10th 3DMC | 2025

Automation | Digitization | Data Science

Metrologically Interpretable Feature Extraction using GenAI for Industrial Machine Vision

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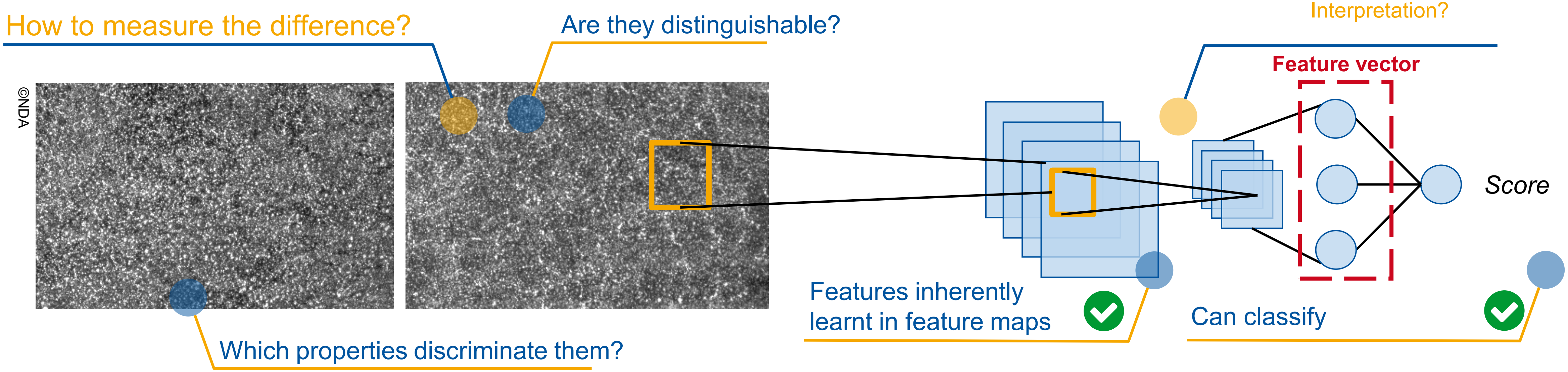
Deep Learning in Industrial Machine Vision

Example: Classification and characterization of surface quality



Traditional machine vision algorithms

Deep Learning in Machine Vision [1]

Metrology

Limited Applicability

Analytically deduced quantities

White Box

Deep Learning?

Complex Problems

Decisions based on opaque criteria

Black Box

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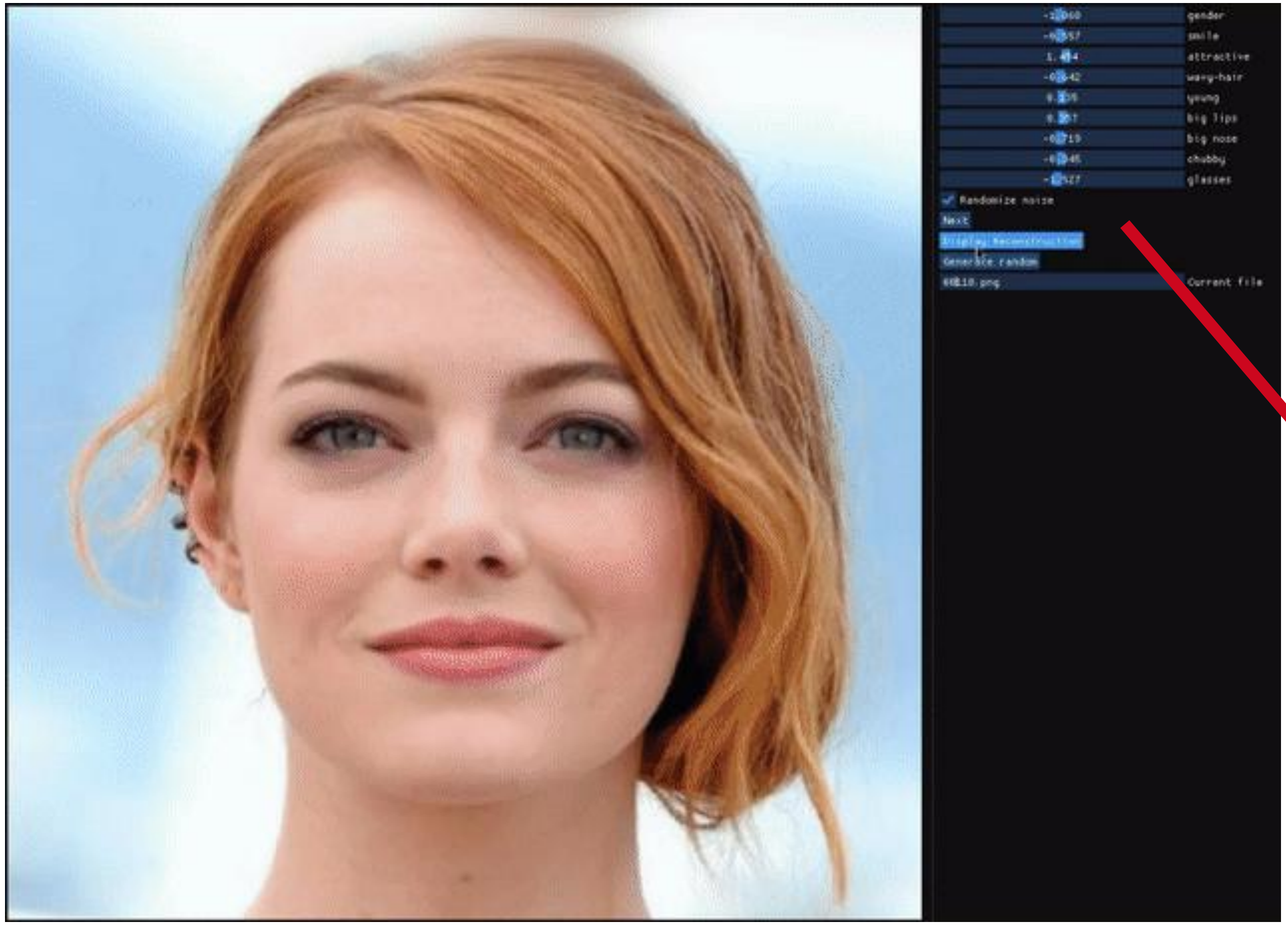
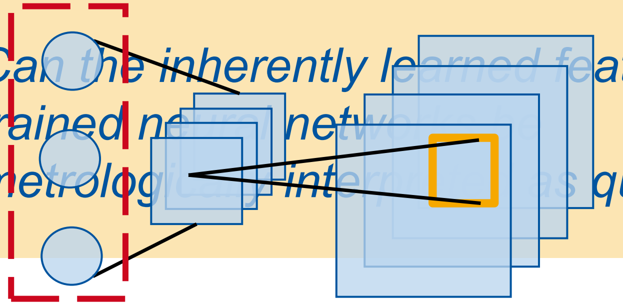
Learning patterns from high-dimensional datasets using Generative AI



Manipulation of face properties using a Style-based Adversarial Latent Autoencoders. ©Pidhorsky[2]

- Learning of complex and high-dimensional image datasets and their underlying patterns
- Self-supervised learning
- Continuously control features and image details via learned feature vectors with StyleGANs[1]



Can the inherently learned features of trained neural networks be metrologically interpreted as quantities?

[1] Karras et al (NVIDIA), 2021, Alias-Free Generative Adversarial Networks, Proc. NeurIPS
[2] Pidhorskyi et al, 2020, Adversarial Latent Autoencoders, CVPR

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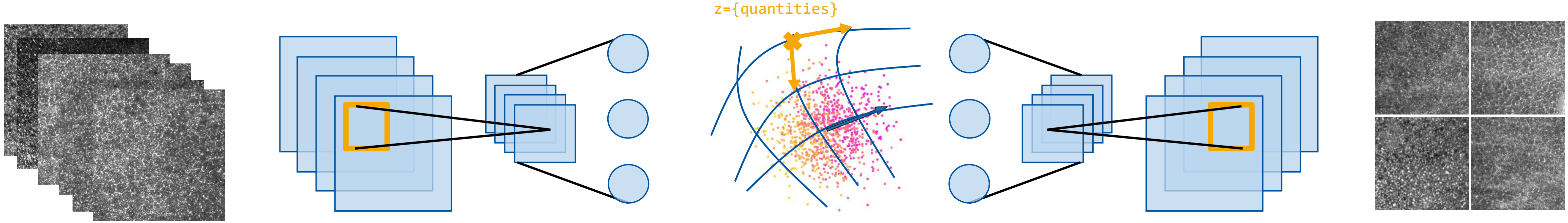
Metrologically Interpretable AI

Framework for a metrologically interpretable feature extraction with generative models[9]

LATENT SPACE

Real image $x \in \mathcal{X} = \mathbb{N}^{64x64}$ — **Encoder network E:** $\mathcal{X} \rightarrow \mathcal{Z}$ — **Feature vector** $z \in \mathcal{Z}$ — **Decoder network G:** $\mathcal{Z} \rightarrow \mathcal{X}$ — **Reconstructed** $\tilde{x} = G(z) \in \mathcal{X}$



Extracting features from the images

Interpretation of learned features using GenAI

1. ***Step: Encode images into a feature vector*** $z = E(x)$

Goal: ***E*** must learn to encode an image into a low-dimensional latent representation $z \in \mathcal{Z}$ for a new image

2. ***Step: Reconstruct image using latent vector*** $z \in \mathcal{Z}$

Goal: Ensure feature consistency and allow for manipulation of features

3. ***Step: Interpret latent space*** $\mathcal{Z}$ ***by means of quantities***

Goal: Understand how to change $z \in \mathcal{Z}$ to change a quantity in the reconstructed image

4. ***Step: Calibrate*** $\mathcal{Z}$ ***to measure by means of the*** z ***vector***

Goal: Scale the found directions to allow for the measurement of quantities

Extract image properties in latent space	Relevant features extracted unsupervised	Feature directions interpreted	Measurement of quantities

[9] Schmitt et al, 2022,Metrologically Interpretable Feature Extraction For Industrial Machine Vision Using Generative Deep Learning

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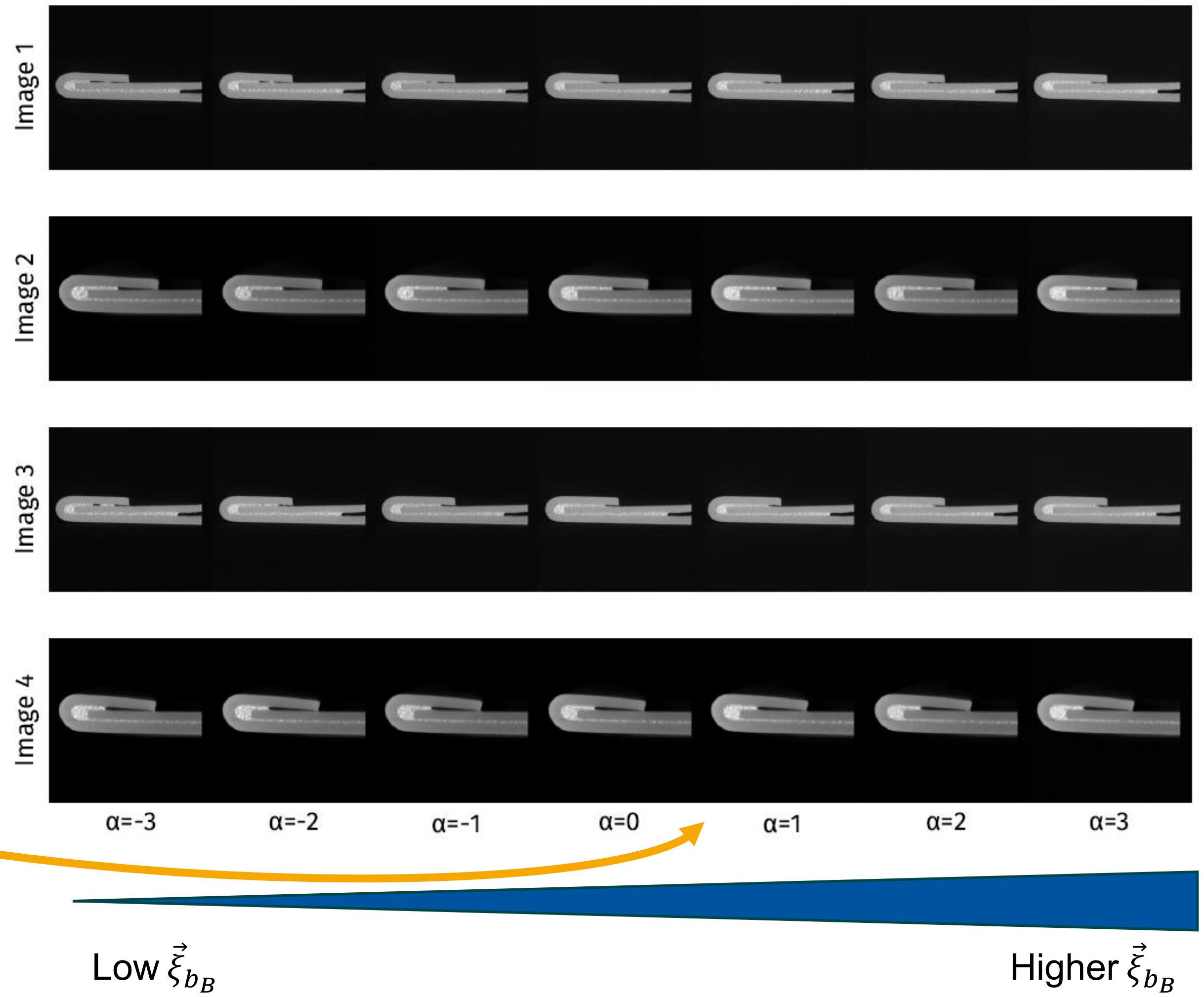
Measurement of quality characteristics in the GAN Latent Spaces

Identification of quality characteristics through latent space interpretation

Properties are learned implicitly in the latent space and must be interpreted first

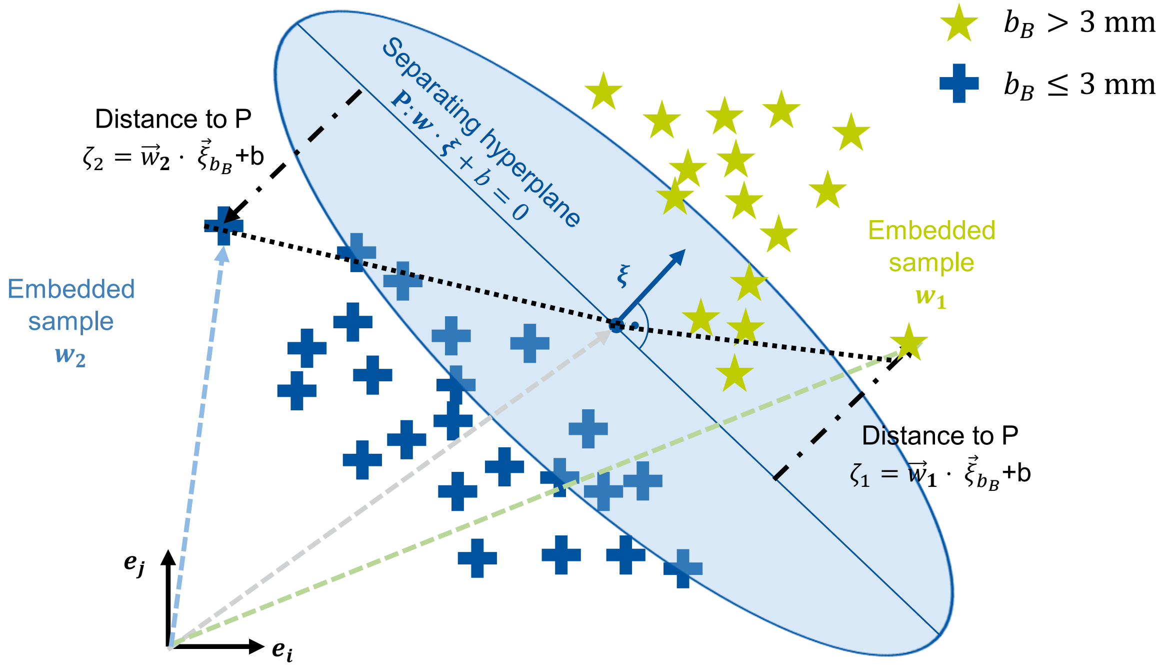
- Identification of latent space variable $\vec{\xi}_{b_B}$ associated to filling degree using Logistic Regression
- Encoding images $x \in \mathcal{X}_{test}$ into the latent space and editing them by shifting along $\vec{\xi}_{b_B}$:

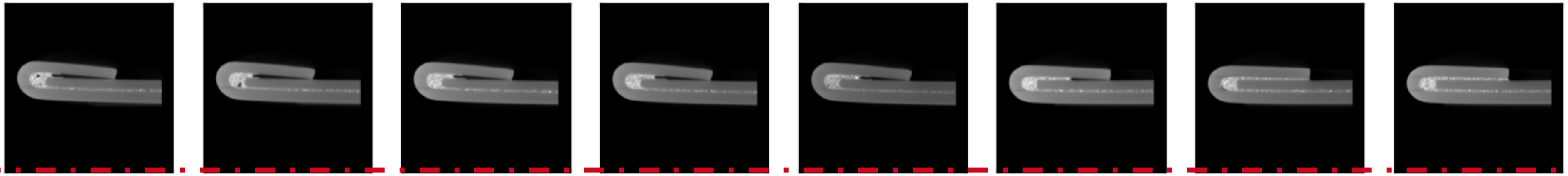
$$\tilde{x} = \mathcal{G}(\mathcal{E}(x)) + \alpha \cdot \vec{\xi}_{b_B}$$



Metrologically Interpretable AI

Assignment of quantity values and existence of a quantity-value scale





b_B = 0.5 mm	b_B = 0.6 mm	b_B = 0.9 mm	b_B = 1.2 mm	b_B = 1.6 mm	b_B = 2.7 mm	b_B = 5.6 mm	b_B = 5.7 mm
ζ = 0.0	ζ = 0.17	ζ = 0.27	ζ = 0.3	ζ = 0.65	ζ = 1.08	ζ = 1.43	ζ = 1.48

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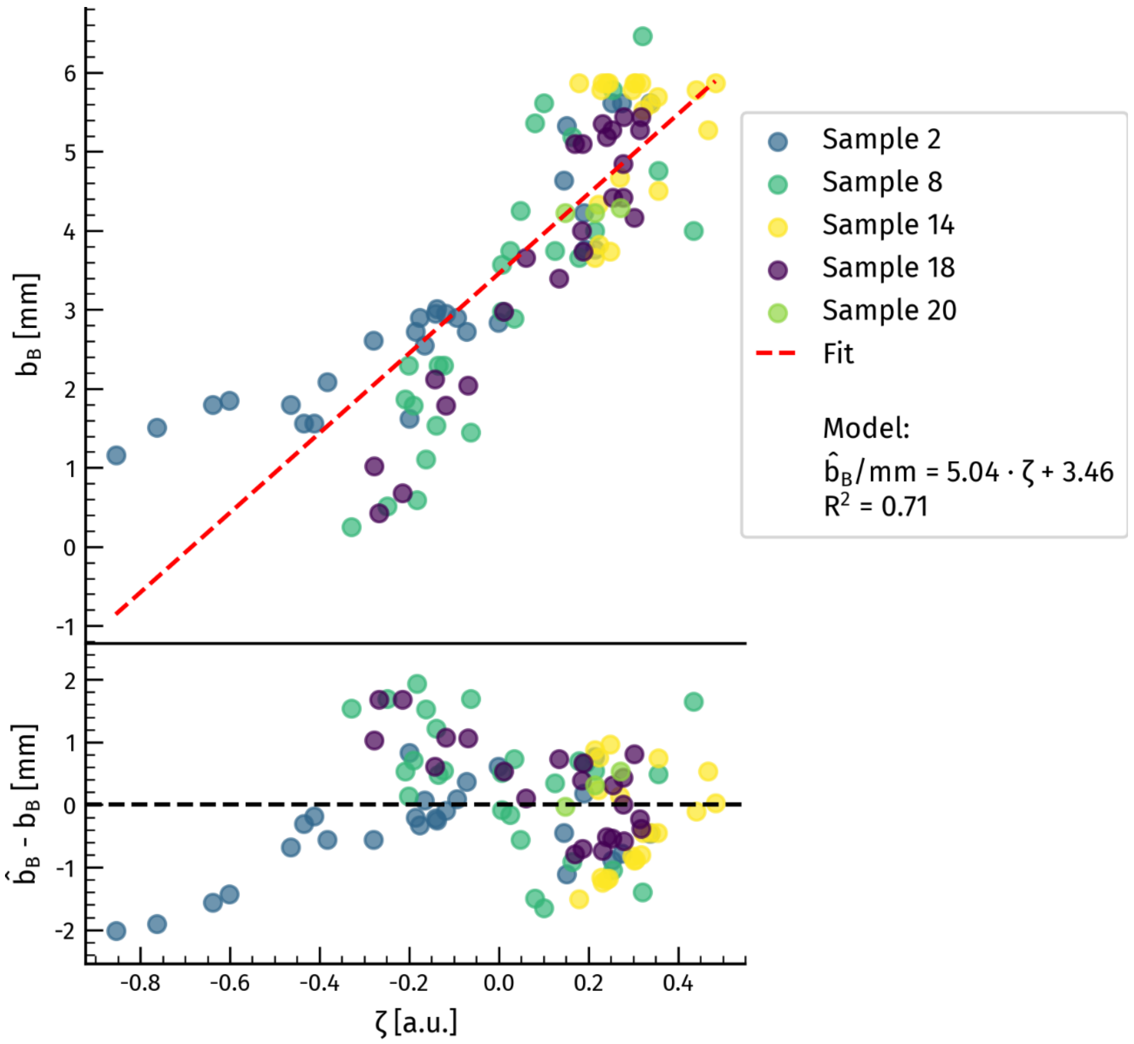
Measurement of quality characteristics in the GAN Latent Spaces
Calibration between of latent space and physical values

- Quantity values in the latent space cannot be directly used in the physical world without establishing references
- By embedding reference images into the latent space, calibration function for expressing the quantity values in the latent space in terms of physical units can be derived

Model: $\hat{b}_B / mm = 5.04 \cdot \zeta + 3.46$

Tab. 7.2: Estimated standard deviations $\bar{s}$ of the measurement errors and Mean Absolute Errors (MAEs) obtained on the test dataset for the different ALAE models.

	dim Z = 16 [mm]	dim Z = 32 [mm]	dim Z = 64 [mm]	dim Z = 128 [mm]
$\bar{s}$	1.23	0.94	0.90	**0.66**
MAE	1.03	0.71	0.71	**0.51**



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Conclusion & Outlook

Metrological properties of features extracted in latent spaces of Generative AI models

(1) Investigate the assignment of **quantity values** in the latent space → **Defined distance measure ζ** ✓

(2) Demonstrate existence of a **quantity-value scale** in the latent space → **Sorting according to ζ** ✓

(3) Investigate the comparison to **reference values** → **Embedding of reference values and Calibration** ✓

Self-supervised learned features can be measured in the latent space ✓

Metrology — **Deep Learning**

Outlook

- Measurement Uncertainty quantification is still missing, but not possible with the networks used in this work yet
- Trustworthiness of the used models to be investigated

Contact

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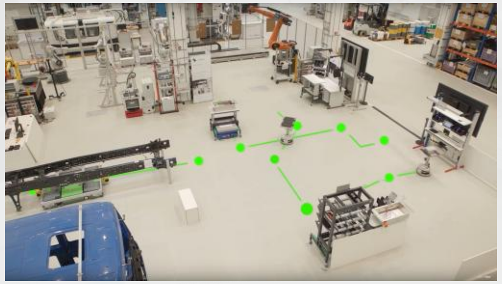

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Thank you!

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