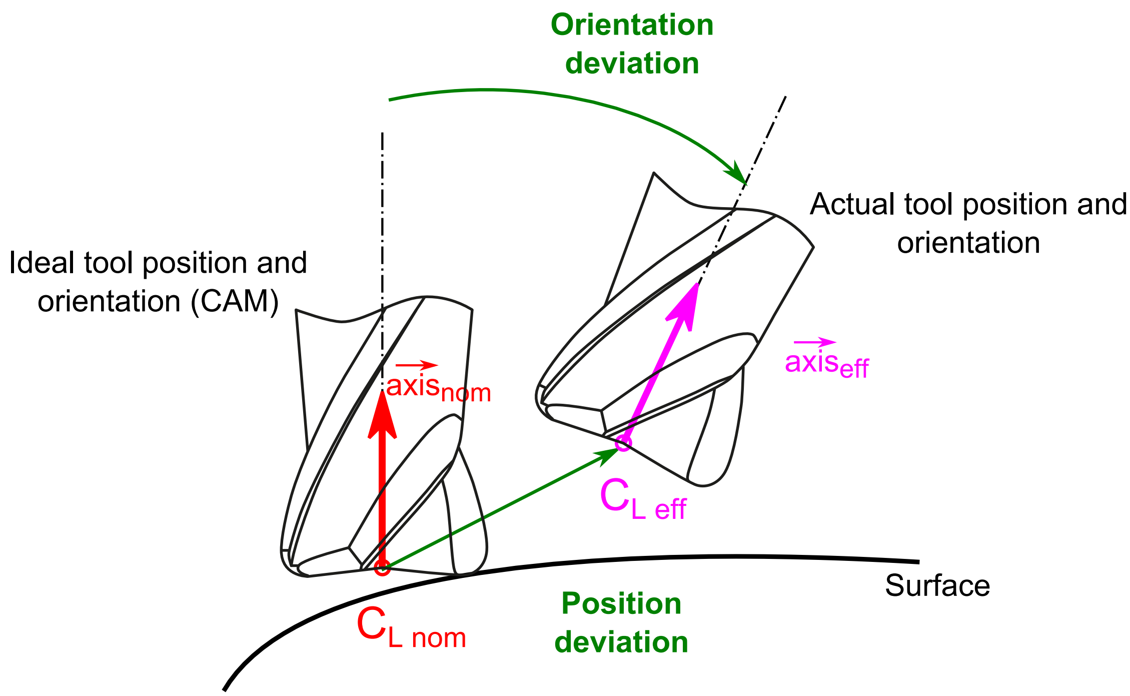
Prof. Christophe TOURNIER LURPA

French National Metrology Institute LNE-Cnam

Automated Production Research Laboratory of ENS Cachan – Univ Paris Saclay

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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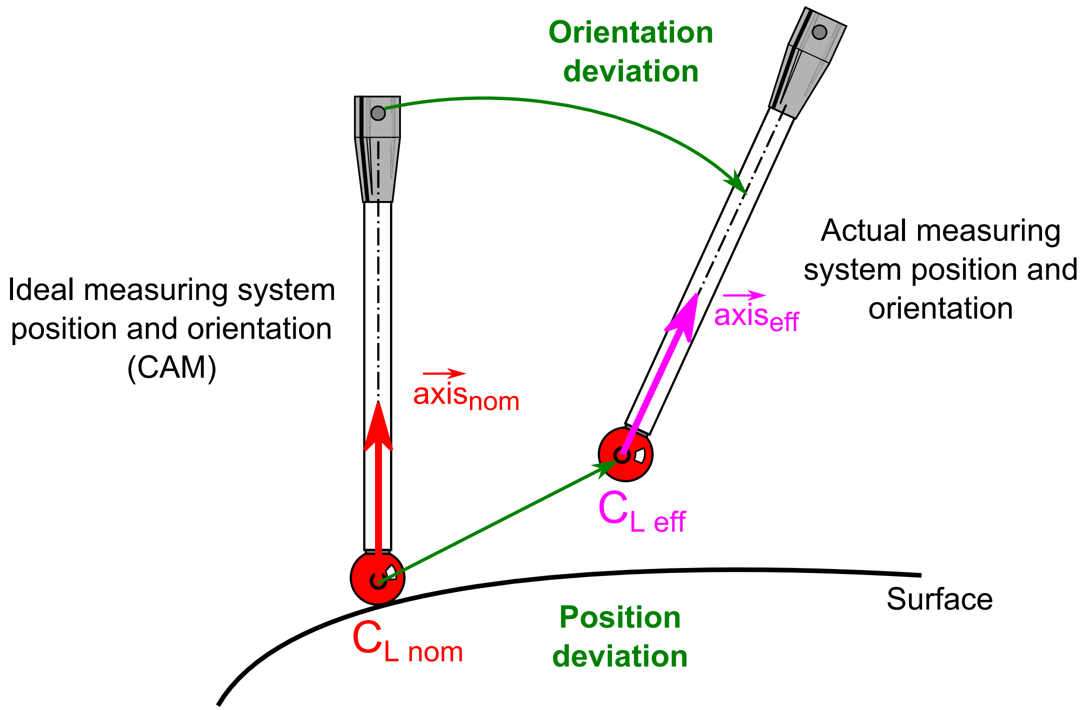

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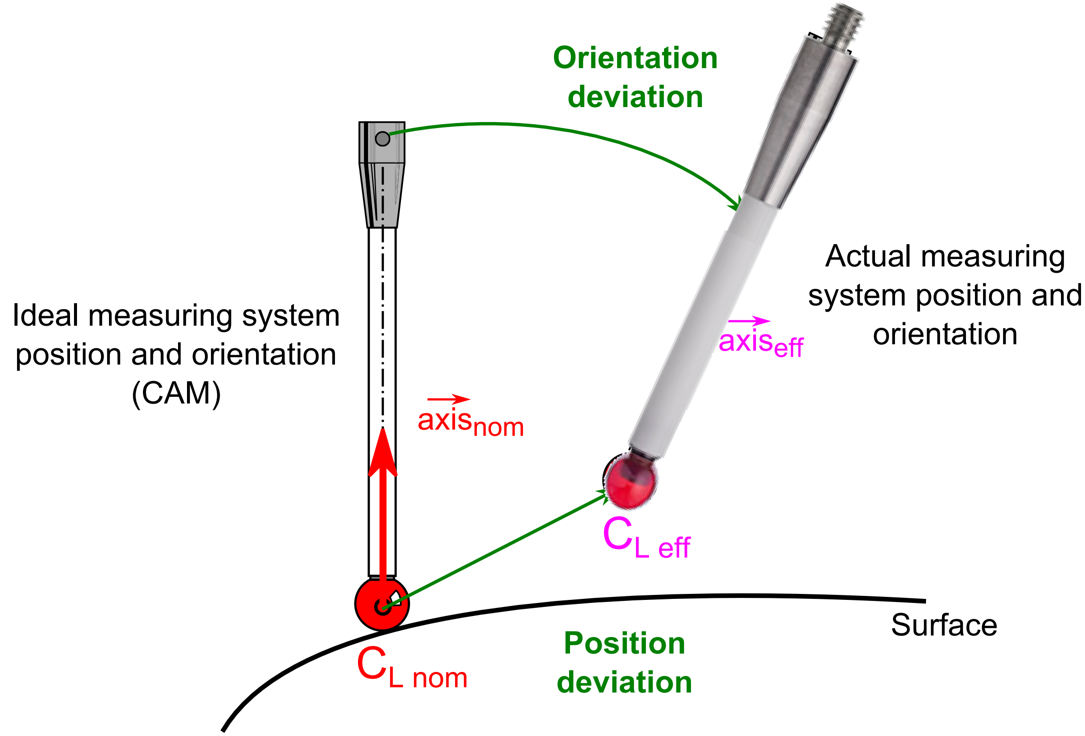

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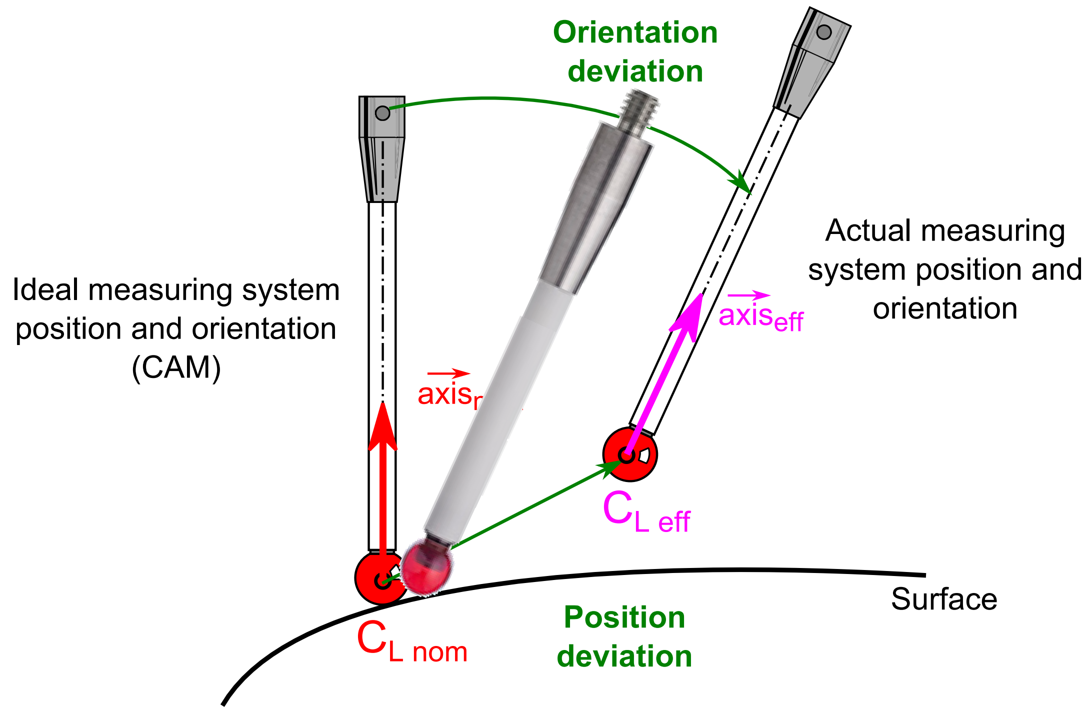

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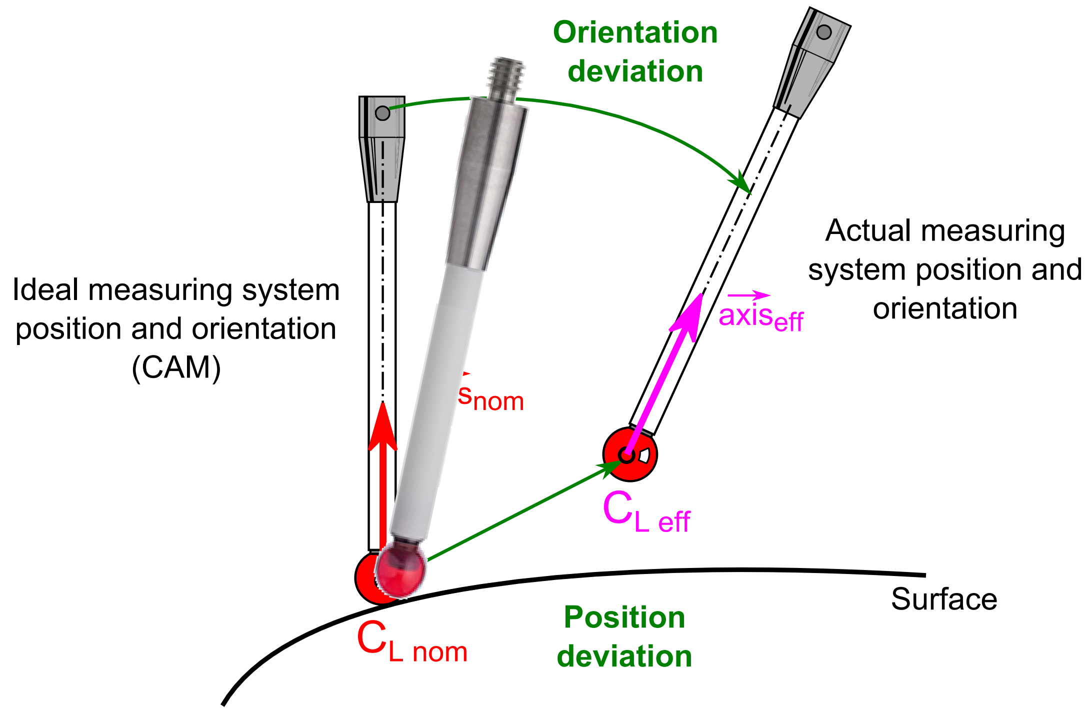

Introduction : Volumetric accuracy

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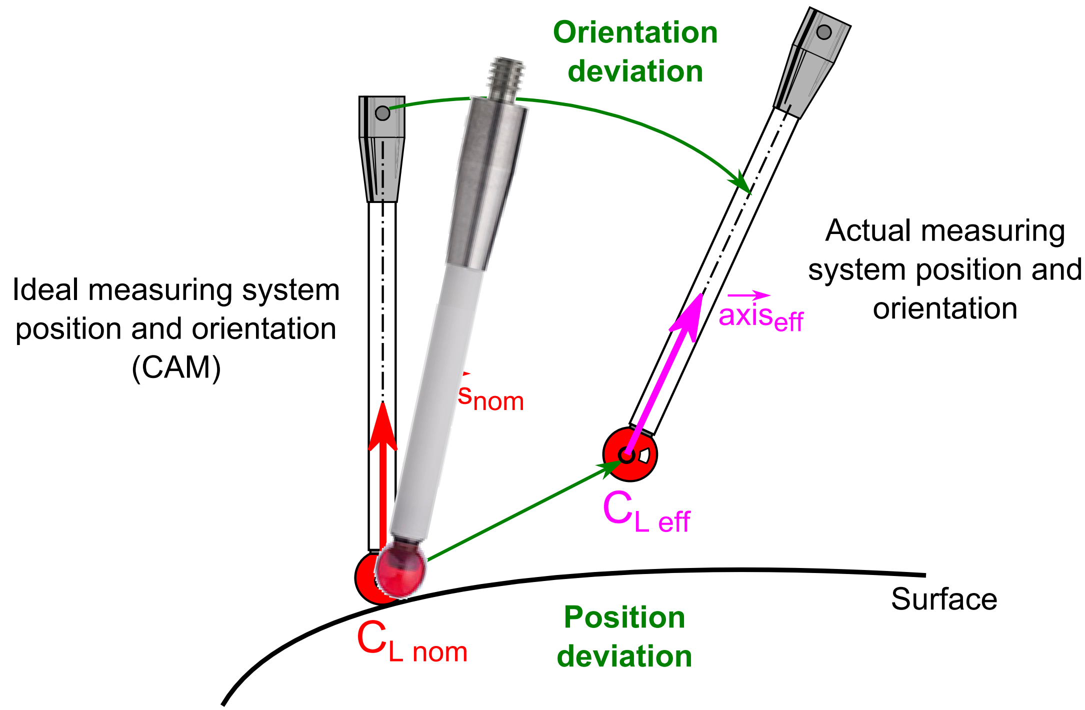
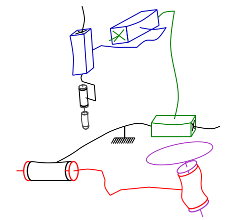


Objectives : Minimization of the volumetric accuracy

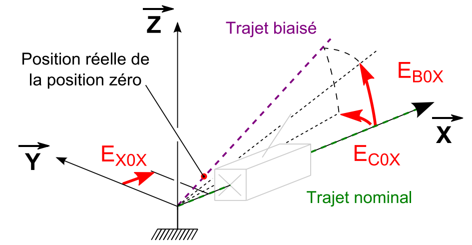
Introduction

Research work

- Geometric errors
- Geometric model of 5-axis machine tools

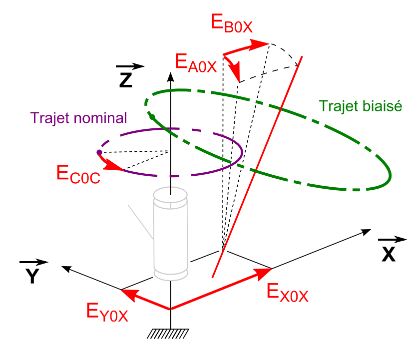


Qualification of geometric models



- Modelling
- Identification
- Simplification of model

Application on actual 5-axis structure



- Measuring process of volumetric accuracy
- Results of predicted volumetric accuracy for models

Conclusion and further works

Geometric errors

ISO 230-1:2012 ISO 230-7:2007

Geometric errors

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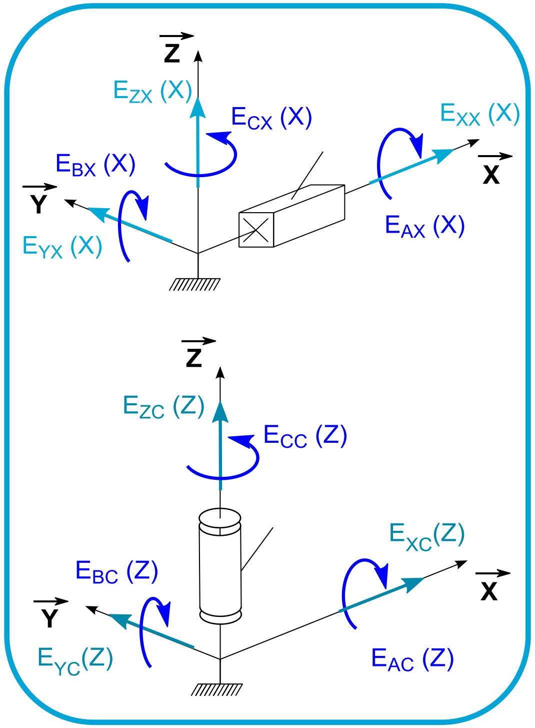
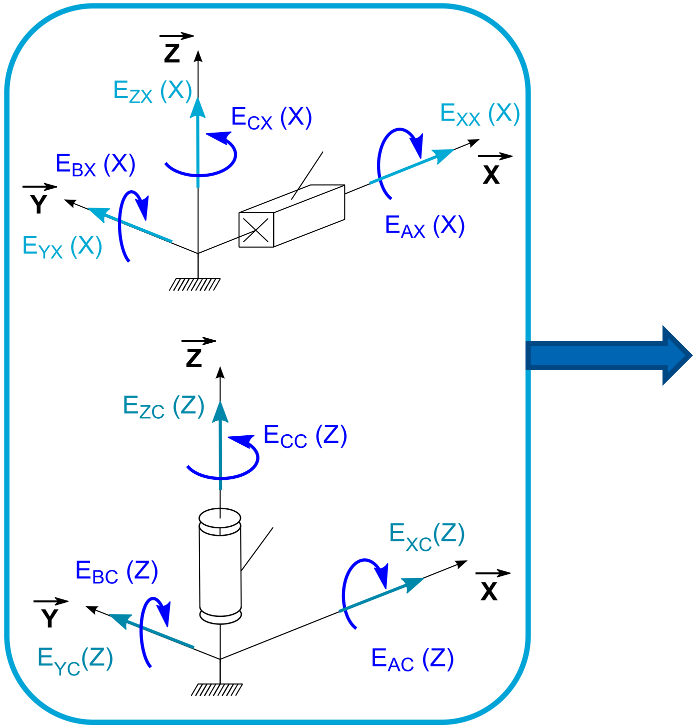


Motion errors

ISO 230-1:2012 ISO 230-7:2007



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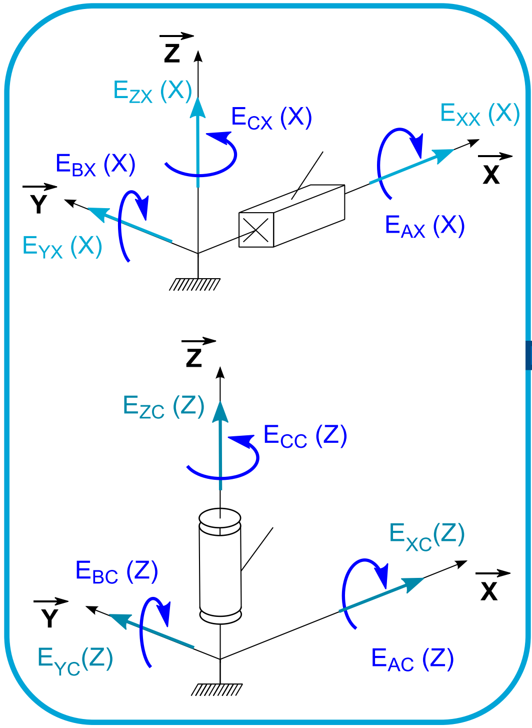

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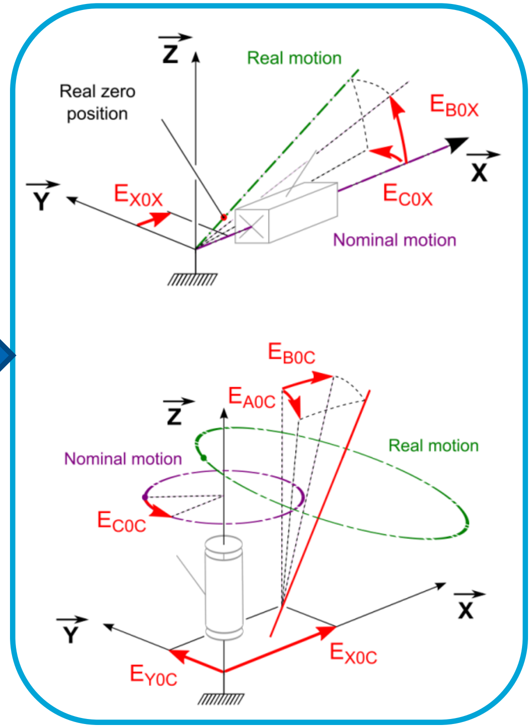
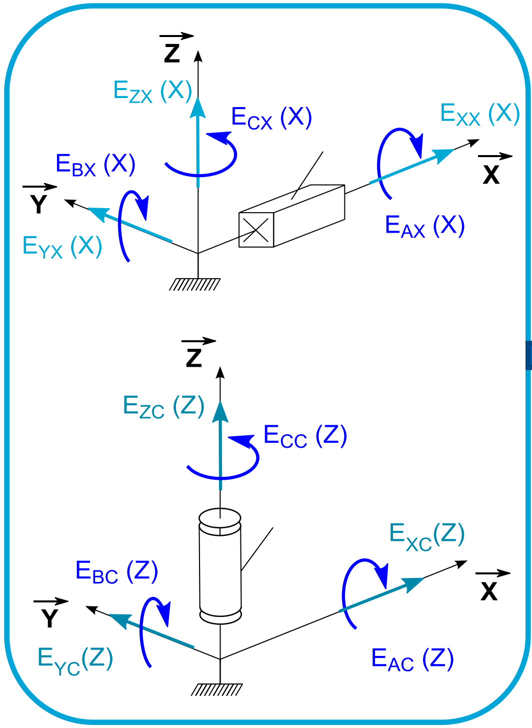


Location and orientation errors of axis average line or axis reference line

ISO 230-1:2012 ISO 230-7:2007



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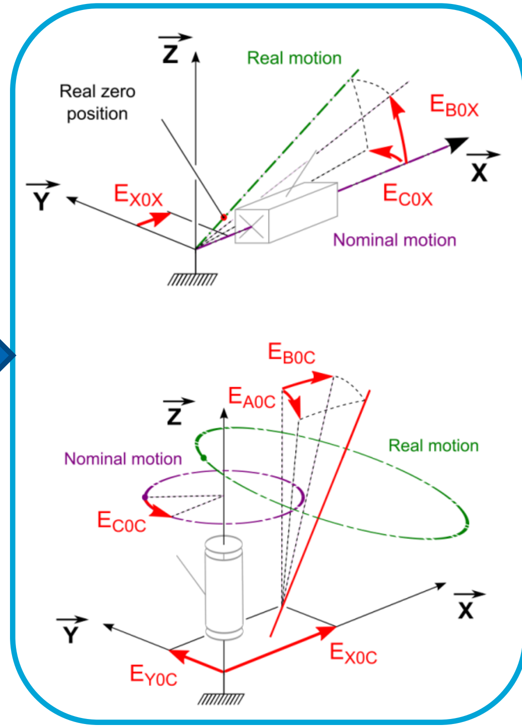

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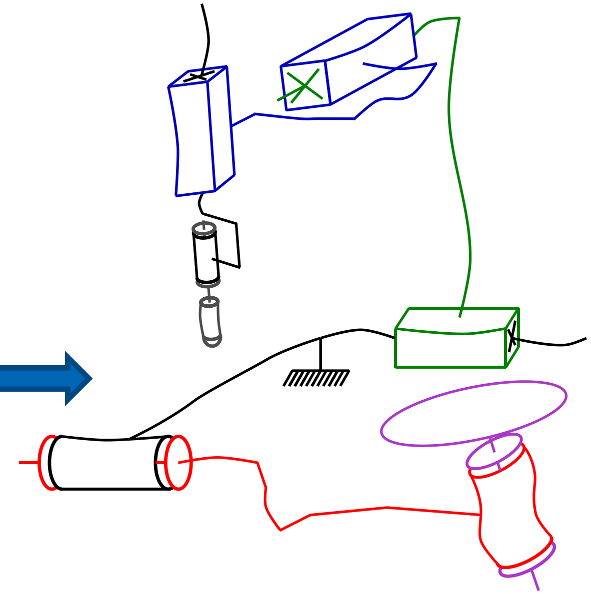

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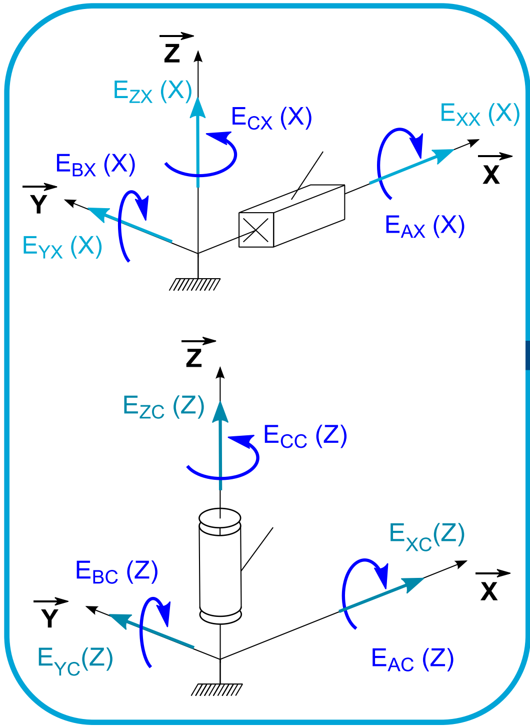

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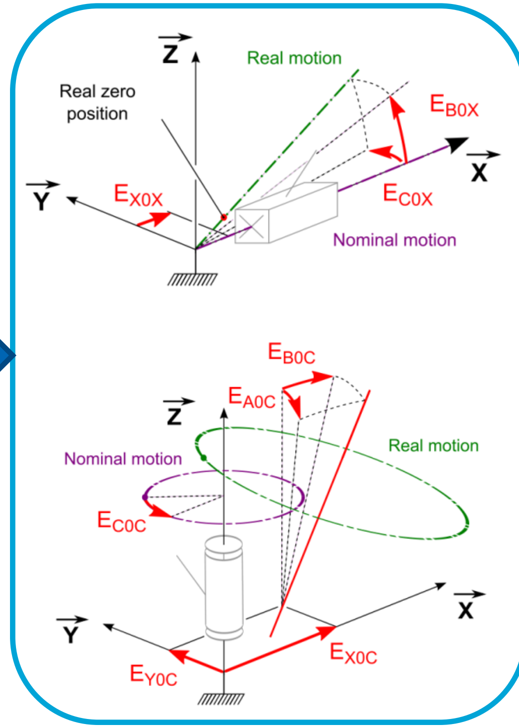

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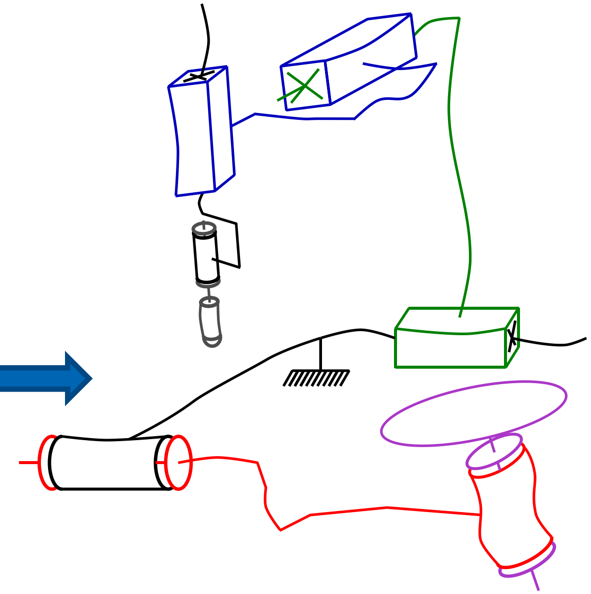

- Intrinsic errors to the axis
- All must be considered

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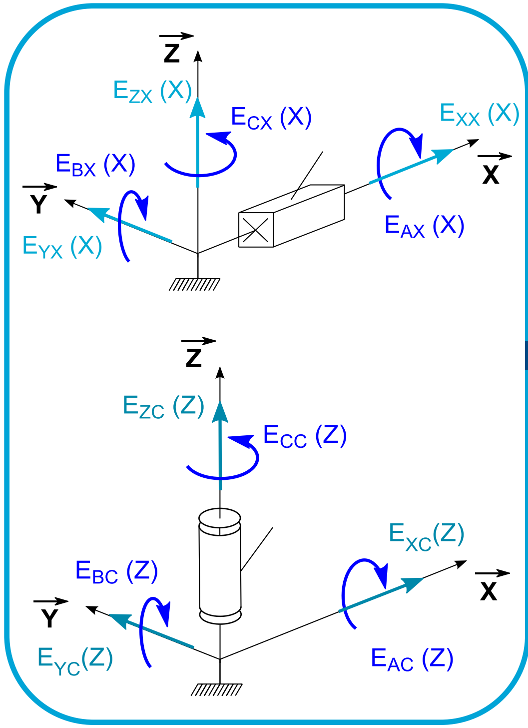

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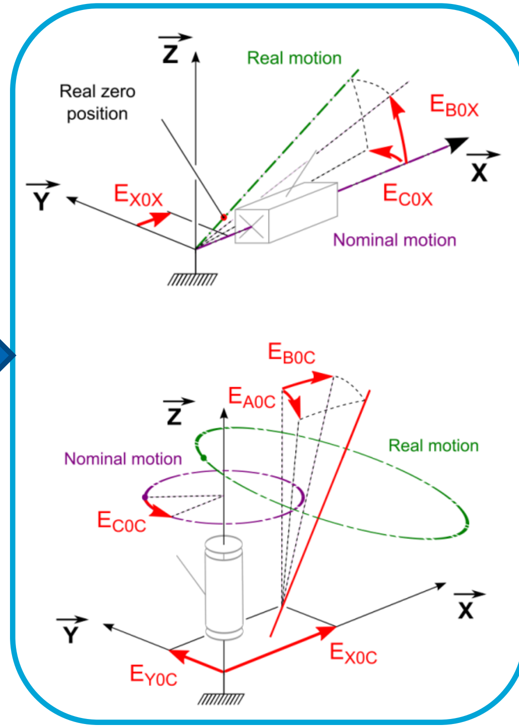

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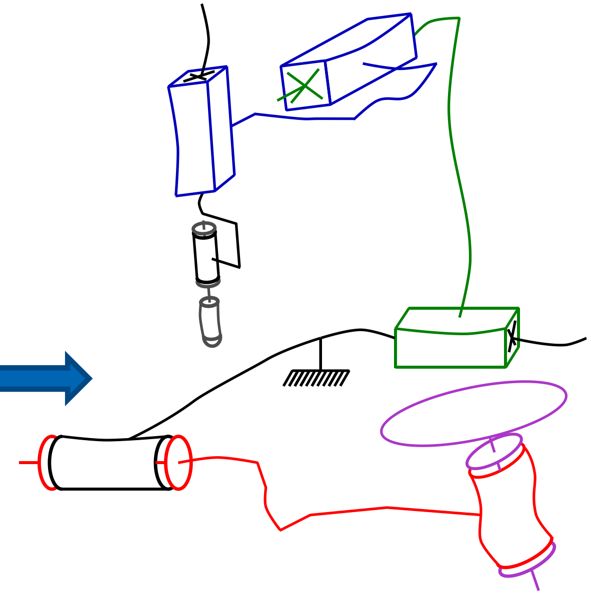

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- The model can be simplified

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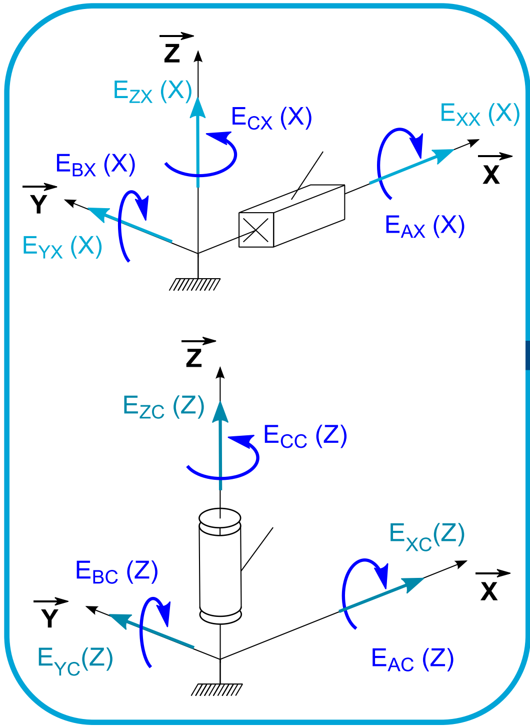

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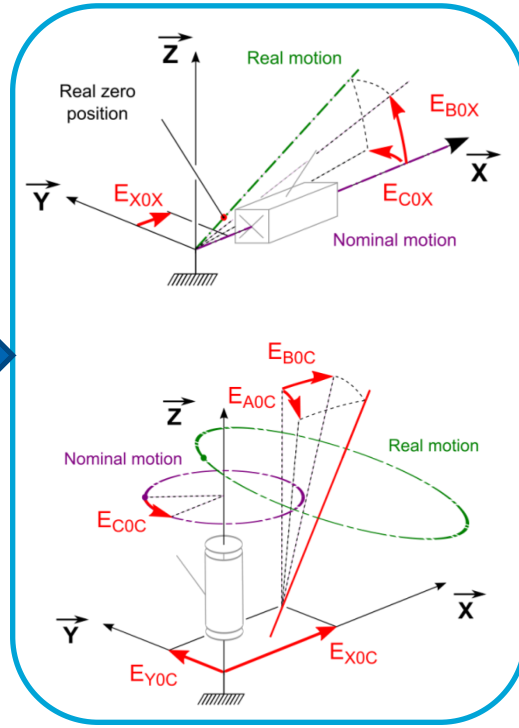

Location and orientation errors of axis average line or axis reference line

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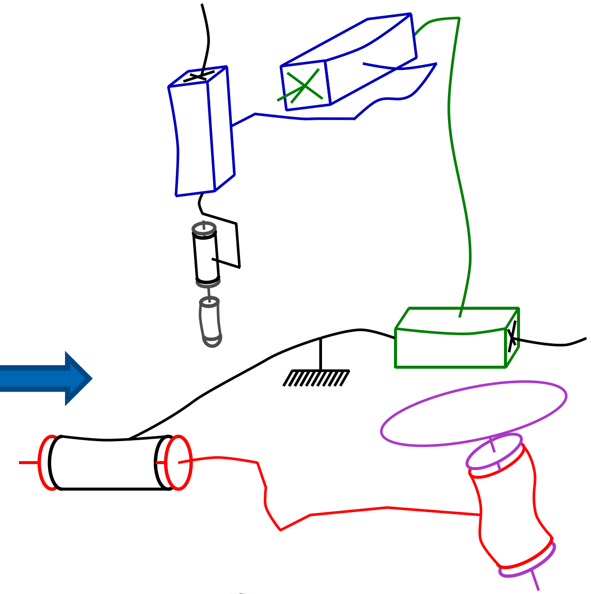

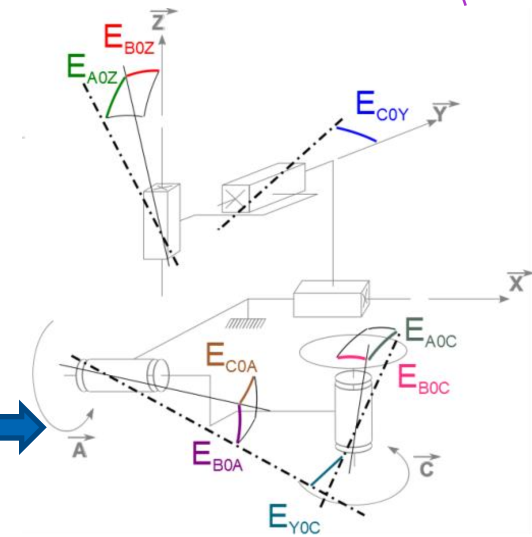

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Geometric errors

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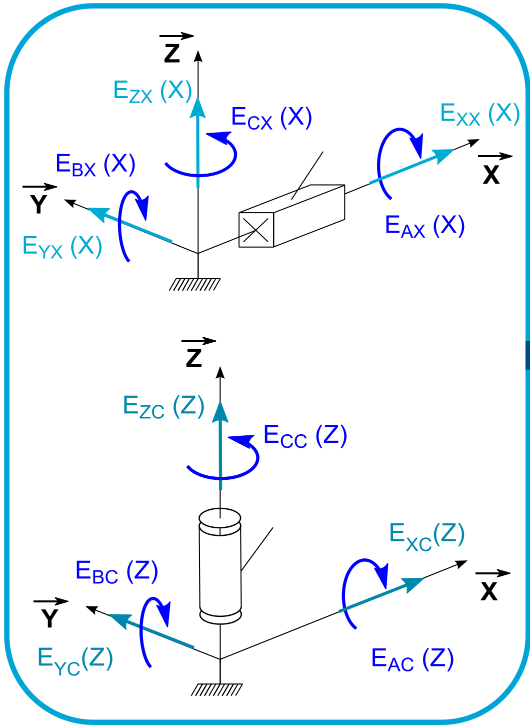

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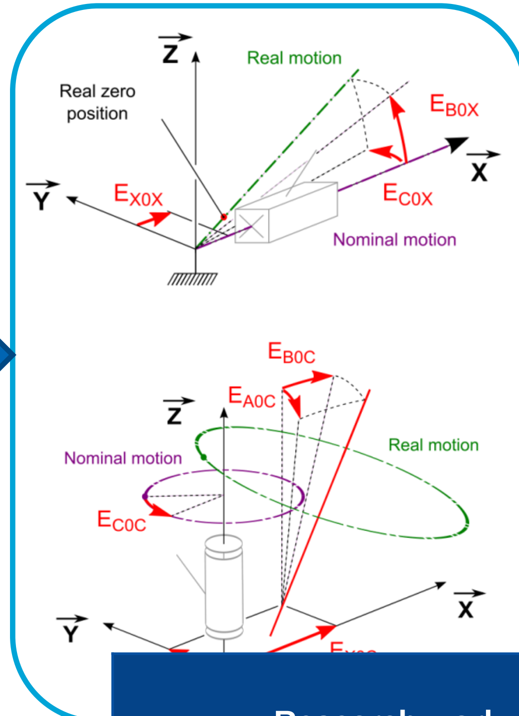
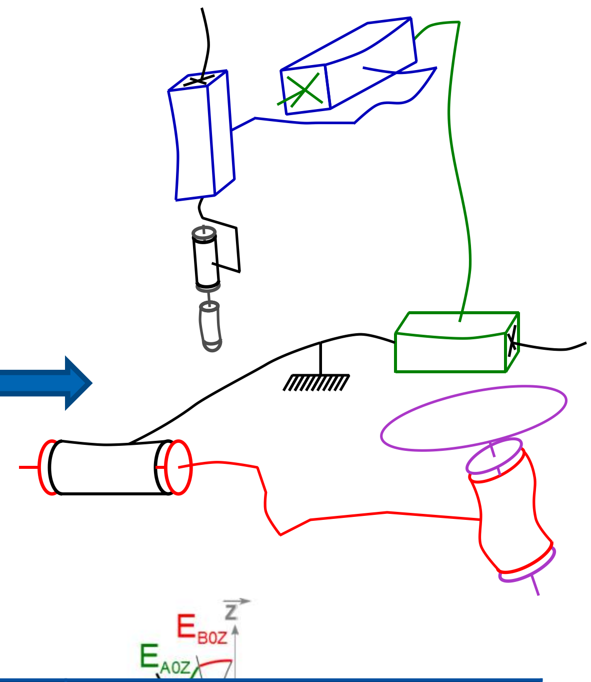


Lo... error...



- Intrinsic errors to the axis
- All must be considered

- Relative...
- The mo...

Research work	Contribution of location and orientation errors of axis in the volumetric errors
[Tsutsumi and Saito, 2003]	~65%
[Zargarbashi and Mayer, 2009]	~68%
[Andolfatto et al, 2011a]	~86%
[Ibaraki et al, 2011]	~70%

Several models and parameters in the literature:

		Motion errors		Location and orientation errors of axis average line or axis reference line				
	References	**Linear axis**	**Rotary axis**	**Location and orientation errors**	**Mounting errors**	**Total**	**Independent errors**	**Identified errors**
5-axis MT	ISO 230	18	12	19	-	49	38	-
	[Abbaszadeh-Mir2002] [Zargarbashi2009]	0	0	30	12	42	20	14
	[Yu2011]	18	12	30	-	60	20	-
	[Bohez2007]	18	12	9	-	39	32	32
	[Lei2002]	18	12	19	12	61	59	13
	[Tsutsumi2003]	0	0	30	-	30	13	8

- Equivalent models but the number of parameters are simplifed
- Variety of identification procedures
- According to the authors, the physical sense of parameters are different



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Considering the identification of parameters quick and easy to implement on machine tools, how to determine a model to best fit the volumetric error?

Outline

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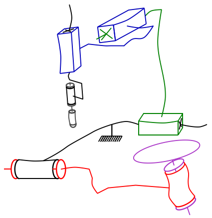

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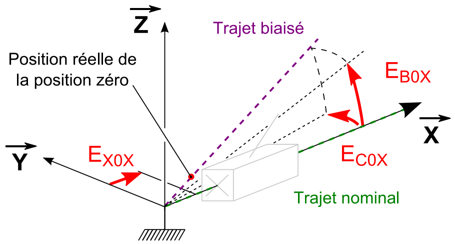

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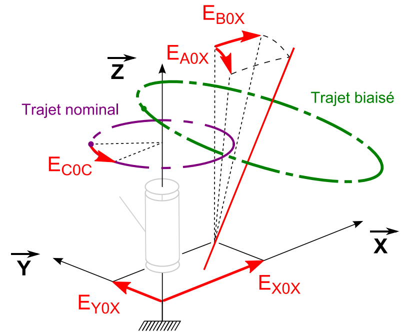

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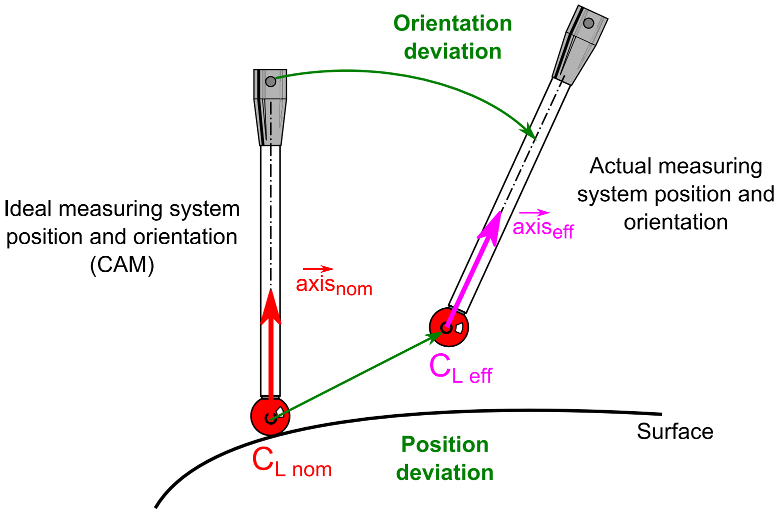
Model for location and orientation errors of axis



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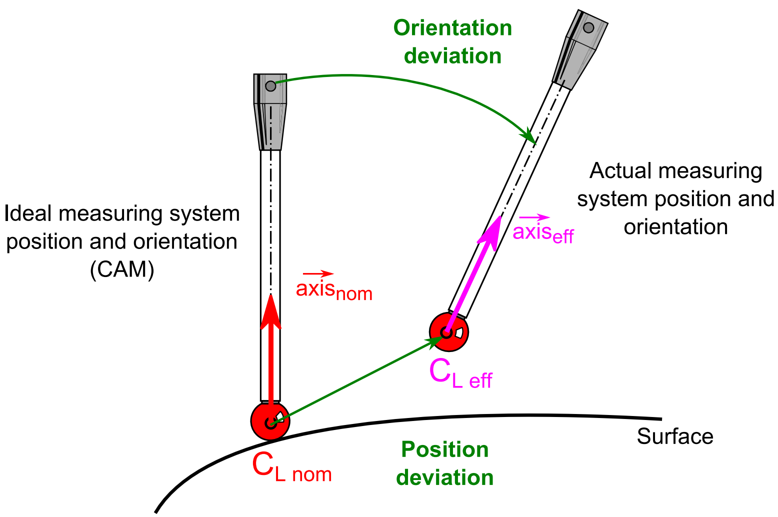

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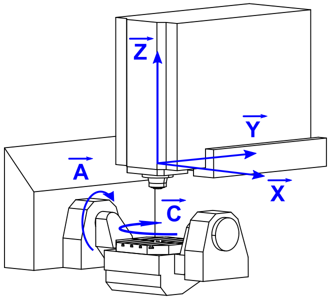

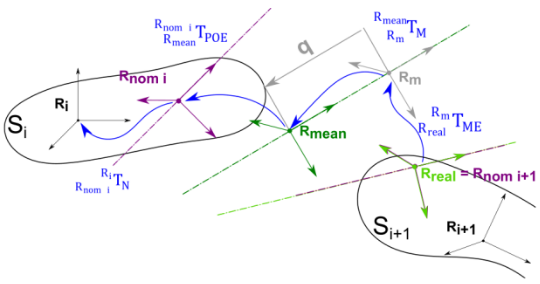

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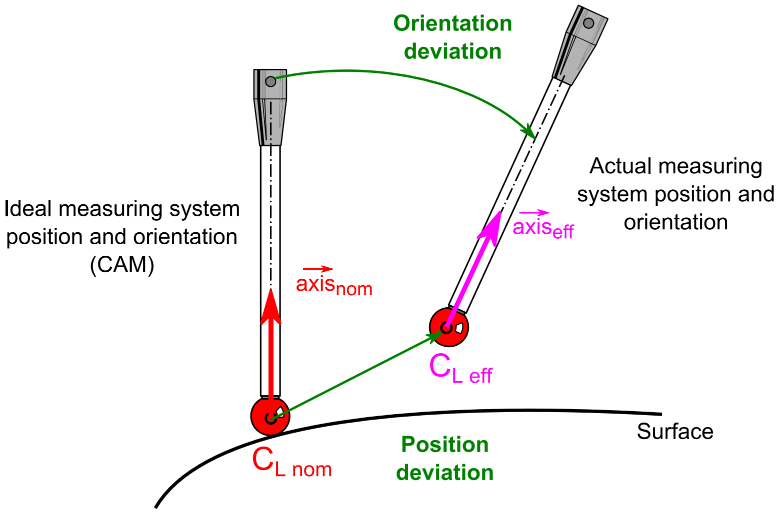

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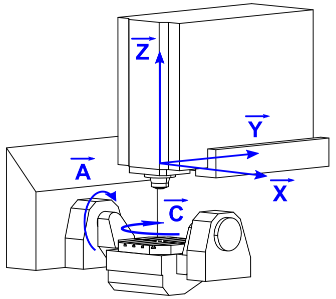
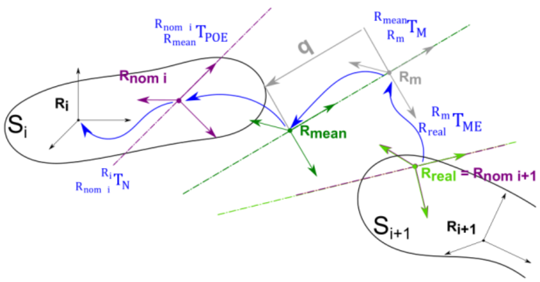
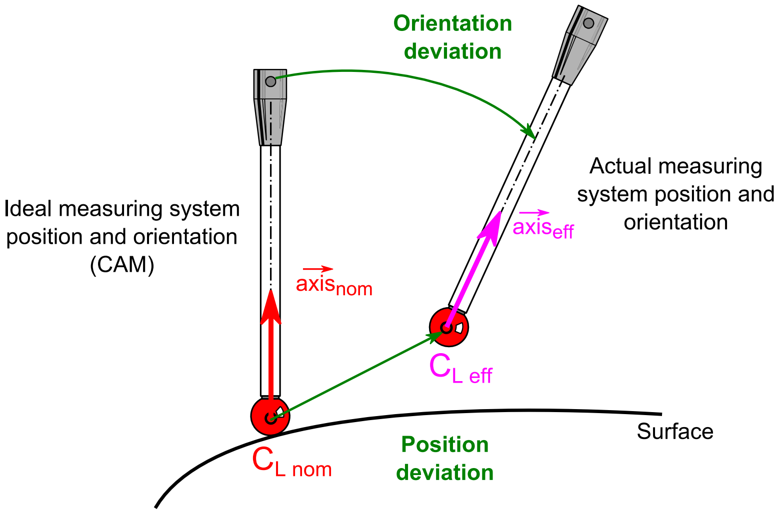




$$V_{xyz} = f(E_{iOj}, X, Y, Z, A, C, nominal\ geometry)$$

Modeling the volumetric error

Model for location and orientation errors of axis



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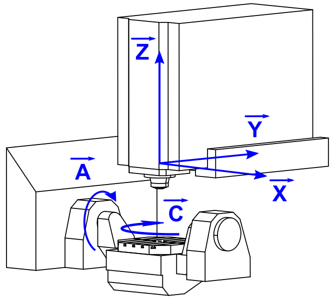

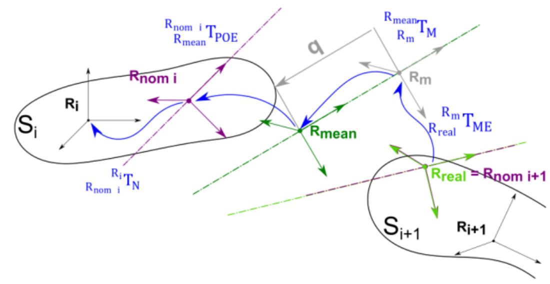

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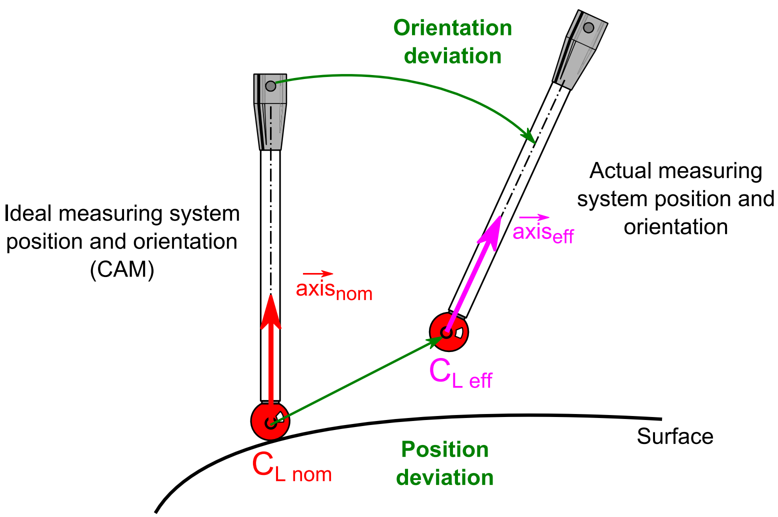

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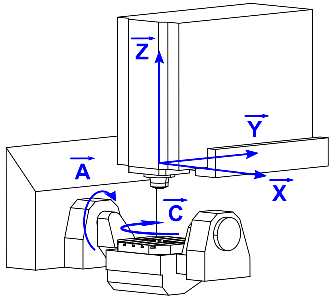

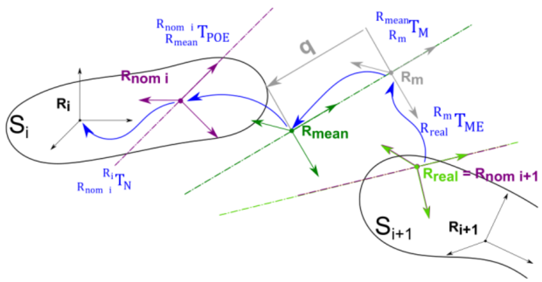

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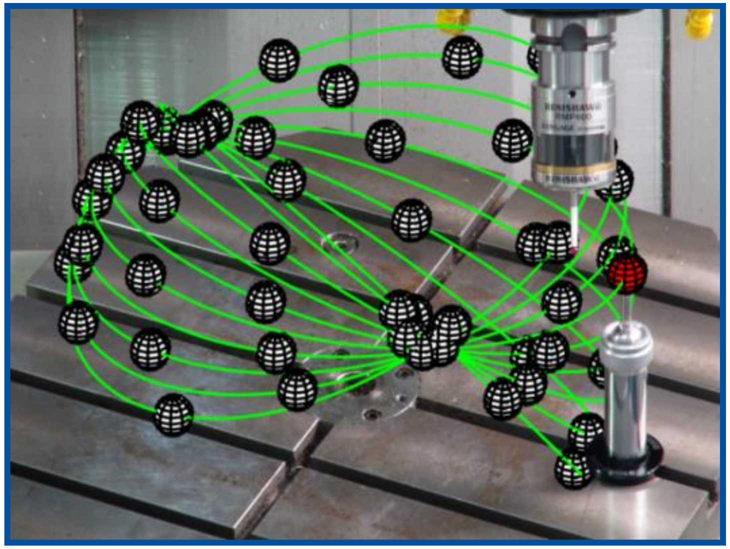
Hypotheses :

- Rigid bodies and rigid lingks
- Without any approximation
- Integrating the tool and workpiece mounting errors

Identify the $\hat{\boldsymbol{E}}_{i0j}$ by volumetric error $\boldsymbol{V}_{XYZ}$ measurement for chosen configurations (X, Y, Z, A, C)



Principle :

- Probing of datum sphere for several (N) configurations (X, Y, Z, A, C)
- Extraction of the centre of the sphere to evaluate $\boldsymbol{V}_{XYZ}$

First order approximation:

$$V_{xyz} = f\left(E_{i0j}, X, Y, Z, A, C, geometry\right)$$

Computation :

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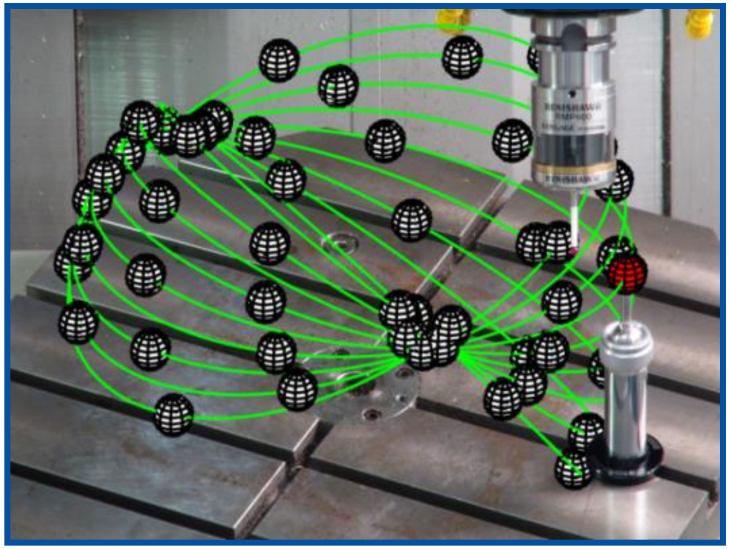

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First order approximation:

$$V_{xyz} = f\left(E_{iOj}, X, Y, Z, A, C, geometry\right) \Rightarrow \boldsymbol{S}_{[n\times 25]} \times \boldsymbol{E}_{[25\times 1]} = \boldsymbol{V}_{XYZ\,[n\times 1]}$$

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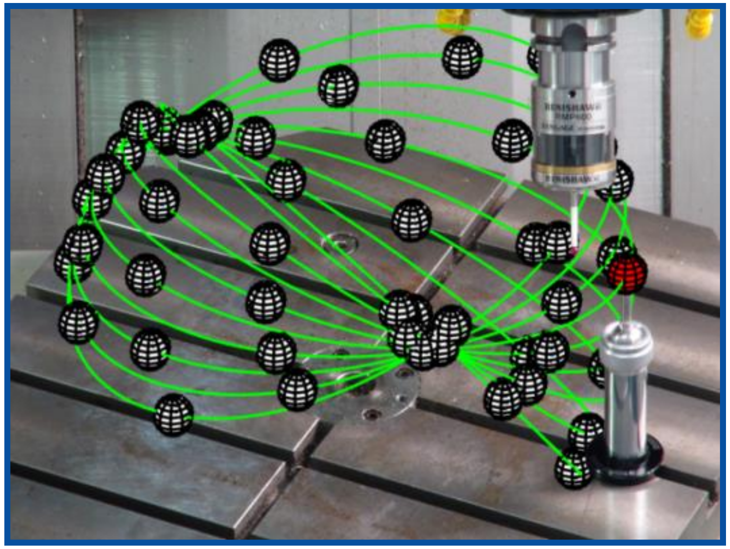

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First order approximation:

$$V_{xyz} = f\left(E_{i0j}, X, Y, Z, A, C, geometry\right) \quad \Rightarrow \quad \boldsymbol{S}_{[n\times 25]} \times \boldsymbol{E}_{[25\times 1]} = \boldsymbol{V}_{XYZ\,[n\times 1]}$$

Computation : $\boldsymbol{V}_{XYZ}$ → **Identification** → $(\boldsymbol{X},\boldsymbol{Y},\boldsymbol{Z},\boldsymbol{A},\boldsymbol{C})$, $\widehat{\boldsymbol{E}}$ → **Simulation by using the model** → $\widehat{\boldsymbol{V}}_{XYZ}$

$$\widehat{\boldsymbol{E}} = \boldsymbol{argmin}\ (\| \boldsymbol{S} \times \boldsymbol{E} - \boldsymbol{V}_{XYZ} \|)$$

$$V_{XYZ} \rightarrow \boxed{\text{Identification}} \rightarrow \hat{E}$$

$$S_{[n\times 25]} \times E_{[25\times 1]} = V_{XYZ\,[n\times 1]}$$

$$\hat{E} = argmin\ (\| S \times E - V_{XYZ} \|)$$

où E = [$d_{x\ tool}\, d_{y\ tool}\, d_{z\ tool}$

$E_{a0z}\ E_{b0z}\ E_{z0z}$

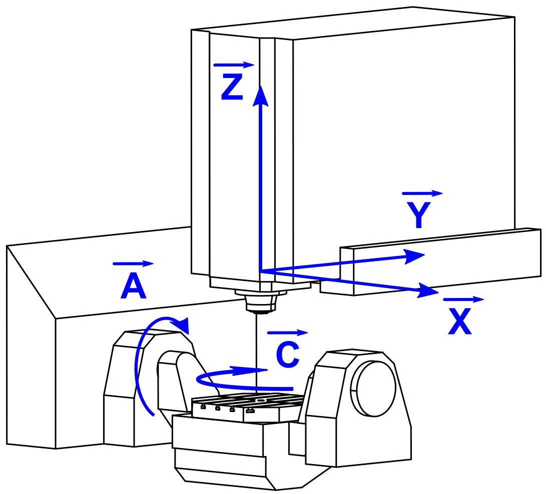
$E_{a0y}\ E_{c0y}\ E_{y0y}$

$E_{b0x}\ E_{c0x}\ E_{x0x}$

$E_{b0a}\ E_{c0a}\ E_{y0a}\ E_{z0a}\ E_{a0a}$

$E_{a0c}\ E_{b0c}\ E_{x0c}\ E_{y0c}\ E_{c0c}$

$d_{x\ w}\ d_{y\ w}\ d_{z\ w}$]^T



Rank studies of $\boldsymbol{S}$:

Simplification of model

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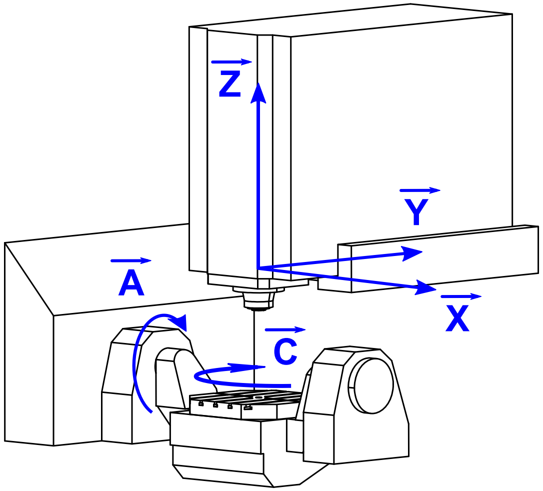
$d_{x\ w}\ d_{y\ w}\ d_{z\ w}]^{T}$



Rank studies of $\boldsymbol{S}$:

$n = 3N$ if components of position δu is considered ➔ rg($\boldsymbol{S}$)=14

$n = 6N$ if V_{xyz} is totally considered ➔ rg($\boldsymbol{S}$)=20

Where N is the number of configurations (X, Y, Z, A, C)

$$V_{XYZ} \rightarrow \boxed{\text{Identification}} \rightarrow \hat{E}$$

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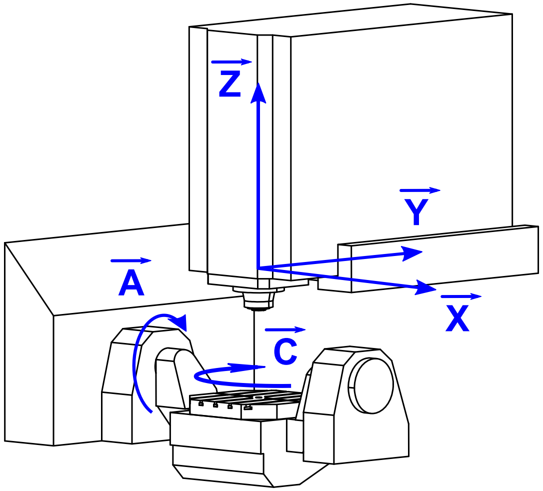

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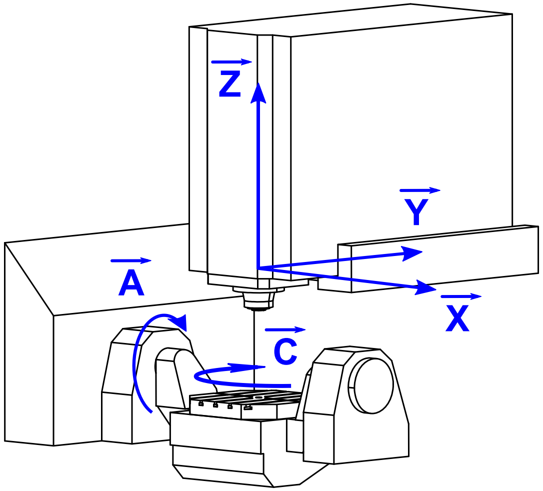

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Where N is the number of configurations (X, Y, Z, A, C)

Whatever the n –values, 20 combinations of E_{i0j} (including the specified simplification in ISO230-1:2012) allow us to solve the inverse problem.

Simplification of model

$$V_{XYZ} \rightarrow \boxed{\text{Identification}} \rightarrow \hat{E}$$

$$\begin{pmatrix} \vec{axis}_{eff} - \vec{axis}_{nom} \\ \vec{C_{L_{eff}}} - \vec{C_{L_{nom}}} \end{pmatrix}_{6\times 1} = \begin{pmatrix} \delta r \\ \delta u \end{pmatrix}_{6\times 1} = V_{xyz}$$

$$S_{[n\times 25]} \times E_{[25\times 1]} = V_{XYZ\,[n\times 1]}$$

$$\hat{E} = argmin\ (\| S \times E - V_{XYZ} \|)$$

où E = $[d_{x\ tool}\, d_{y\ tool}\, d_{z\ tool}$

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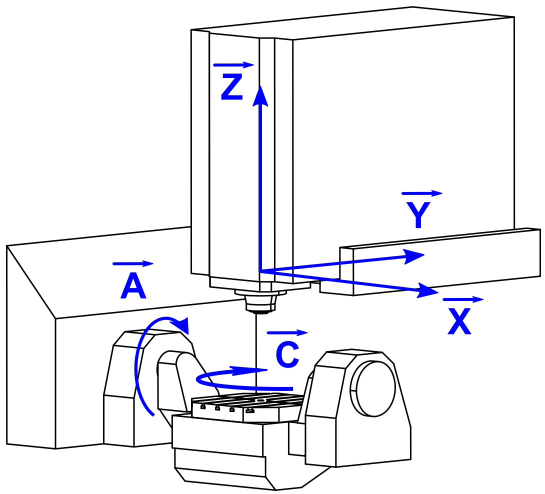

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Whatever the n –values, 20 combinations of E_{i0j} (including the specified simplification in ISO230-1:2012) allow us to solve the inverse problem.

Qualification of simplified models

Qualification of simplified models

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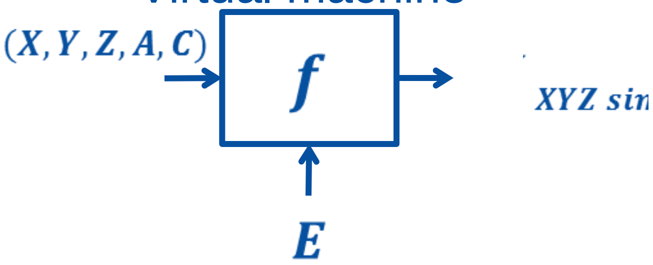
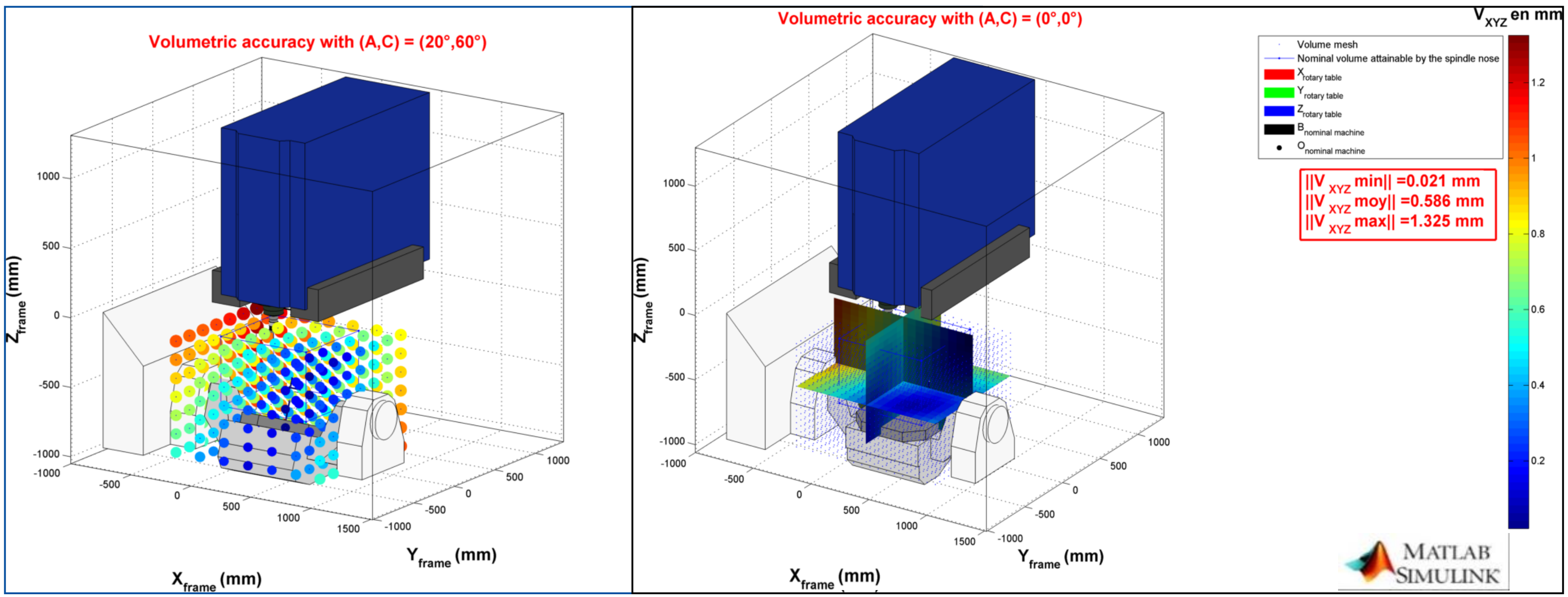
Qualification of simplified models

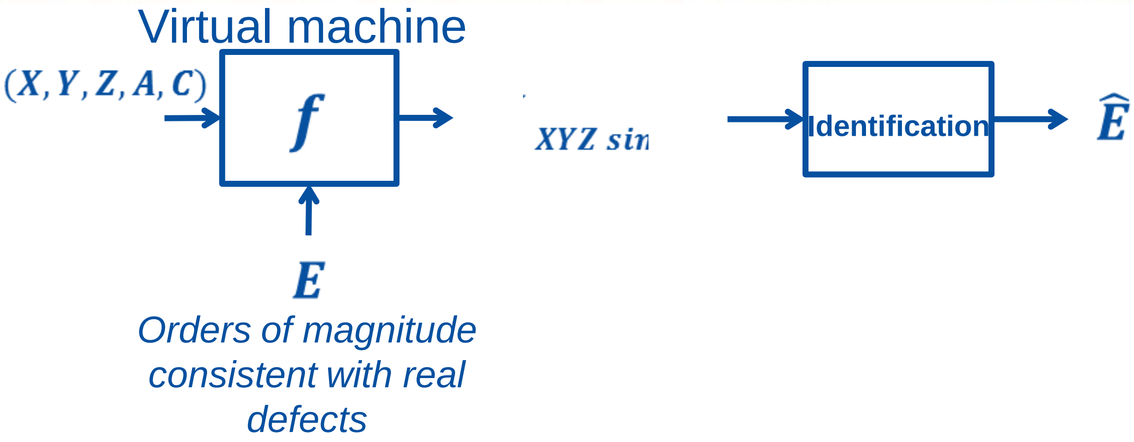
Virtual machine



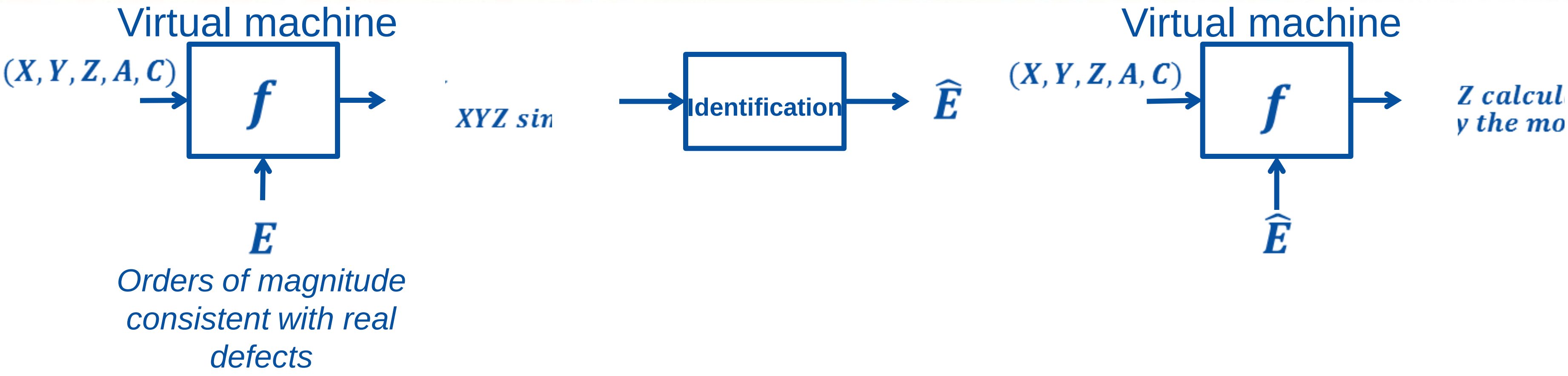
Orders of magnitude consistent with real defects



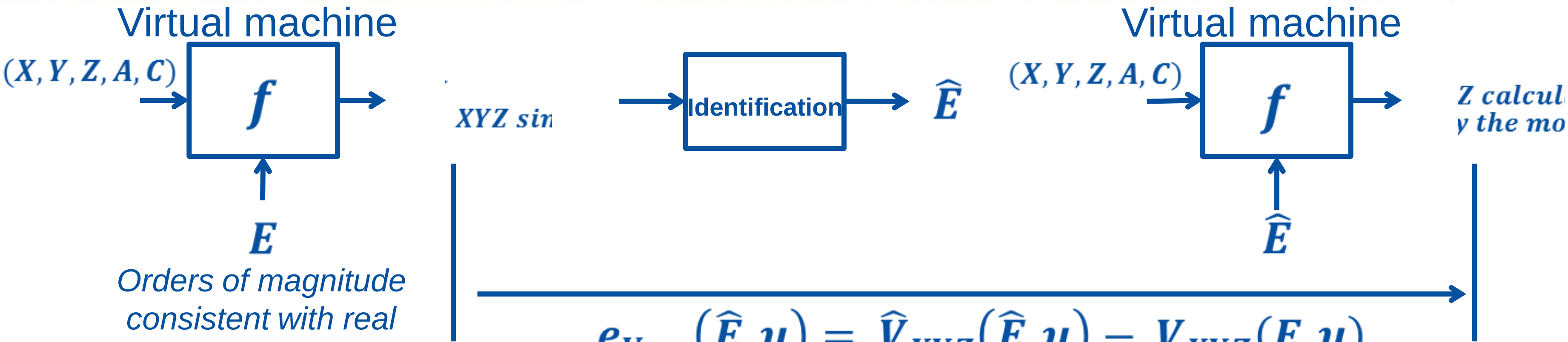
Qualification of simplified models



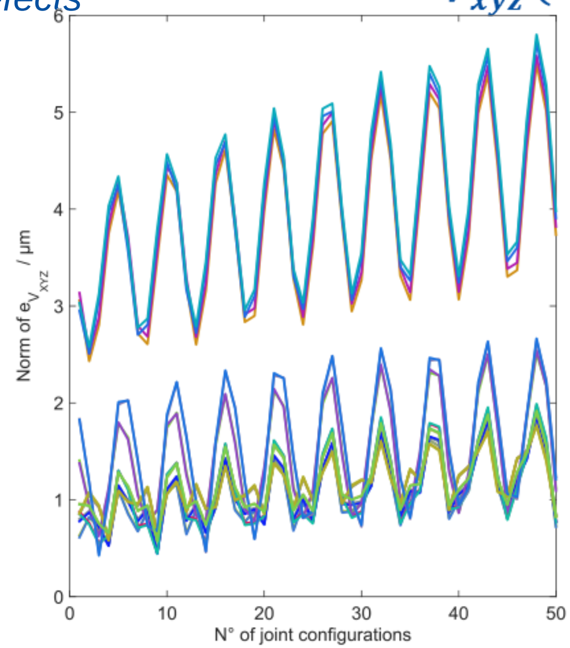
Qualification of simplified models

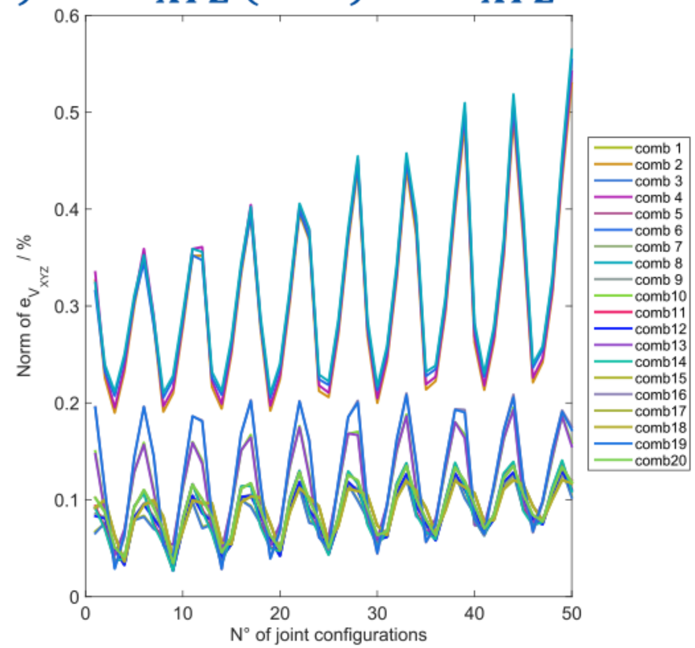


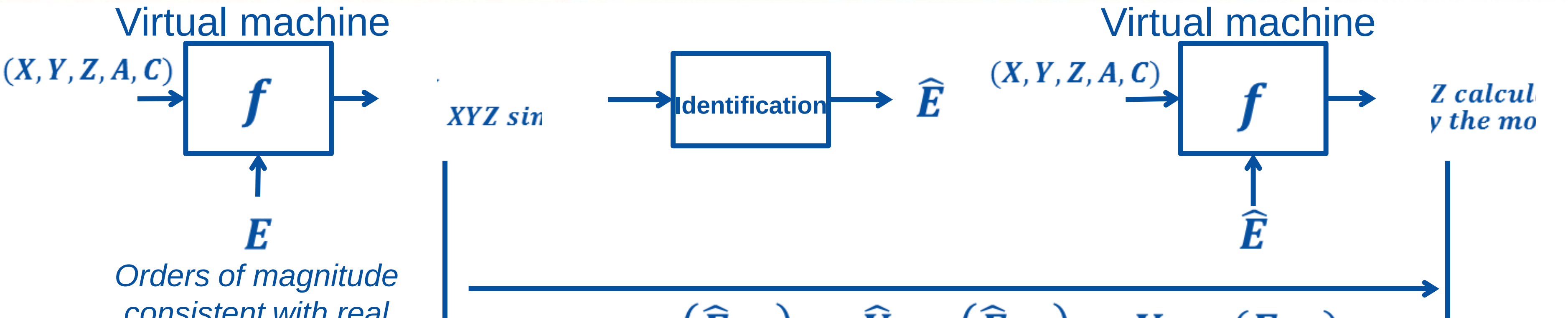
Qualification of simplified models



$$e_{V_{xyz}}(\hat{E}, u) = \hat{V}_{XYZ}(\hat{E}, u) - V_{XYZ}(E, u)$$







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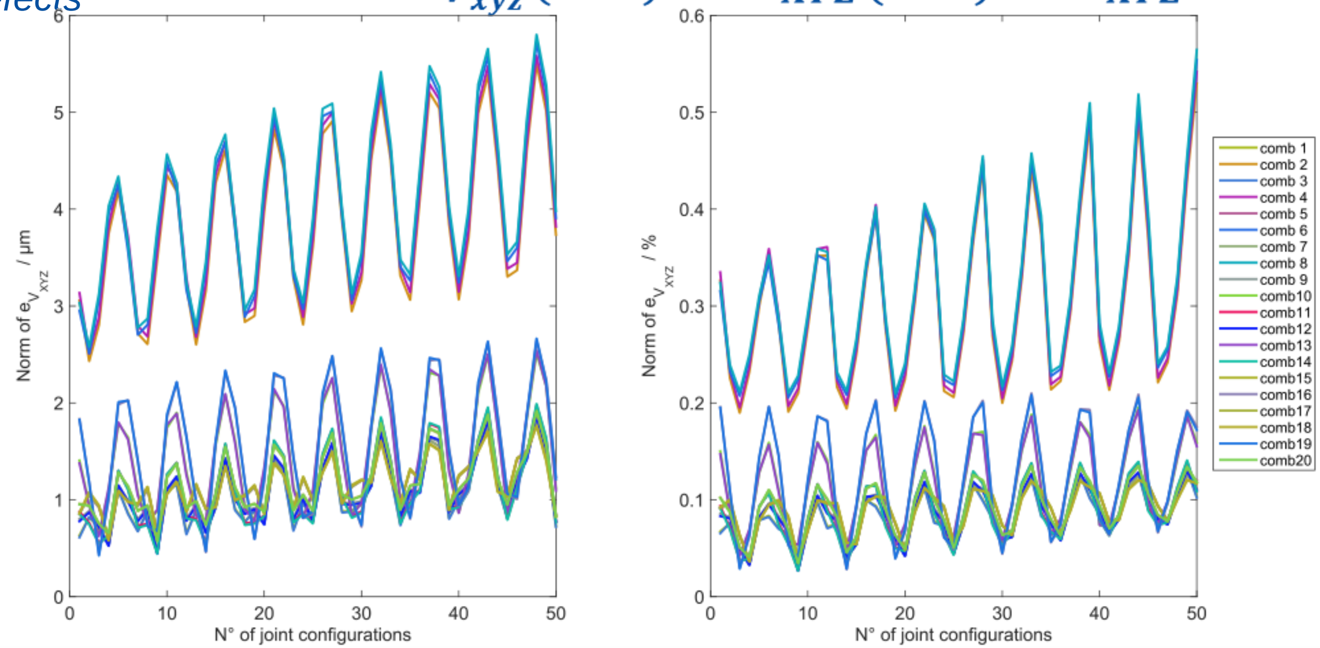


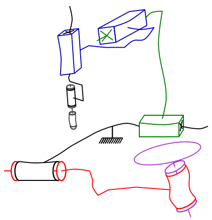
Some simplified models better characterize the volumetric error.
What about the actual volumetric error on real machine?

Outline

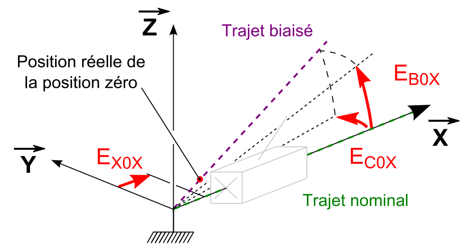
Introduction

Research work

- Geometric errors
- Geometric model of 5-axis machine tools

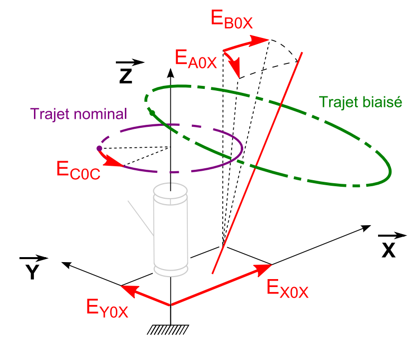


Qualification of geometric models



- Modelling
- Identification
- Simplification of model

Application on actual 5-axis structure



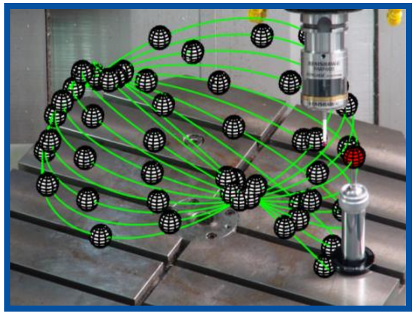
- Measuring process of volumetric accuracy
- Results of predicted volumetric accuracy for models

Conclusion and further works

$(X, Y, Z,$

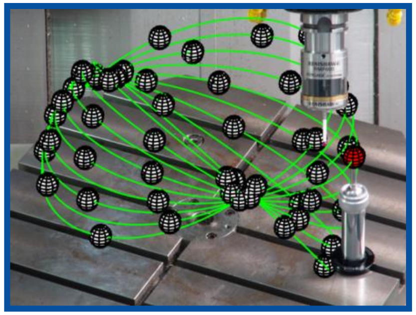
Measurement on actual 5-axis UCP710 at LURPA

$\rightarrow V_{XYZ}$



Application

$(X, Y, Z,$ → **Measurement on actual 5-axis UCP710 at LURPA** → V_{XYZ}



Constraints : Fast setting-up and measurement

Avoid collecting data with any pre-existing error compensations and uncontrolled processing performed by industrial CNC (Siemens 840D)

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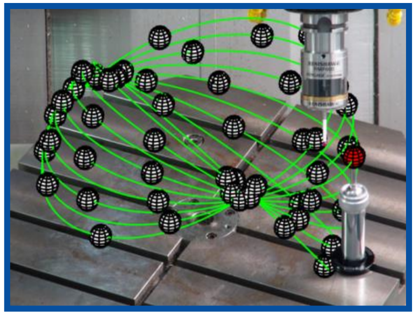

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Integration : Direct measurement of machine tools encoders, not including CNC

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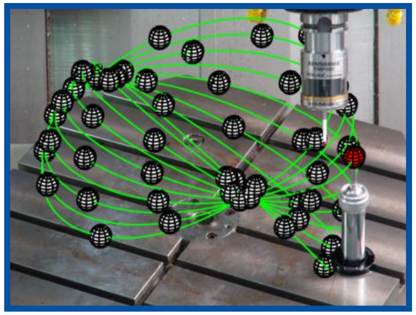

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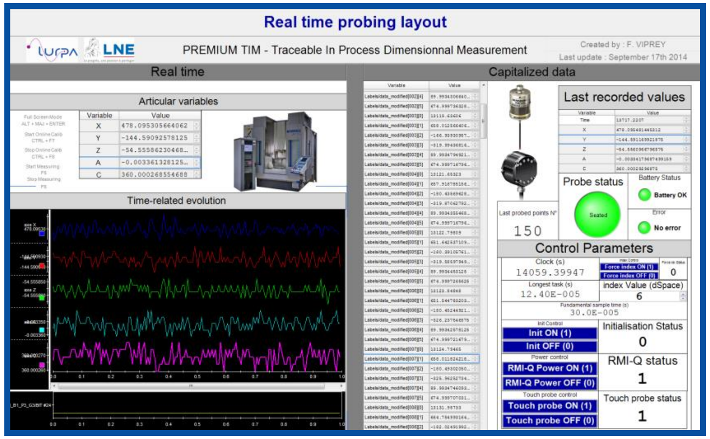
Integration : Direct measurement of machine tools encoders, not including CNC

9 probed points in specific approach directions are defined in the MCS



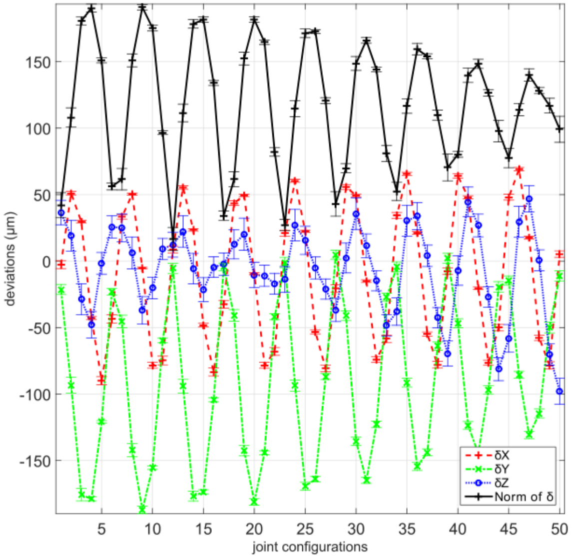
dSPACE MATLAB SIMULINK

F=33,33 kHz

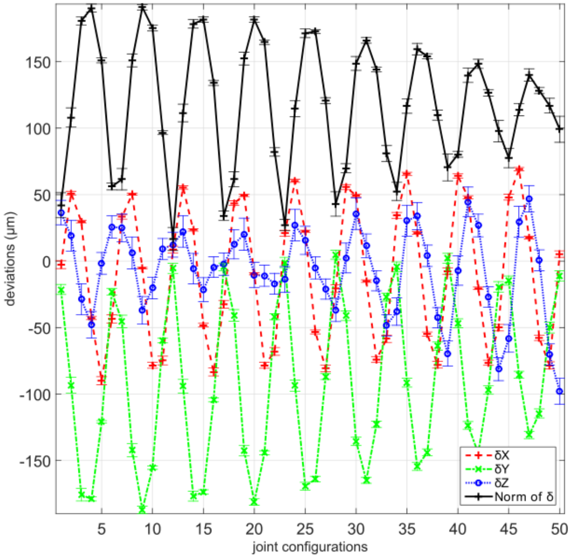
Resolution = 10 nm

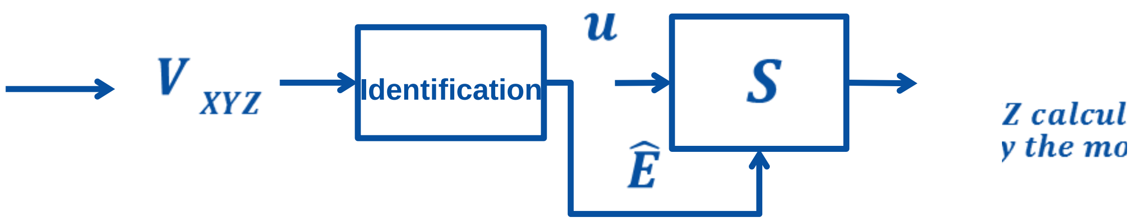
$U_{(k=2)\ touch\ probe}$= 0,25 µm $U_{(k=2)\ reproducibility}$ = 0,97 µm

Results



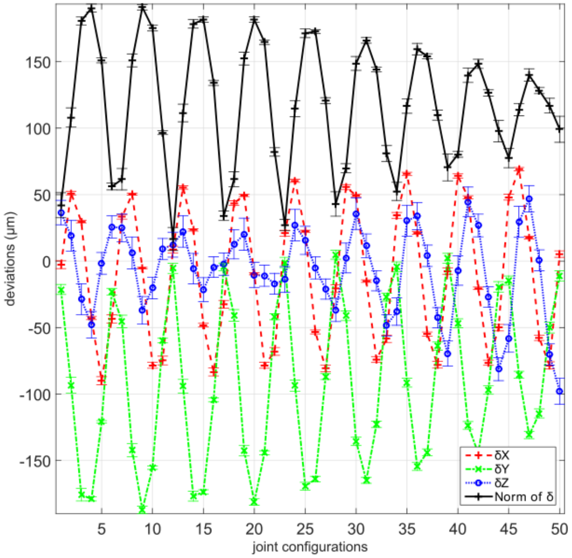
Results

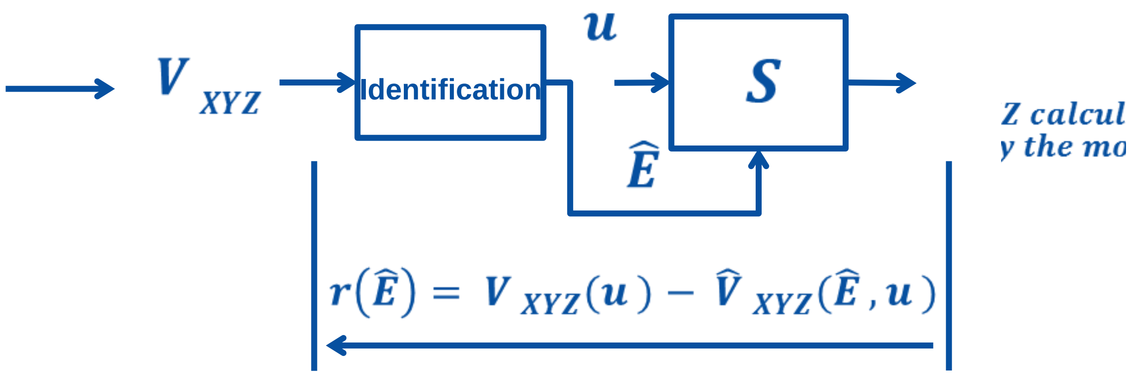




Constraints :

- Minimization the condition number of S
- Compensation of temporal deviations during the measurement





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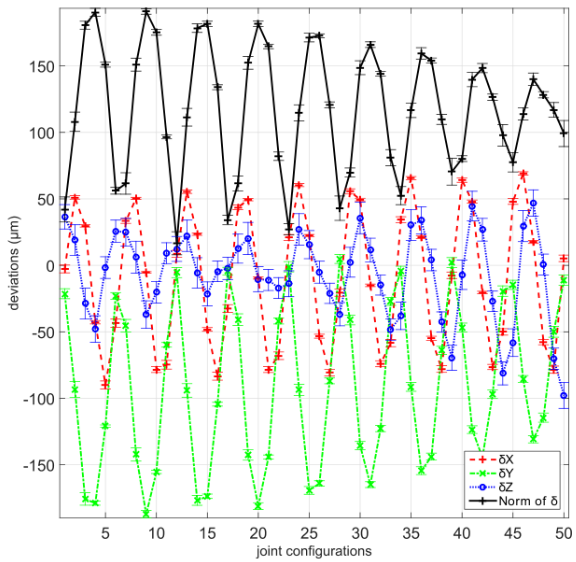

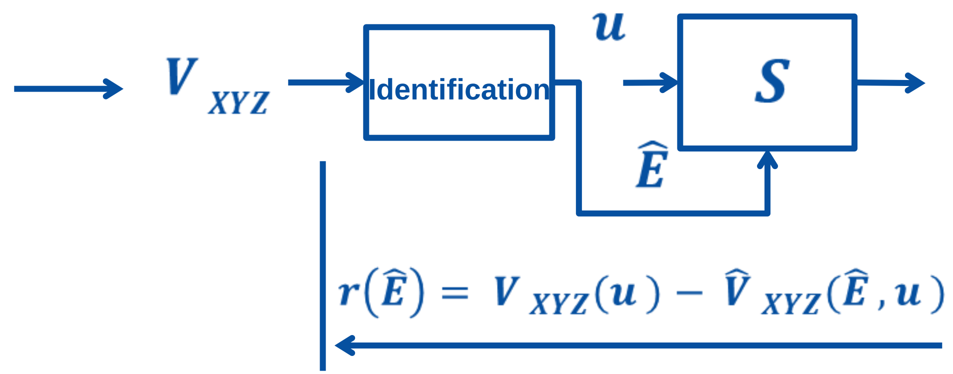

Z calcul
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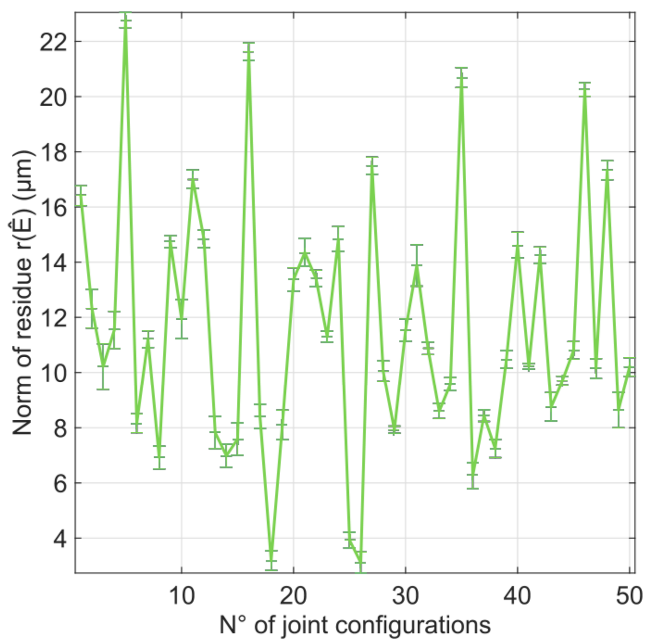

~90% of volumetric error is mapped

All combinations describe the measurement in the similar way.
The combinations are different but they provide the same effects on N configurations.

Robustness of the identification process

-Study of the condition number in function of A-values, C-values, and position of datum sphere on the rotary table;

-Study of the identification convergence according to the number and the values (X, Y, Z, A, C) of the configurations;

-Study of the identification residue according to the inverse problem resolution (QR decomposition, Moore–Penrose pseudoinverse, SVD decomposition, Truncated SVD);

-Confrontation of the identified models on other configurations:

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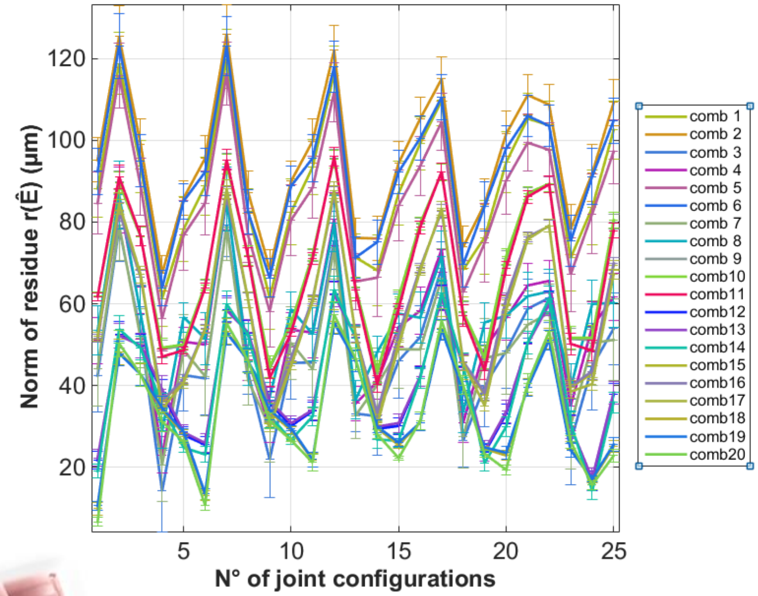

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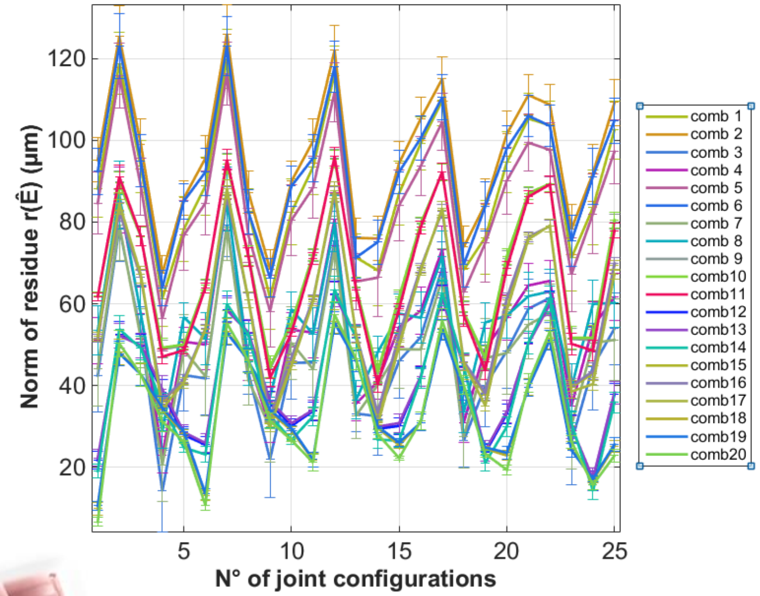
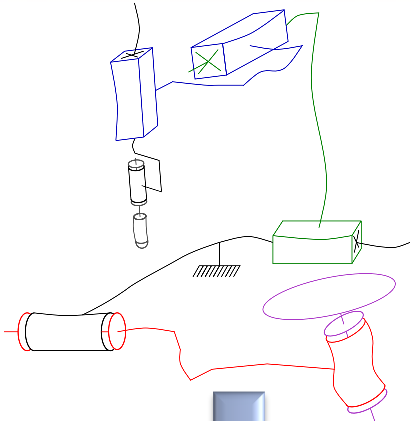
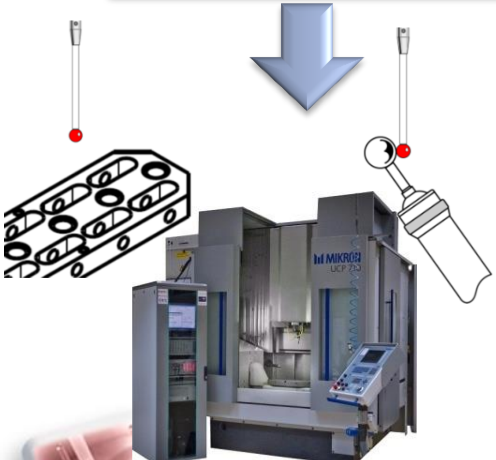


The identified combinations present different behaviors.
To minimize the volumetric error, the specified combination in the ISO 230 ensures the best fit (in the case of Mikron UCP710 machine tool).

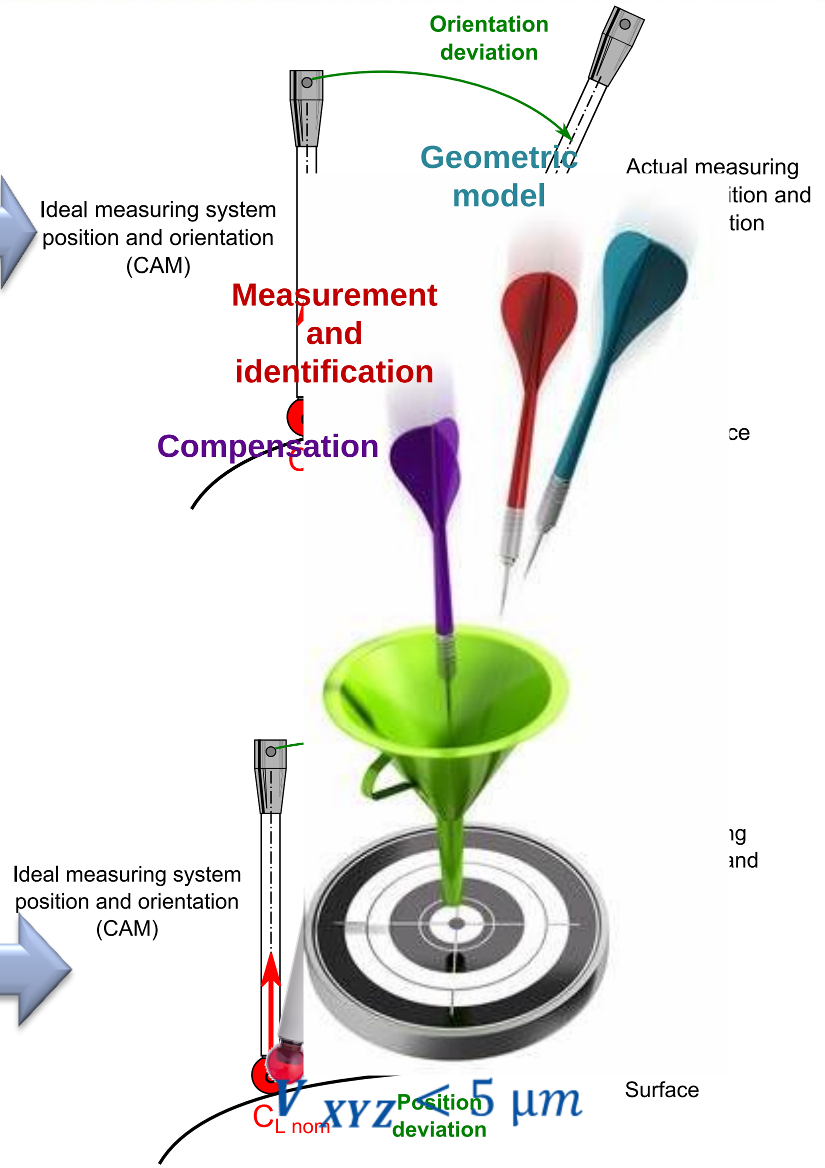


Geometric model

Measurement and identification



Compensation



Conclusion

Litterature

- Variety of geometric models without clear justification of chosen parameters

Qualification of geometric models

- Modeling based on ISO 230
- 20 simplifed models to compute the inverse problem

Application on actual 5-axis structure

- Development of measurement procedure without any pre-existing error compensations and uncontrolled processing in industrial CNC
- Identification of model parameters
- Similar behaviors obtained with 20 different models on selected configurations for identification, but these behaviors are different for other configurations

Further works

- Improvement of the model by combining both location and orientation errors as well as the motion errors
- Using the model for compensation during machining and in-process measurement

➔ ***Submission of a journal paper for publication***

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Heidenhain Student Scholarship

Thank you for your attention!

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EMRP
European Metrology Research Programme
Programme of EURAMET

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EURAMET

Fabien VIPREY – LNE – LURPA
fabien.viprey@lne.fr

Christophe TOURNIER – LURPA
Sylvain LAVERNHE – LURPA
Hichem NOUIRA – LNE

LURPA
ENS CACHAN
université PARIS-SACLAY

French National Metrology Institute LNE-Cnam
Automated Production Research Laboratory of ENS Cachan – Univ Paris Saclay