3D METROLOGY CONFERENCE

Geometric partitioning by holistic approximation

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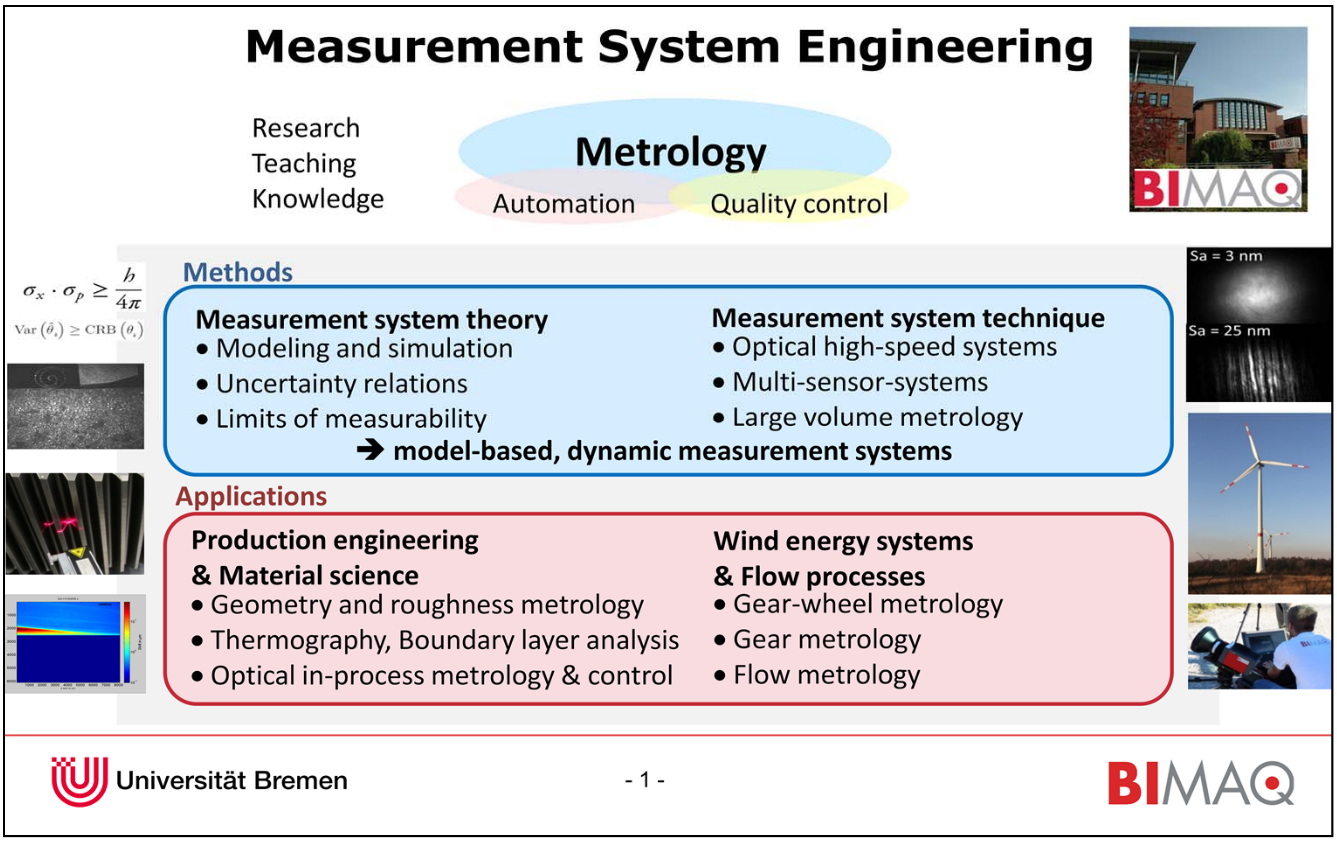
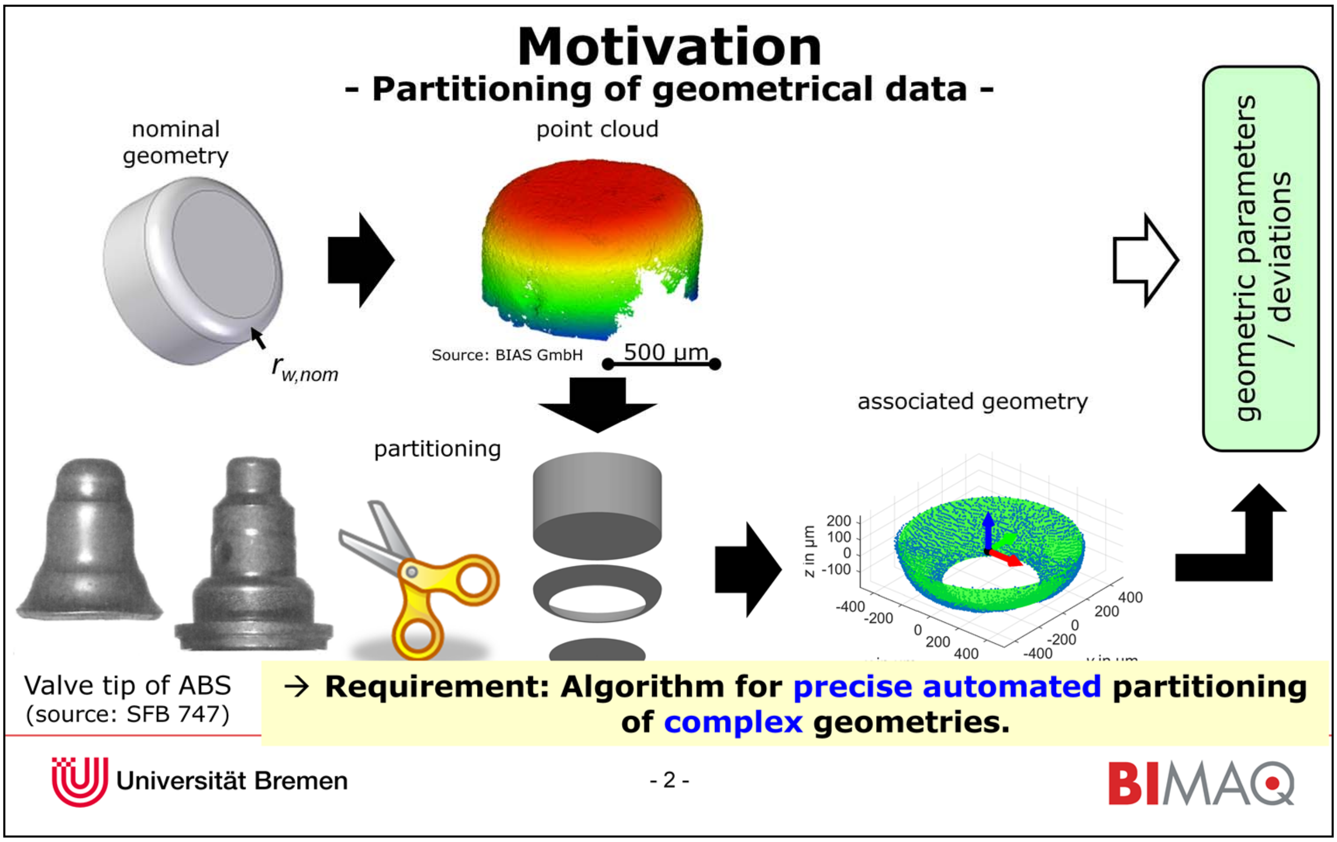
3D Metrology Conference – 3DMC
2019, London, UK

BIMAQ
Bremen Institute for
Metrology, Automation
and Quality Science



Bremen Institute for Metrology, Automation and Quality Science (BIMAQ), University of Bremen:

Research fields.



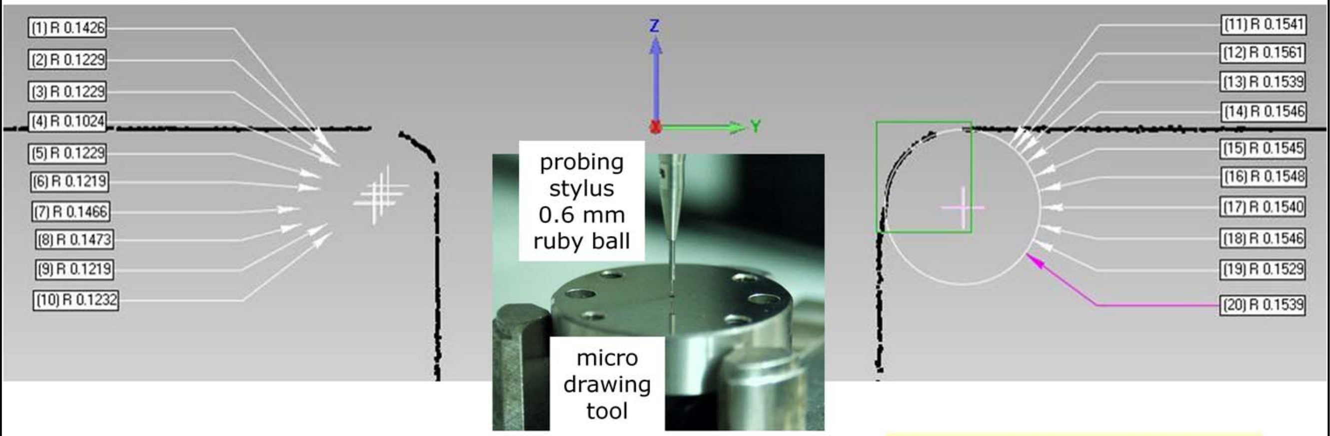
Workpiece: drawed micro cup (D < 1 mm).

Cold formed micro workpieces are contained in numerous applications, e.g. valves of antilock braking systems (ABS)

Partitioning is one of 4 major operations within ISO GPS.

Motivation
- Manual partitioning -

- Example: Micro drawing tool



span: 53.7 µm (30 % of nominal datum)

→ **no automation**
→ **poor reproducibility**

State of the art

- Geometric partitioning / segmentation -

Precise automated evaluation of complex dimensional data

	Metrology software	Edge detection	Attribute clustering	Region growing	Holistic Approximation (HA)
precise	-/+	-	o	-	**+**
automated	o	+	+	+	**+**
complex geometry	-	+	+	+	**?**
restrictions		sensitive to noise	sensitive to noise	over-/under-segmentation	**combination of simple geometries**

→ Approach: Holistic approximation (HA) extended with root point iteration

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Holistic approximation:

- converges reliably
- tested for micro features
- outlier detection possible

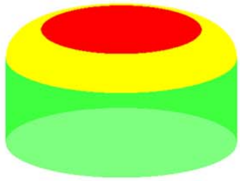
Outline

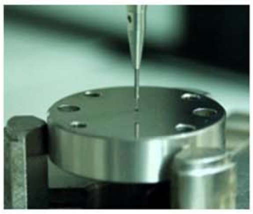
Holistic approximation

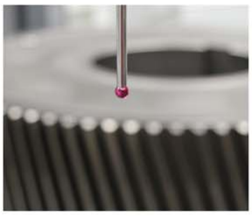
- Method

- Results
  - a) Micro cup (3D)
  - b) Drawing die (ellipse)
  - c) Gear / involute

- Summary & outlook







Method

- Approximation approach -

Holistic approximation

I. Geometric model
→ transformation parameters: $\vec{a}_p$
→ shape parameters: $\vec{a}_g$

$\left.\begin{matrix}\vec{a}_p\\ \vec{a}_g\end{matrix}\right\} \rightarrow d_i \leftarrow \vec{x}_i$ (i^{th} measuring point)

II. Separation rules
→ point associations with variable numbers of points: $\vec{n} = [n_A, n_B, n_C, \ldots]$

III. Least squares approximation:

$$\min_{\vec{a}_p,\vec{a}_g,\vec{\boldsymbol{n}}} \left[\sum_{i=1}^{n_{\mathbf{A}}} \left(d_{\boldsymbol{A},i}(\vec{a}_p,\vec{a}_g)\right)^2 + \sum_{\mathbf{j}=1}^{n_{\boldsymbol{B}}} \left(d_{\boldsymbol{B},\boldsymbol{j}}(\vec{a}_p,\vec{a}_g)\right)^2 + \sum_{\mathbf{k}=1}^{n_{\boldsymbol{C}}} \left(d_{\boldsymbol{C},\boldsymbol{k}}(\vec{a}_p,\vec{a}_g)\right)^2 + \cdots \right]^{\frac{1}{2}}$$

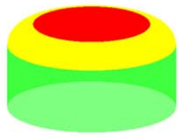
→ **Automated combination of partitioning and approximation.**

Characteristics:

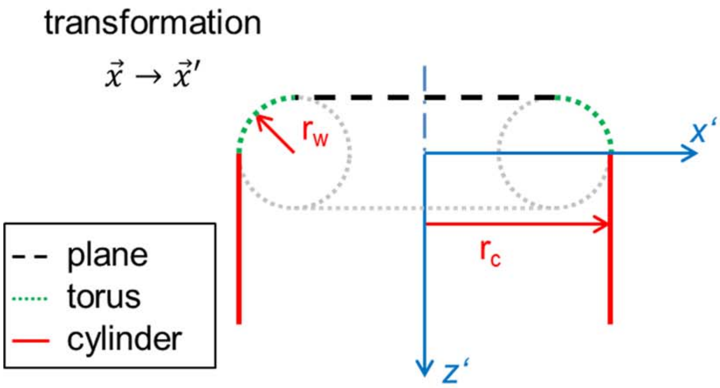
- Exchange of norm possible (e.g. Chebyshev for shape deviations)
- Combination with statistic approaches for automated outlier detection

Results

- a) Micro cup (plane, cylinder and torus) -



Geometric model



transformation parameters:

$$\vec{a}_p = [\Delta x, \Delta y, \Delta z, \varphi_x, \varphi_y]$$

shape parameters:

$$\vec{\boldsymbol{a}}_g = [\boldsymbol{r}_c, \boldsymbol{r}_w]$$

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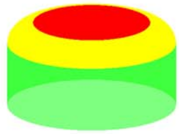
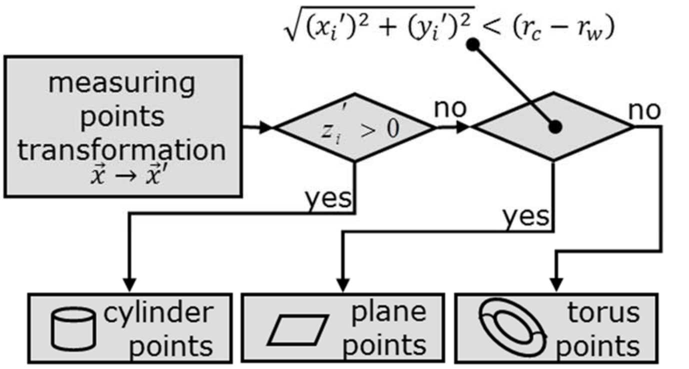
Parameter extraction for dimensional inspection

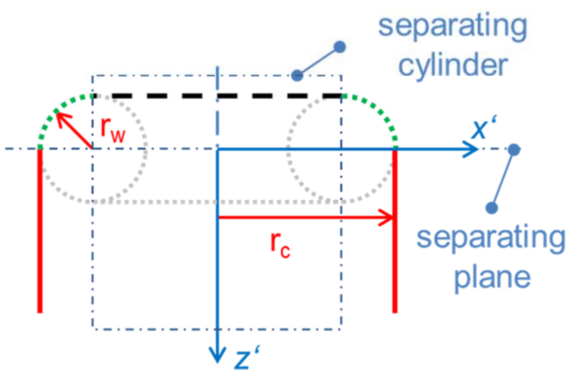
Results

- a) Micro cup (3D) -

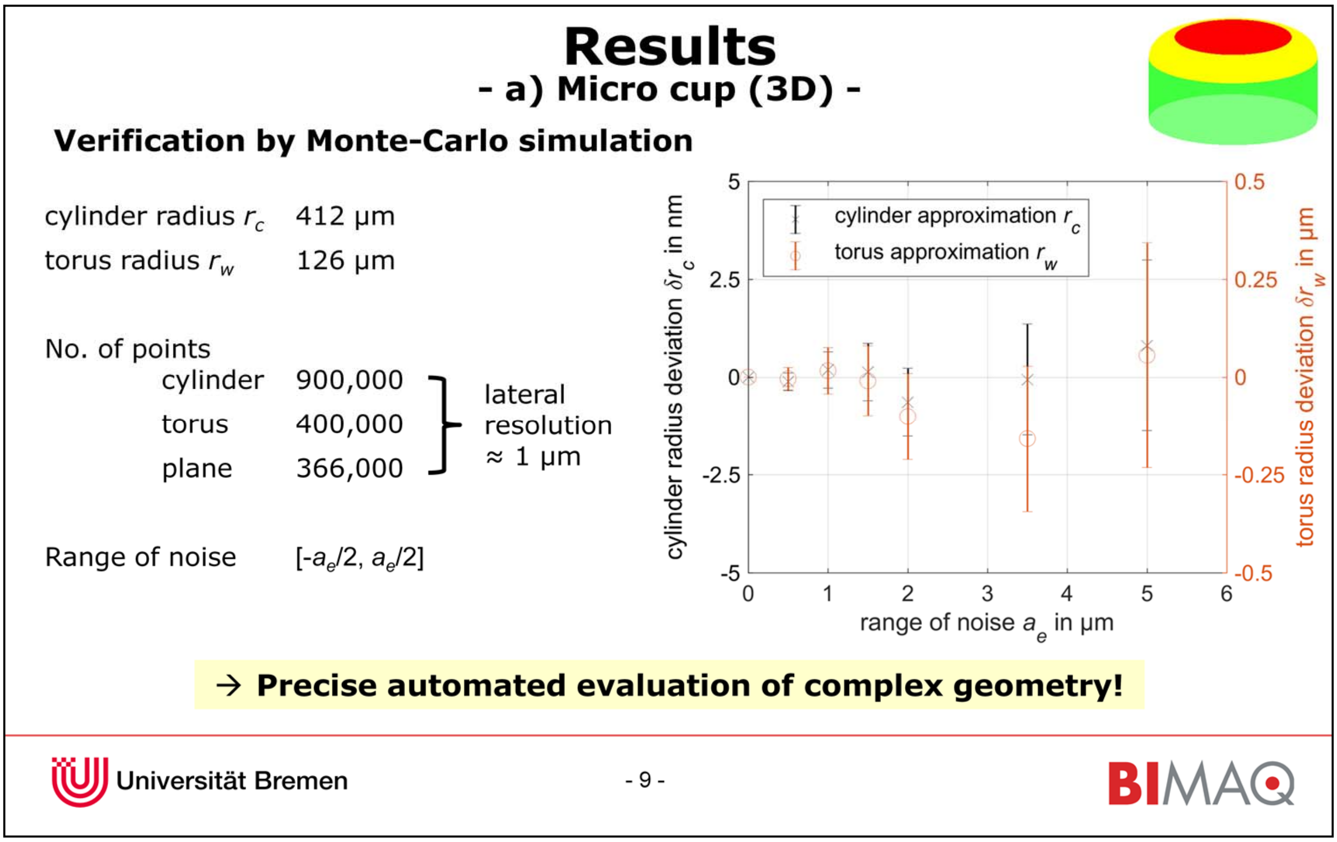


Separation rules





→ **Optimal assignment based on approximated geometric parameters**



Advantages of simulation (100 repetitions with equally distributed noise):

- Referencing measurement data difficult for micro cups
- Measuring data contain deviations

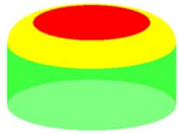
Results:

→ no systematic deviations / agreement with theory
→ Random deviations < 22 nm (cylinder radius)
< 0.6 a_e (torus radius)

Note: Error bars are standard errors not enhanced uncertainties.

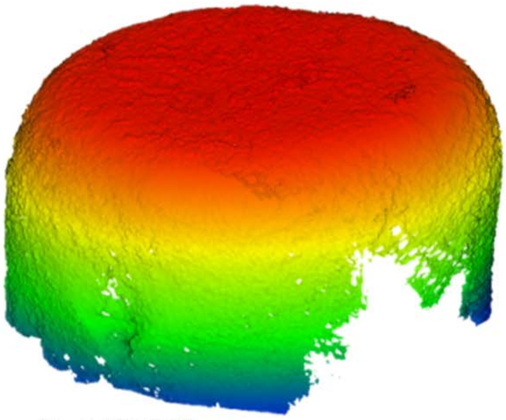
Results

- a) Micro cup (3D) -



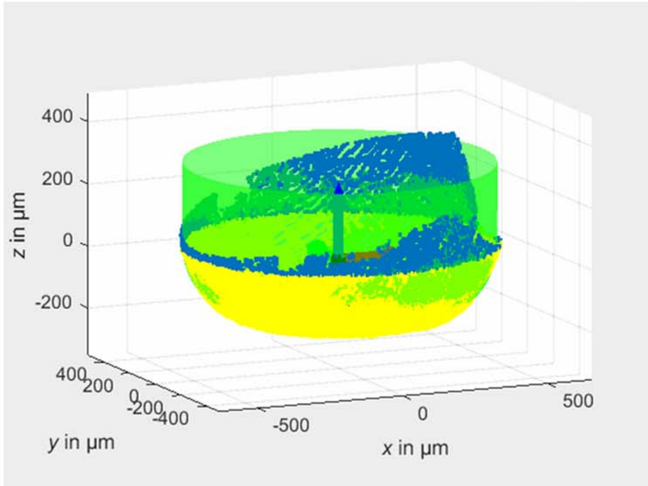
Validation with experimental data

Surface acquired by digital holography:



Source: BIAS GmbH

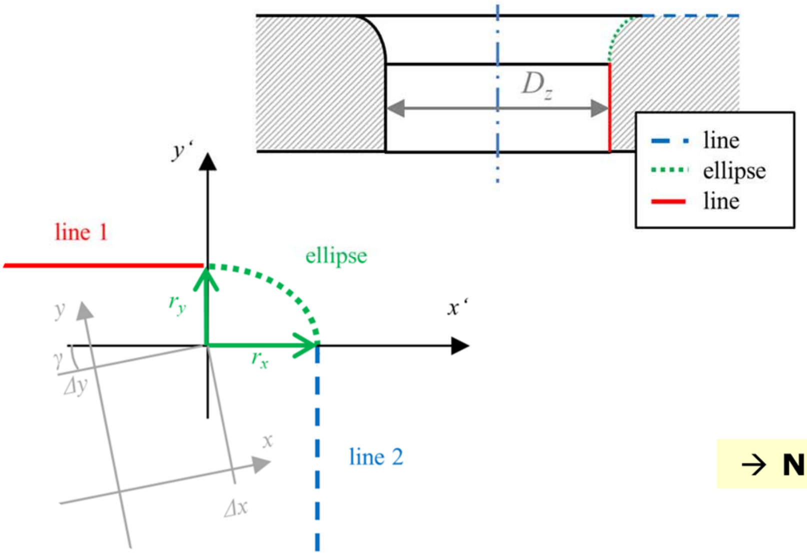
500 µm



Results

- b) Drawing die (ellipse) -

Geometric model



transformation parameters:

$$\vec{a}_p = [\Delta x, \Delta y, \Delta z, \varphi_x, \varphi_y]$$

shape parameters:

$$\boldsymbol{\vec{a}_g} = [\boldsymbol{r_x}, \boldsymbol{r_y}]$$

→ No analytic solution for d_i.

Root point iteration

- Calculation of orthogonal distance -

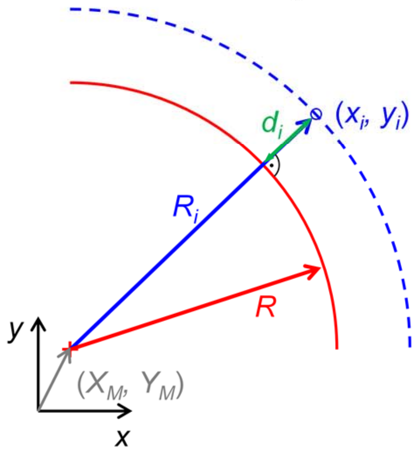
Circle

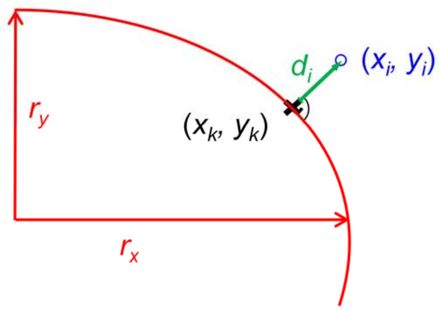
$$d_i = f(\vec{a}_p, \vec{a}_g) = \sqrt{(x_i - X_M)^2 + (y_i - Y_M)^2} - R$$

Ellipse

$$d_i = f(\vec{a}_p, \vec{a}_g, \vec{\boldsymbol{x}}_{\boldsymbol{k}})$$

analytic ← solution → numeric





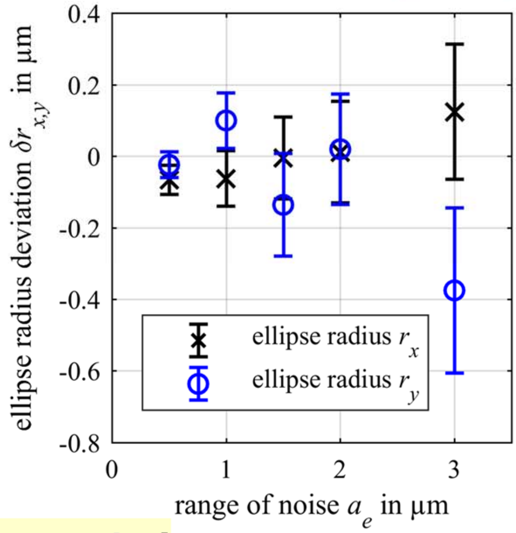
→ Enhanced holistic approximation with root point iteration.

Results

- b) Drawing die (ellipse) -

Verification by Monte-Carlo simulation

ellipse half axis r_x	373 µm
ellipse half axis r_y	324 µm
No. of points per element	55
Range of noise	$[-a_e/2, a_e/2]$



→ **Precise automated evaluation of complex geometry!**

Analysis of variances (ANOVA): The prerequisites of independent evaluations and Gaussian distributed random variables are fulfilled, but a Levene's test revealed that equal variances could not be assumed. Therefore, a Welch ANOVA was used to analyze systematic deviations. The Welch test delivered $F_{rx}(4; 229) = 0.34$ and $F_{ry}(4; 222) = 1.35$. Both values are below

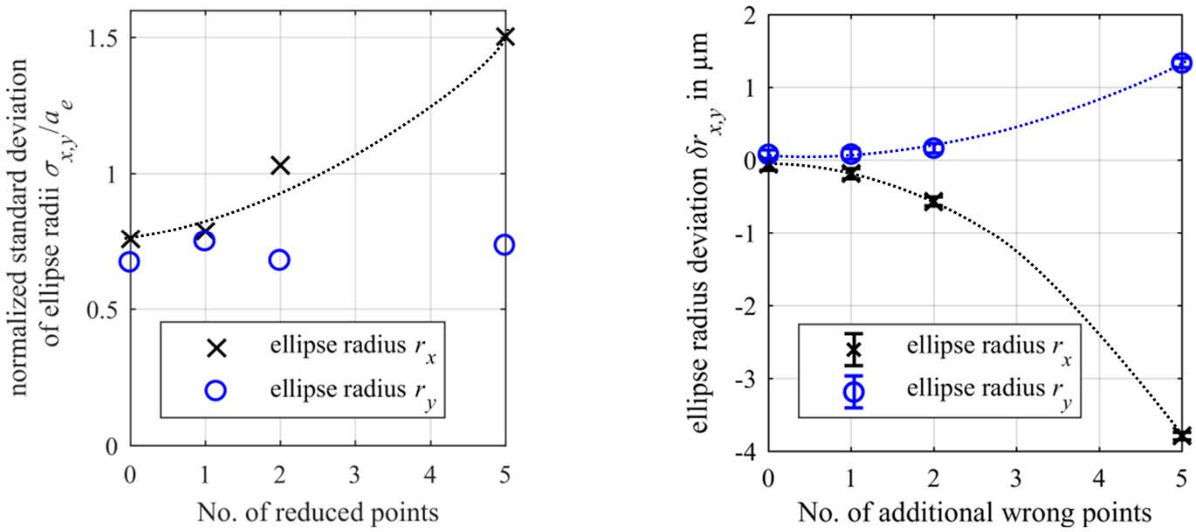
the critical values $F_{crit}(0.05; 4; 229)$ $F_{crit}(0.05; 4; 222) = 2.41$. Thus, with a probability of error of 5 %, it can

be assumed that no systematic influence within the HA leads to significant deviations of both approximated radii.

Results

- b) Drawing die (ellipse) -

Influence of non-optimal partitioning



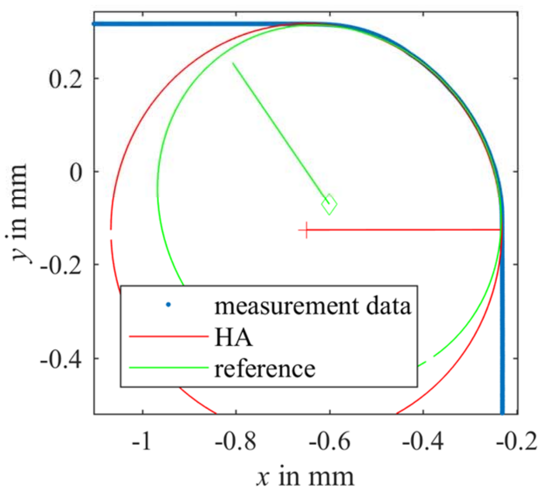
Evaluation with less than the maximum number of possible points increases the normalized standard deviation for r_x (increased random deviation).

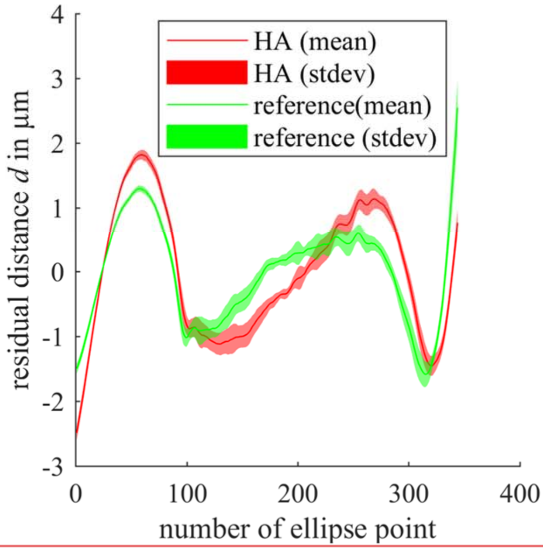
Evaluation with additional wrong points (of the lines) leads to an systematic error (deviation larger than standard error).

Results

- b) Drawing die (ellipse) -

Validation with experimental data



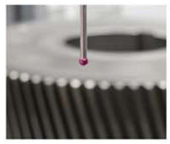


The ellipse results are not expected to be better than evaluated with commercial software (after manual partitining).

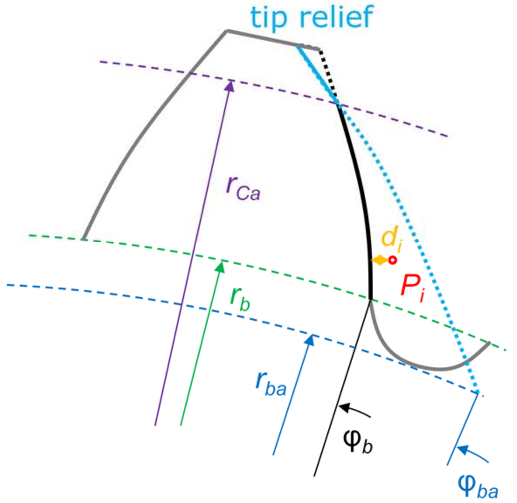
Differences due to different degrees of freedom.

Direct comparison with nominal data only possible with HA results!

Results
- c) Gear / involute -



Geometric model



$$d_i = f(\vec{a}_p, \vec{a}_g)$$

transformation parameters:

$$\vec{a}_p = [\Delta x, \Delta y, \Delta z, \varphi_x, \varphi_y, \varphi_b]$$

shape parameters:

$$\vec{\boldsymbol{a}}_{\boldsymbol{g}} = [\boldsymbol{r_b}, \boldsymbol{r_{ba}}, \boldsymbol{r_{Ca}}]$$

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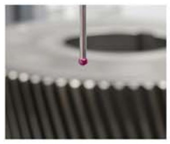
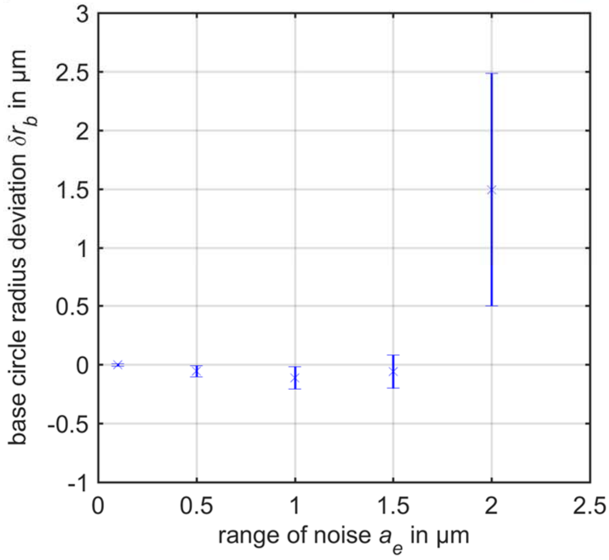
Identification of
unknown gear parameters

Results
- c) Gear / involute -



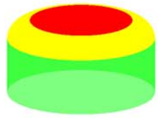
Verification by Monte-Carlo simulation

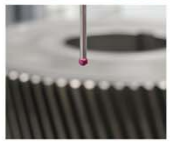
Normal module m_n	5 mm
Pressure angle α	20°
Number of teeth n	21
Helix angle β	0°
Pressure angle tip relief α_{Ca}	30°
No. of points / profile	101
Range of noise	$[-a_e/2, a_e/2]$



→ Precise automated evaluation of complex geometry!

Summary & outlook





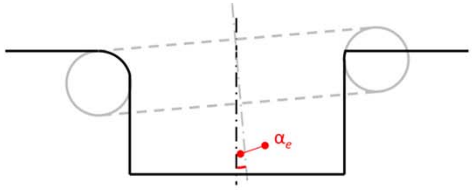
Automated evaluation of geometric features in measurement data of combined geometric elements

Holistic approximation (HA):

- Automated: Holistic approximation applied for various applications
- Precise: Uncertainties < 1 µm
- Complexity: Root point iteration enables evaluation of higher order geometric elements

Outlook

- outlier detection
- sensitivity to higher number of degrees of freedom
- weighted approximation



Contact & acknowledgment

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Gefördert durch die Deutsche Forschungsgemeinschaft (DFG) – FI 1989/2-1.
Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – FI 1989/2-1.