Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
National Metrology Institute

3DMC 3D METROLOGY CONFERENCE

Traceability of dimensional measurements of large workpieces

Applications in PTB's Competence Center Wind

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Physikalisch-Technische Bundesanstalt (PTB)
Working Group 5.32 – Coordinate Measuring Systems

GEMIMEG-II

Supported by:

Federal Ministry for Economic Affairs and Climate Action

on the basis of a decision by the German Bundestag

Outline

I. Metrological challenges and PTB’s work

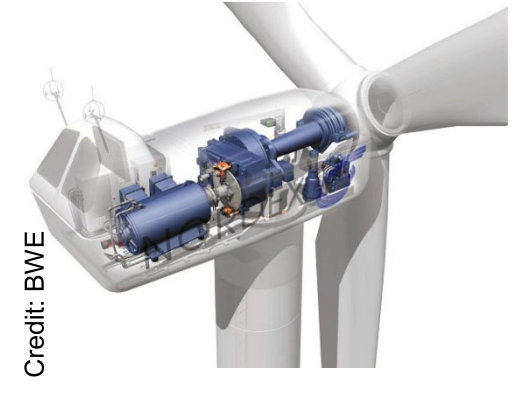
II. Traceability using Multilateration

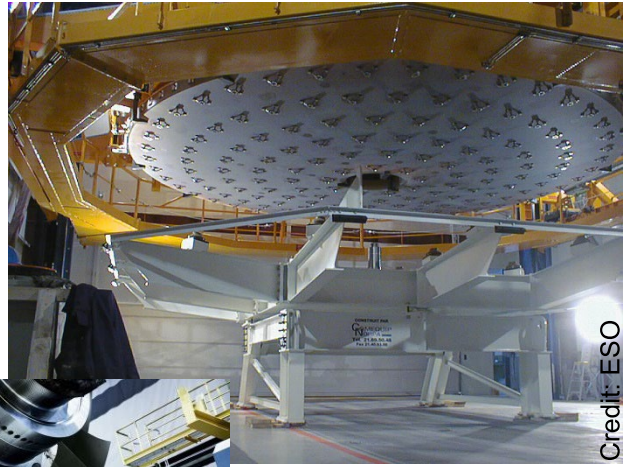
III. Use of Digital-Metrological Twins

IV. Geometry error mapping

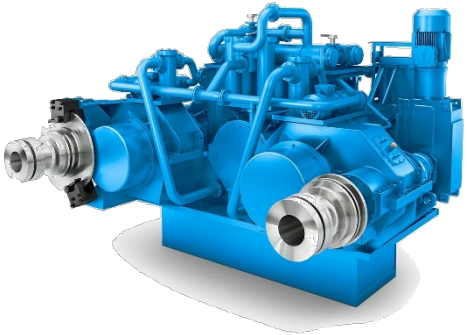
V. Process digitalization using DCCs

I. Large workpieces


Credit: BWE


Credit: ESO


Credit: Siemens


Credit: Flender

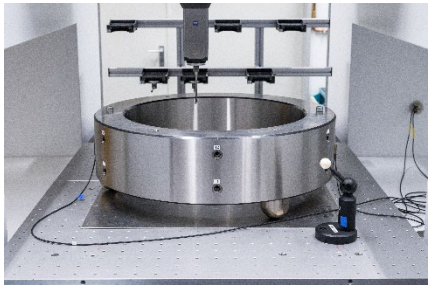
Energy transformation
- Wind turbines
- Gas turbines

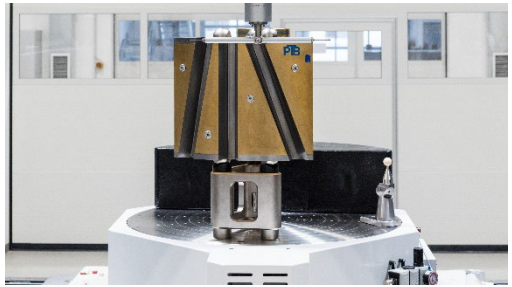
Telescope parts

Ship building

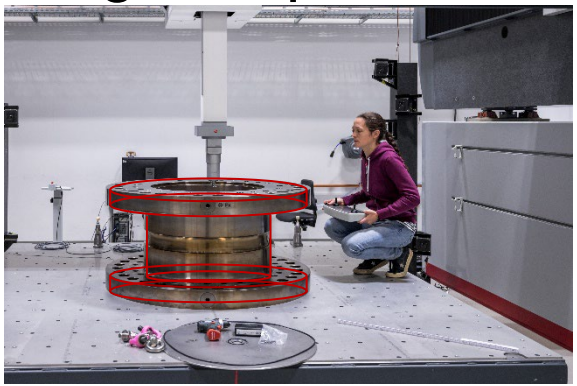
PTB’s focus on wind energy systems

Drivetrain components





Large torque standards



$F \cdot l$

in

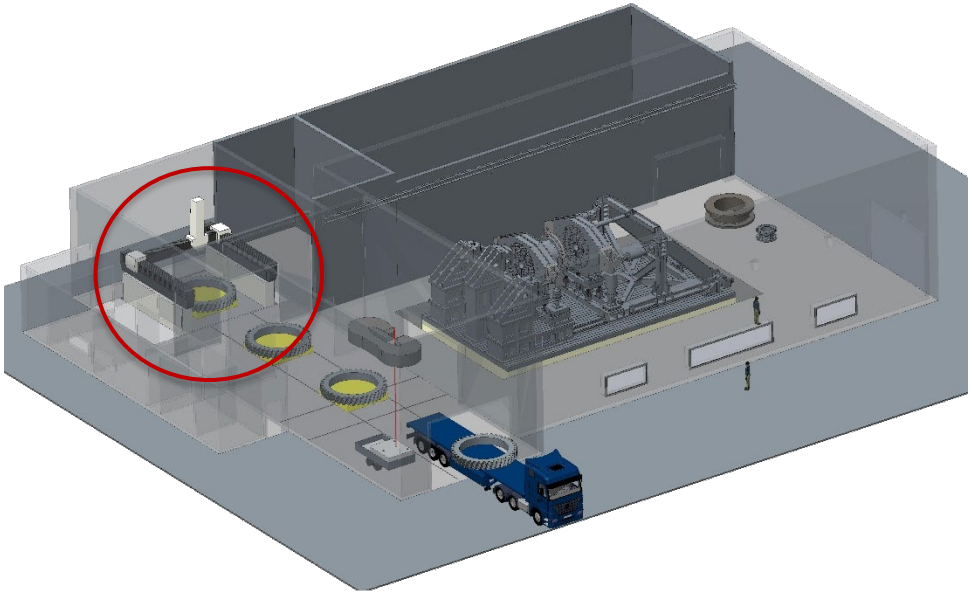
$\longrightarrow$

$N \cdot m$

CMM in Competence Center Wind

Leitz PMM-G 50.40.20

- $E_{0,\mathrm{MPE}} = 3.3\ \mu\mathrm{m} + 2.5\ \mu\mathrm{m/m}$
- Probe exchange system
- Tactile and different optical sensors
- Rotary table ($D = 1\ \mathrm{m}$)
- $T = 20.0\ °\mathrm{C} \pm 0.1\ \mathrm{K}$
- Separated pre-climatization room



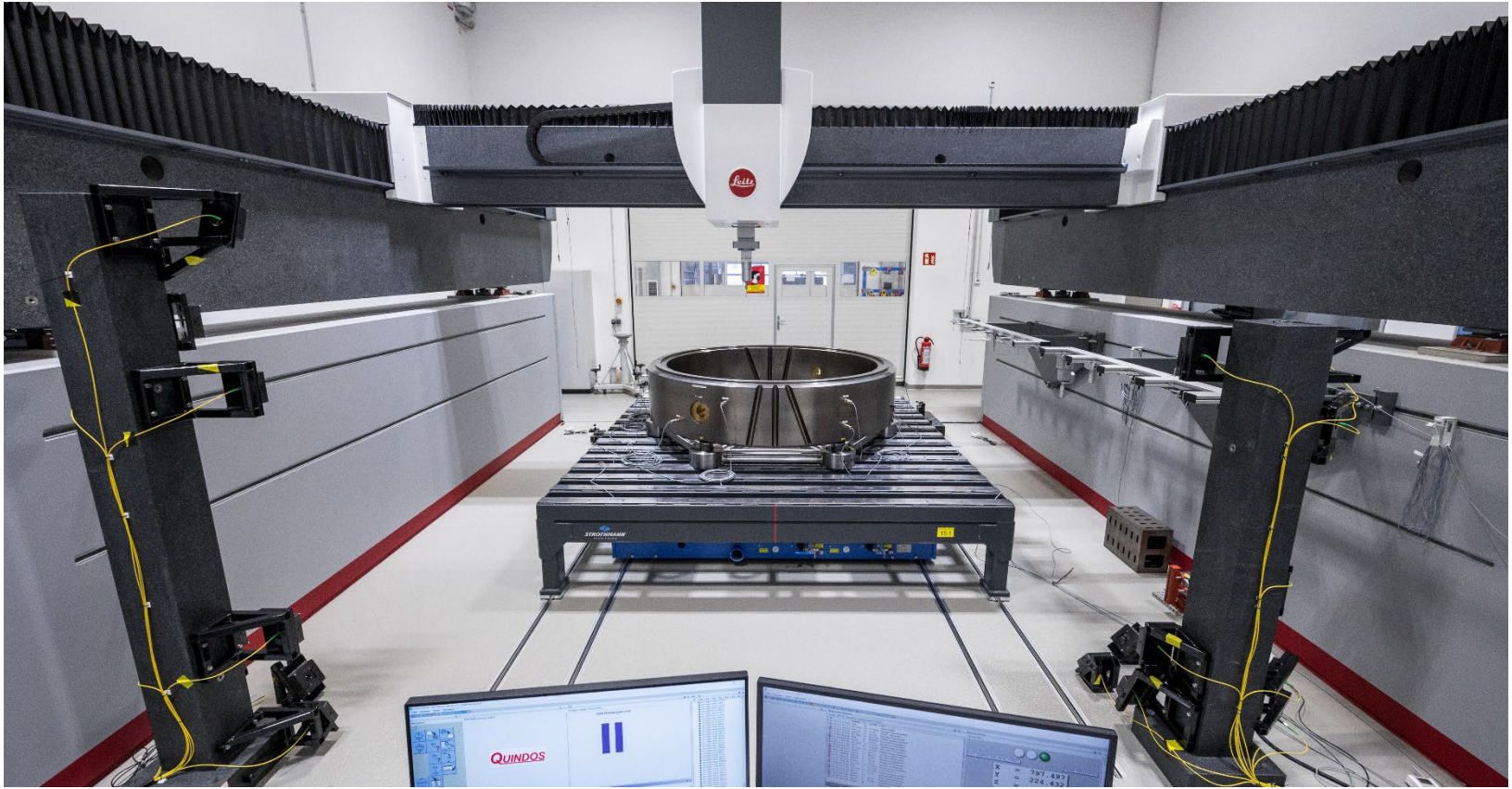
Metrological challenges

- Tolerances for large workpieces often similar to small parts
- Higher uncertainty of LVM instruments:
  - Thermal stability
  - Geometry errors (Guideway)
  - Workpiece size and mass

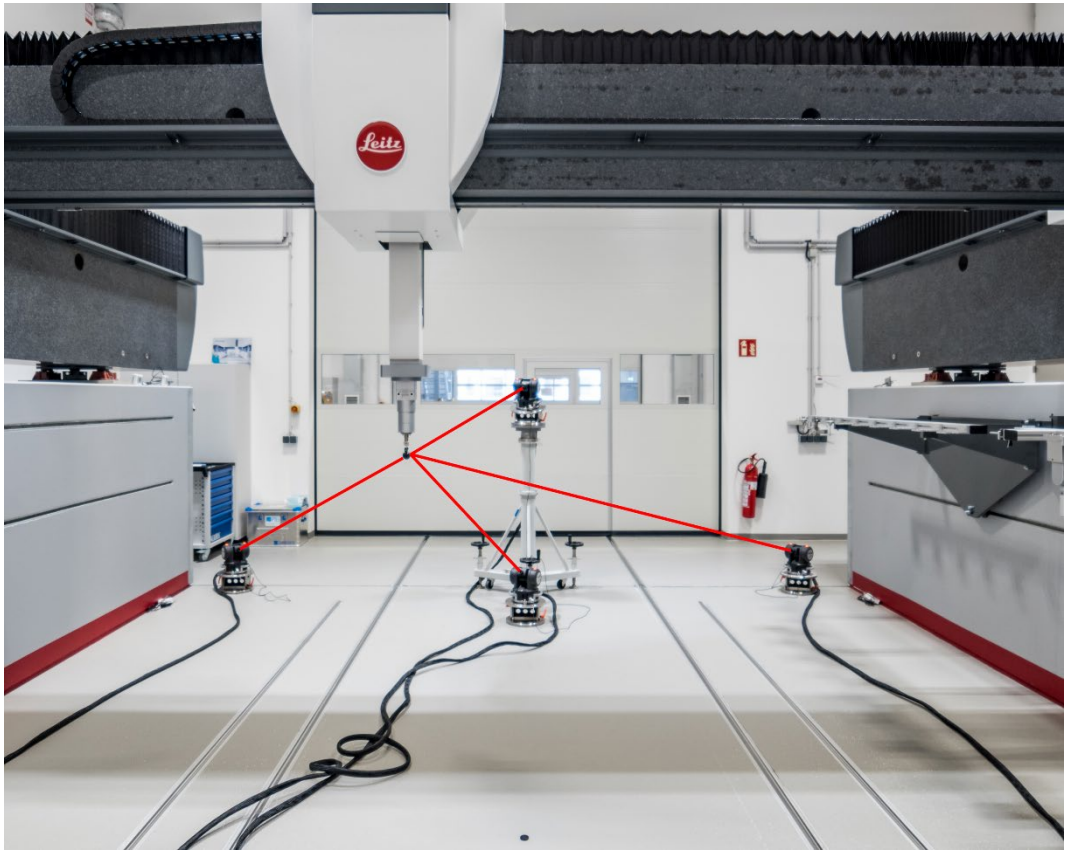
Our goals:

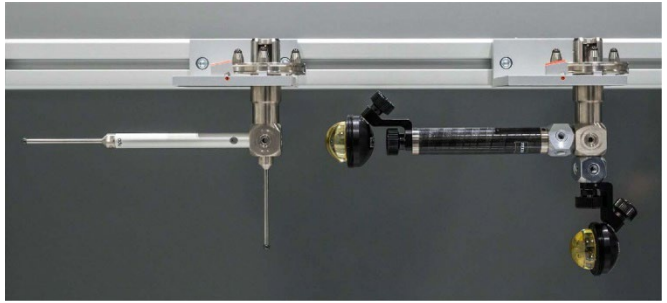
- Reduction of measurement/calibration uncertainty
- Traceability for large spectrum of measurement tasks

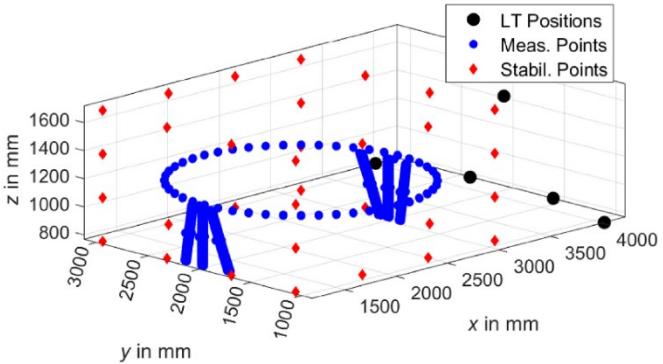
II. M3D3 Calibration Strategy



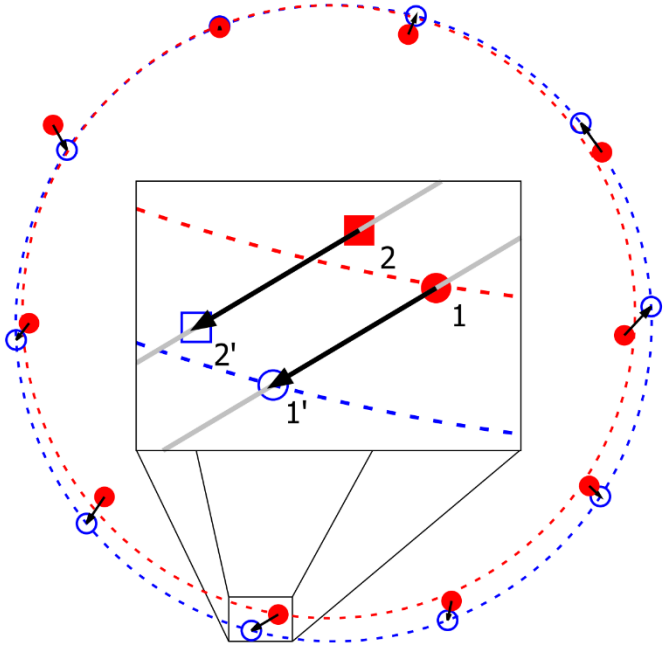
M3D3 Calibration Strategy







M3D3 Calibration Strategy

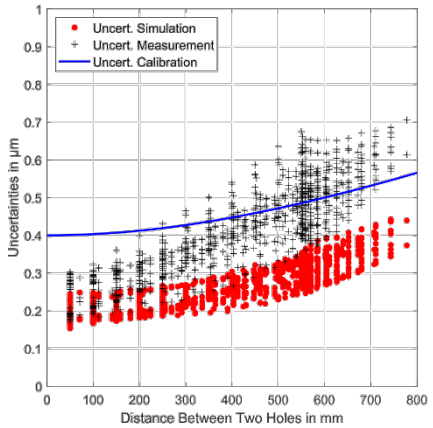


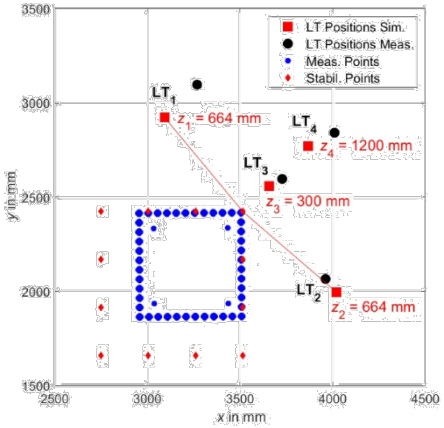
- Measuring points
- Probe position during LT measurement
- LT measuring point
- Corrected measuring point

- Measurement of workpiece
- Repetition using interferometric multilateration
- Traceability by
  - frequency calibration
  - calibrated environmental sensors
- Reduction of measurement uncertainty

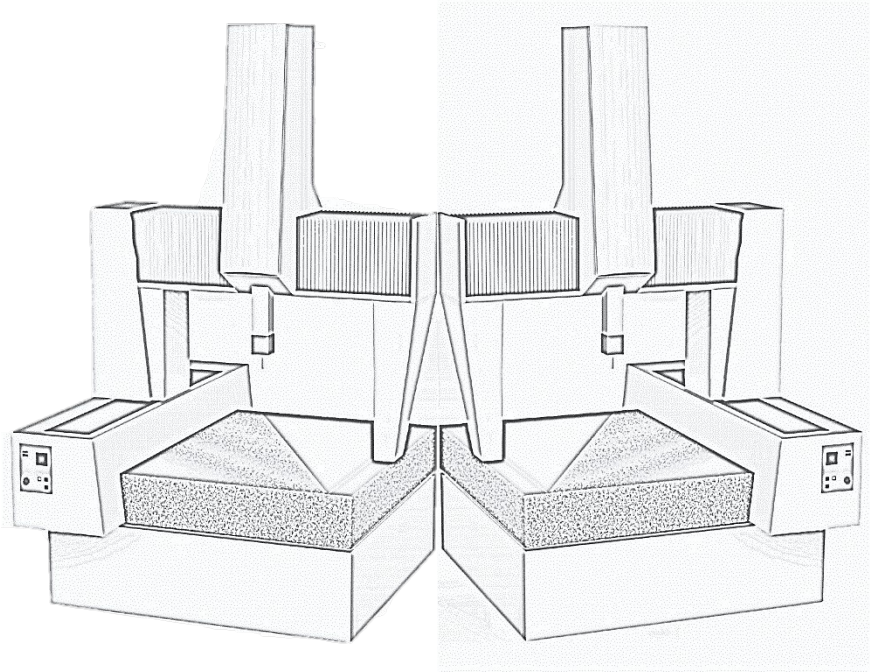
M3D3 Calibration Strategy

- Validated against calibrated hole plate
- Critical parameters
  - Number and positioning of stabilisation points
  - Viewing conditions and positioning of the LaserTracers
  - Bonus: Number of LaserTracers (€€€)





III. The Digital-Metrological Twin



A digital metrological twin (D-MT) is a **numerical model that depicts a specific measurement process and indicates an associated measurement uncertainty** for a specific measured value, which is traceable to the units of the international system of units. Moreover, it complies with the requirements that

- the measurement uncertainty is **calculated according to recognized standards** and guidelines,
- all **input parameters are traceably determined** and are stated with the corresponding measurement uncertainty and
- the calculated measurement uncertainty is **validated** by traceable measurements.

Härtig et al. (2023) https://doi.org/10.1515/teme-2023-0066

Virtual Coordinate Measuring Machine VCMM

- **Goal:** Determination of measurement uncertainty for complex tasks
- **Path:** Monte Carlo Simulations (MC)

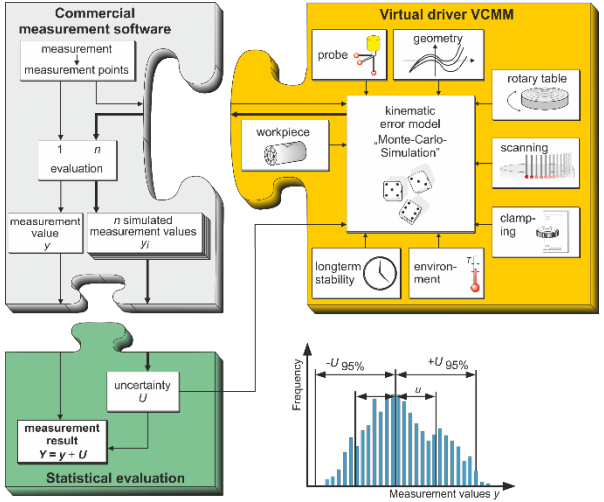
i. Precise characterization of CMM and measurement task

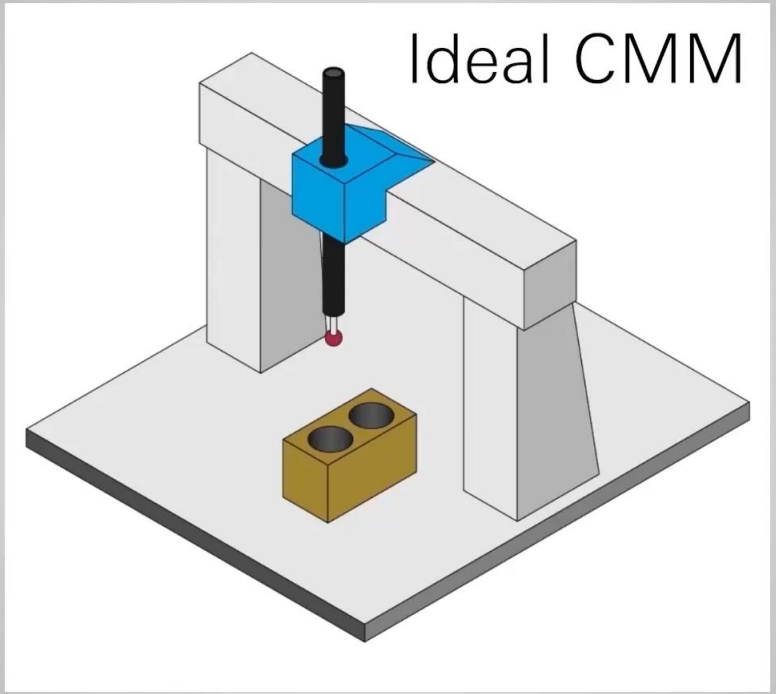
ii. Determination of influences on MU

iii. Performance of a measurement

iv. Simulation of many similar measurements

v. Statistical analysis

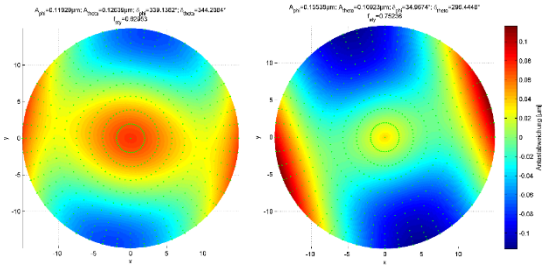


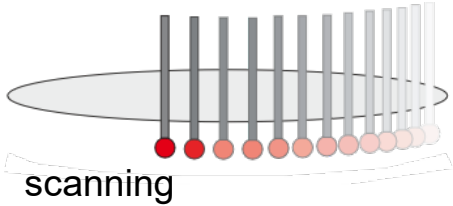


Principle of the "Virtual Coordinate Measuring Machine"

Which contributions are considered?

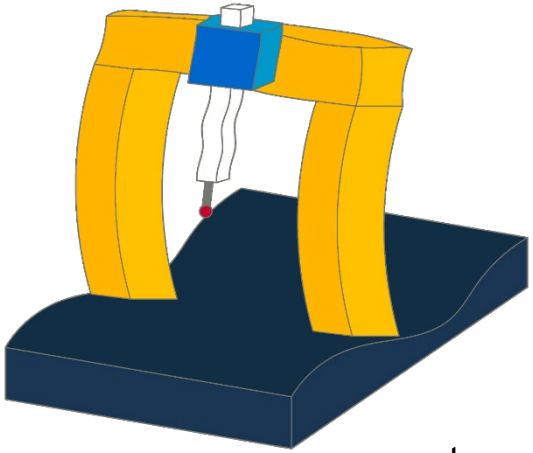
probing deviation



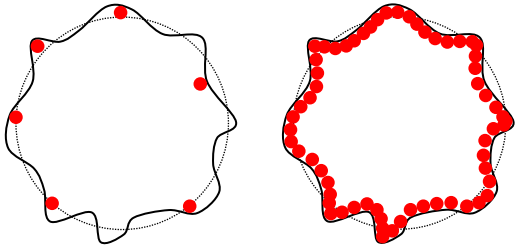


scanning

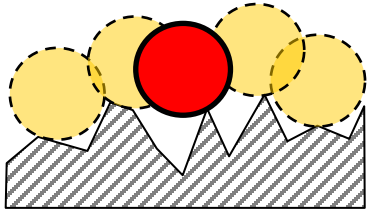
environmental conditions



geometry errors



undersampling



workpiece properties

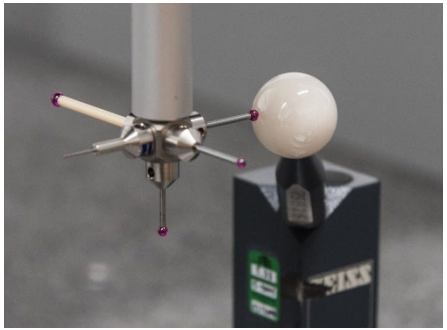
Parametrization and Traceability

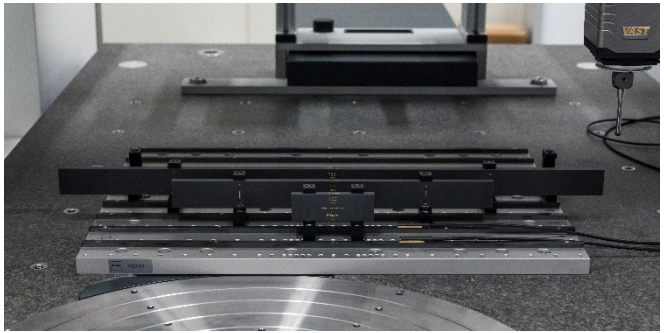
Parameters from:

- Long-term observations (e. g. *T*, *p*, *relH*, …)
- Test / comparison measurements
- Expert knowledge (e. g. production process, manufacturer‘s information, …)

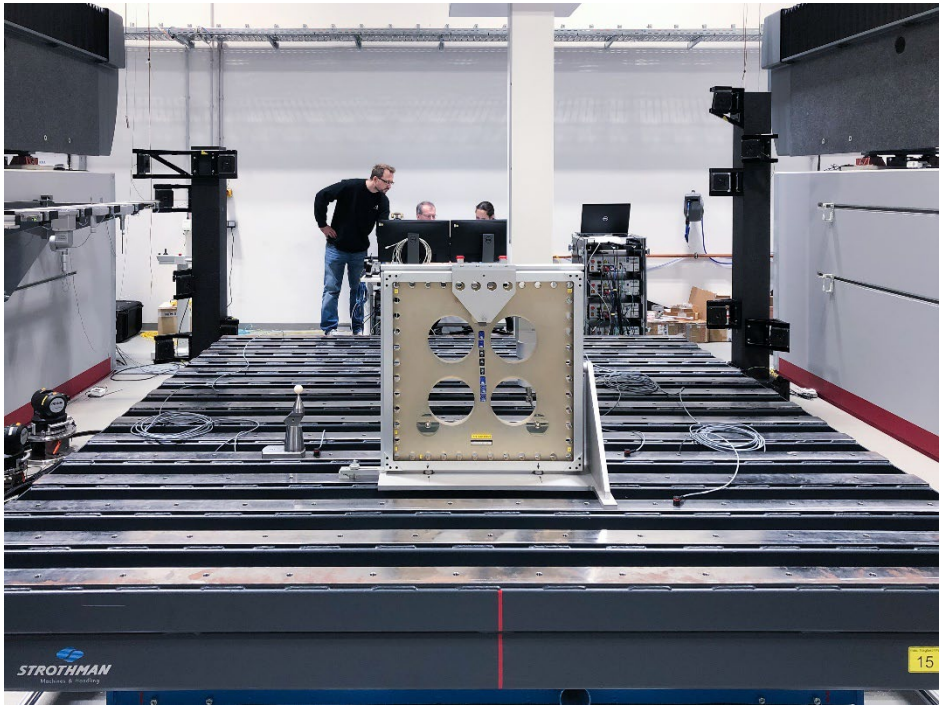
Traceability by:

- Calibrated sensors
- Use of calibrated measurement standards
- Certified analysis algorithms





Problems for large volume CMM

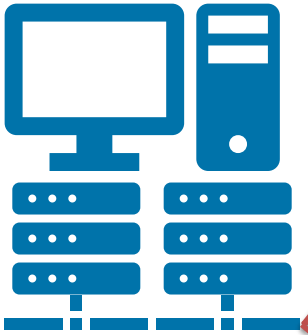


1 m³ □ 40 m³

- **Availability** of material standards
- **Cost** of material standards
- **Handling** of material standards
- **Achievable uncertainty**

IV. Error Mapping of large volume CMM

PTB
IT center

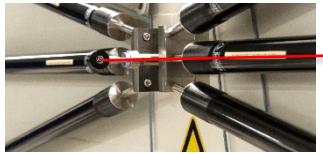


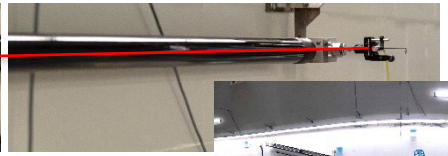
central
interferometer
unit

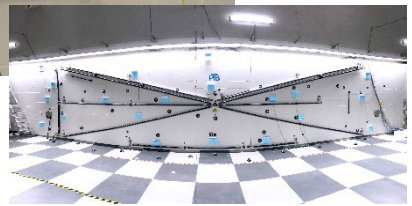
optical fiber
distribution

CMM laboratories

Reference Wall



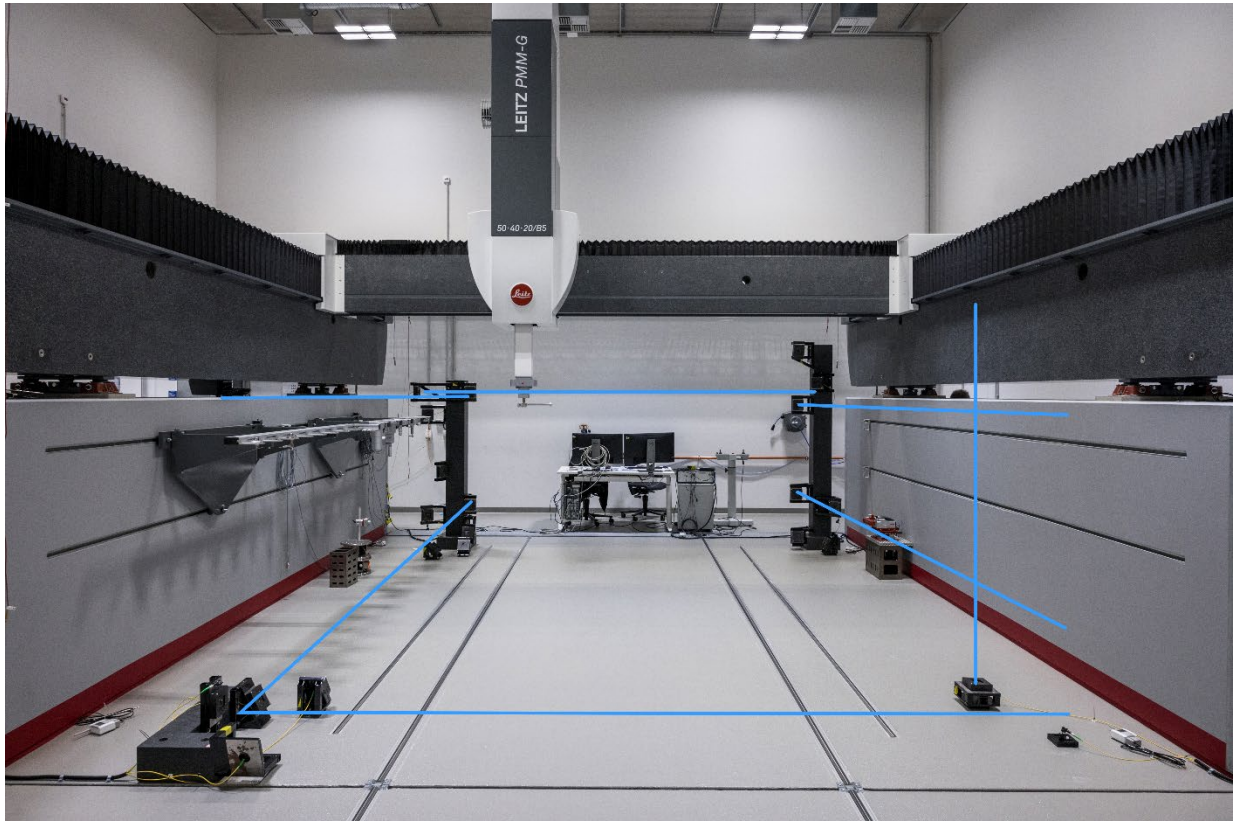




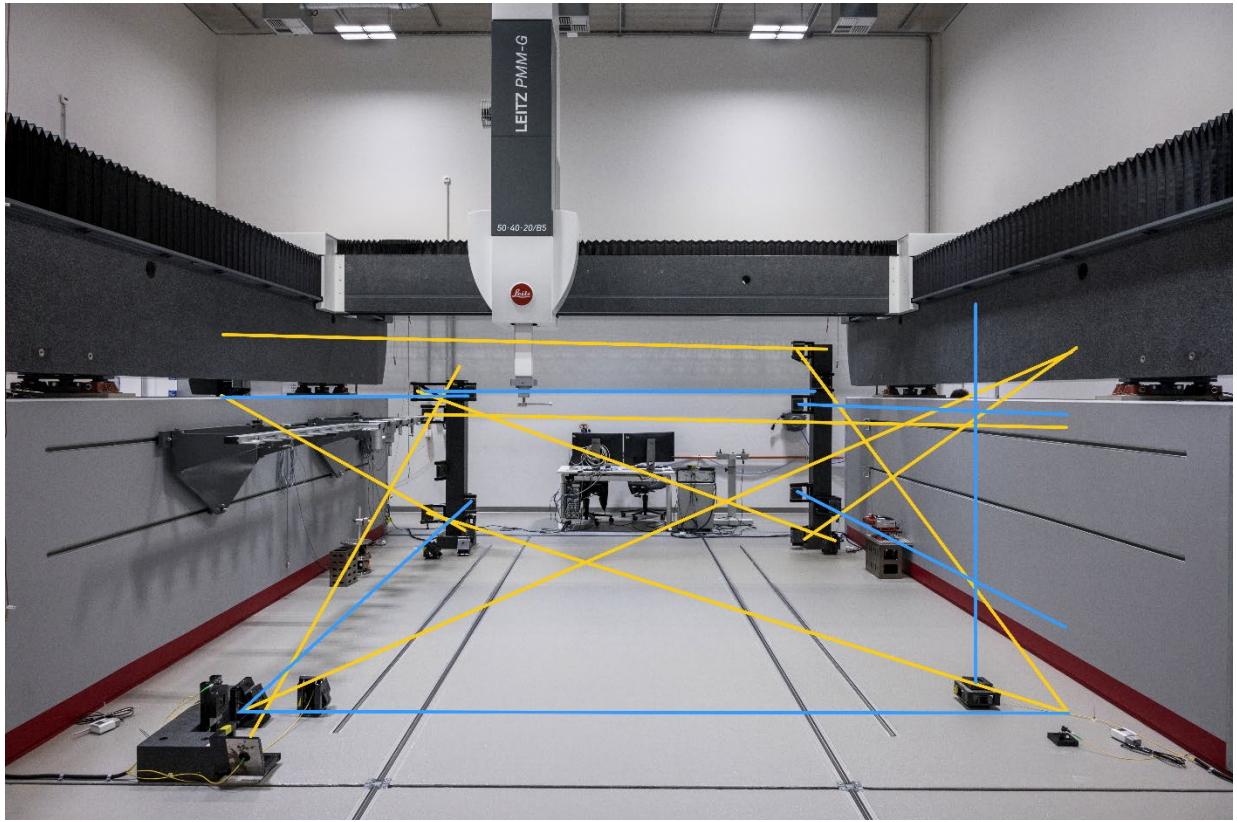
50 m comparator

Error Mapping of CMM

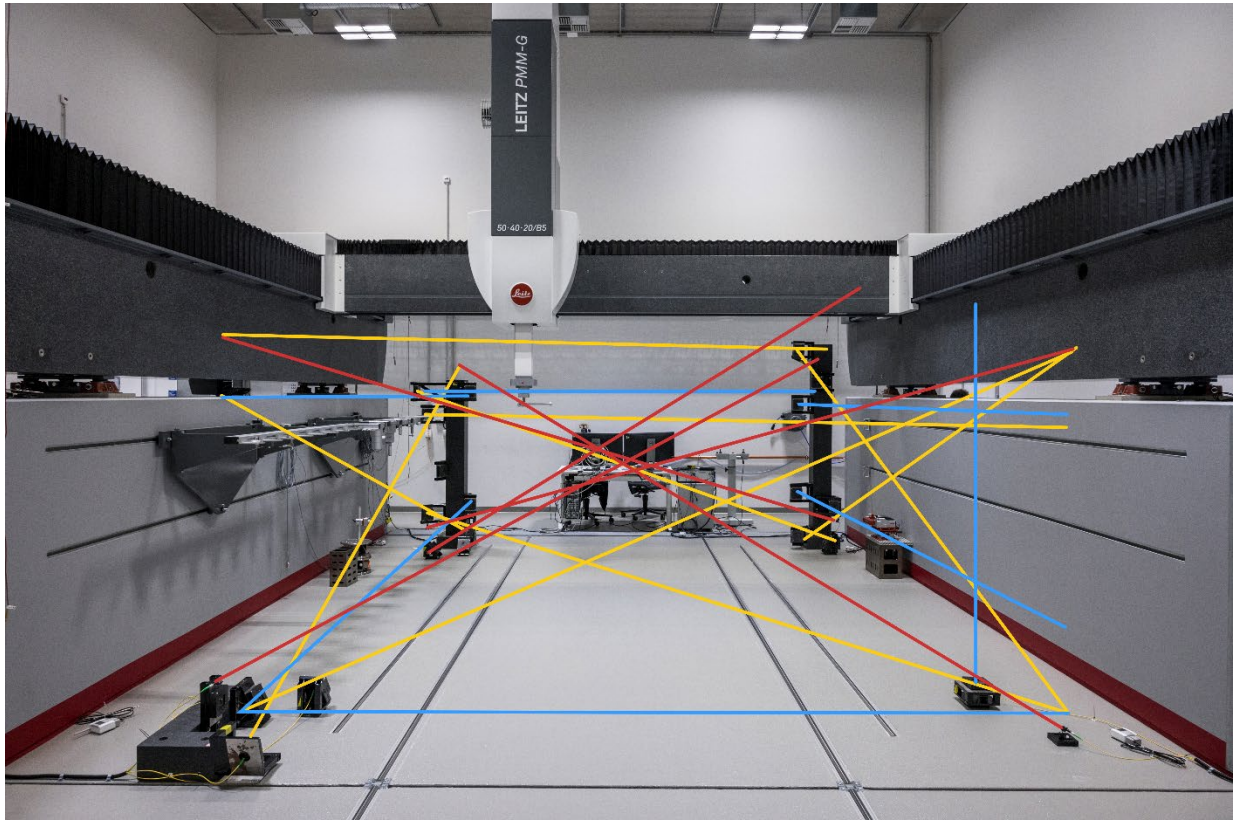
Error Mapping of CMM – Axes



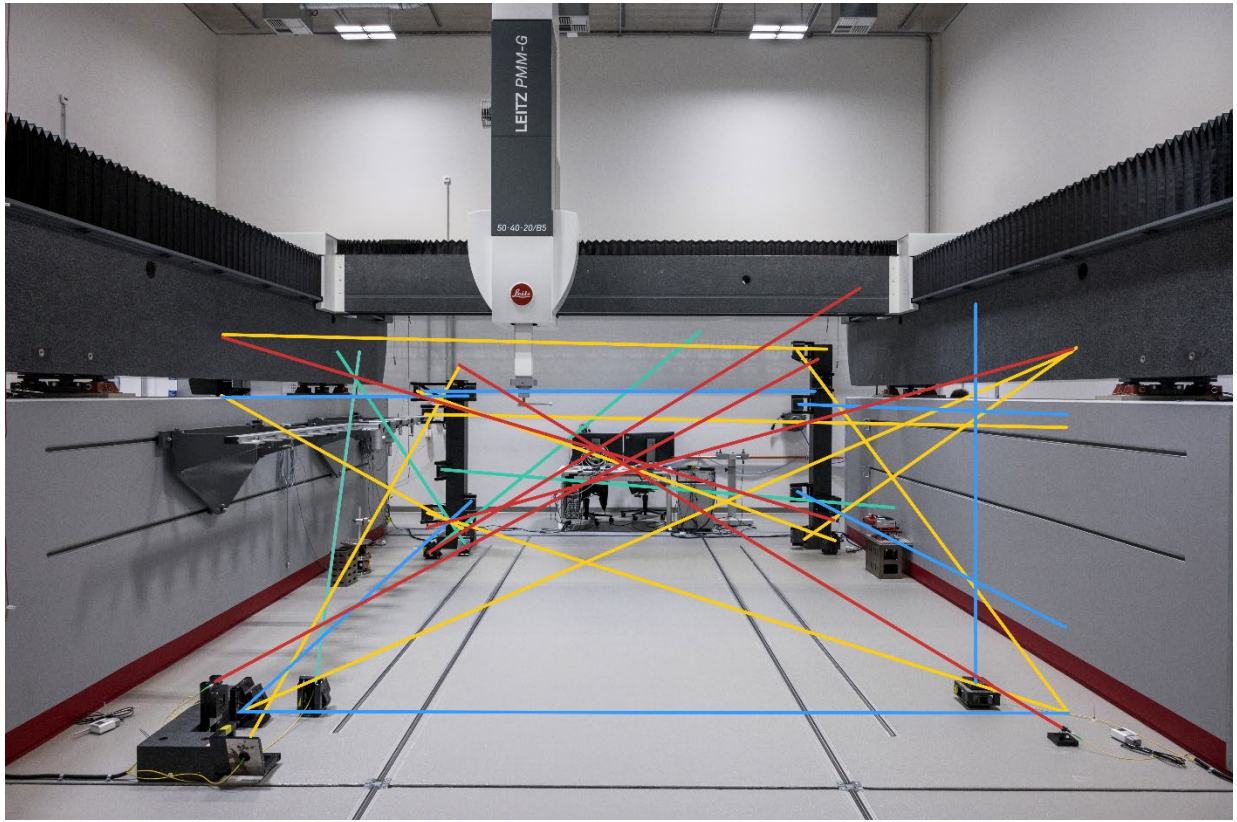
Error Mapping of CMM – Areal Diagonals



Error Mapping of CMM – Spatial Diagonals



Error Mapping of CMM – Partial Diagonals



Error Mapping of CMM – 240x timelapse

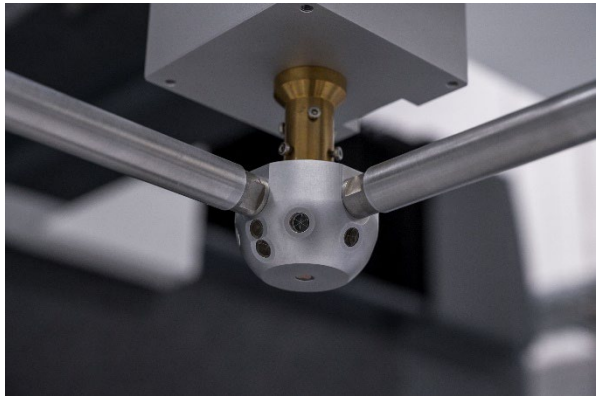
Error Mapping of CMM – Summary

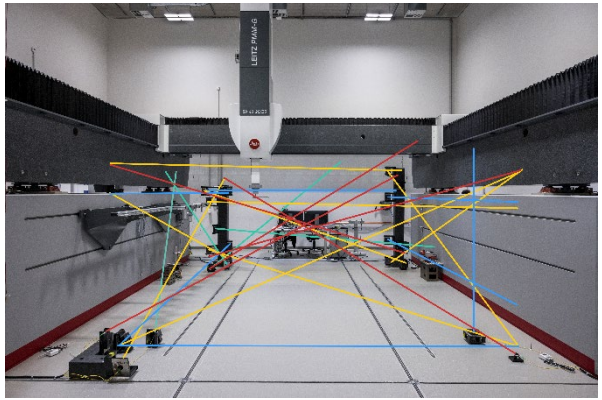
- Custom-made L-shaped reflector
- 24 fixed corner cubes (3 on each boom)
- Automatic reflector pick-up by CMM from storage position

- Duration: 212 minutes

→ Overnight runs before measurements

→ Traceable input parameters to VCMM





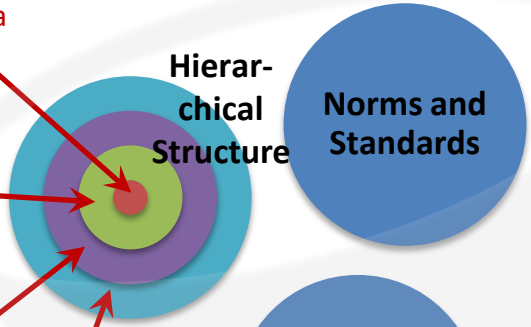
V. Process digitalization using DCCs

1.: Administrative Data
- regulated

2.: Results of the Calibration
- regulated:
  - ➢ $Y = y \pm U(k)$ [SI]
- not regulated:
  - ➢ individual data
  - ➢ …

3.: Comments
- not regulated

4.: Document
- human readable

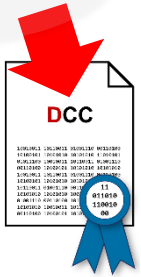


Norms and Standards

- SI
- VIM
- GUM
- CODATA
- 17025

XML as Exchange Format

- international accepted
- approved
- cryptographically signable



Brief introduction to XML

DCC uses e**X**tensible **M**arkup **L**anguage

- Schema can be tested
- Established and rarely modified
- Can be signed:

  XAdES □ Qualified Signature

Some XML Basics:

- Elements

```
<elementname></elementname>
```

- Tags

```
<elementname>content</elementname>
```

- Attributes

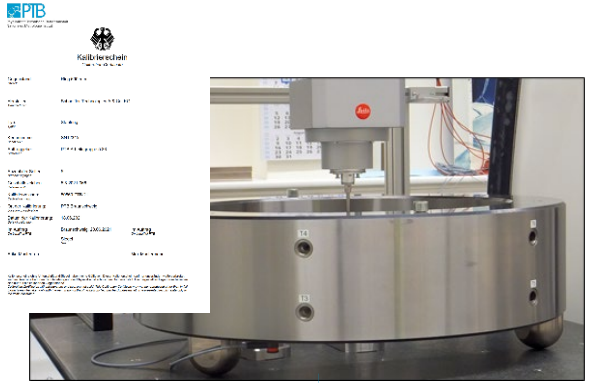
```
attributname="attribute value"
attributname='attribute value’
```

- Qualified Names

```
[prefix:]local_part
```

DCCs for material standards

Gauge blocks



Bearing ring

Calibration sphere

```
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    <dcc:content lang="de">Absolute Länge</dcc:content>
    <dcc:content lang="en">Absolute length</dcc:content>
  </dcc:name>
  <si:real>
    <si:value>0.069999123</si:value>
    <si:unit>\metre</si:unit>
    <si:expandedUnc>
      <si:uncertainty>1.23E-08</si:uncertainty>
      <si:coverageFactor>2</si:coverageFactor>
      <si:coverageProbability>0.95</si:coverageProbability>
    </si:expandedUnc>
  </si:real>
</dcc:quantity>
<dcc:quantity refType="length_ISO3650deviationFromNominalLength">
<dcc:influenceConditions>
```

```
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  <dcc:description>
  <dcc:data>
    <dcc:list>
      <dcc:name>
      <dcc:description>
      <dcc:list>
      <dcc:list>
        <dcc:name>
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        </dcc:name>
        <dcc:quantity>
          <dcc:name>
            <dcc:content lang="de">Durchmesser</dcc:content>
          </dcc:name>
          <si:real>
            <si:value>599.999</si:value>
            <si:unit>\milli\metre</si:unit>
            <si:expandedUnc>
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            </si:expandedUnc>
          </si:real>
          <dcc:measurementMethod>
        </dcc:quantity>
      </dcc:list>
    </dcc:list>
  </dcc:data>
</dcc:result>
```

```
<dcc:measurementResult refType="length_features" refId="I123">
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  <dcc:description>
  <dcc:usedMethods>
  <dcc:measuringEquipments>
  <dcc:influenceConditions>
  <dcc:results>
    <dcc:result refType="length_diameter">
      <dcc:name>
        <dcc:content lang="de">Durchmesser</dcc:content>
      </dcc:name>
      <dcc:description>
      <dcc:data>
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          <dcc:name>
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          </dcc:name>
          <si:real>
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            <si:expandedUnc>
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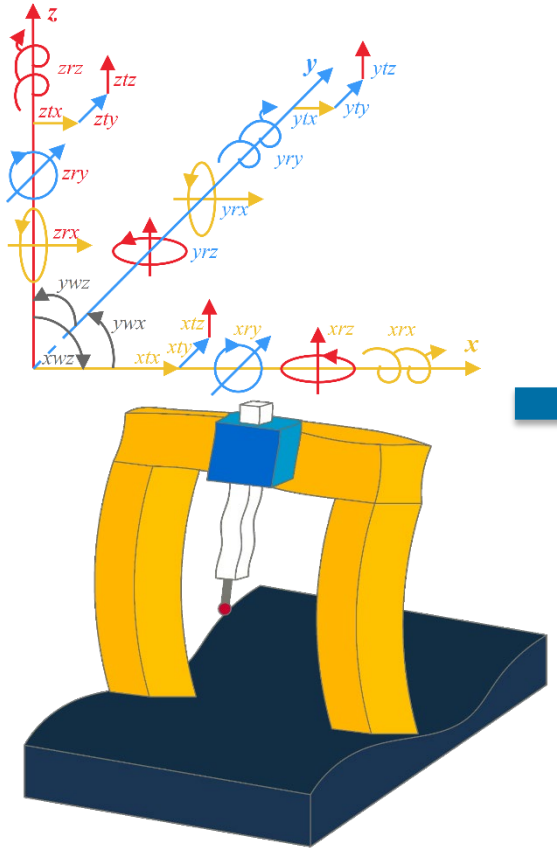
VCMM geometry error parameters DCC




```
<dcc:measurementResults>
    <dcc:measurementResult>
        <dcc:name>
            <dcc:content>VCMM parameter set</dcc:content>
        </dcc:name>
        <dcc:description>
        <dcc:results>
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                <dcc:name>
                    <dcc:content>Geometry errors</dcc:content>
                </dcc:name>
                <dcc:data>
                    <dcc:list refType="VCMM_x">
                        <dcc:list refType="VCMM_xTranslation">
                            <dcc:list refType="VCMM_xtx">
                            <dcc:list refType="VCMM_xty">
                            <dcc:list refType="VCMM_xtz">
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                            <dcc:list refType="VCMM_xry">
                            <dcc:list refType="VCMM_xrz">
                        </dcc:list>
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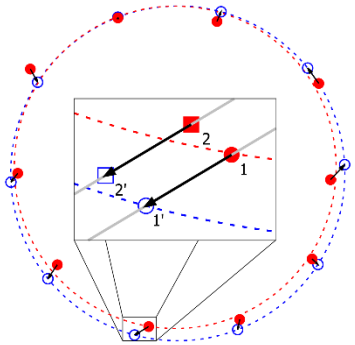
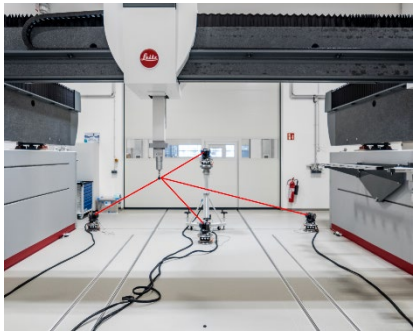
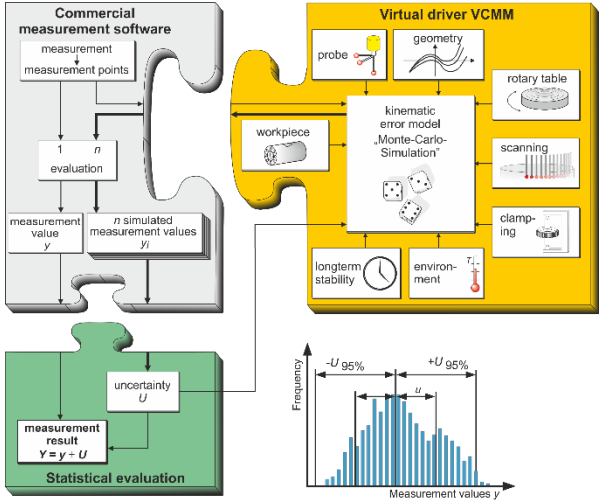
Summary

- Traceable calibration strategy using M3D3





- Traceable process using D-MT and DCCs

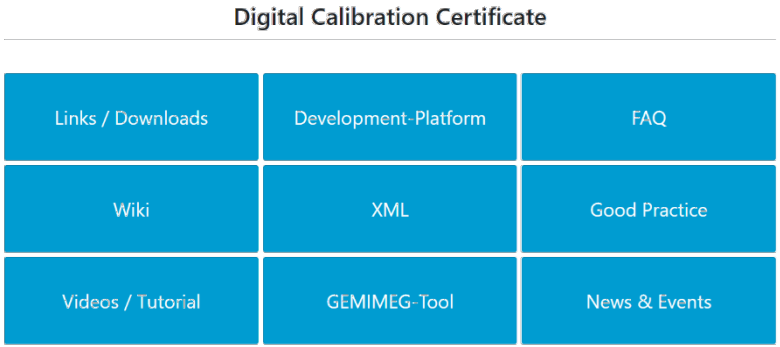


Further reading

Rafeld et al. 2022 (https://doi.org/10.1088/1361-6501/ac407c)
Wübbeler et al. 2022 (https://doi.org/10.3390/metrology2010008)

www.ptb.de/dcc:

- Current DCC Schema (3.2)
- GEMiMEG-II Tool
- DCC Wiki with Good Practice Examples
- refType Wording „basic“
- Video Tutorials



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As of 09/23

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