In-Situ Surface Roughness Measurement of Laser Beam Melted Parts – a Feasibility Study of Layer Image Analysis

Joschka zur Jacobsmühlen[1], **Stefan Kleszczynski**[2], Alexander Ladewig[3], Gerd Witt[2] and Dorit Merhof[1]

[1]RWTH Aachen University
[2]University of Duisburg-Essen
[3]MTU Aero Engines AG

Motivation of Studies

Laser Beam Melting of Metal Components

- Production of complex and individual components
- Of special interest for aerospace and aero engine industry
- First production lines established at MTU Aero Engines AG in Munich, Germany

- **High requirements**
  - quality assurance
  - process stability
  - reproducibility

MTU Aero Engines AG

Motivation

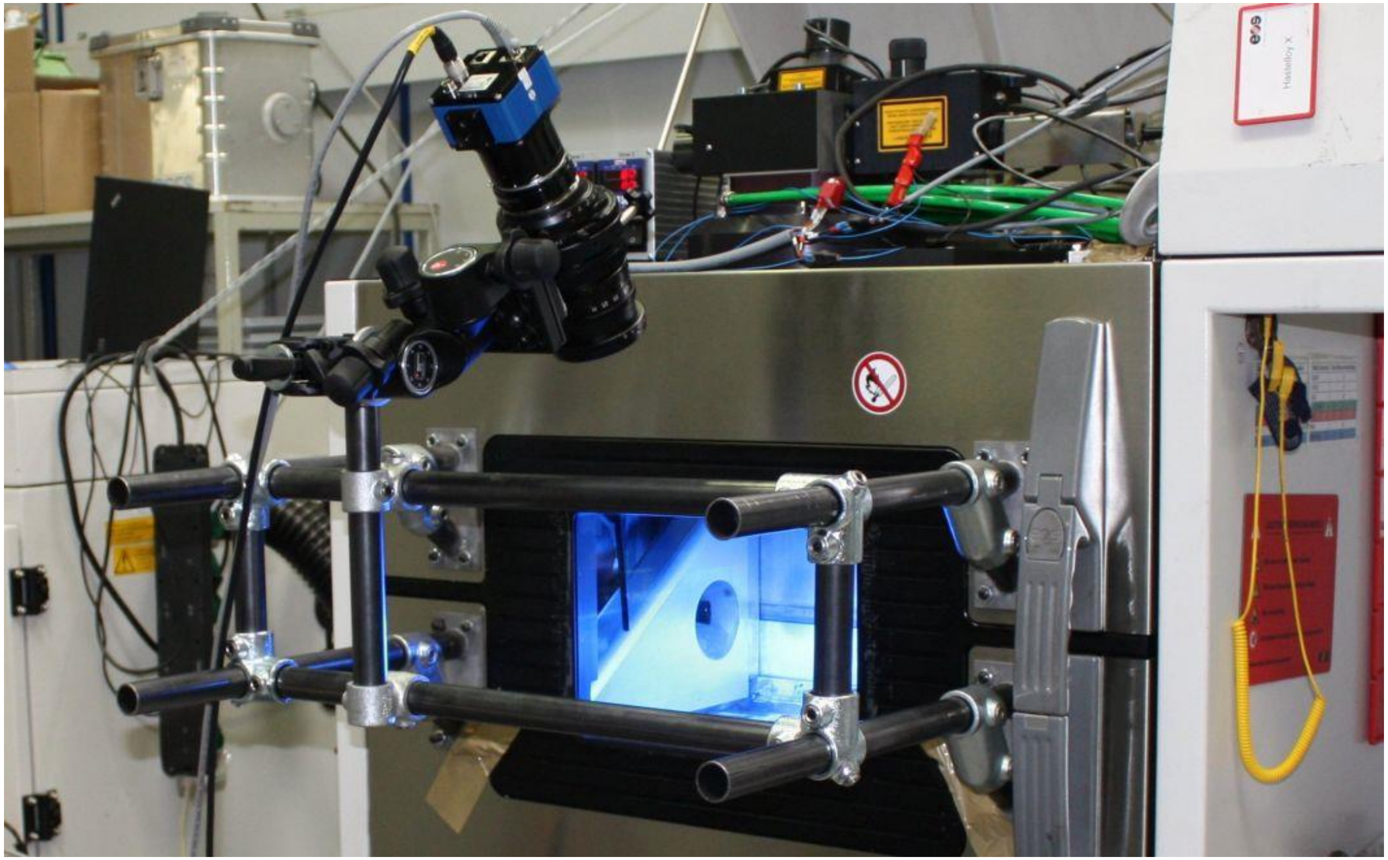
Surface Roughness

Target of optimization in LBM produced parts
- Reduce post-processing
- Optimize internal structures for which post-processing is impossible (e.g. channels)

Related Work
- Minimization of surface roughness (Yasa and Kruth, 2011)
- Identification of dependencies between roughness and process parameters (Strano, 2013)
- Inline 3D surface metrology using optical coherence tomography (Schmitt, 2013)

In-situ measurement is highly desirable
- Inspect surface roughness of internal surfaces
- Check fulfilment of design requirements

Layer Image Acquisition



zur Jacobsmühlen, J.; Kleszczynski, S.; Schneider, D. & Witt, G.
High Resolution Imaging for Inspection of Laser Beam Melting Systems
IEEE International Instrumentation and Measurement Technology Conference (I^{2}MTC), **2013**

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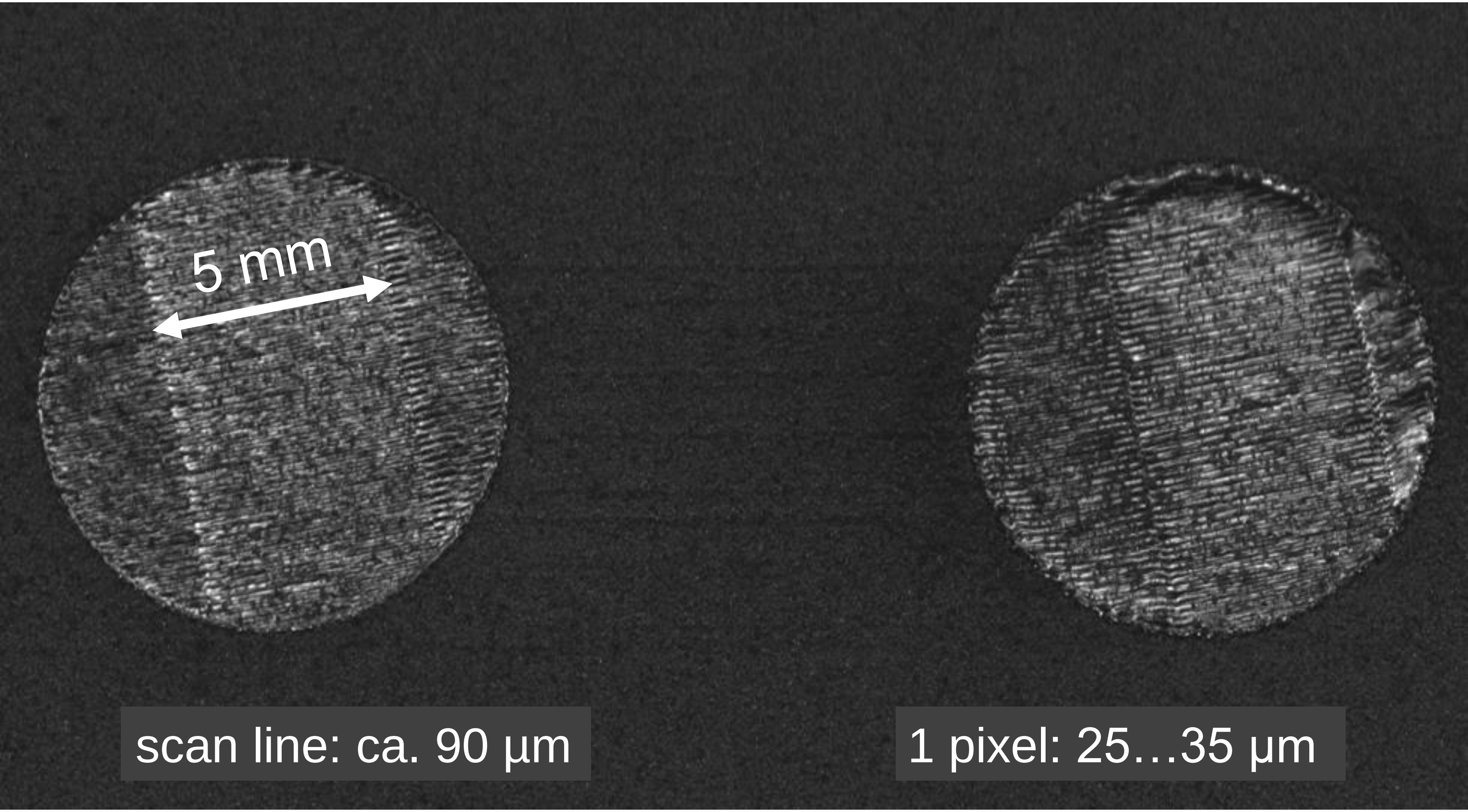
Layer Images



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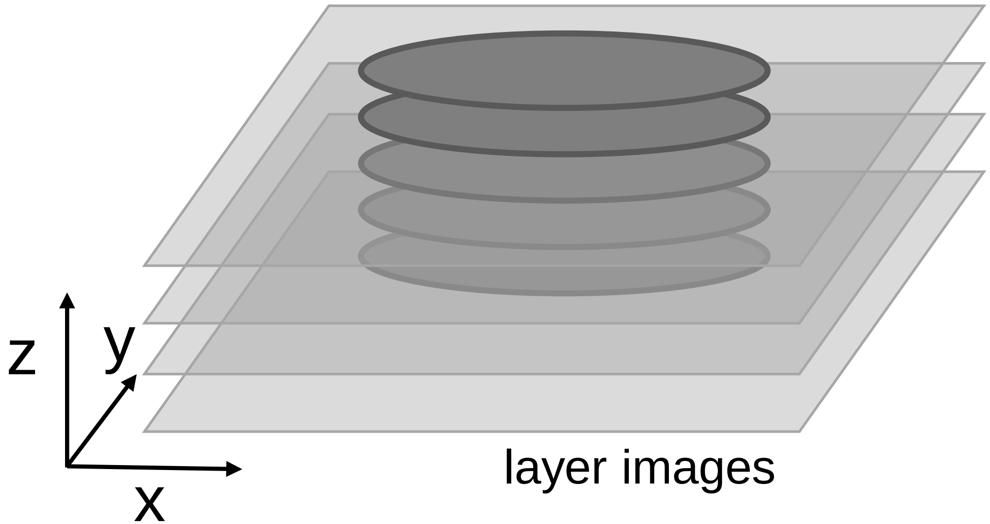
Objective

Replicate physical surface roughness measurements



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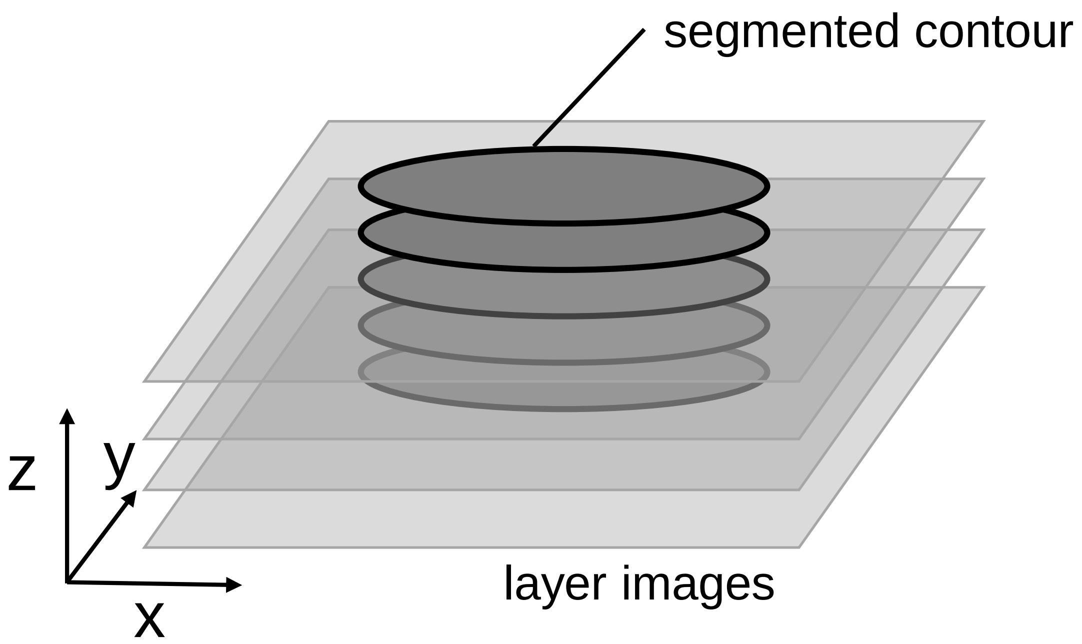

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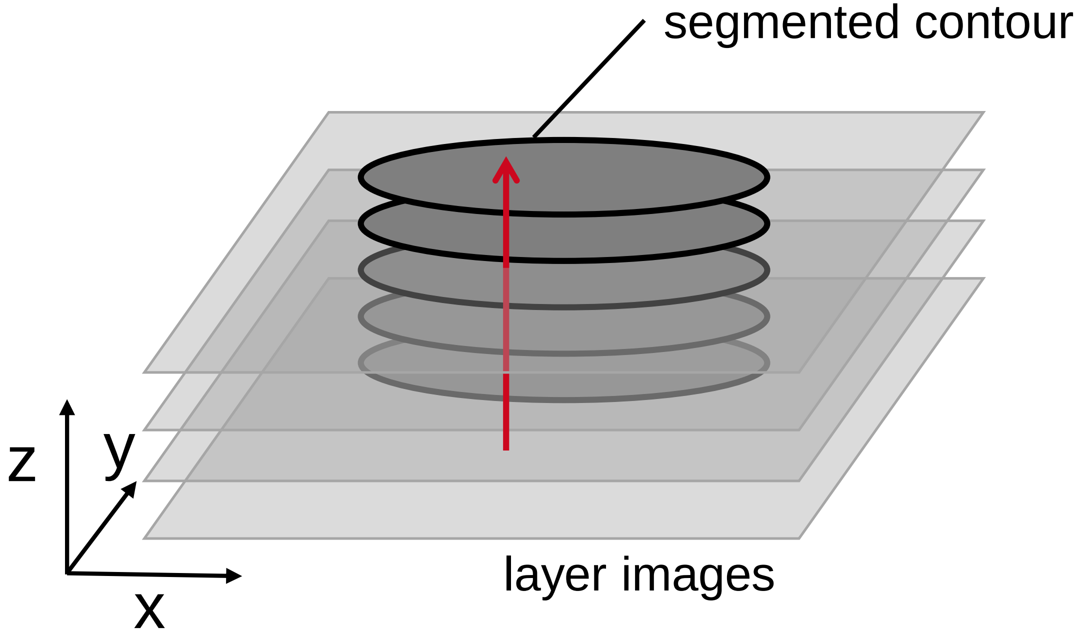

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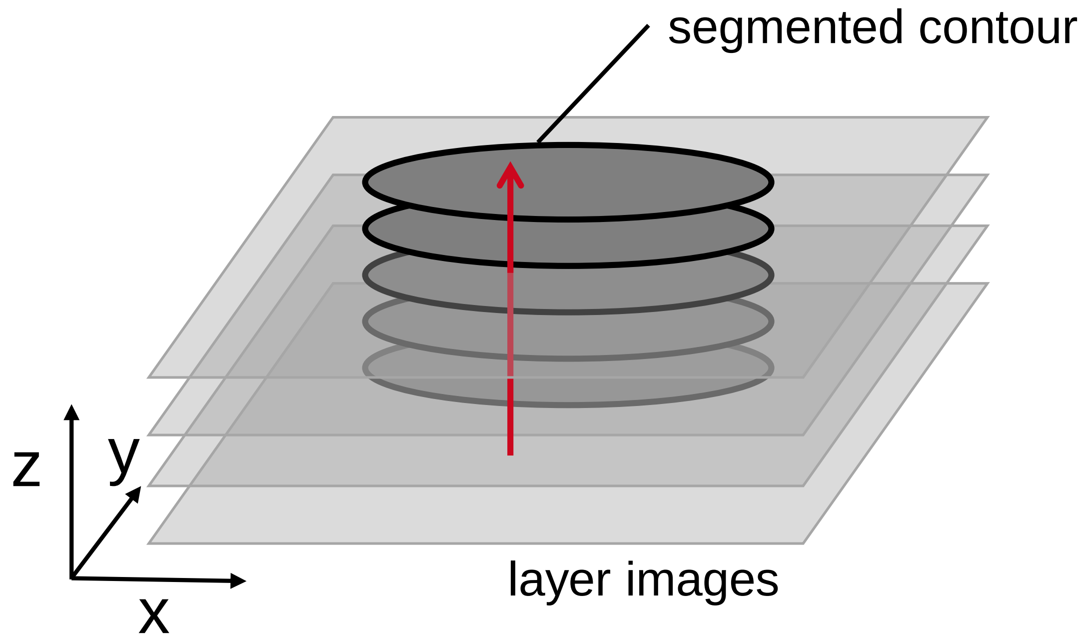

- Extract surface profiles

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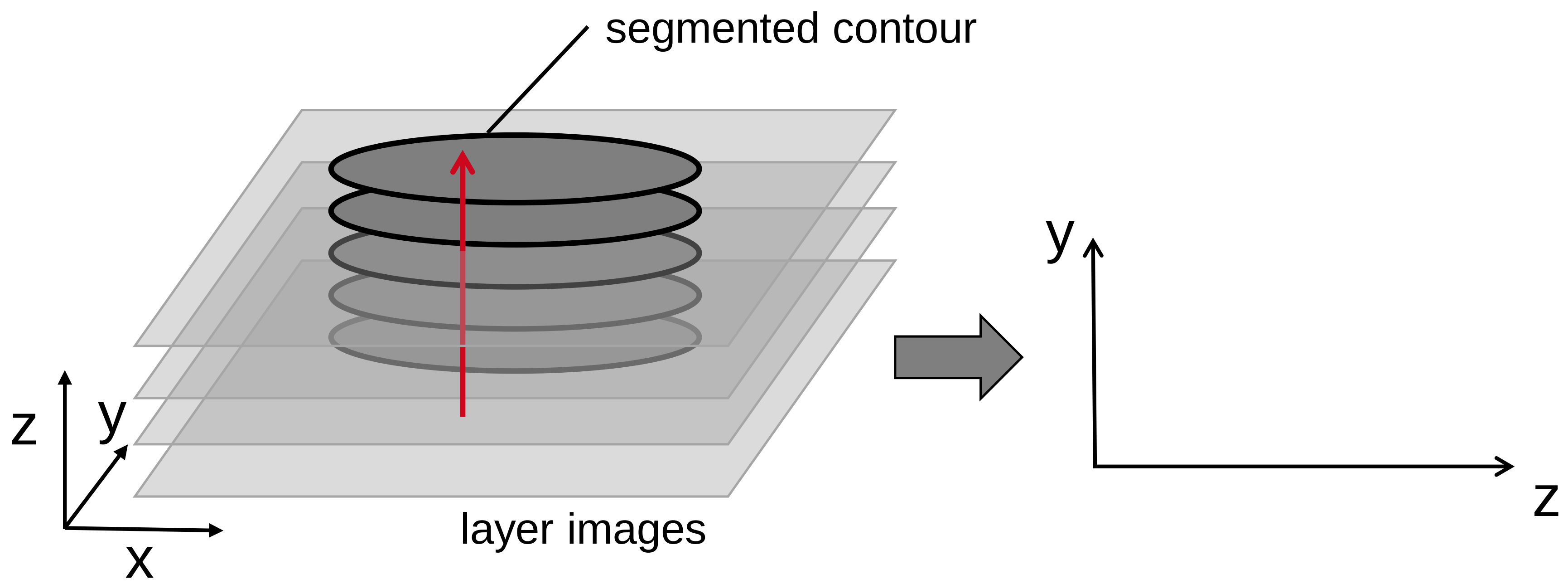
Replicate physical surface roughness measurements



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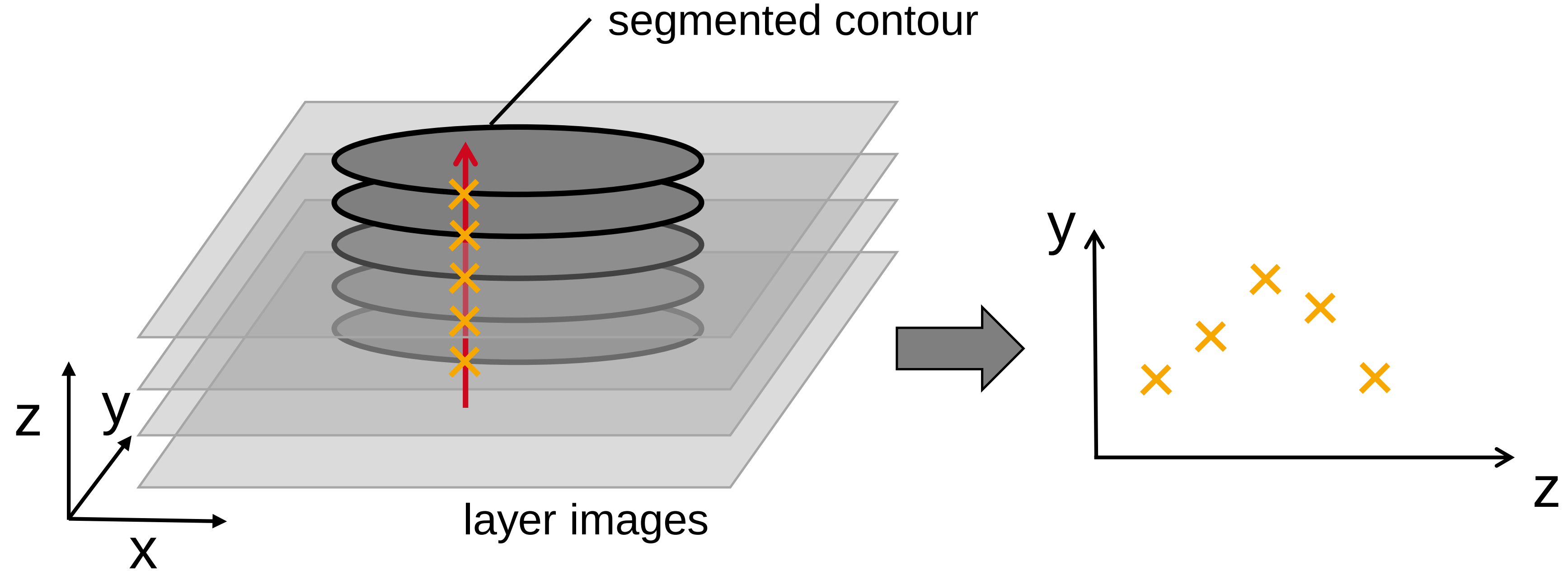

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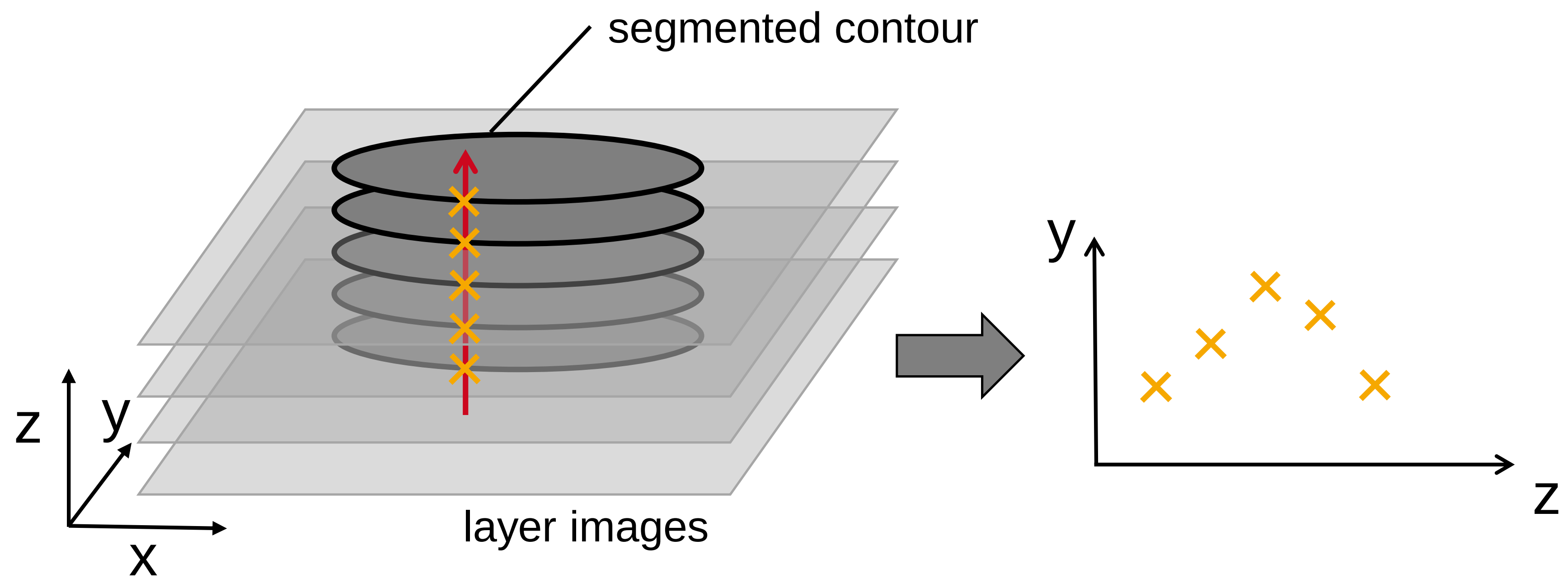

- Extract surface profiles
- Compute surface roughness

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Outline

- Motivation
- Experimental Setup and Physical Measurements
- Segmentation of Part Contours
- Surface Profile Reconstruction
- Surface Roughness Measurements
- Results
- Discussion and Conclusion

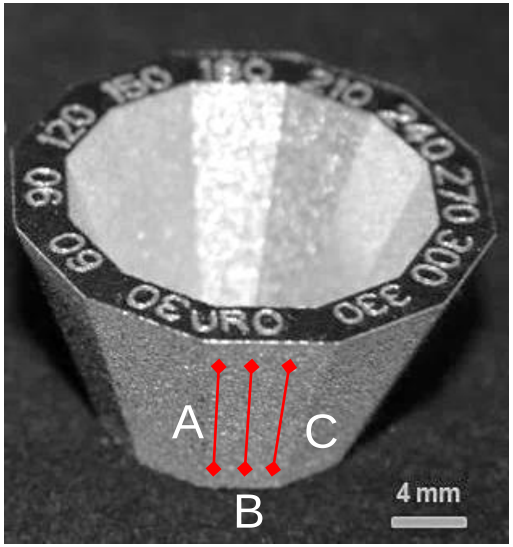
Experimental Setup and Physical Measurements

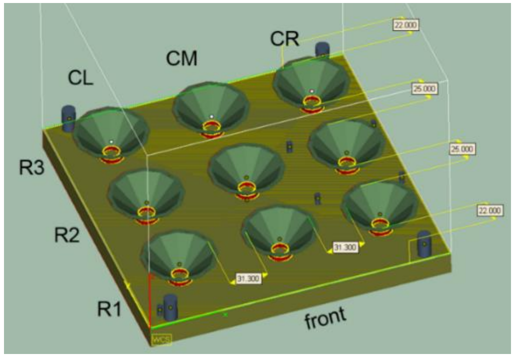
EOSINT M270, NickelAlloy IN718

- 2x 12 faces for measurements (outside and inside), placed at multiples of 30°
- Measurement of R_z (EN ISO 4287) using Mitutoyo SJ-400 profilometer:
  - divide each profile (*A* - *C*) into five segments
  - measure maximum peak-to-peak distance for each segment $R_z\,(i)$
  - compute average

$$R_z = \frac{1}{5}\sum_{i=1}^{5} R_z(i)$$

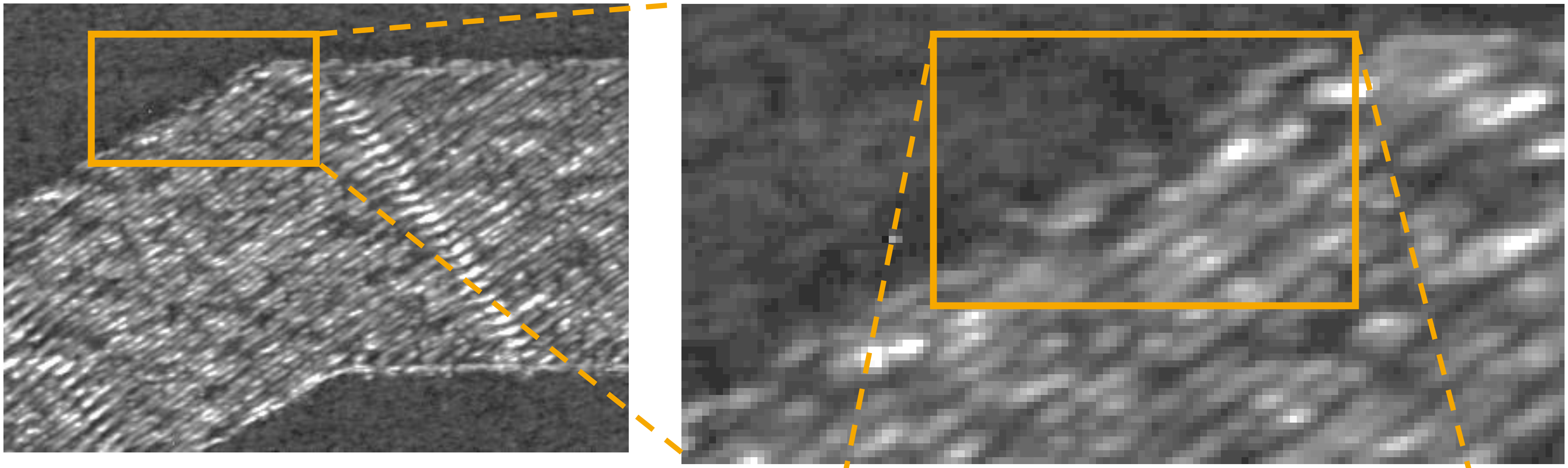
- Average of three R_z measurements yields surface roughness for each pyramid face
- Part is built nine times: 216 measurements



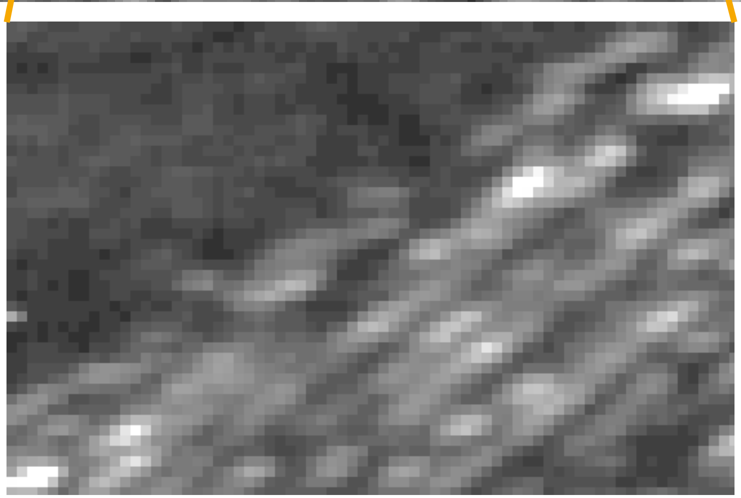


Kleszczynski, S.; Ladewig, A.; Friedberger, K.; zur Jacobsmühlen, J.; Merhof, D. & Witt, G.
Position Dependency of Surface Roughness in Parts from Laser Beam Melting Systems
Proceedings of the 26th Internation Solid Freeform Fabrication (SFF) Symposium, **2015**

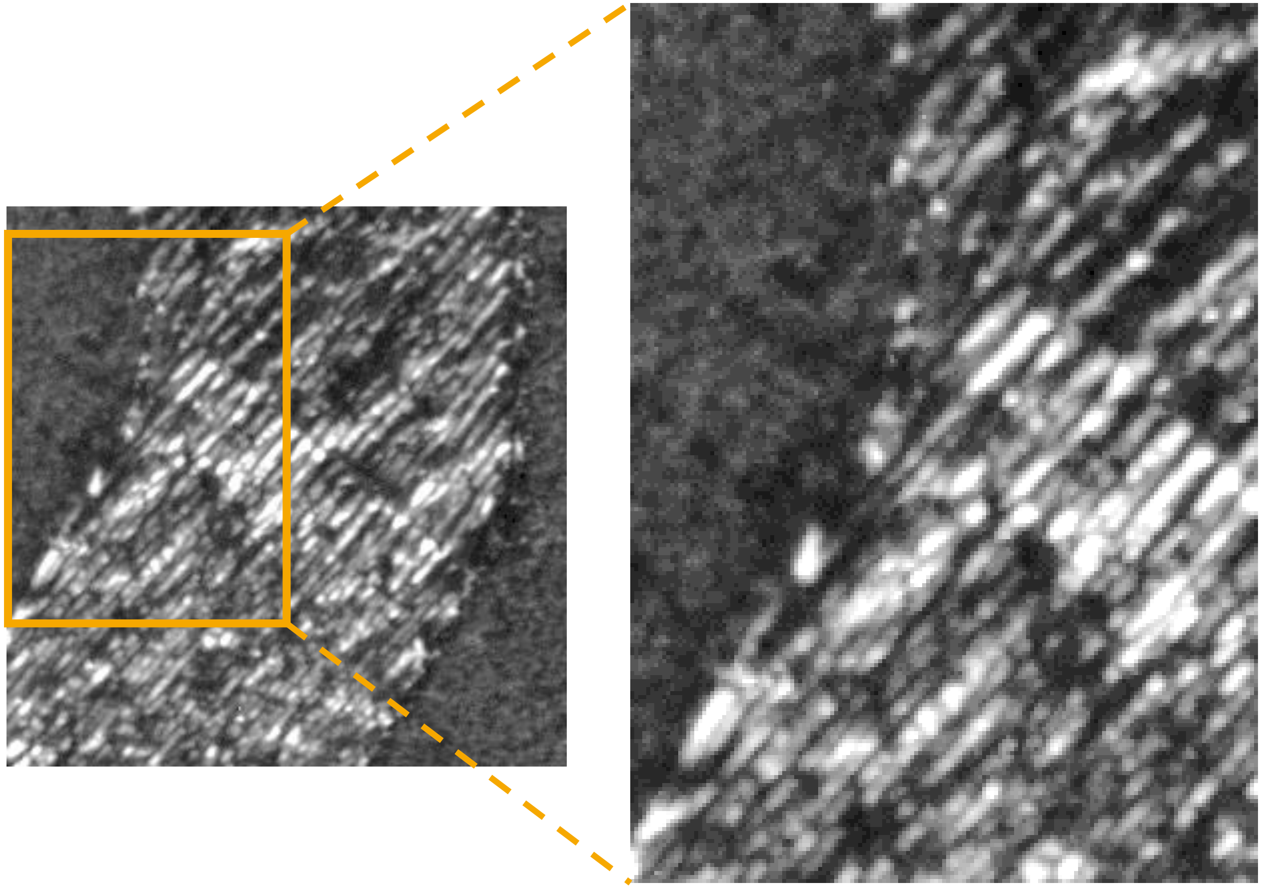
Segmentation of Part Contours



- Goal: identify part boundary
- Powder appears as noise-like background
  - edge detection yields false positive edges



Difficult Regions

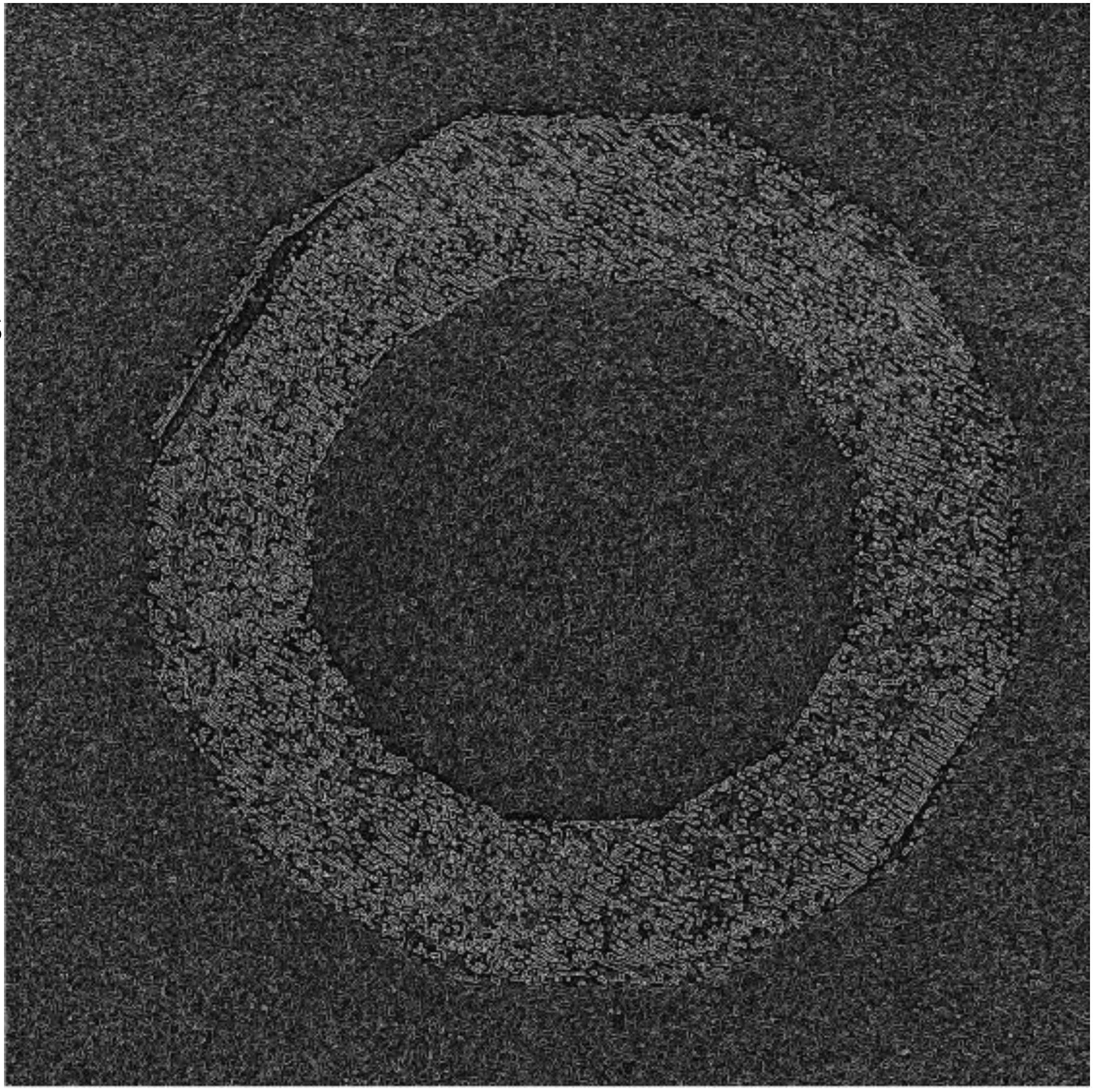


Segmentation of Part Contours: Edge Detection 1

Problems

- Multiscale results
  (fine to coarse)
- Many edges in powder regions
  (fine scale)
- Combine scales for optimum
  result

➢ But: no closed boundary!



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Design of steerable filters for feature detection using canny-like criteria
Pattern Analysis and Machine Intelligence, IEEE Transactions on, **2004**, *26*, 1007 -1019

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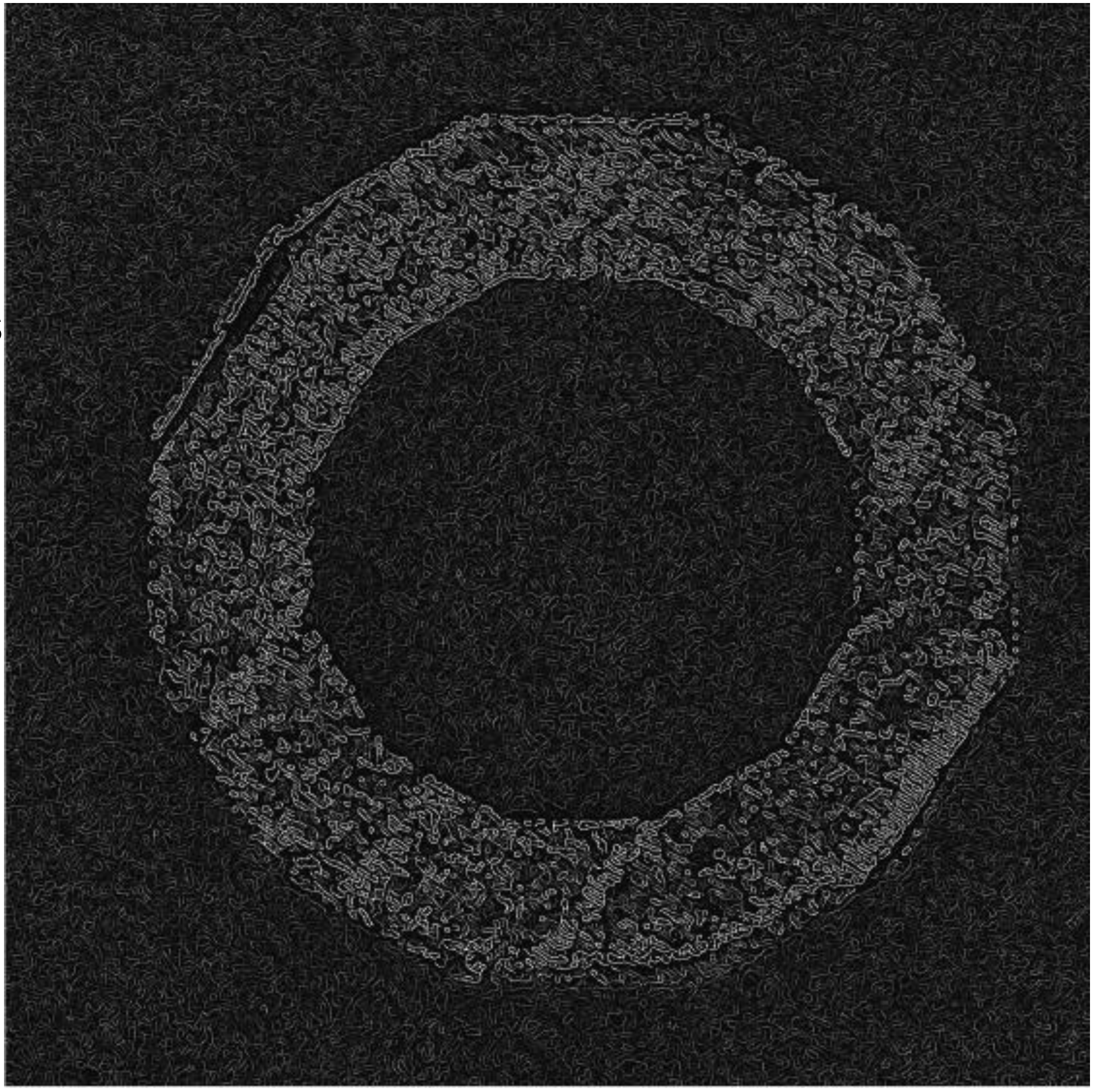

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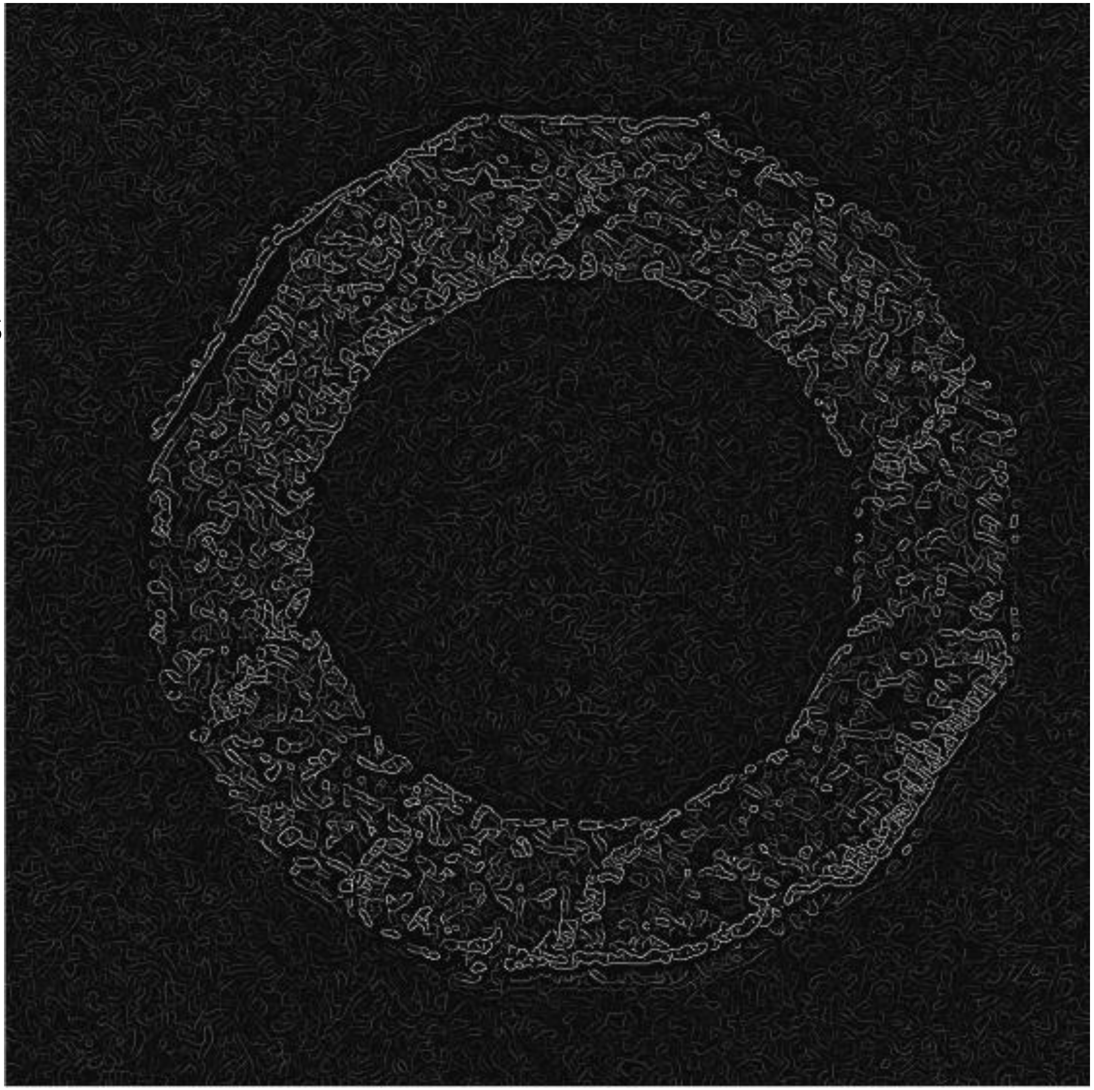

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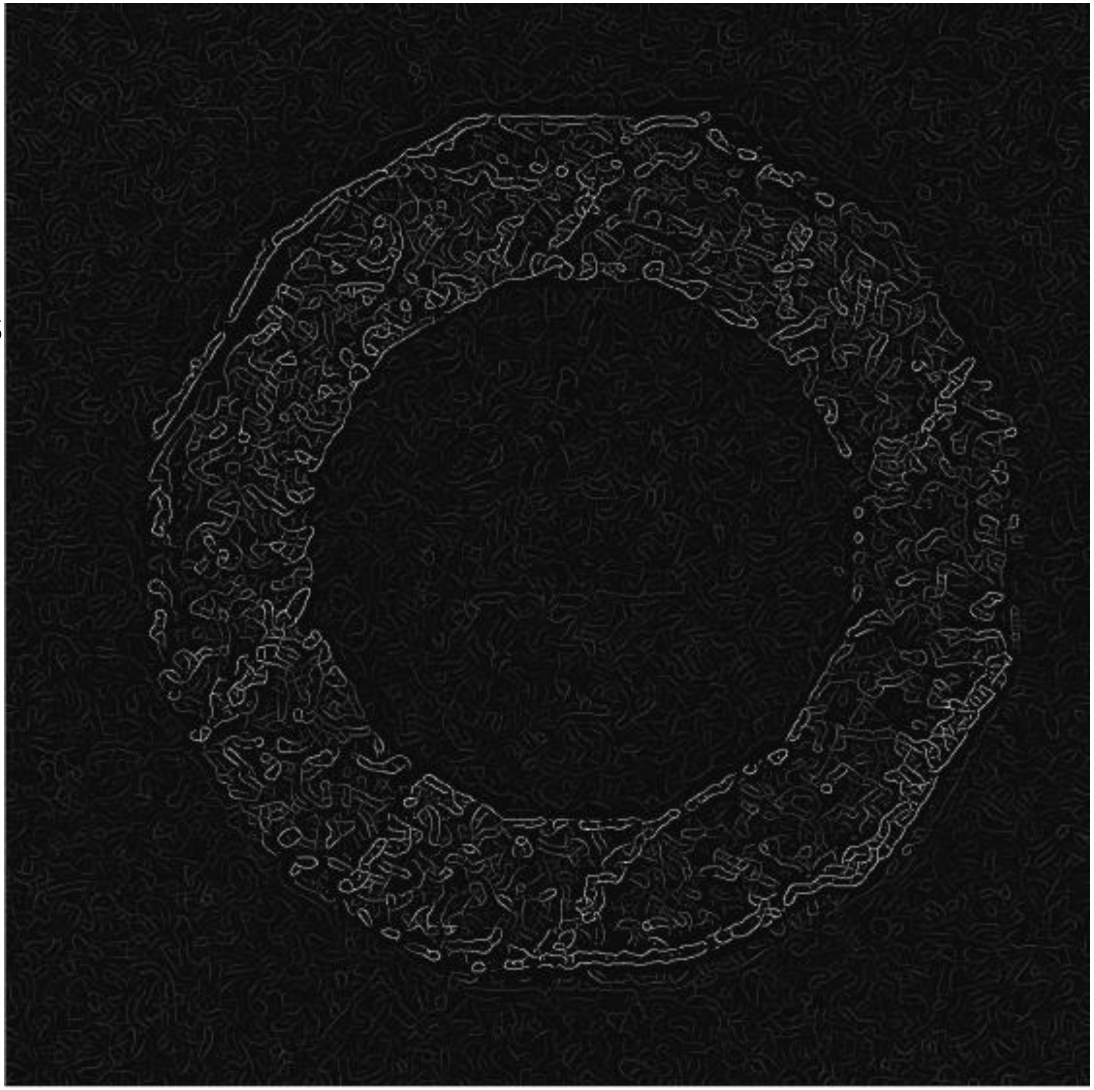

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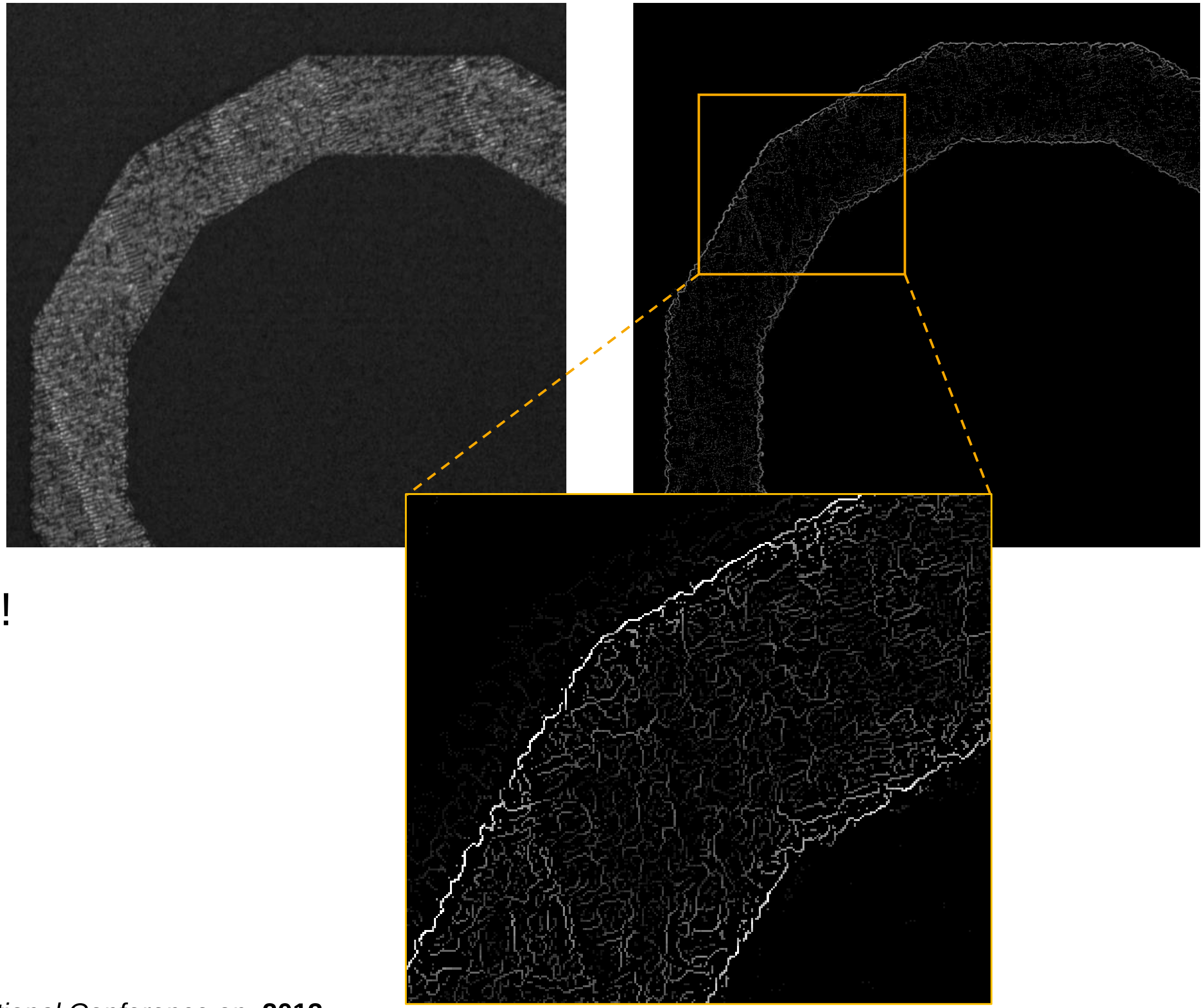
Segmentation of Part Contours: Edge Detection 2

Robust Detection

- Structured Forests for edge detection
  - Incorporate texture information
  - Edges correlate to subjective results

➢ Still no closed boundary!



Dollár, P. & Zitnick, C.
Structured Forests for Fast Edge Detection
Computer Vision (ICCV), 2013 IEEE International Conference on, **2013**

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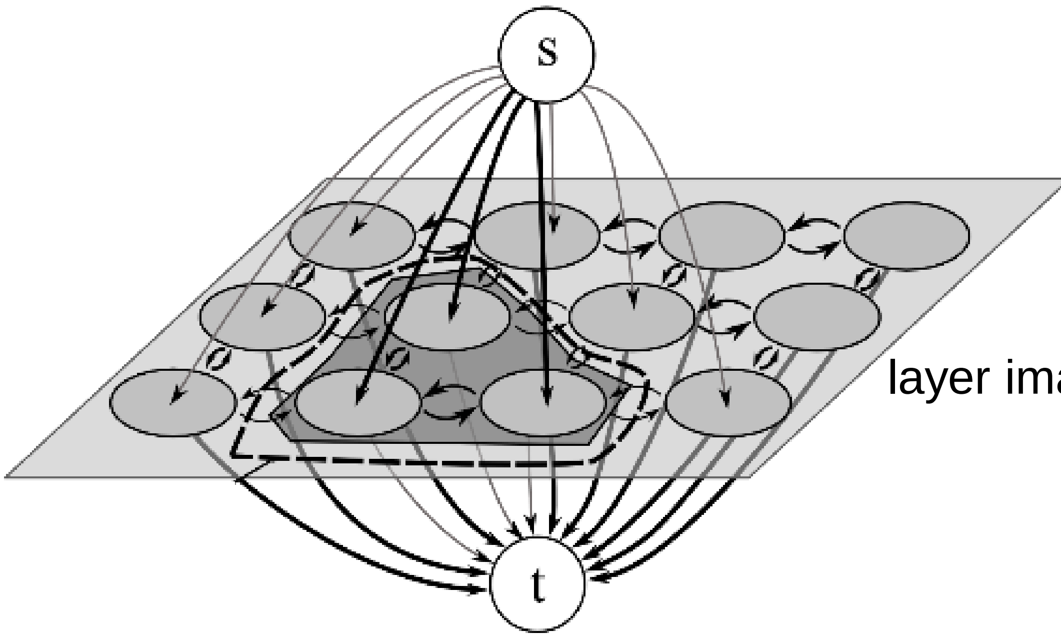
Segmentation of Part Contours: Graph Cuts

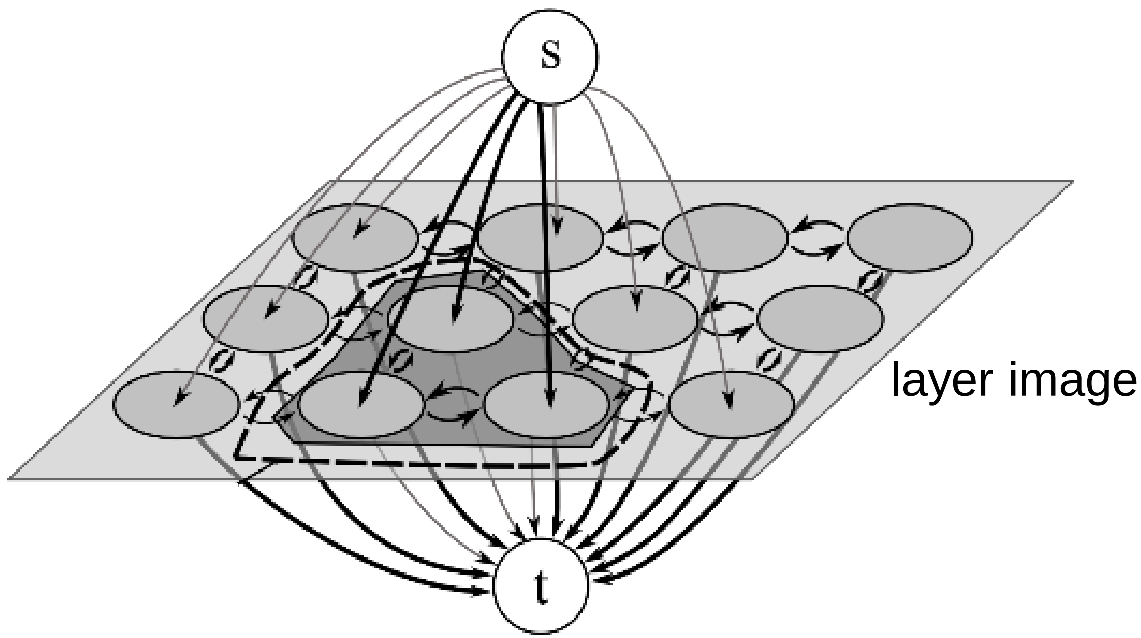
Find Optimum Region Boundaries



layer image

Find Optimum Region Boundaries

- Represent each image pixel as node in a graph



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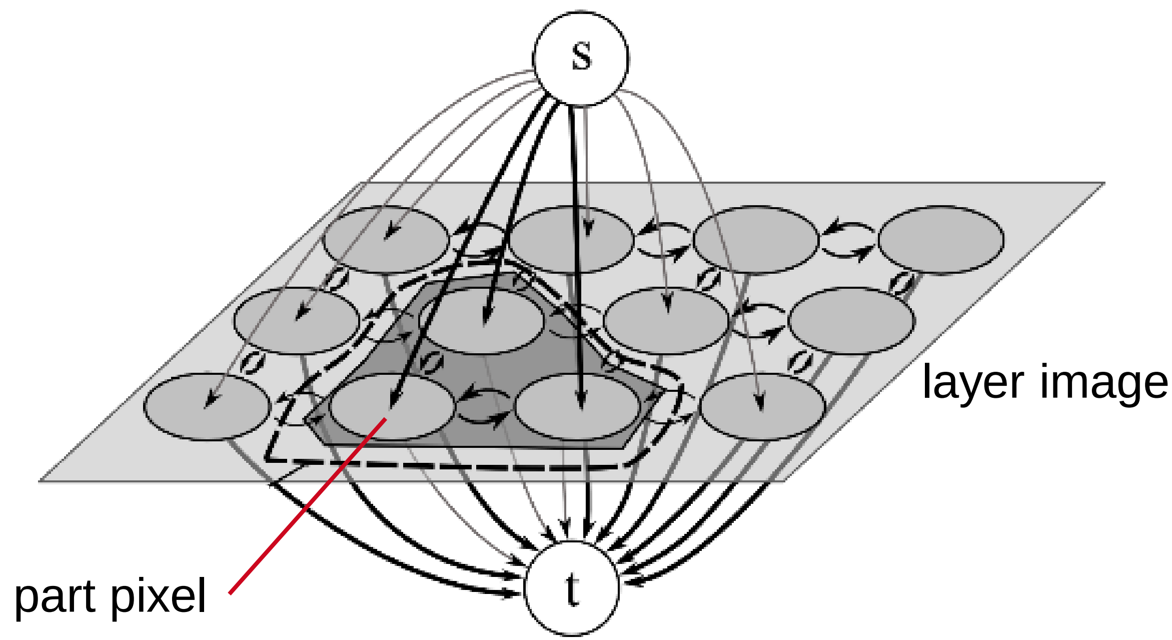

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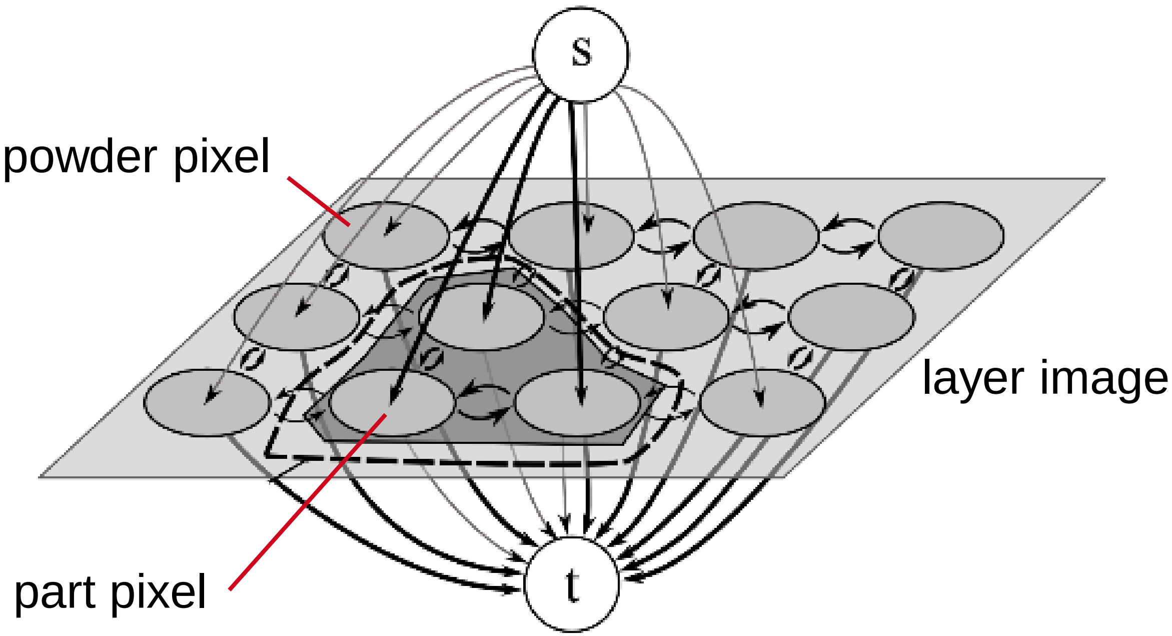

Segmentation of Part Contours: Graph Cuts

Find Optimum Region Boundaries

- Represent each image pixel as node in a graph
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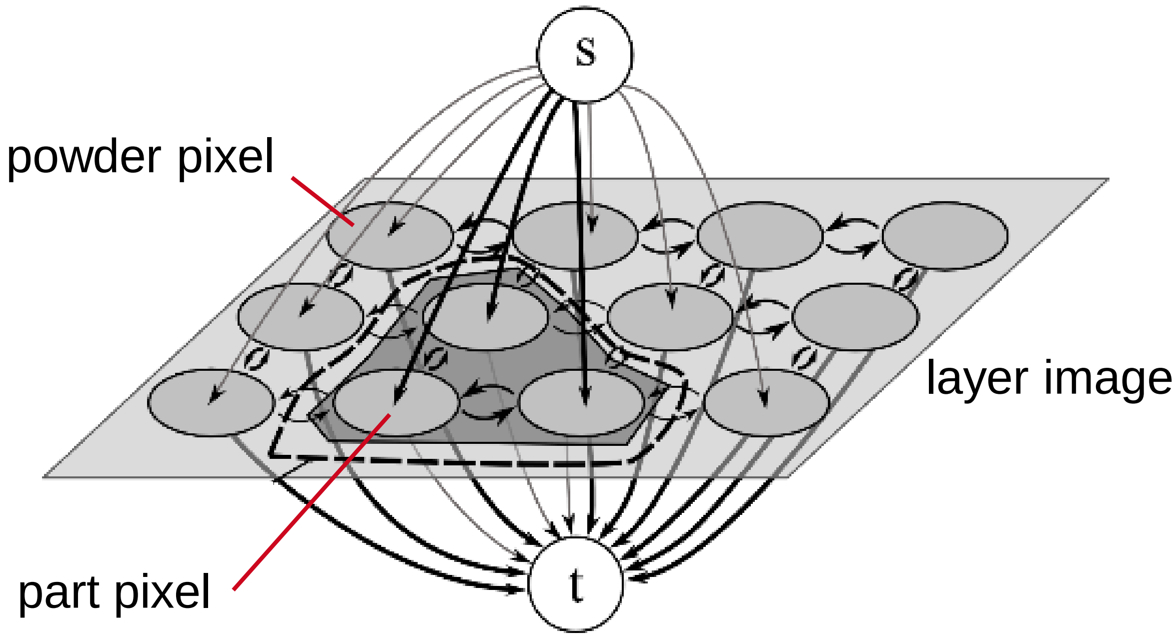

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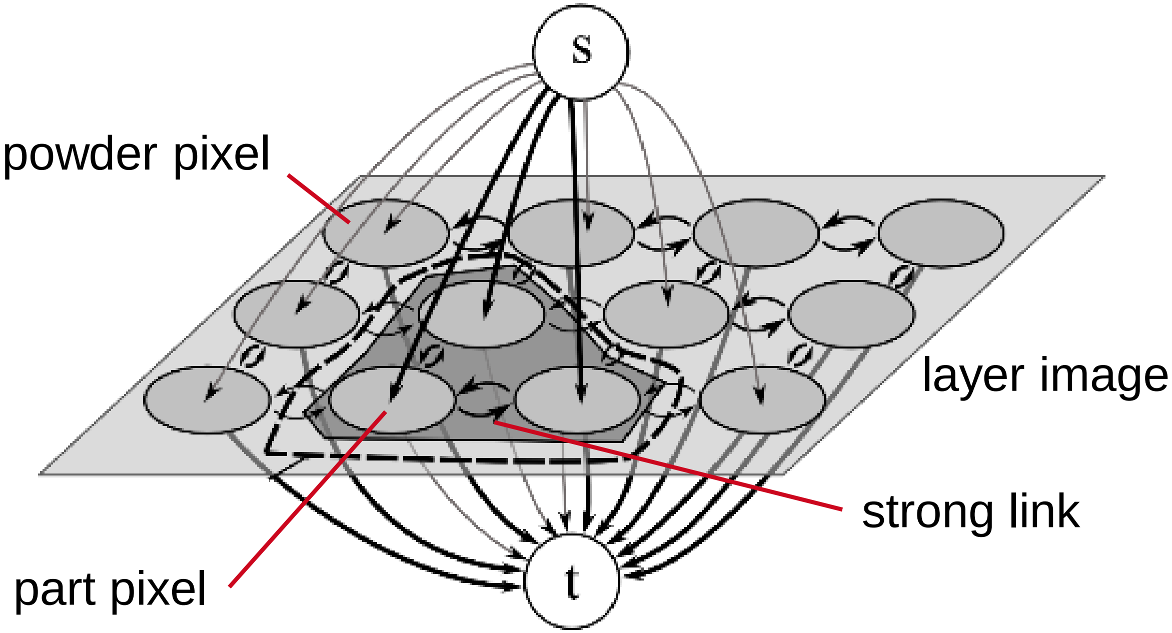
  -



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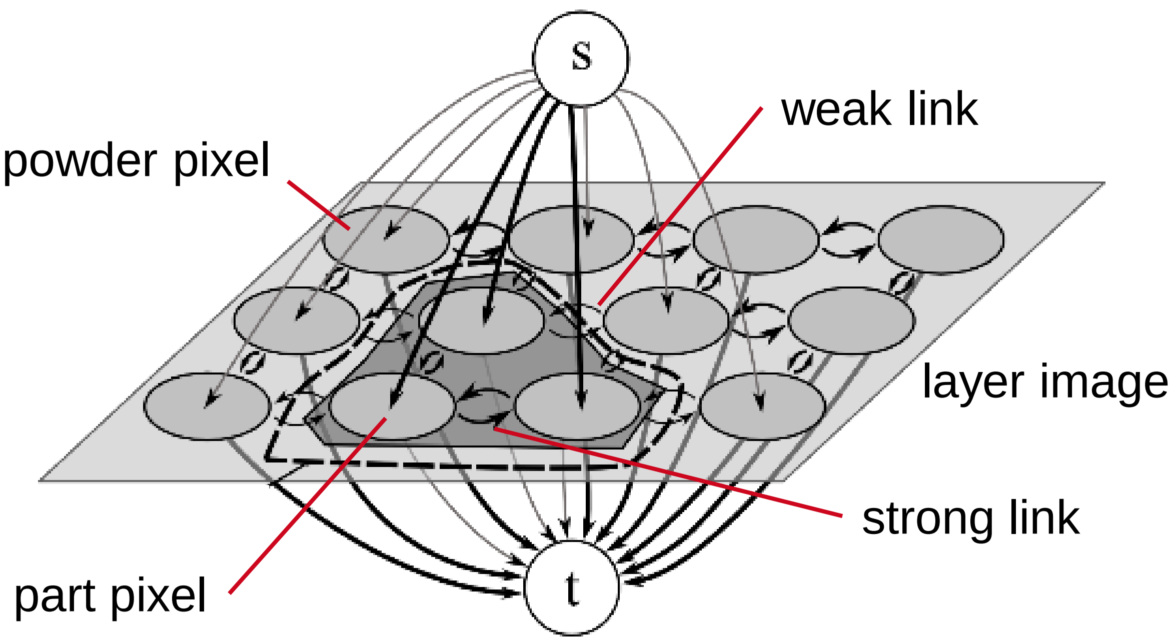

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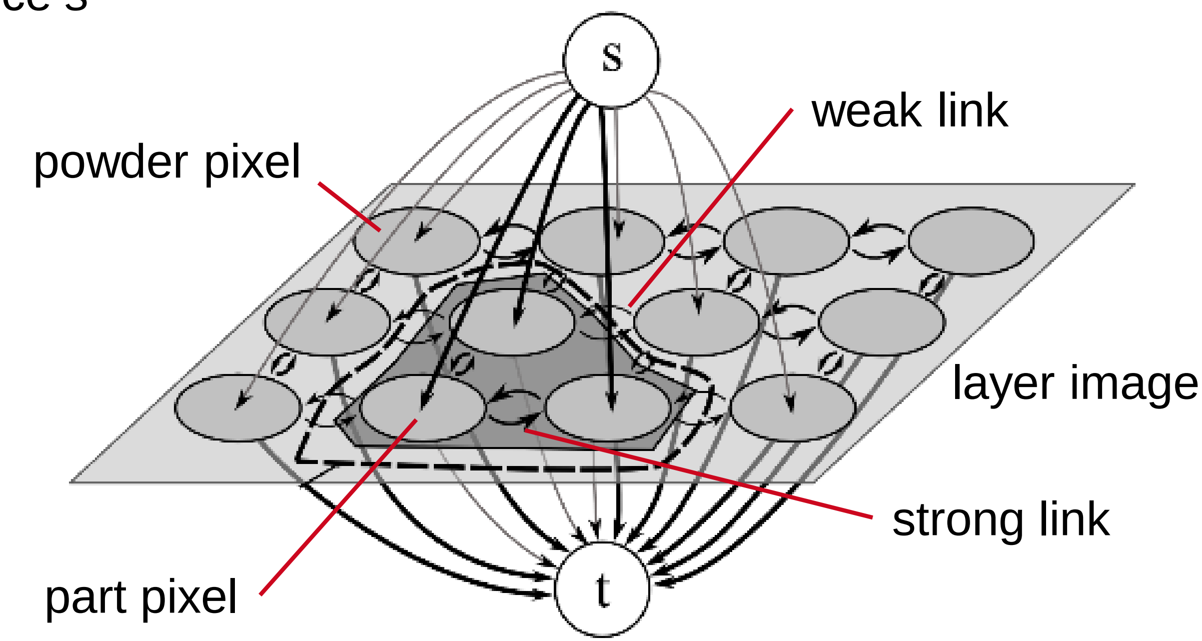
- Maximize flow between source *s* and target *t*



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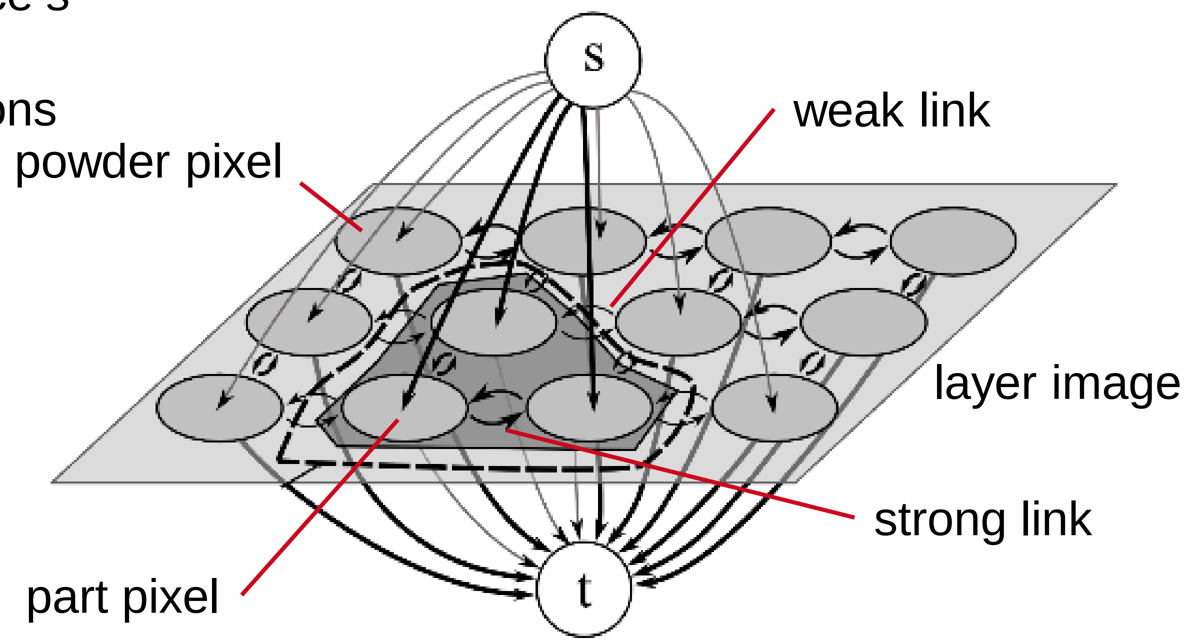

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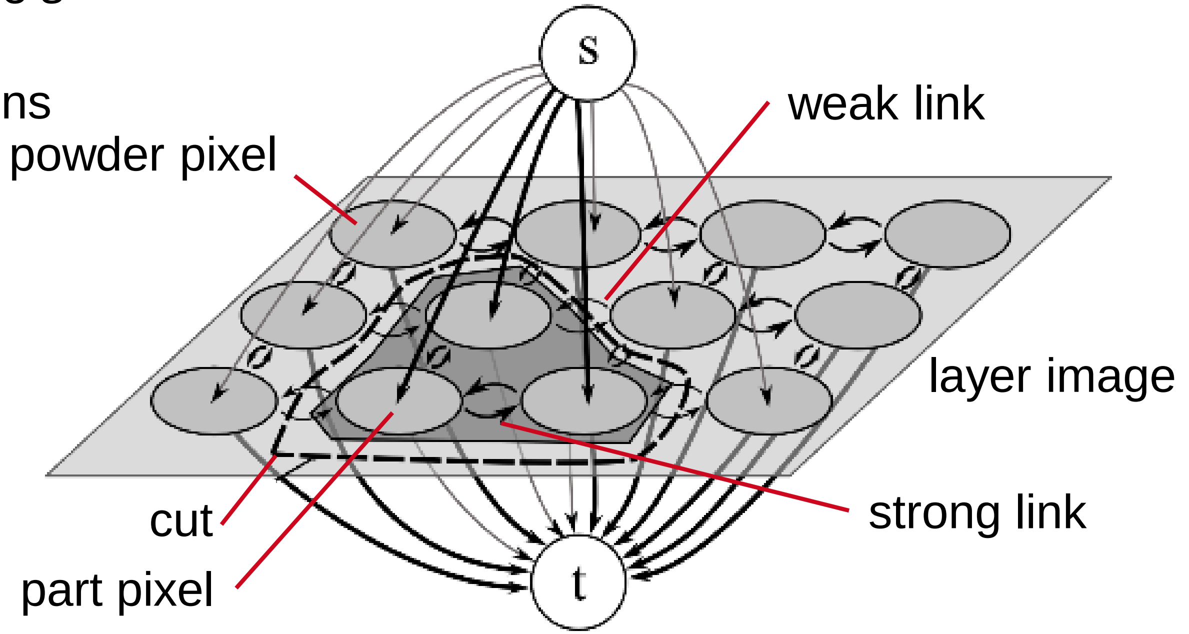

Segmentation of Part Contours

Weight Assignment

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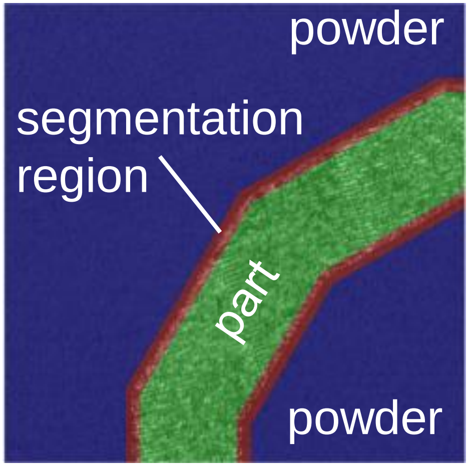
- Set labels for definitive part and powder regions („keep regions“)



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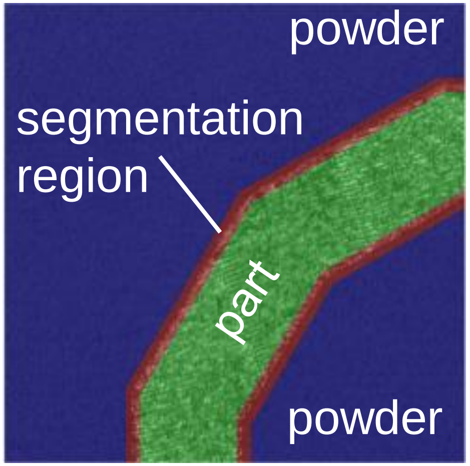

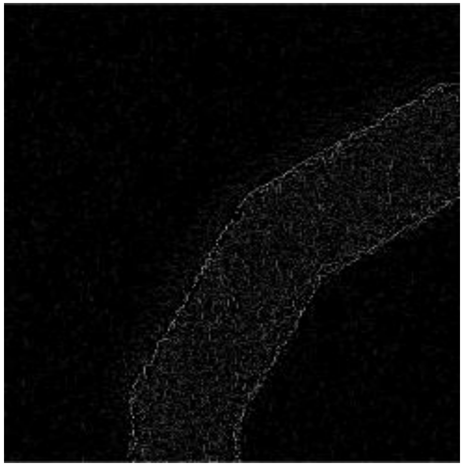

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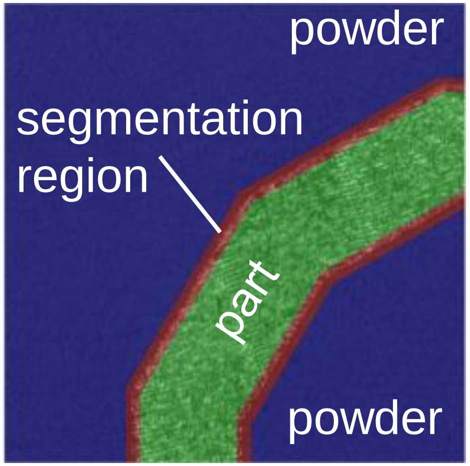

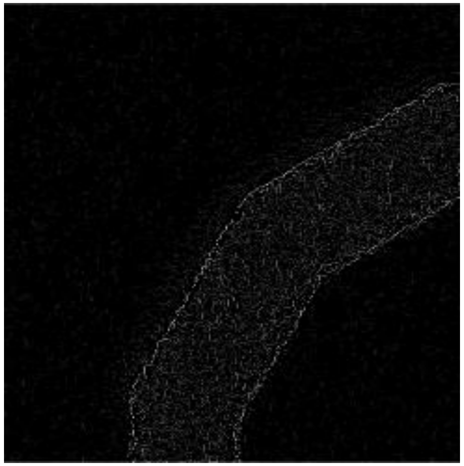

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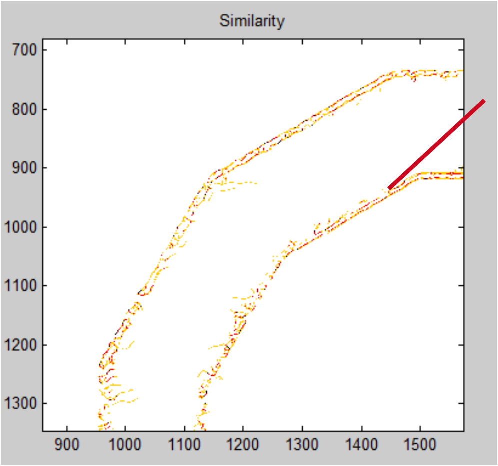
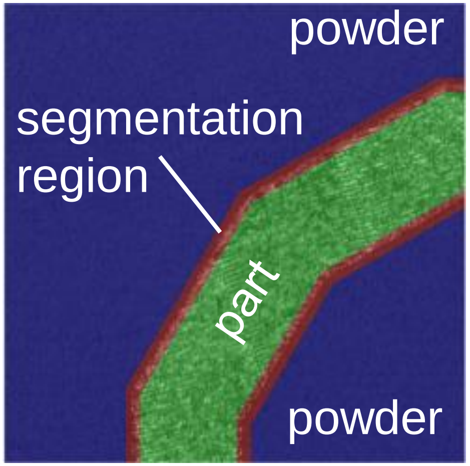
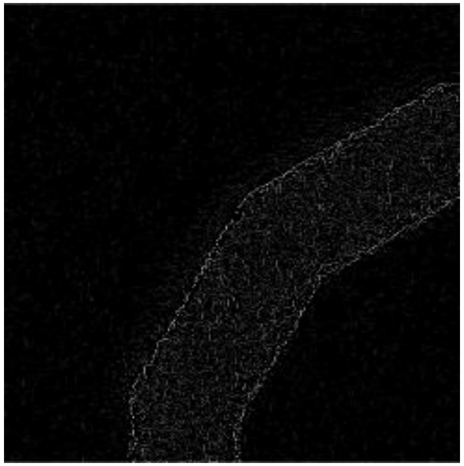


low similarity on edges





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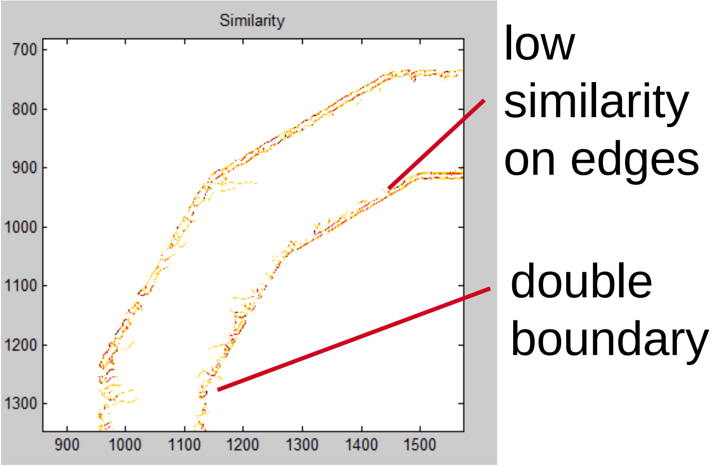

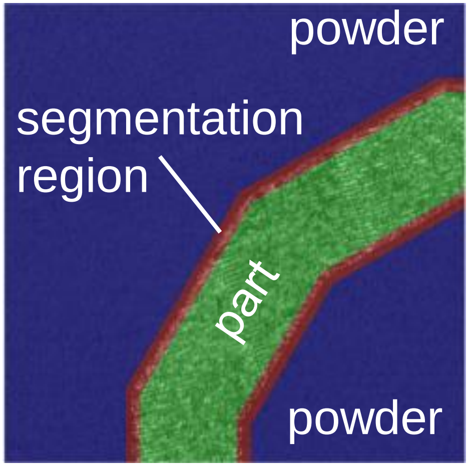

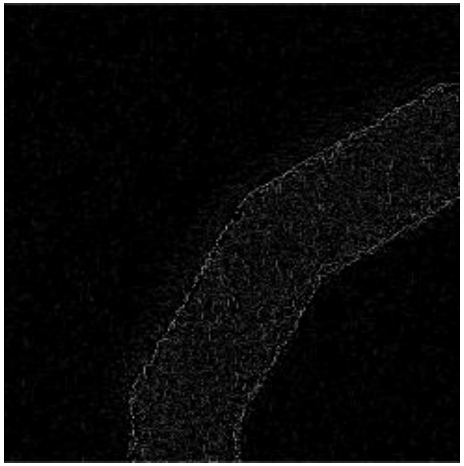

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Weight Assignment

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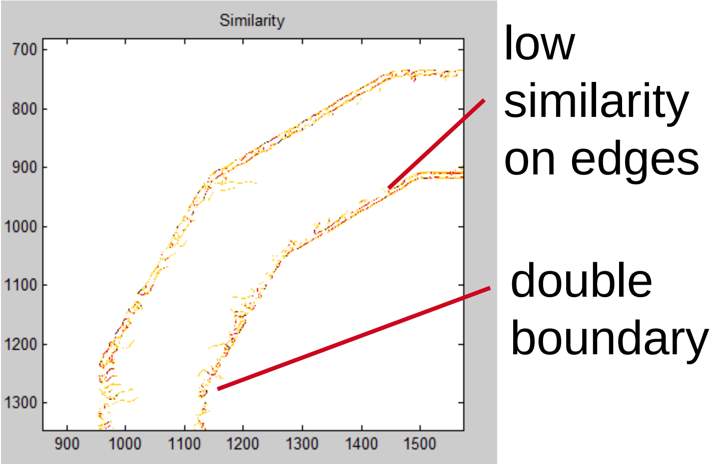
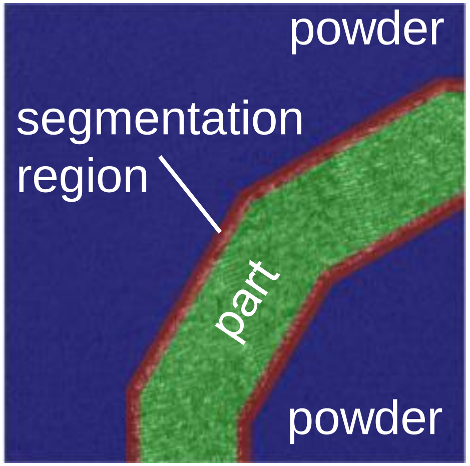
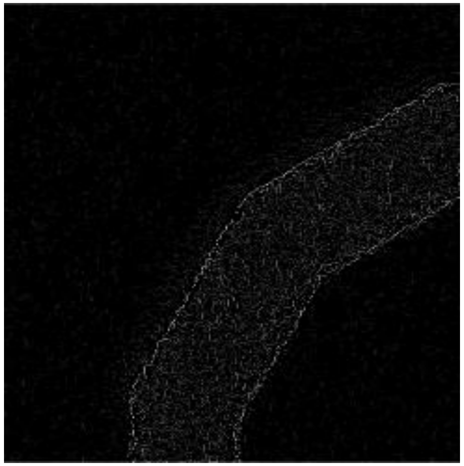
- Assign lower weights to outer regions („prefer outer boundary for cut“)







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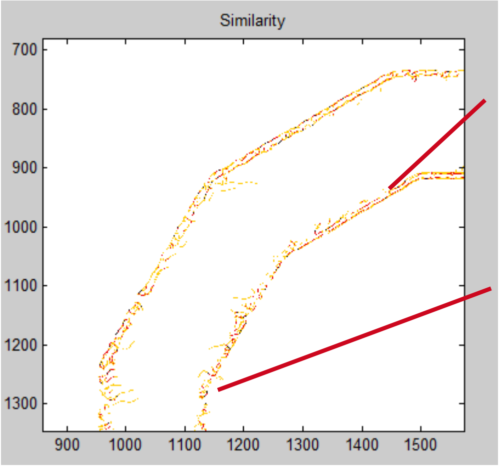
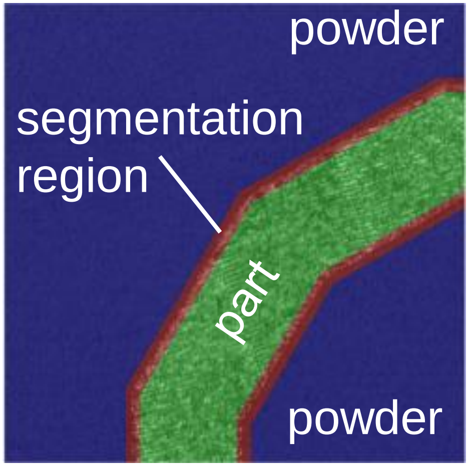
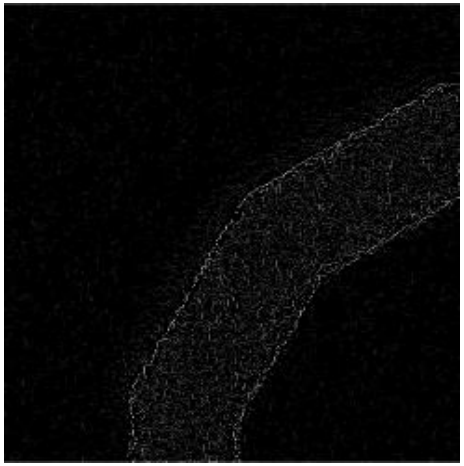
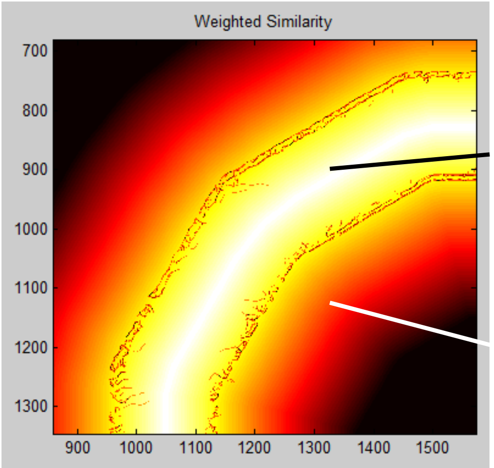




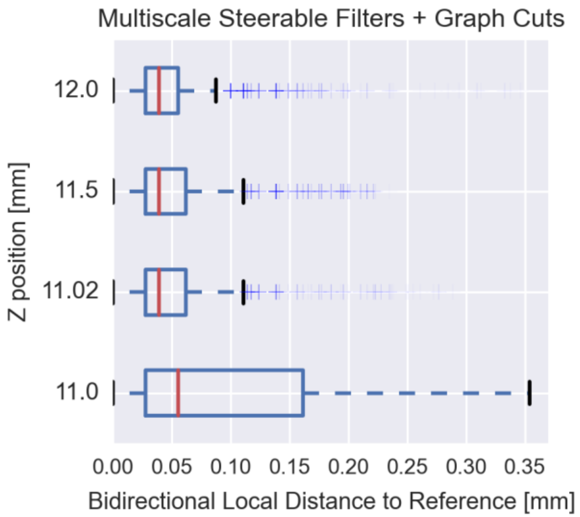




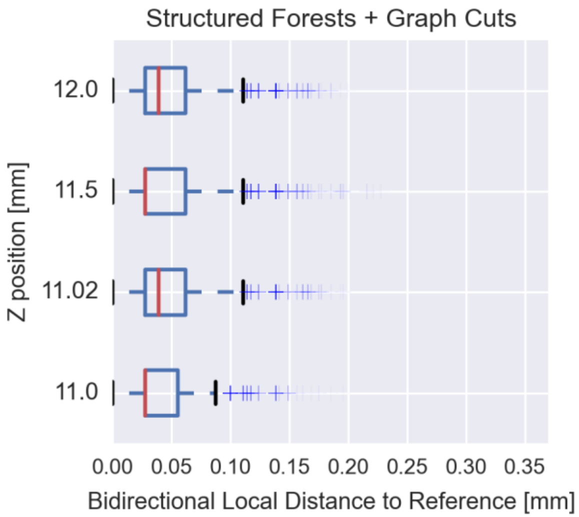
Segmentation of Part Contours: Accuracy

Comparison of Edge Detectors

- Compared to manually annotated ground truth
- bidirectional local distance measure



Median: 39.1 µm



Median: 27.7 µm

Kim et al. Bidirectional local distance measure for comparing segmentations
Medical Physics, **2012**, *39*, 6779-6790

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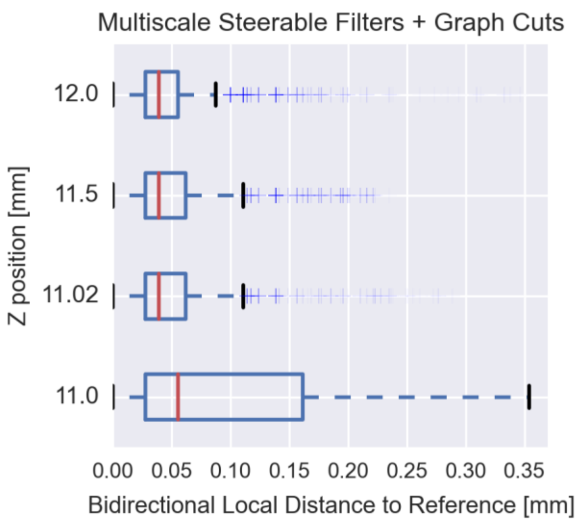

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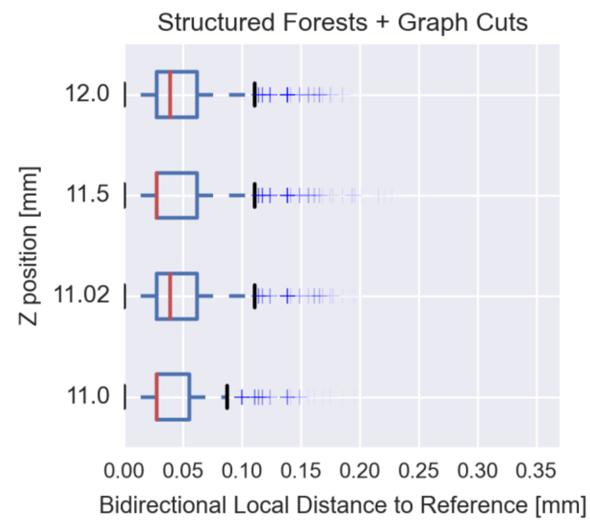

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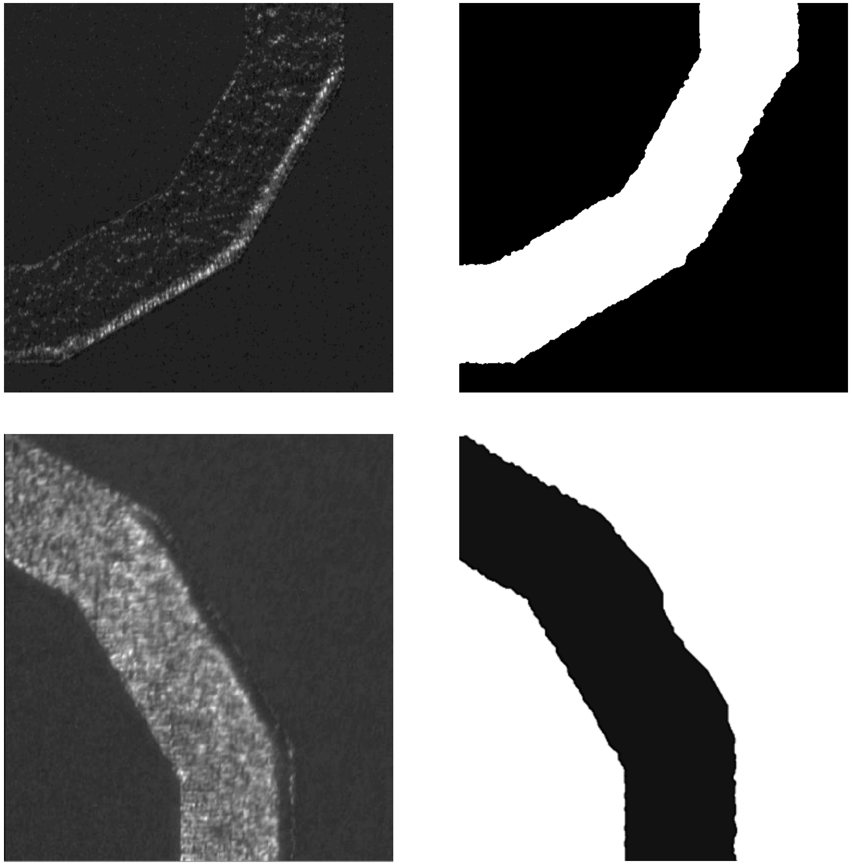
Segmentation of Part Contours: Errors

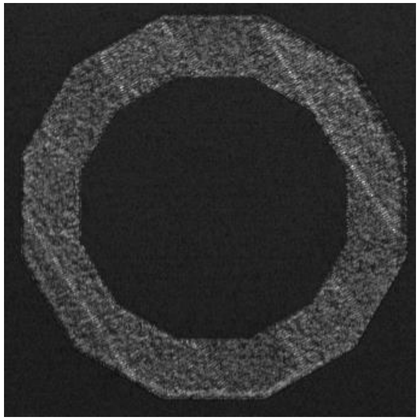
Glare / shadows introduce edges inside of part

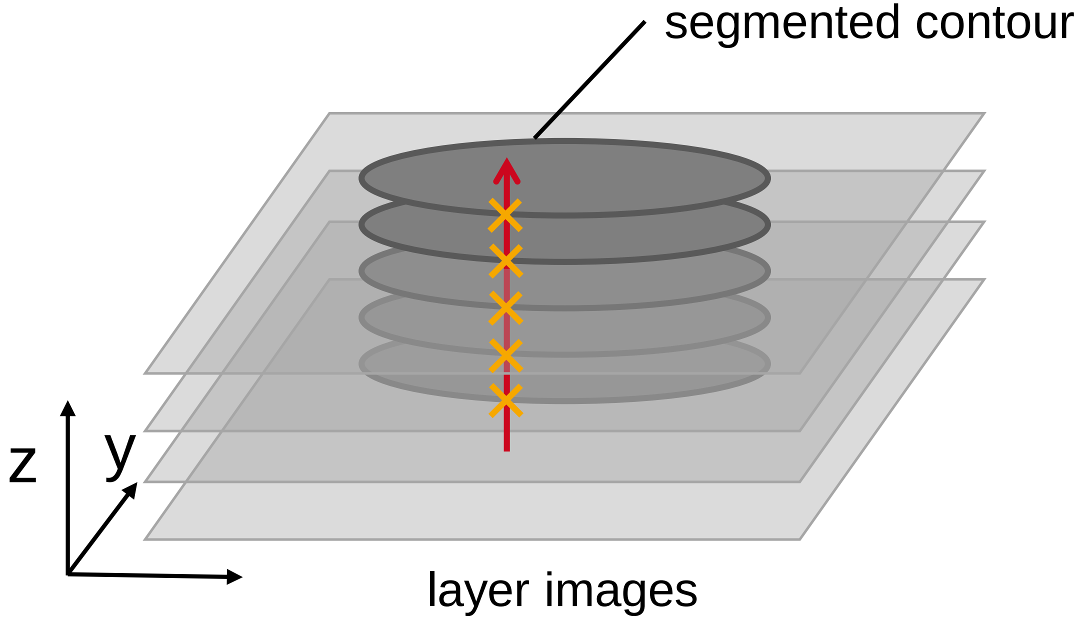


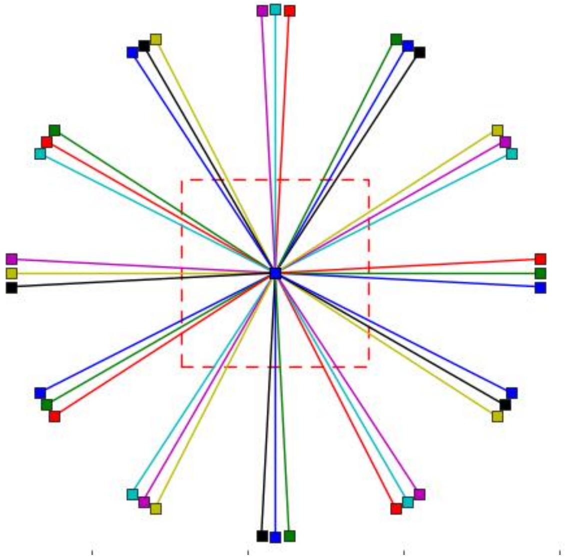
Surface Profile Reconstruction

Measurement Profiles

- Measure surface roughness of pyramid segments
- Use multiple profiles to capture roughness statistics
  - Additional rays at +/- 3° for each face



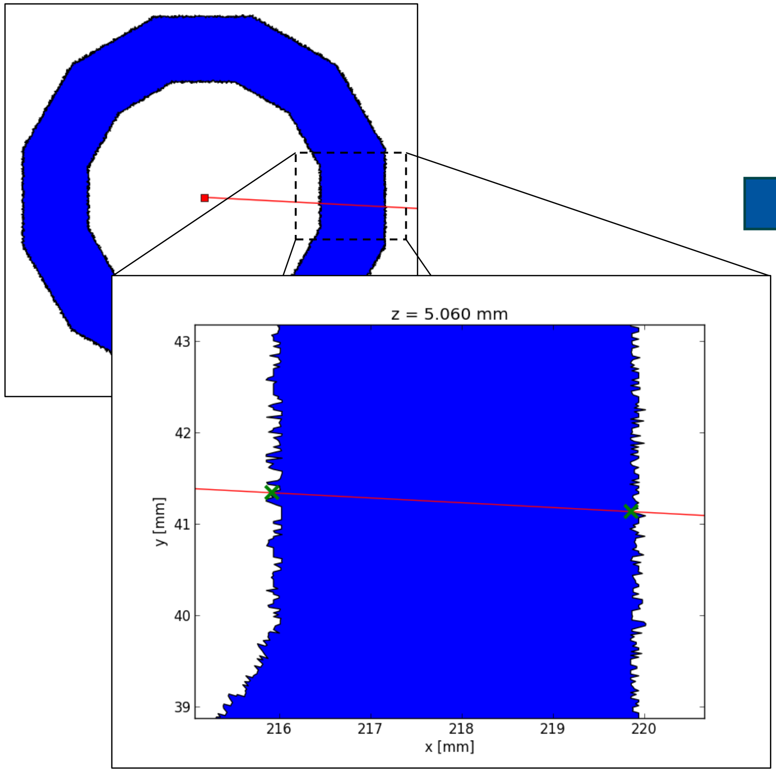


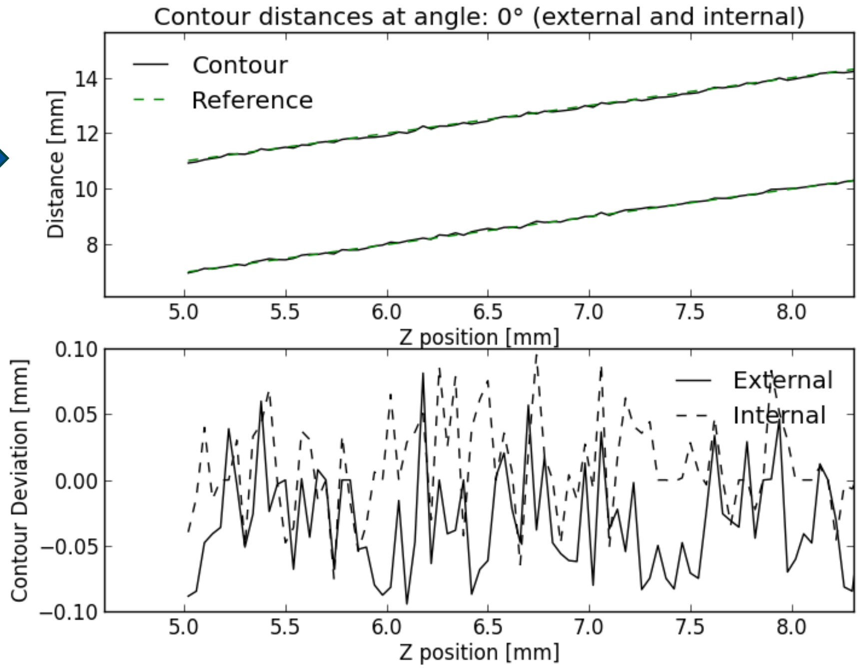


Surface Profile Reconstruction

Measurement of Internal and External Contour

- Intersections of radial rays and contours yield surface points
- Surface profile as difference of segmented contour and reference geometry





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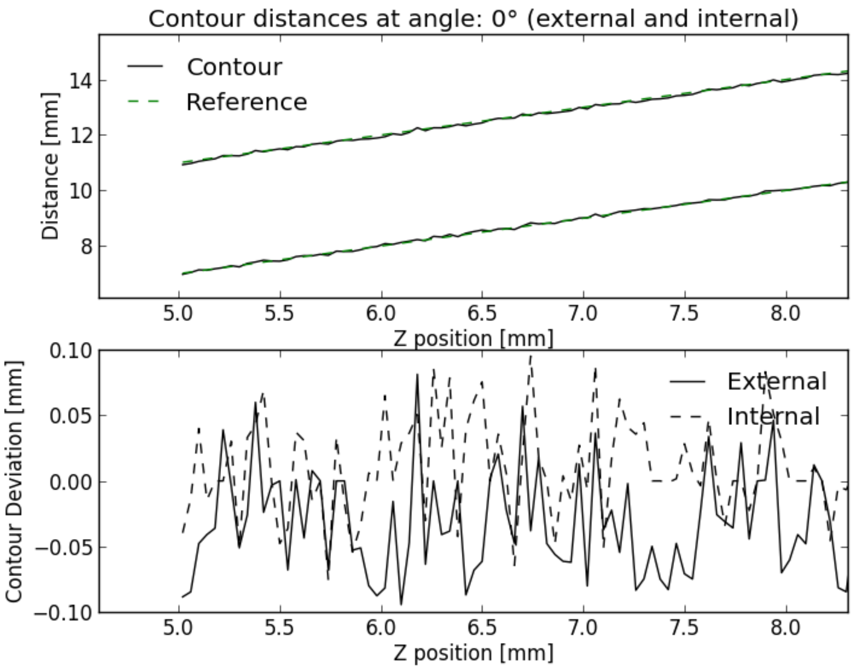
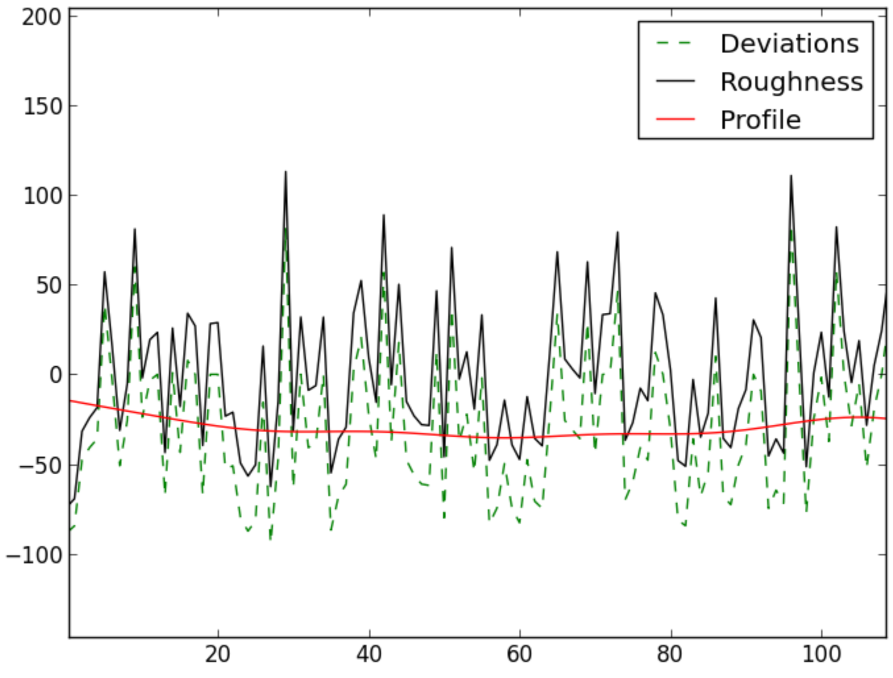
Surface Profile Reconstruction

Roughness Component from Filtration according to ISO16610-21

- Limit wavelength λ_c=2,5 mm





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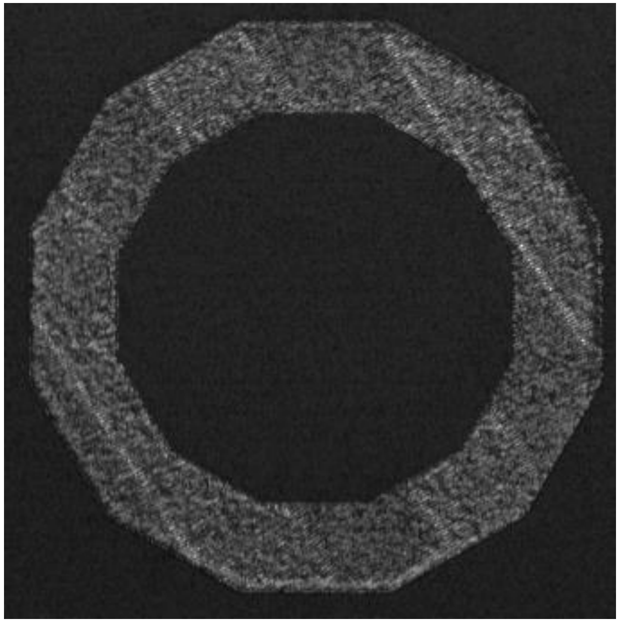
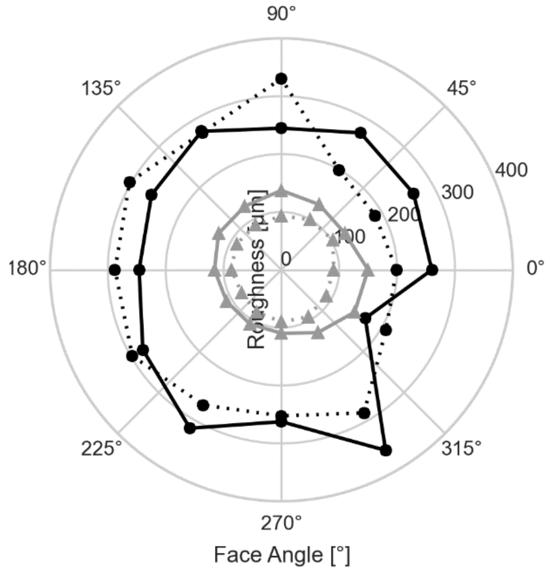
Surface Roughness Measurement

Visualization

- Determine R_z from reconstructed surface profiles (ISO16610-21)
- Average three values of R_z for each face





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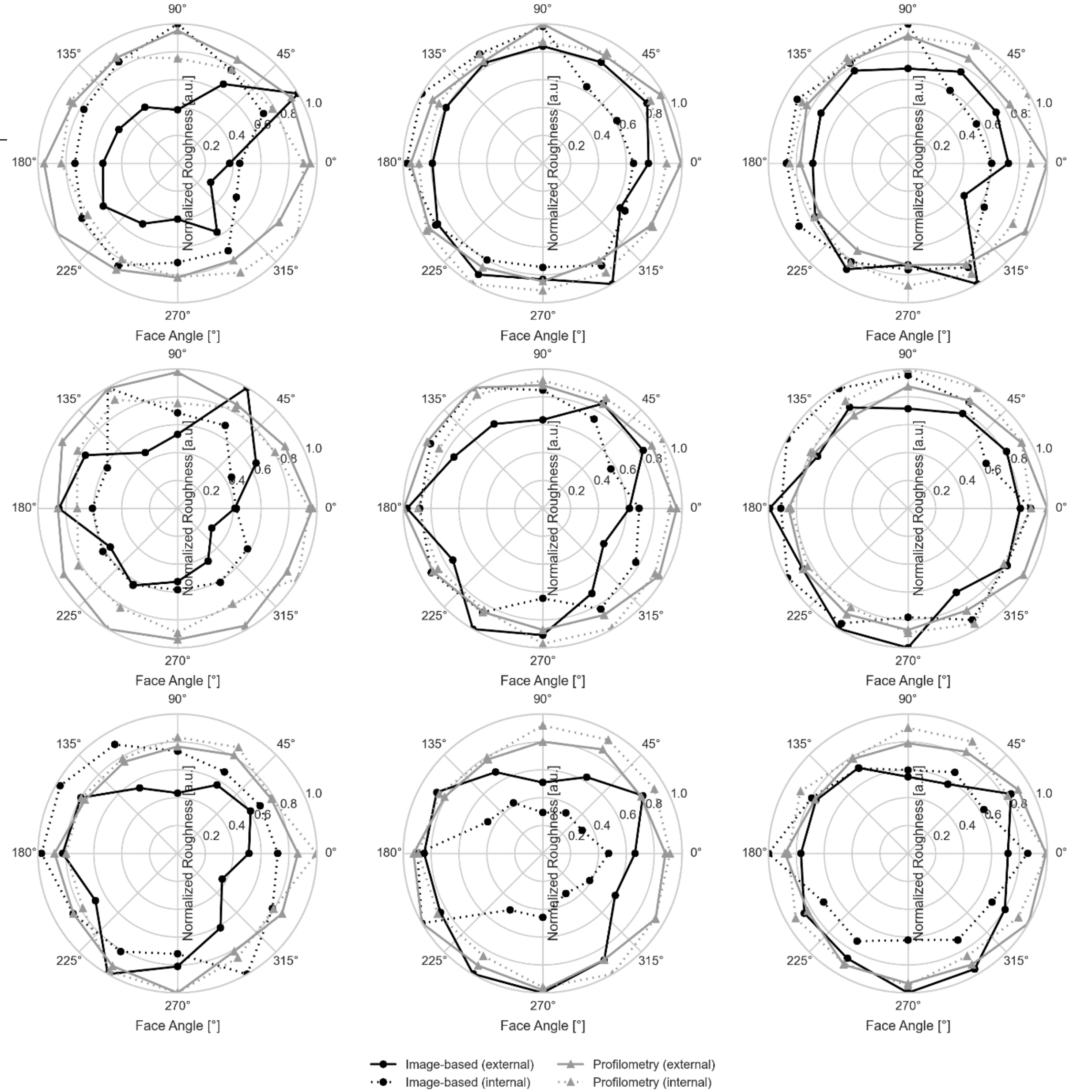
Results

Compare to profilometer measurements (gray)

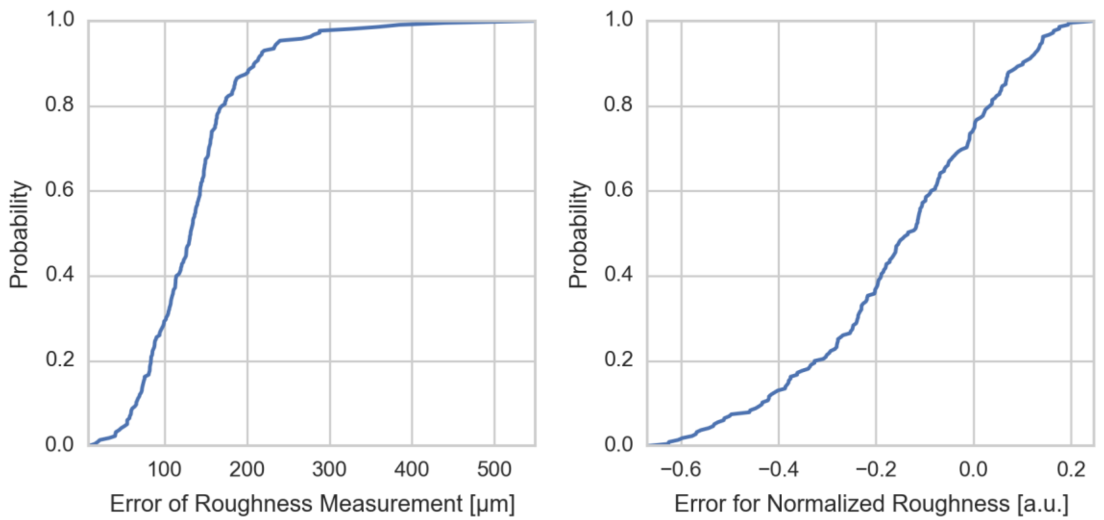
- Normalized values for analysis of correlation
- Deviations are not captured correctly

No consistent correlation



Results

- Comparison against profilometer measurements
  - Absolute error [µm]
  - Error between normalized measurements



Median: 131.3 µm Median: -0.135

- Absolute error is very high (reference value range: 70…160 µm)
- Most normalized roughness values are too low (some large outliers)

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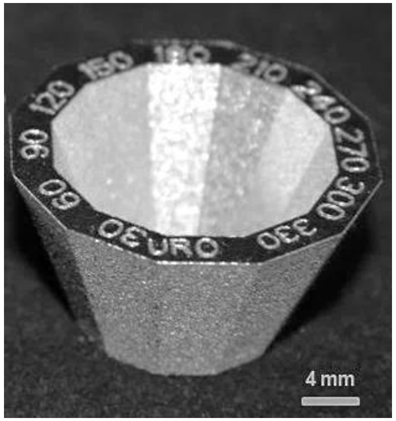
Discussion



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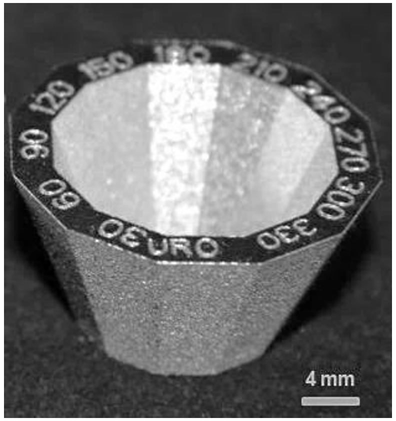
- Image resolution (20…30 µm/px) may be too low to capture roughness deviations (20…50 µm)



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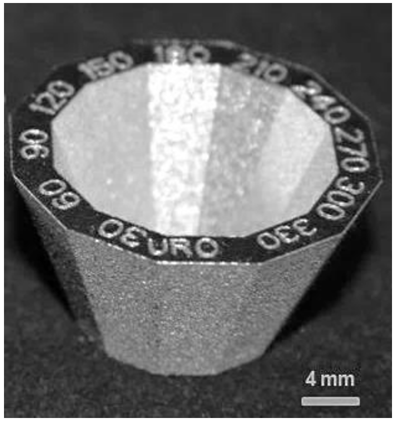

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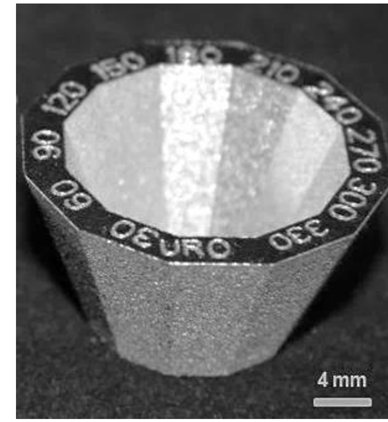

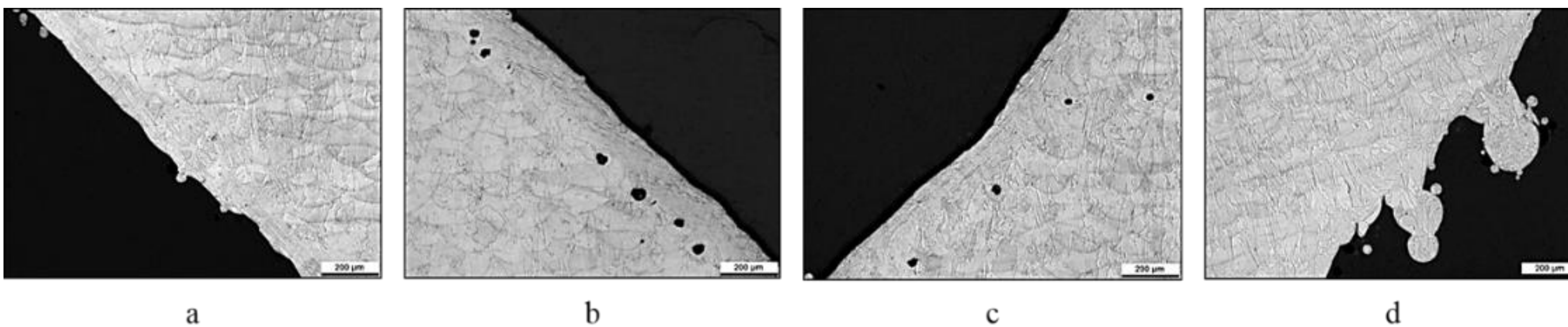

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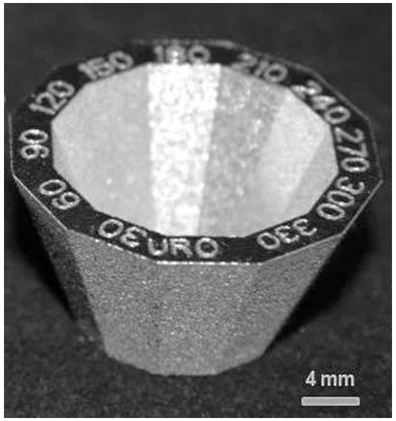

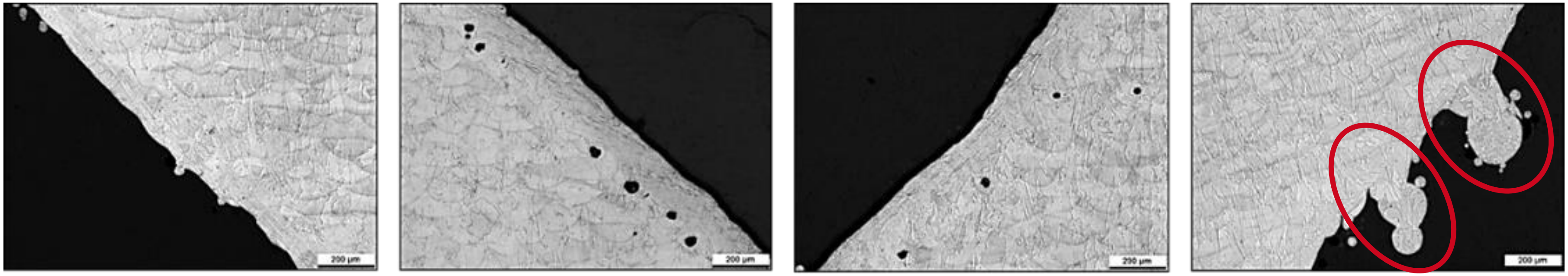

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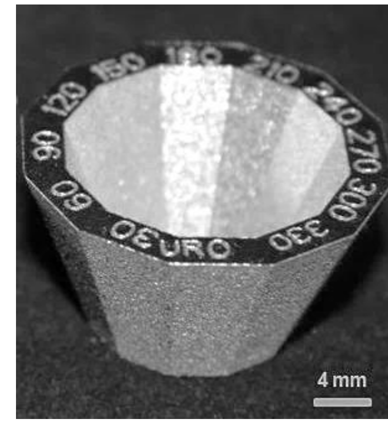

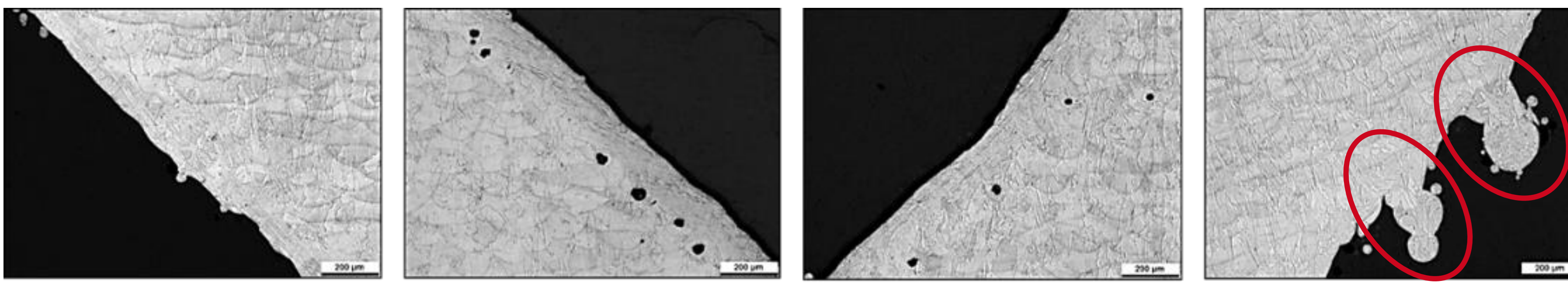

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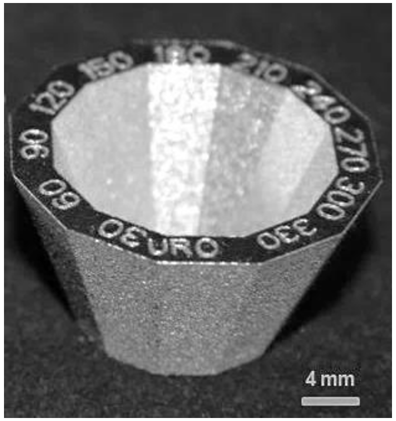
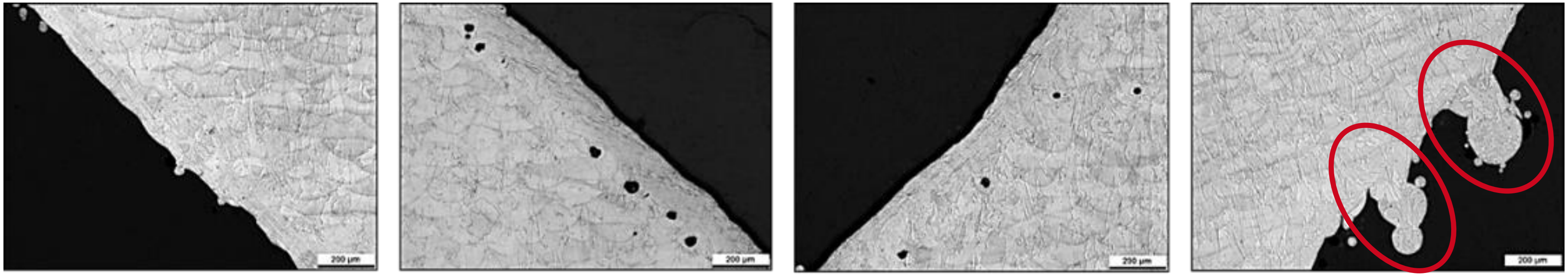
- Accuracy of segmentation: median error 27.7 µm
- Melt extensions below current layer are possible cause of roughness deviations
    - Cannot be captured by layer images





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- Image-based method for in-situ measurement of surface roughness
  - Replicates physical measurement method
  - Extract surface profiles from contour segmentation
- High measurement errors compared to reference profilometry in experiments
- Not suitable for direct quantitative measurements

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In-Situ Surface Roughness Measurement of Laser Beam Melted Parts – a Feasibility Study of Layer Image Analysis

Joschka zur Jacobsmühlen[1], **Stefan Kleszczynski**[2], Alexander Ladewig[3], Gerd Witt[2] and Dorit Merhof[1]

[1]RWTH Aachen University
[2]University of Duisburg-Essen
[3]MTU Aero Engines AG

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