Explanation of Surface Deviations by Manufacturing Modes

Jose Urbano, Dieter Bestle
Brandenburg University of Technology Cottbus-Senftenberg

Ulf Gerstberger, Marcus Mayer
Rolls-Royce Deutschland Ltd & Co KG

Towards a Fully-Automated Robust Design Procedure

Deviation Representation Compatible with Design Procedure

Decomposition into Manufacturing Modes

Application to a High-Pressure Turbine Blade

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EUROPÄISCHE UNION
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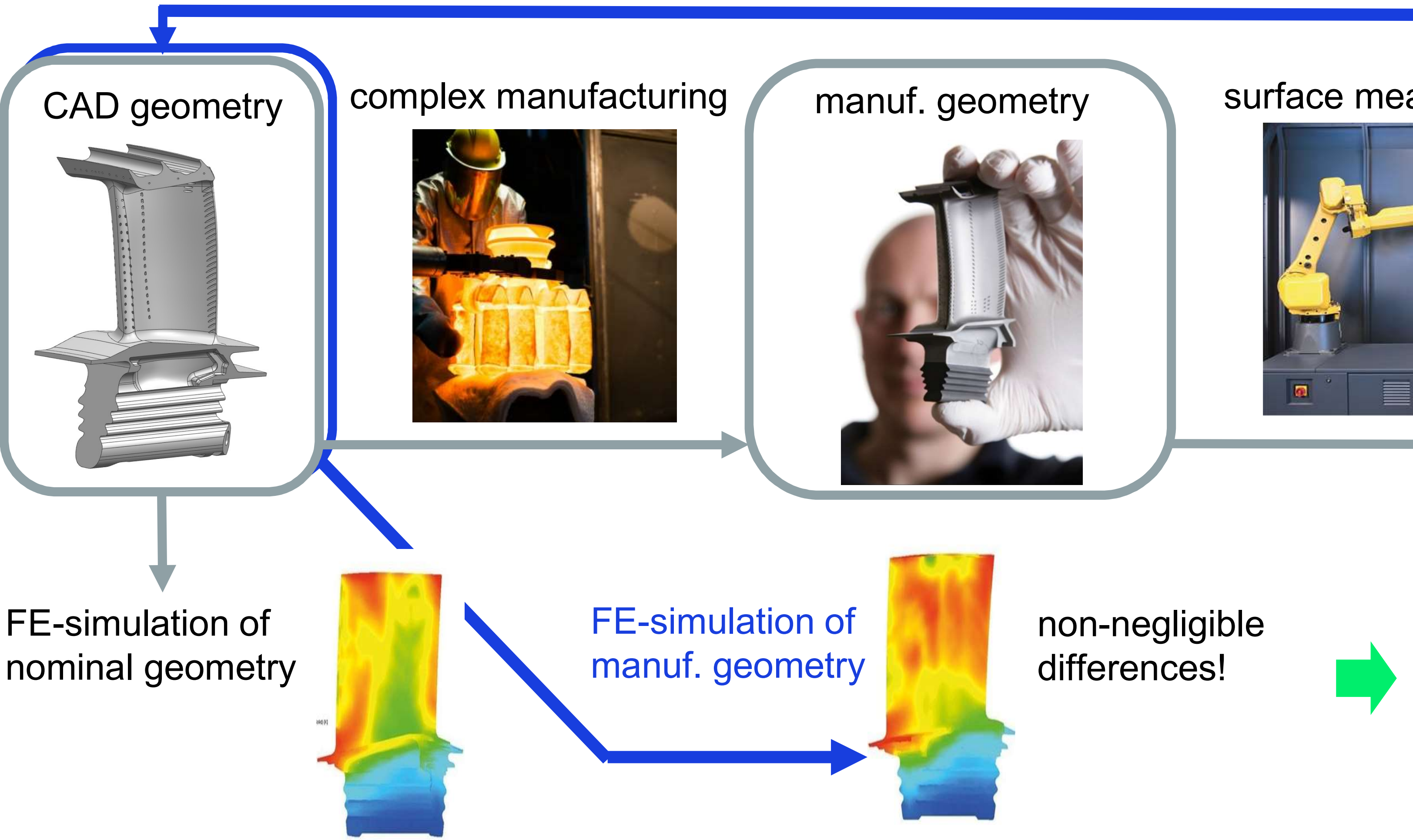
Funded by European Regional Development Fund and Brandenburg Ministry of Economic Affairs and Energy

Towards a Fully-Automated Robust Design Procedure

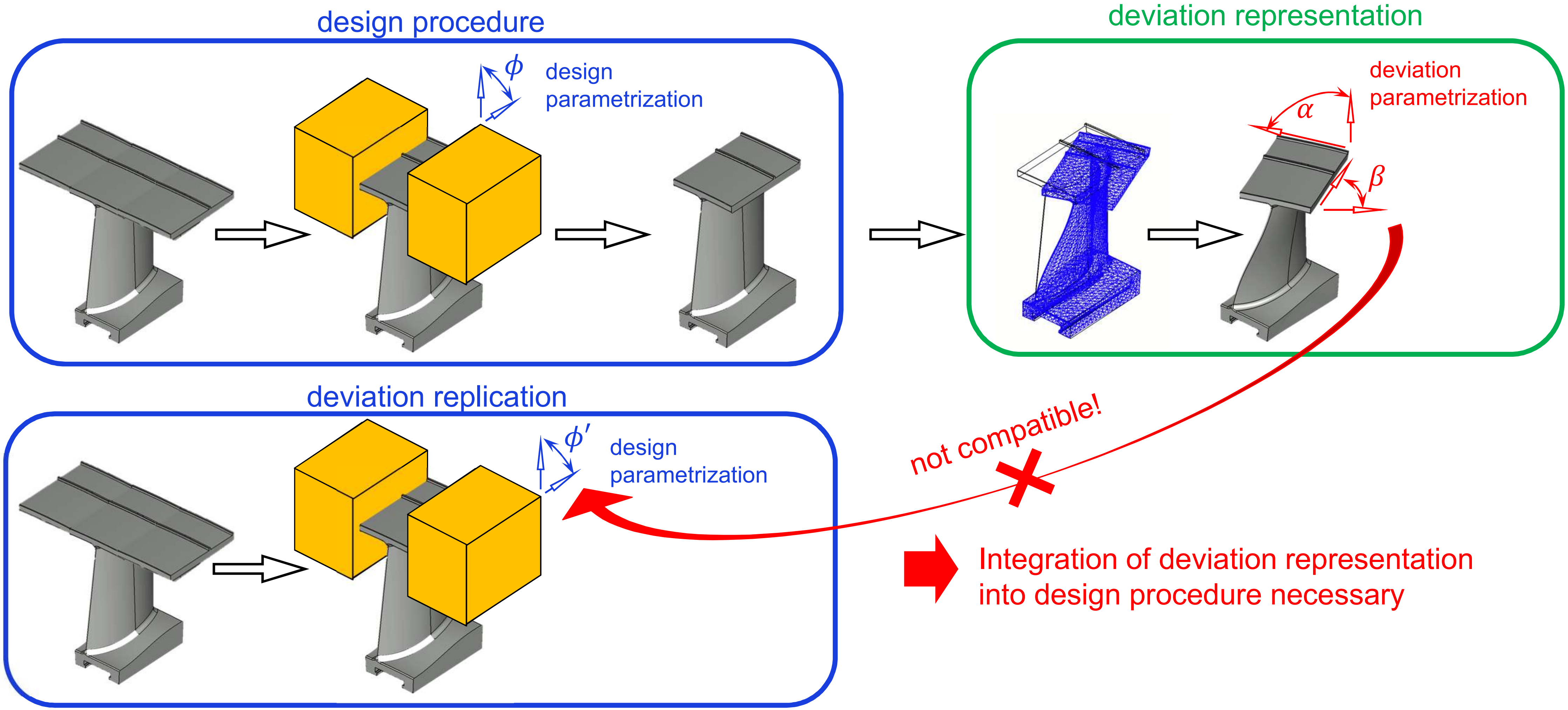
- Need for consideration of manufacturing variabilities



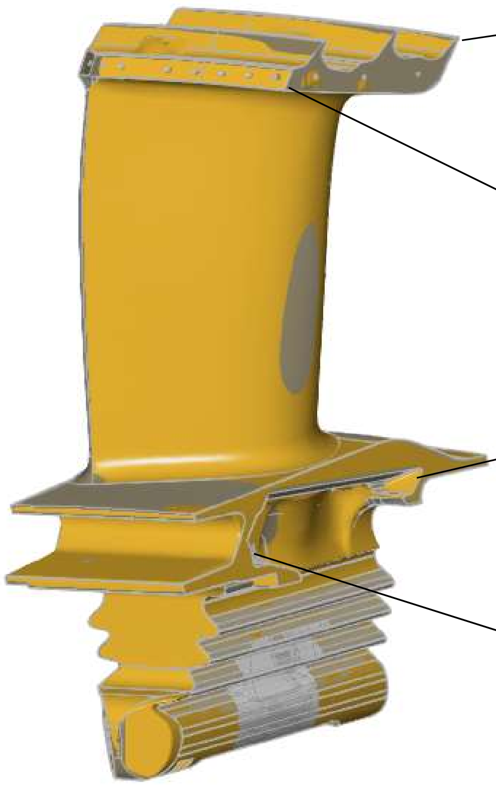
Goal: Consideration of all possible manufacturing deviations already during design process

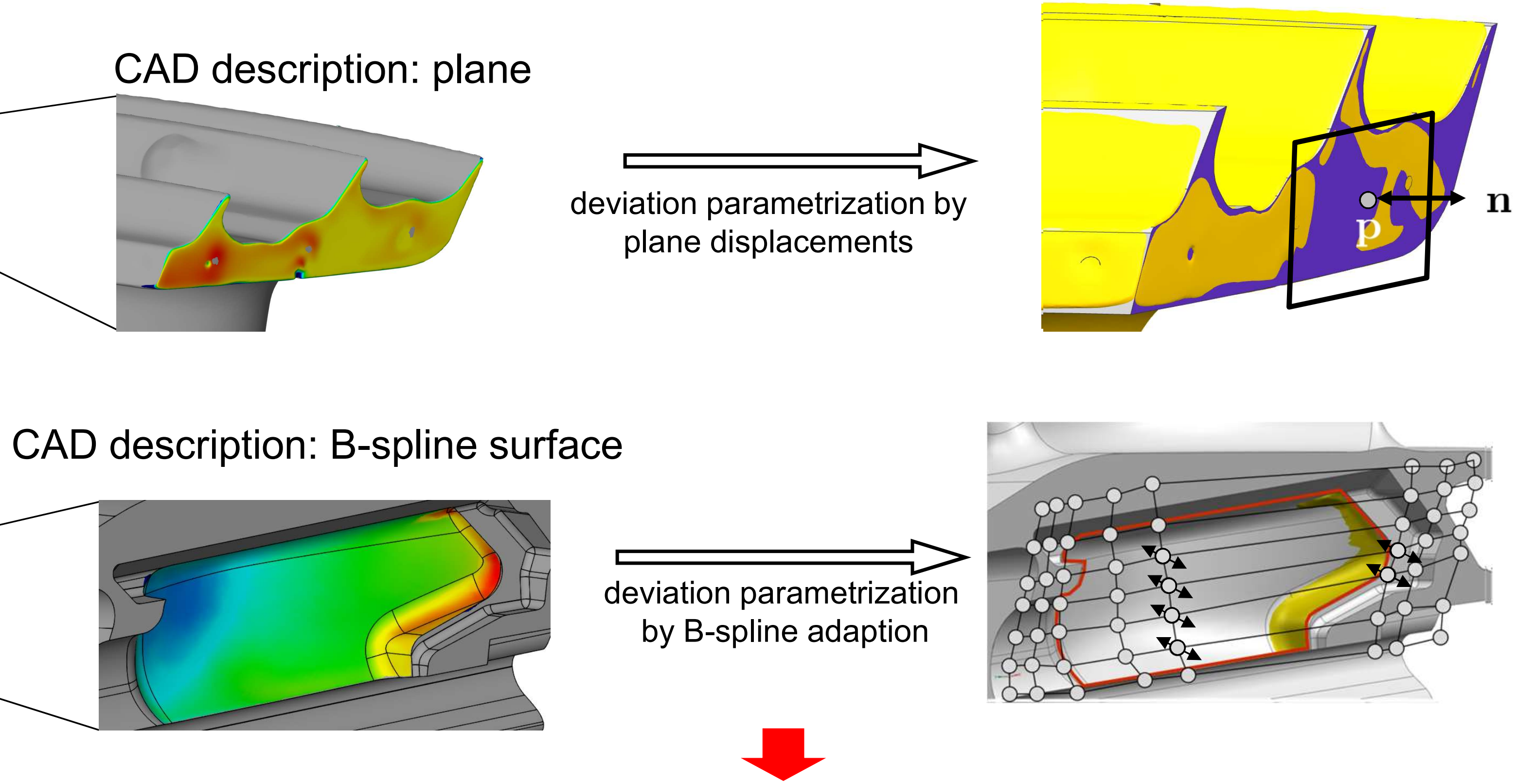
- Current challenges for fully-automated robust design

1. design parametrization ≠ deviation parametrization



- Current challenges for fully-automated robust design
  1. design parametrization ≠ deviation parametrization
  2. different features → different deviation parametrizations





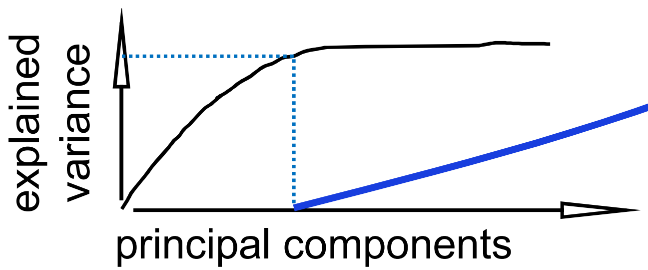
robust design automation requires
more capable generic parametrizations

- Current challenges for fully-automated robust design
  1. design parametrization ≠ deviation parametrization
  2. different features → different deviation parametrizations
  3. multiple measurements → multiple stochastic parameters

common practice:

i. collect deviation vectors and perform PCA

ii. consider principal components for highest explained variance



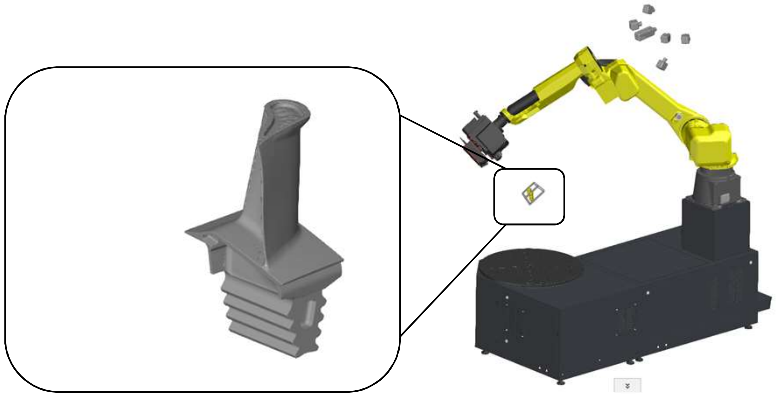
typical reductions:
637 → 100 components (Beck, et. al, 2019)
80 → 15 components (Voigt, et. al, 2018)

efficient robust optimization requires far fewer uncertain parameters

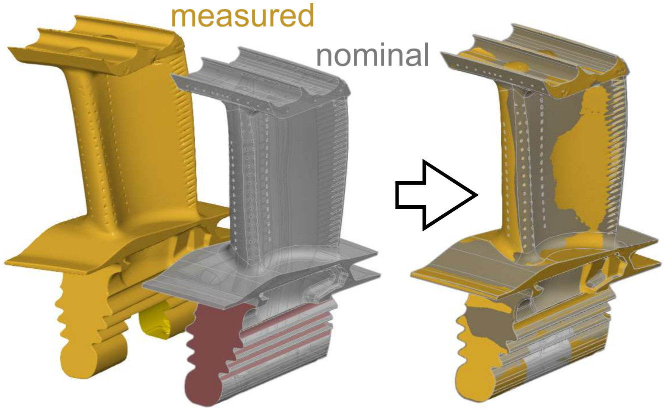
Deviation Representation Compatible with Design Procedure

- Preparation of surface measurements

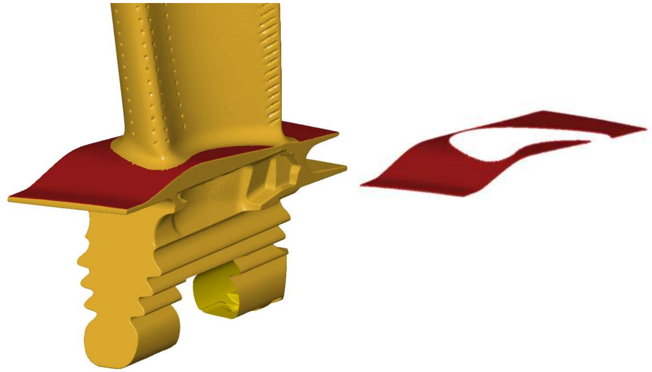
1. Surface measurement



2. Alignment to nominal geometry

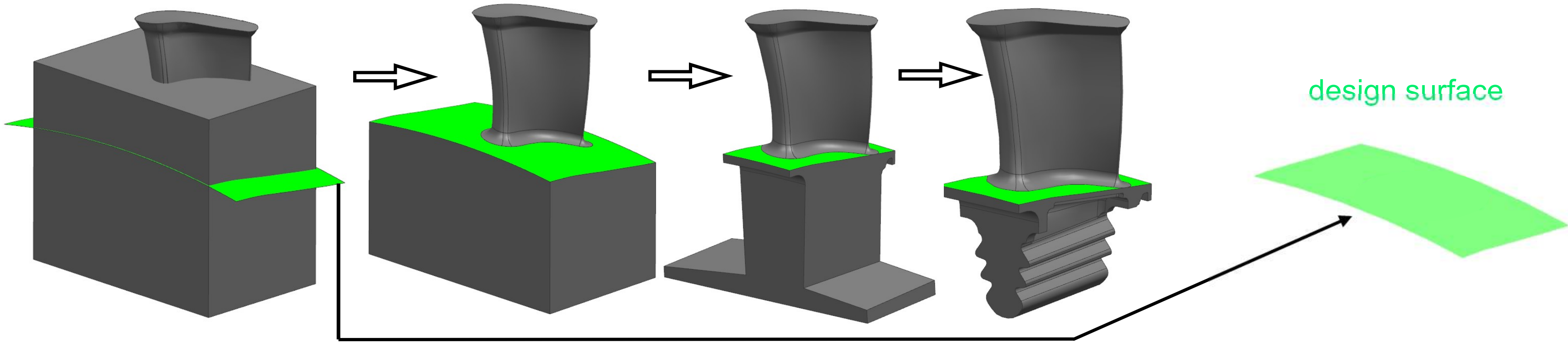


3. Segmentation of surface of interest

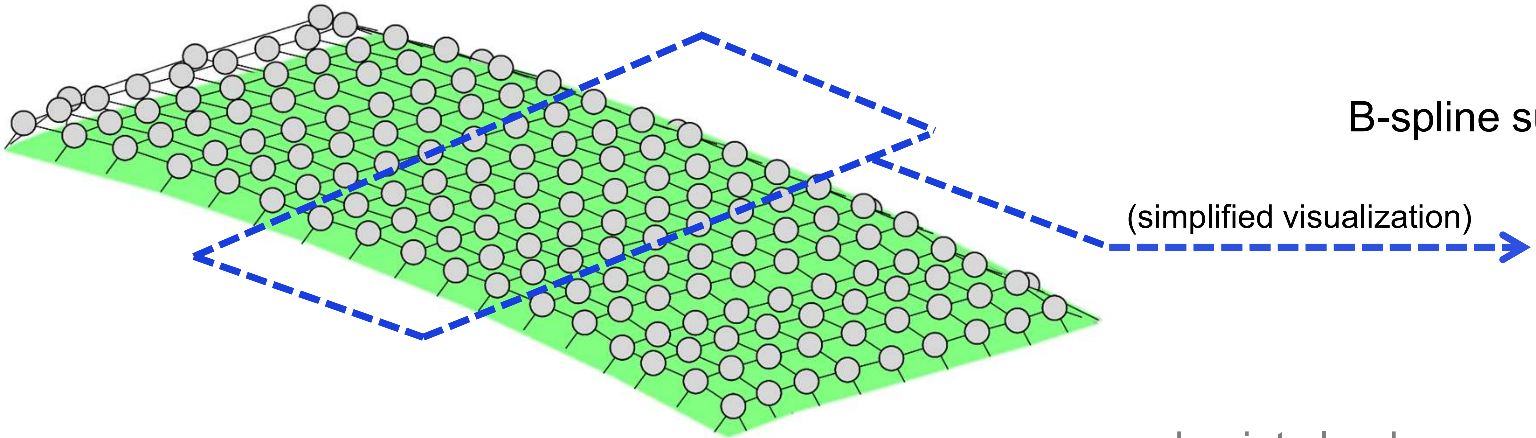


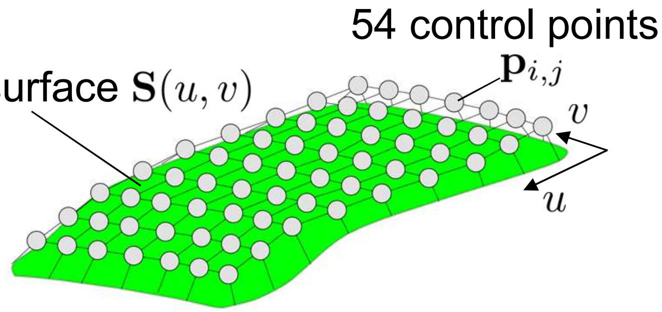
- Preparation of CAD surfaces

1. Extraction of design surface from design procedure



2. Re-parametrization of design surface as B-spline surface with increased number of control points



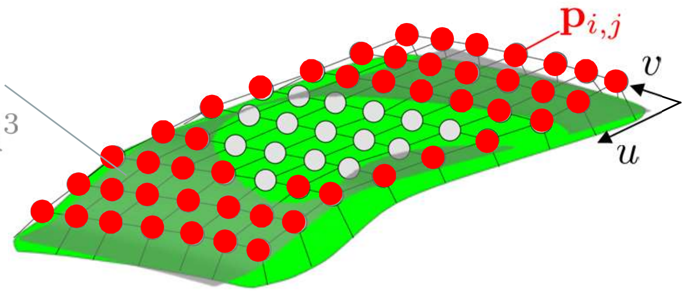


3. Selection of relevant control points

$$\mathcal{I} = \left\{ (i,j) \in [0,n] \times [0,m] \subset \mathbb{N}^2 \,\middle|\, \exists \mathbf{r} \in \mathcal{M} : \|\mathbf{p}_{i,j} - \mathbf{r}\| \leq \delta_{\mathcal{I}} \right\}$$

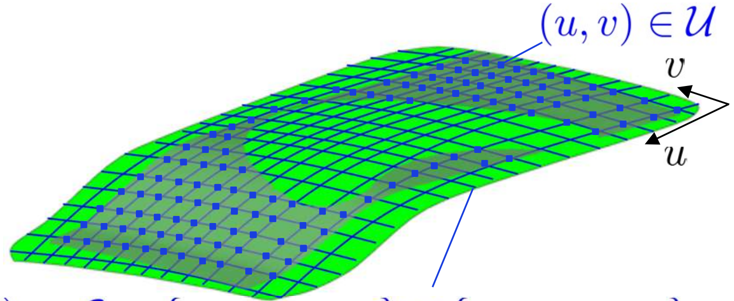
measured point cloud

$\mathcal{M} = \{\mathbf{r}_1, \ldots, \mathbf{r}_M\}, \ \mathbf{r} \in \mathbb{R}^3$



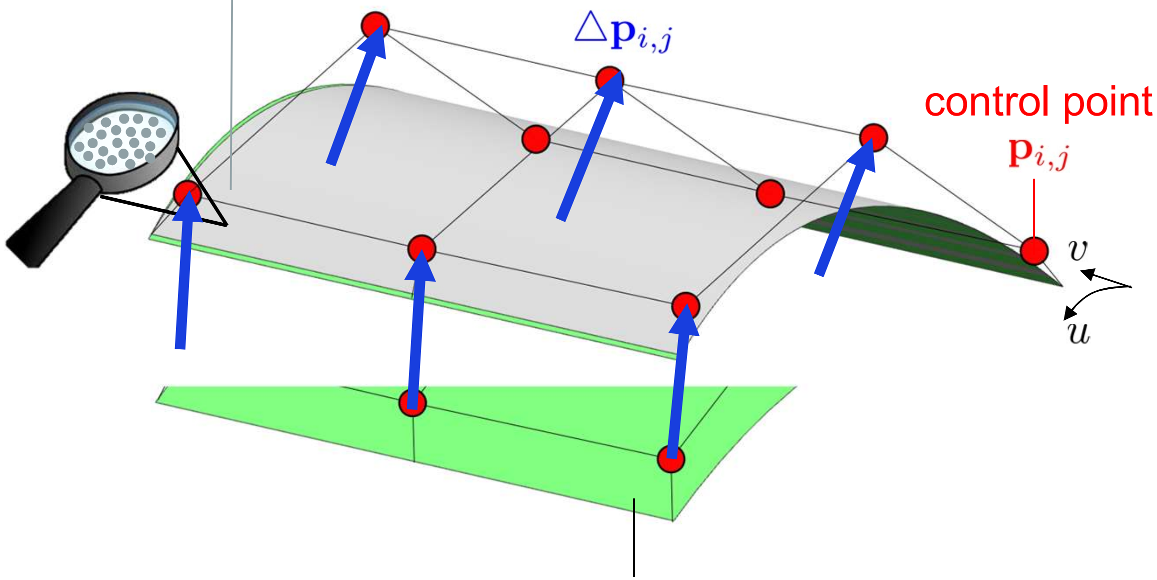
4. Association of B-spline parameters (u,v) with point cloud

$$k(u,v) = \underset{\kappa:\, \mathbf{r}_\kappa \in \mathcal{M}}{\operatorname{argmin}} \|\mathbf{S}(u,v) - \mathbf{r}_\kappa\|, \quad \mathcal{U} = \left\{ (u,v) \in \mathcal{G} \,\middle|\, \|\mathbf{S}(u,v) - \mathbf{r}_{k(u,v)}\| \leq \delta_{\mathcal{U}} \right\}$$



fine grid on $\mathbf{S}(u,v)$: $\mathcal{G} = \{u_1, \ldots, u_{n'}\} \times \{v_1, \ldots, v_{m'}\}$

- B-spline morphing using surface measurements



re-parametrized B-spline surface

$$\mathbf{S}(u,v) = \sum_{i=0}^{n}\sum_{j=0}^{m} N_i^q(u) N_j^q(v) \mathbf{p}_{i,j}$$

B-spline morphing formulation

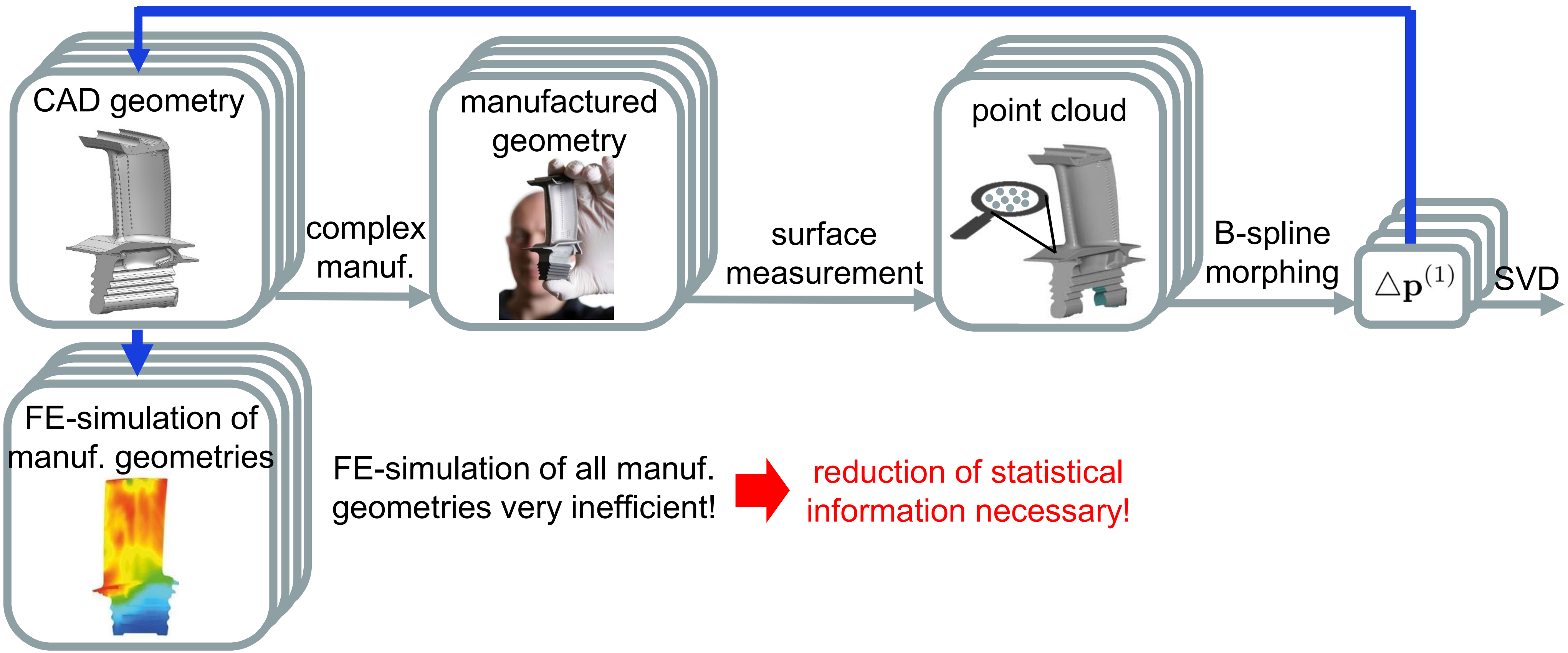
$$\hat{\mathbf{S}}(u,v) = \sum_{i=0}^{n}\sum_{j=0}^{m} N_i^q(u) N_j^q(v) \left(\mathbf{p}_{i,j} + \triangle\mathbf{p}_{i,j}\right) \stackrel{!}{=} \mathbf{r}_{k(u,v)}$$

$$\sum_{(i,j)\in\mathcal{I}} N_i^q(u) N_j^q(v) \triangle\mathbf{p}_{i,j} = \mathbf{r}_{k(u,v)} - \mathbf{S}(u,v)$$

$$\mathbf{NP} = \mathbf{D}$$

solution of the overdetermined system of linear equations with linear regression

- Analysis of multiple deviating surfaces is computationally inefficient



- Computation of manufacturing modes (Urbano et.al., 2019):

  - Collect control point deviations of scan population to construct data matrix:

$$\triangle\mathbf{p}^{(i)} = [\ldots \triangle p^x_{i,j} \ldots | \ldots \triangle p^y_{i,j} \ldots | \ldots \triangle p^z_{i,j} \ldots]^\intercal, \quad \triangle\bar{\mathbf{p}} = \tfrac{1}{S}\textstyle\sum_s^S \triangle\mathbf{p}^{(s)},$$
$$\mathbf{X} = [\triangle\mathbf{p}^{(1)} - \triangle\bar{\mathbf{p}}, \ldots, \triangle\mathbf{p}^{(S)} - \triangle\bar{\mathbf{p}}].$$

  - Perform singular-value decomposition of data matrix:

$$\mathbf{X} = \textstyle\sum_{i=1}^r \sigma_i\, \mathbf{u}_i\, \mathbf{v}_i^\intercal,$$

for arbitrary surface deviations

$$\mathbf{x} = \mathbf{X}\boldsymbol{\alpha} = (\mathbf{U}\boldsymbol{\Sigma}\mathbf{V}^\intercal)\,\boldsymbol{\alpha} = \textstyle\sum_{i=1}^r (\sigma_i \mathbf{u}_i \mathbf{v}_i^\intercal)\,\boldsymbol{\alpha}$$
$$\equiv \textstyle\sum_{i=1}^r (\sigma_i \mathbf{v}_i^\intercal \boldsymbol{\alpha})\,\mathbf{u}_i =: \textstyle\sum_{i=1}^r \beta_i \mathbf{u}_i$$

uncorrelated manuf. modes

  - Projection of control point displacements $\triangle\mathbf{q}$ of arbitrary surface scan

$$\beta_i = \mathbf{u}_i^\intercal (\triangle\mathbf{q} - \triangle\bar{\mathbf{p}}) \quad \textit{(mode amplitude)}$$
$$\triangle\mathbf{q} = \triangle\bar{\mathbf{p}} + \beta_1\mathbf{u}_1 + \beta_2\mathbf{u}_2 + \cdots + \beta_r\mathbf{u}_r$$

- Computation of an accurate low-order truncation:

  - Compute reconstruction error $e_R^{(s),\,t}$ for surface scan (s) and truncation order t :

    i. Approximate control point displacements: $\mathbf{x}^{(s),\,t} := \triangle\bar{\mathbf{p}} + \sum_{i=1}^{t} \beta_i^{(s)} \mathbf{u}_i \to \triangle\mathbf{p}_{i,j}^{(s),\,t}$ for $t < r$

    ii. Create partially reconstructed surface: $\hat{\mathbf{S}}^{(s),\,t}(u,v) := \mathbf{S}(u,v) + \sum_{(i,j)\in\mathcal{I}} N_i^q(u) N_j^q(v) \triangle\mathbf{p}_{i,j}^{(s),\,t}$

    iii. Compare with morphed surface: $e_R^{(s),\,t}(u,v) := \left| \left(\hat{\mathbf{S}}^{(s)}(u,v) - \hat{\mathbf{S}}^{(s),\,t}(u,v) \right)^{\mathsf{T}} \mathbf{n}(u,v) \right|$

  - Obtain observable manufacturing modes:

$$t^* = \min\ t \ \text{ s.t. } \ \bar{e}_R(t) \le \underbrace{e_S + \bar{e}_C + \bar{e}_M}_{\text{process uncertainty}},$$

where:

e_S : measurement error,

$\bar{e}_C$: re-parametrization error,

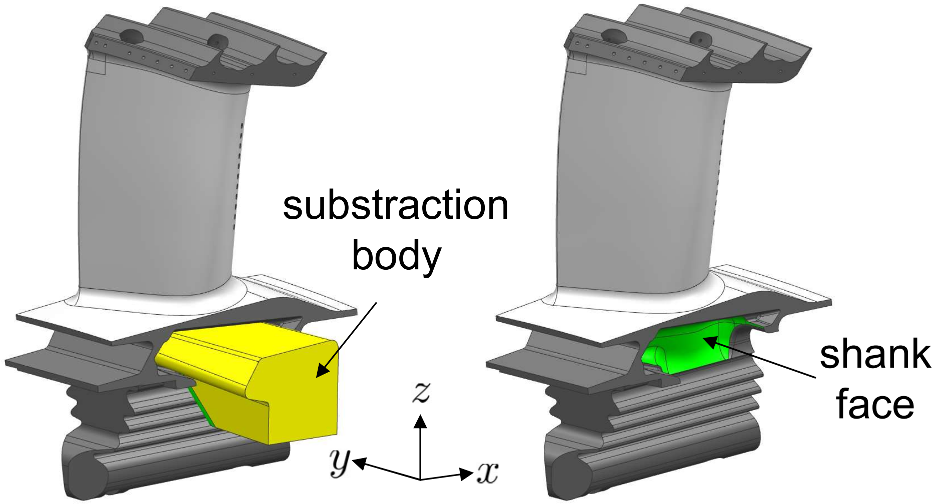
$\bar{e}_M$: morphing error.

Re-parametrization e_C , morphing e_M and reconstruction e_R errors evaluated locally at each pair $(u,v) \in \mathcal{U}$.

Obtain corresponding global errors $\bar{e}_C, \bar{e}_M, \bar{e}_R$ by taking percentiles over pairs $(u,v) \in \mathcal{U}$ and surface measurements

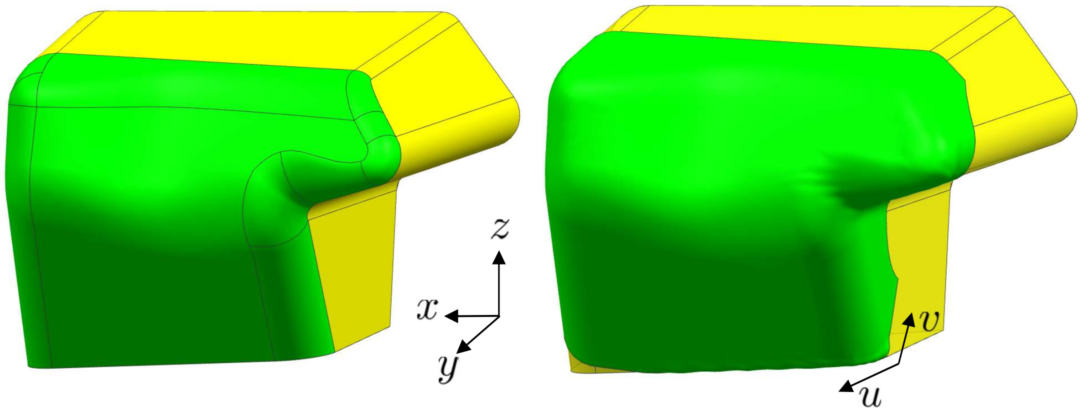
Application to the Shank Face of a High-Pressure Turbine Blade

- Design process of the shank face:



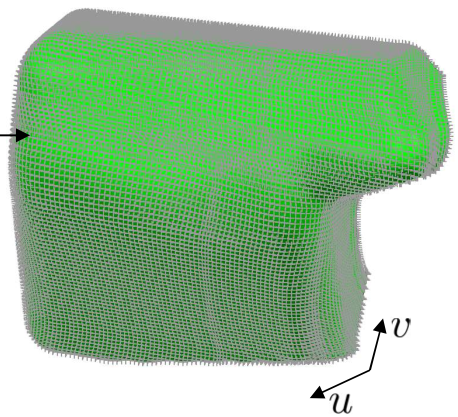
before substraction   after substraction

- Re-parametrization of the shank face:



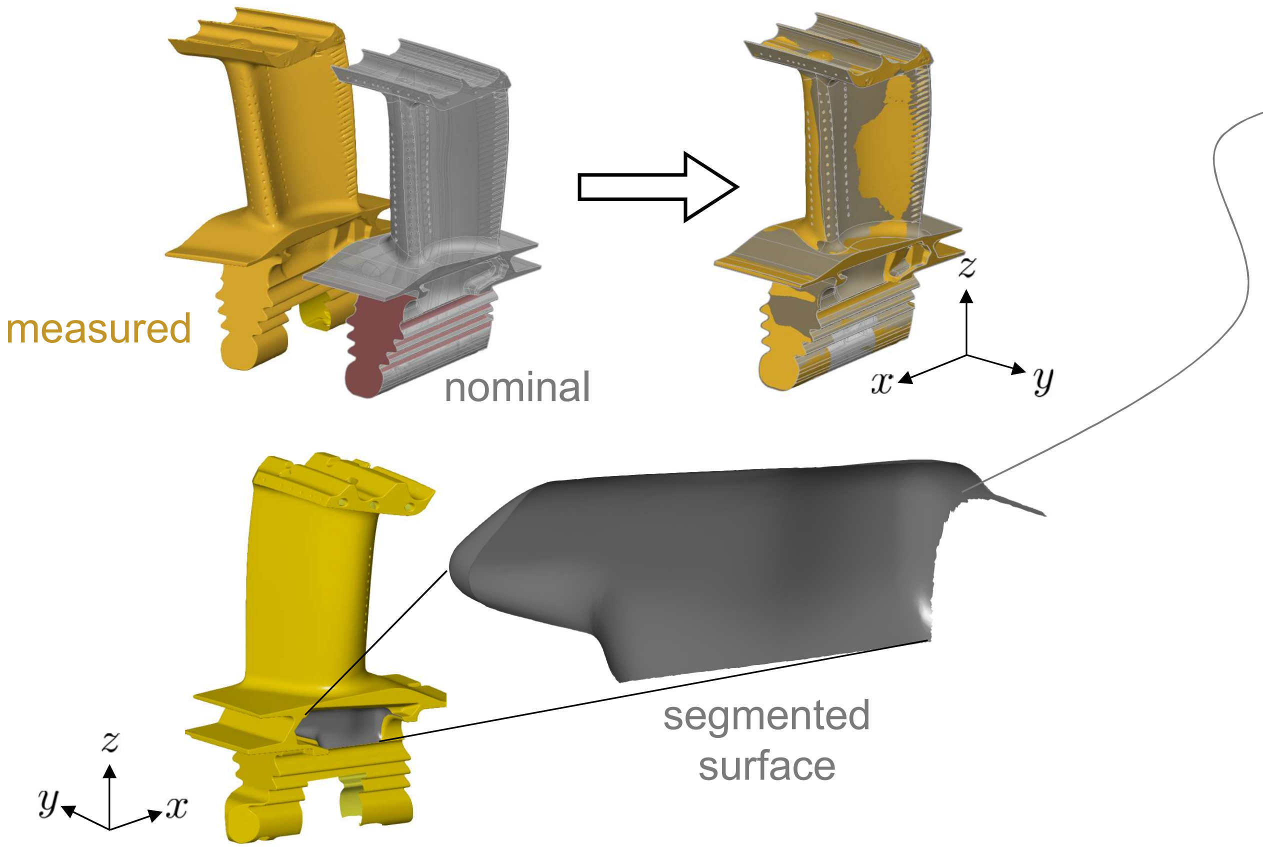
nominal compound surface   re-parametrized B-spline surface

127 X 98 control points



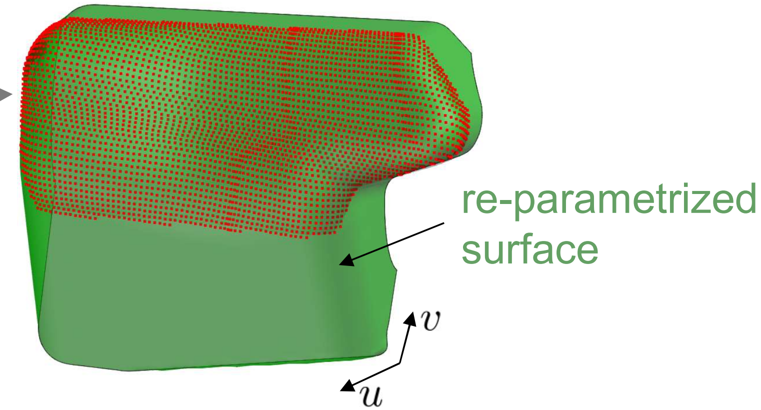
maximum re-parametrization error $\bar{e}_C = 2\ \mu\mathrm{m}$

- Alignment and segmentation of the surface scans:

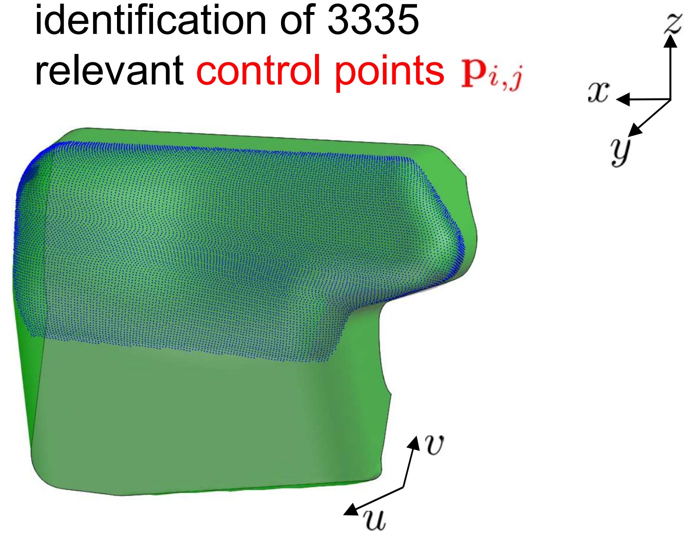


The authors thank the TU Dresden for the preparation and provision of the optical geometry measurements used in this investigation

- Preparation of the re-parametrized surface:



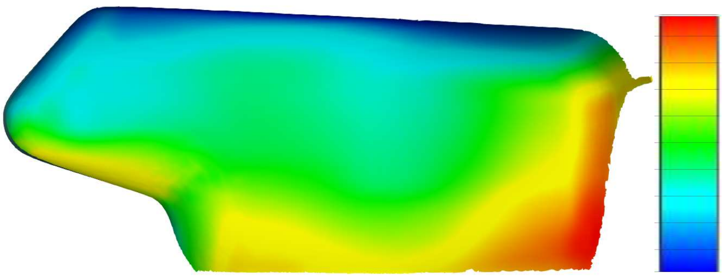
identification of 3335
relevant control points $\mathbf{p}_{i,j}$



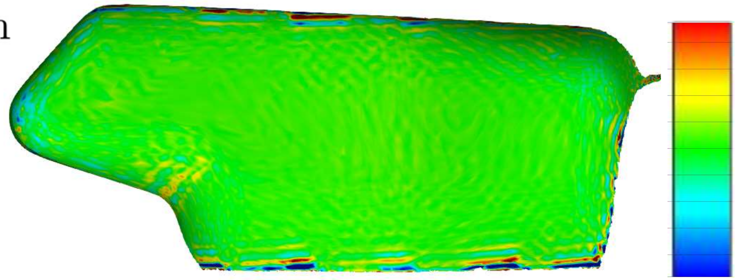
identification 12932
relevant normalized pairs $(u, v) \in \mathcal{U}$

- Morphing of 57 surface scans:

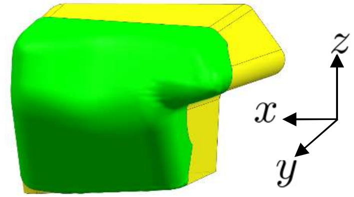
$y-$deviation, nominal - scan



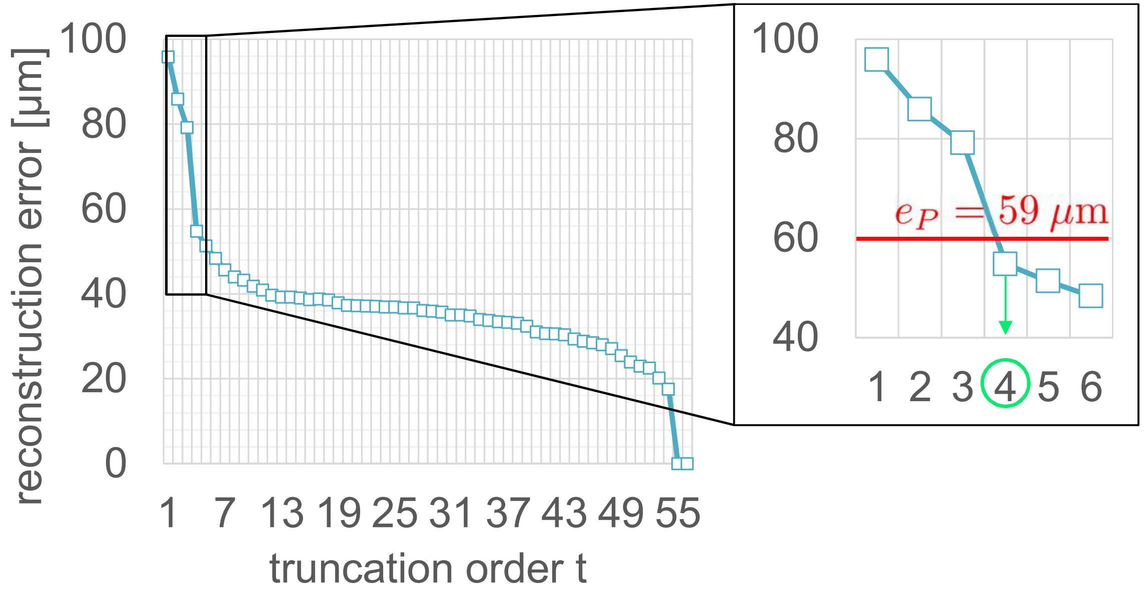
$y-$deviation, morphing - scan



sign convention based on substraction body



- SVD and global reconstruction error:



- Calculation of process uncertainty:

measurement error (joint precision and accuracy estimations) $e_S = 35\ \mu m$

re-parametrization error $\bar{e}_C = 2\ \mu m$

morphing error $+\ \bar{e}_M = 22\ \mu m$

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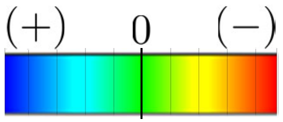
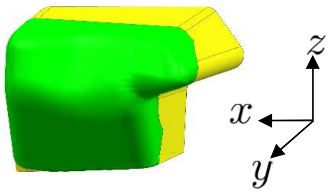
process error $e_P = 59\ \mu m$

only 4 observable manufacturing modes!

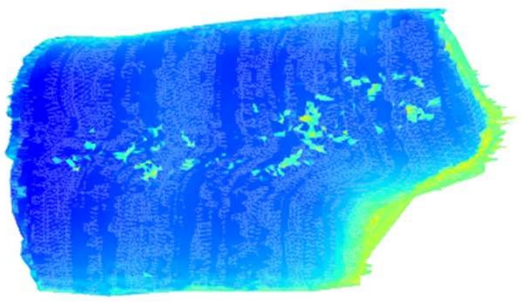
- Analysis of manufacturing modes:

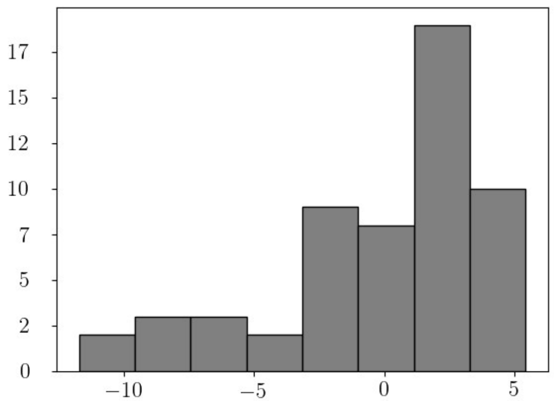
$y-$deviation from nominal





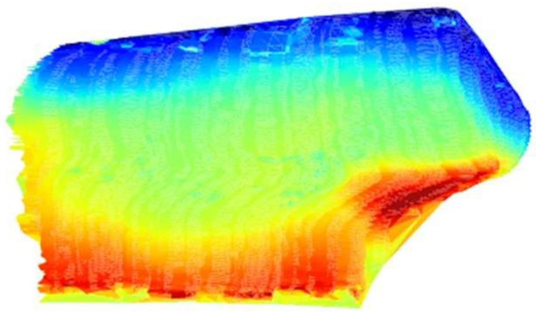
mode 1

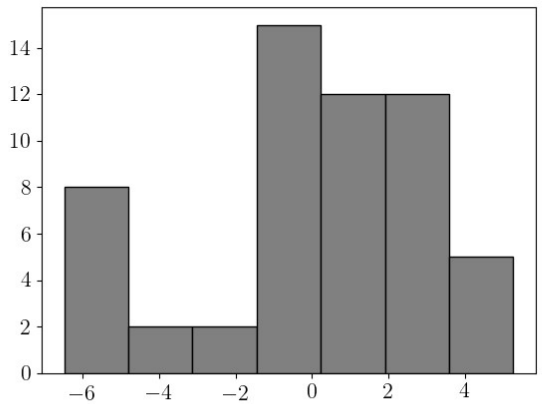




mode amplitude β_1

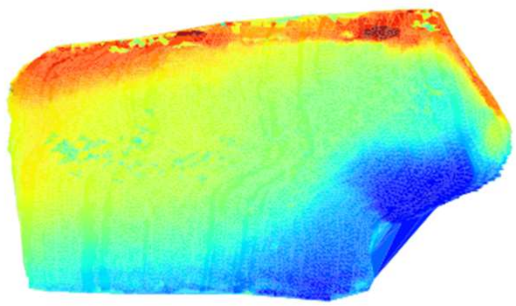
mode 2

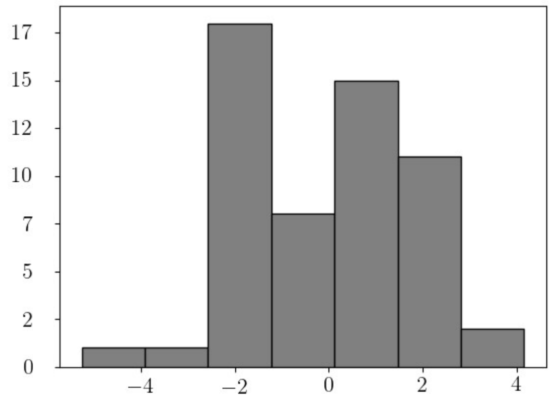




mode amplitude β_2

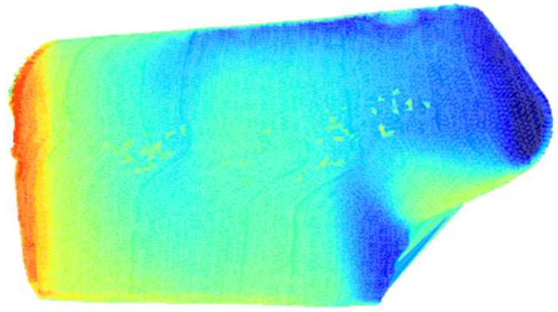
mode 3

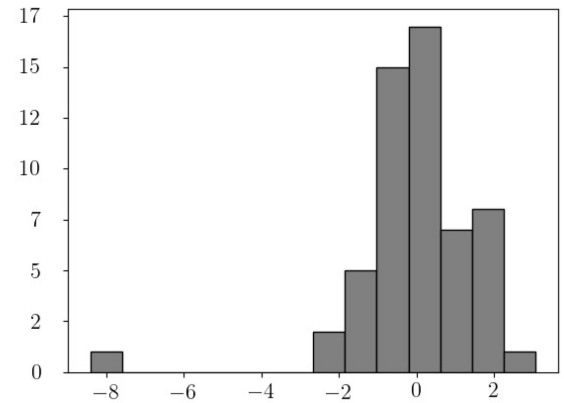




mode amplitude β_3

mode 4





mode amplitude β_4

Conclusions

1. Re-parametrization of design surfaces as B-spline surfaces with high number of control points facilitates representation of complex manufacturing deviations and may be easily integrated into the design process.

2. Surface deviations of arbitrary features may be captured using control point displacements, which may be easily obtained from linear regression. On going work considers automatic B-spline re-parametrization of any geometric feature.

3. Singular value decomposition of control point displacements produces uncorrelated manufacturing modes. Furthermore, by using the information threshold a dramatic reduction in statistical information may be obtained.

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