First steps to automation of visual inspection

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Motivation & background

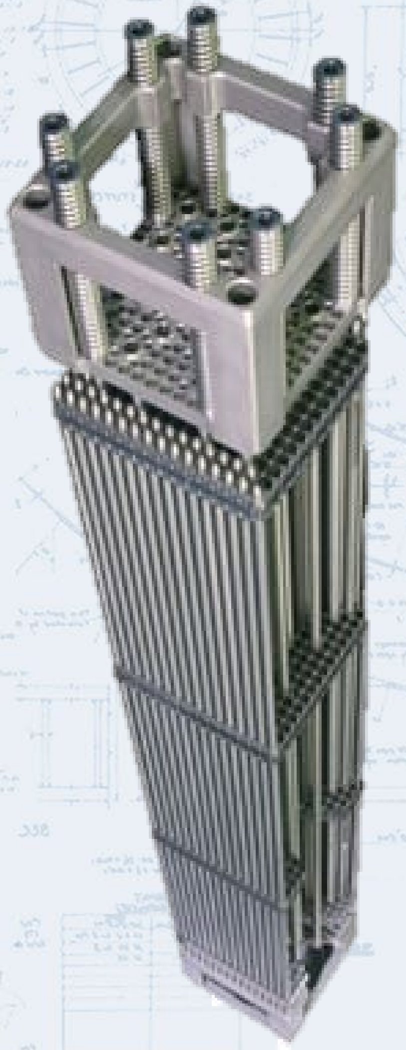
FA length ~ **4 meters**

Features of interest ~ **few milimeters**

Scan length ~ **ten minutes**

Image processing may help with:

- Visualization
- Human readability
- Automation of routine tasks
- Detection of unusual



www.kernbrennstoff.de

What is controlled?

- Rod geometry
- Rod surface
- Fuel geometry
- Whatever unusual

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Student involvement

- 2018/19 – Jaroslav Knotek – diploma thesis
- 2019/20 – Jan Palášek – diploma thesis
- 2020/21 – Adam Harmanec – diploma thesis
- 2021-2023 – Tomáš Karella – doctoral activities – ongoing utility model, ongoing patent
- 2021 - Jaroslav Knotek – ongoing PhD. thesis
- 2021/22 – Ondřej Novák – diploma thesis
- 2024 – Vojtěch Bláha – ongoing diploma thesis
- 2024 – Daniil Sultanov – ongoing bachelor thesis

Data from visual inspection

camera screen content

Bigger context is necessary

- Spatial
  - 20 cm above or below
  - Interaction of FAs
- Temporal
  - changes from the previous inspection
- Technical
  - Comparison of same fuel designs

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One Image Overview

- Conversion from time domain into spatial
  - Preserving details
  - 200MB-> 20MB
- Pros
  - Faster zoomable overview
  - Effective comparison
  - Easy reference (annotated images, GUI)

One Image Overview

- Faster and more effective inspection outcomes
- Full context
- Color encoding of surface anomalies
- Geometry from metadata
  - Frame rotation -> fuel bow
  - Position of grids -> carcass growth
- Unlock for other measurements
  - Rod bow measurements
  - Rod growth measurement
  - Statistics above surface corrosion

One Image Overview … a naïve construction

- Simple stitching
  - A cut from each n-th frame
- Issues
  - Camera / FA vibrations during movement
  - Variations in Camera / FA movement speed
  - No valuable metadata
  - Impossible to do photogrammetry

One Image Overview
the way to automation

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Upgrade of the scanning process

- Constant speed of the camera/fuel during recording
- One setup of lights for the whole outage
- File naming conventions and folder structure

Data in the same format!

Replicability!

Reproducibility!

OIO construction

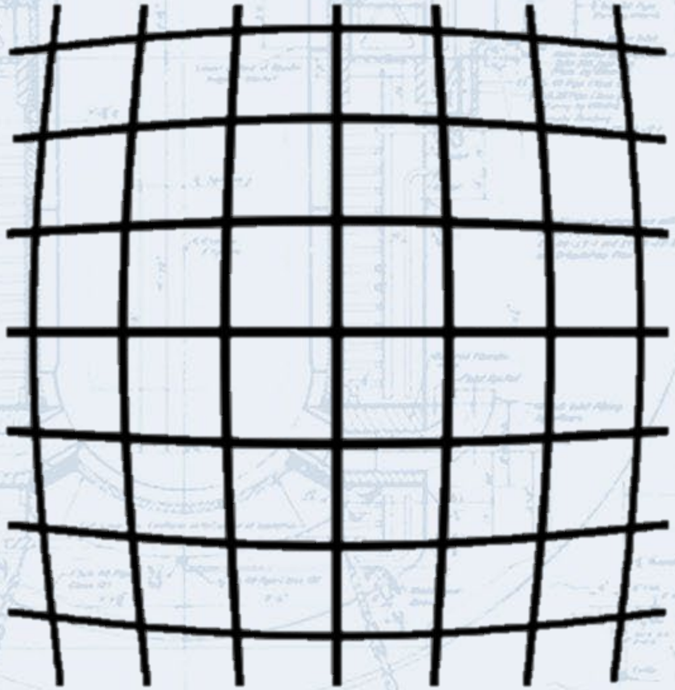
1. Compute frame position in OIO – “camera speed”
2. Compensate camera tilt and vibrations
3. Rectify lens distortion
4. Register frames
5. Merge images

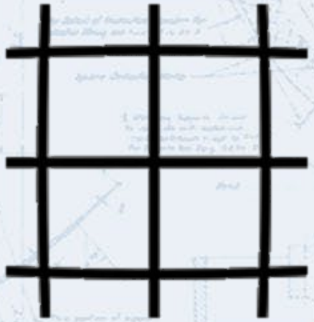
OIO - Camera speed estimation

$$\Delta = \max_{\Delta \in \langle a,b \rangle} \sum_{x} \sum_{y} F_i(x, y + \Delta) * F_{i+k}(x, h + y)\ px$$

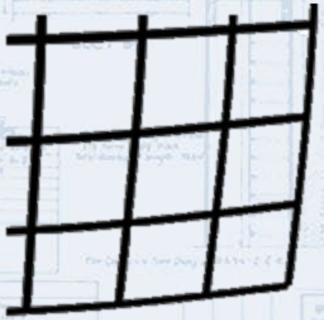
$$v = \frac{h + \Delta}{\frac{k}{fps}}\ px/s$$

OIO – lens distortion handling

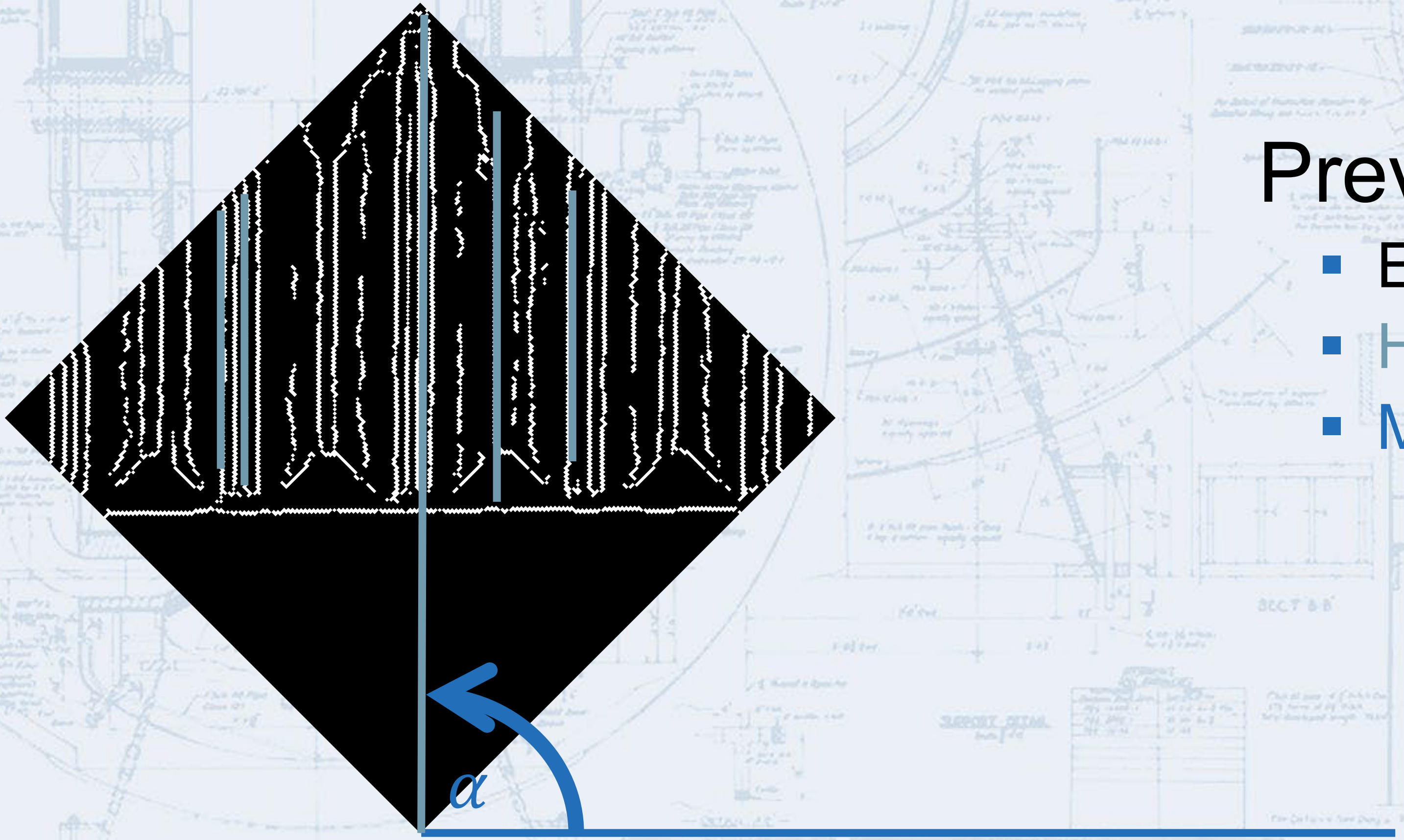




vs.



Frame rotation estimation



Prevailing direction of rods

- Edges
- Hough lines
- Median angle

Frame rotation – edge detector - blur

$$B_{ij} = \frac{1}{2\pi\sigma^2} e^{\frac{(i-k+1)^2+(j-k+1)^2}{2\sigma^2}}$$

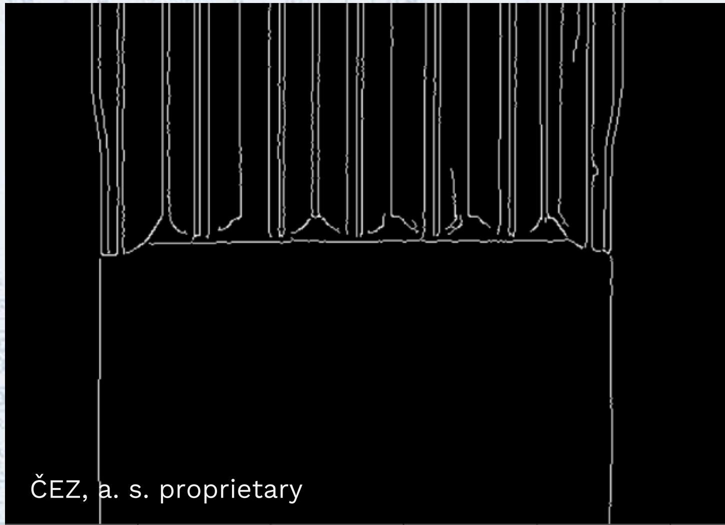
$$1 \leq i,j \leq (2k+1)$$

Frame rotation – edge detector

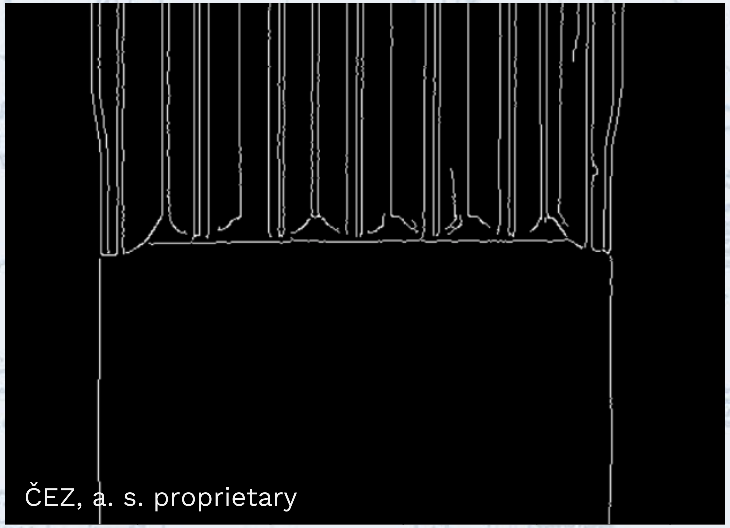
$$e(x, y) = \sum_{dx=0}^{2} \sum_{dy=0}^{2} f(dx, dy) g(x + gx, y + dy)$$

1	**0**	**-1**
2	0	-2
1	0	-1

1	**2**	**1**
0	0	0
-1	-2	-1



Frame rotation – Hough lines



$$[x_1, y_1], [x_2, y_2]$$

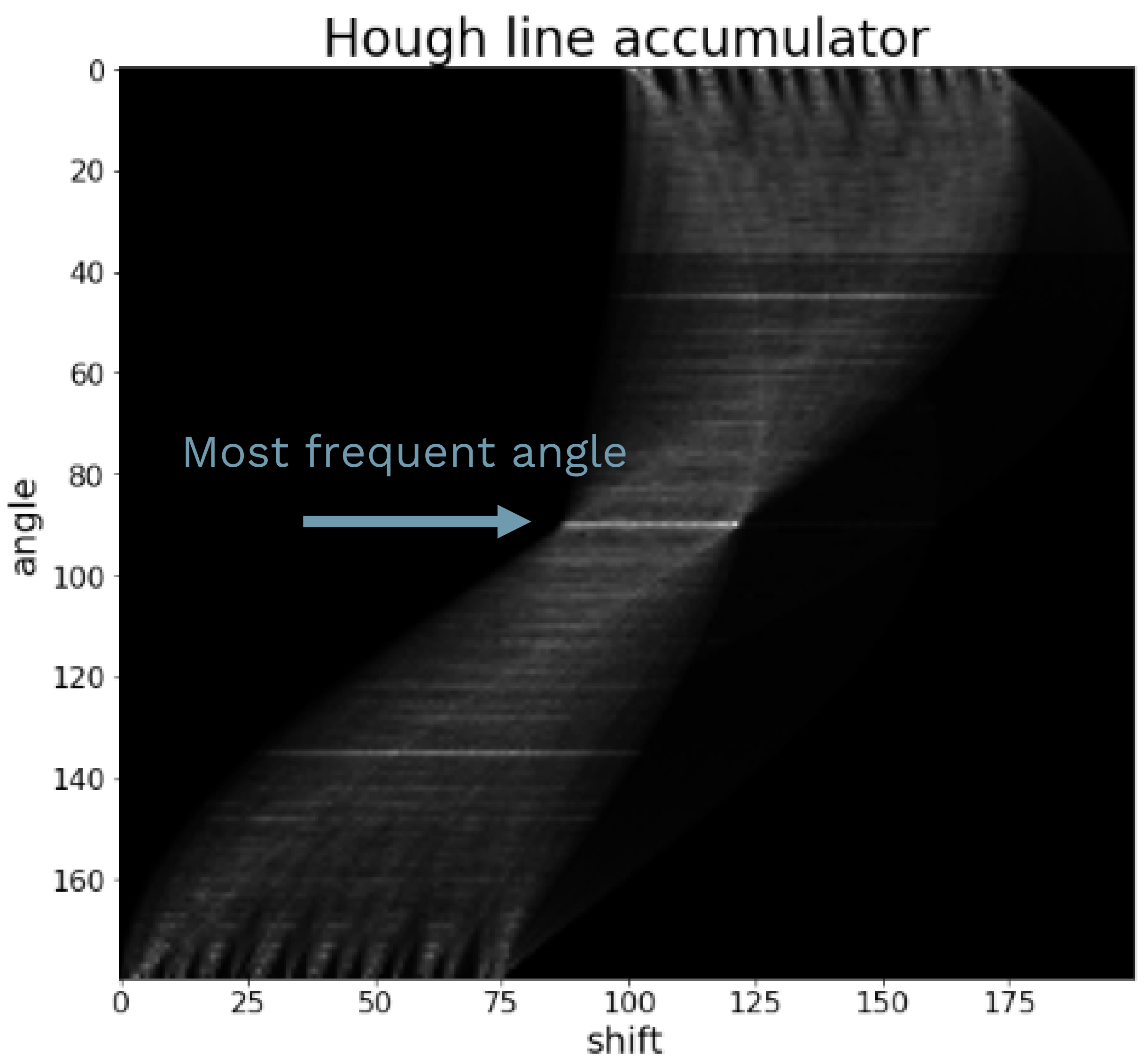
$$\boldsymbol{b} = \frac{x_1 y_2 - x_2 y_1}{x_2 - x_1},$$

$$a = \frac{y_1 - b}{x_1},$$

$$\boldsymbol{\alpha} = \operatorname{tg} a$$

For every point pair +1 in accumulator

Most frequent angle



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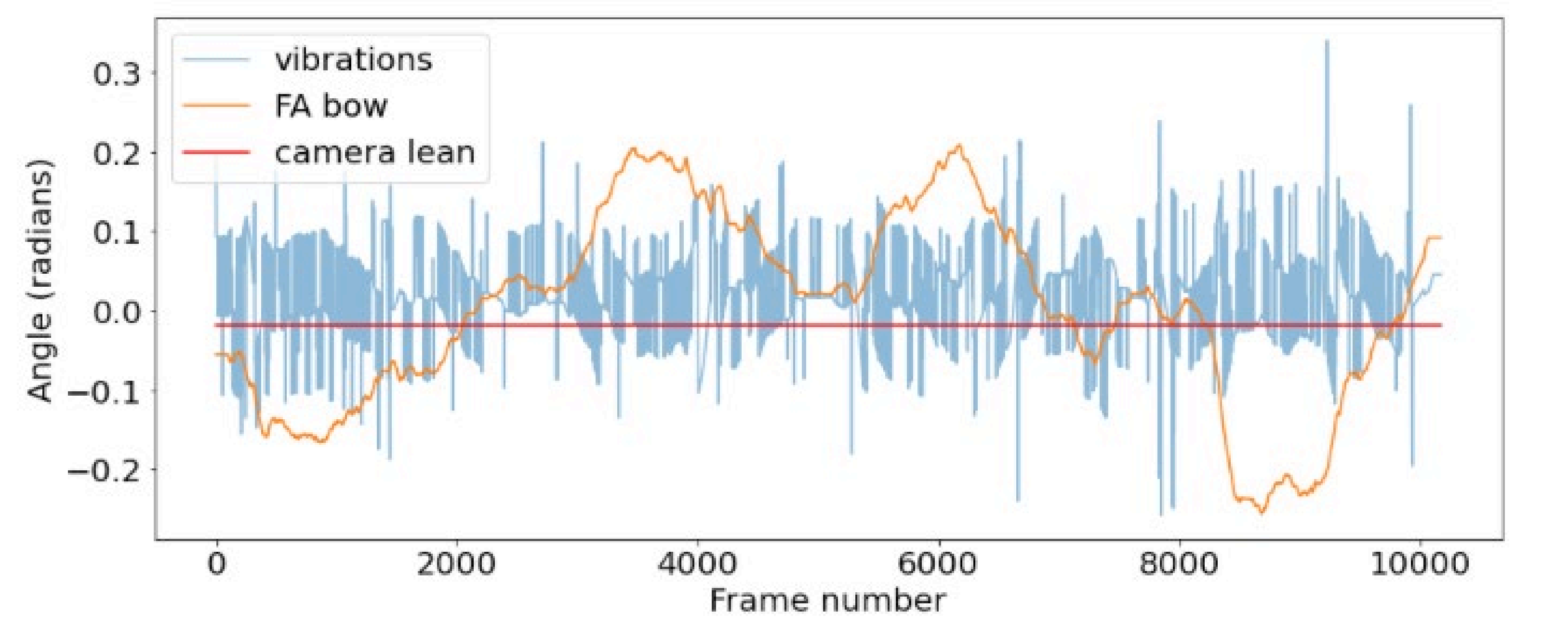
Frame rotation - decomposition

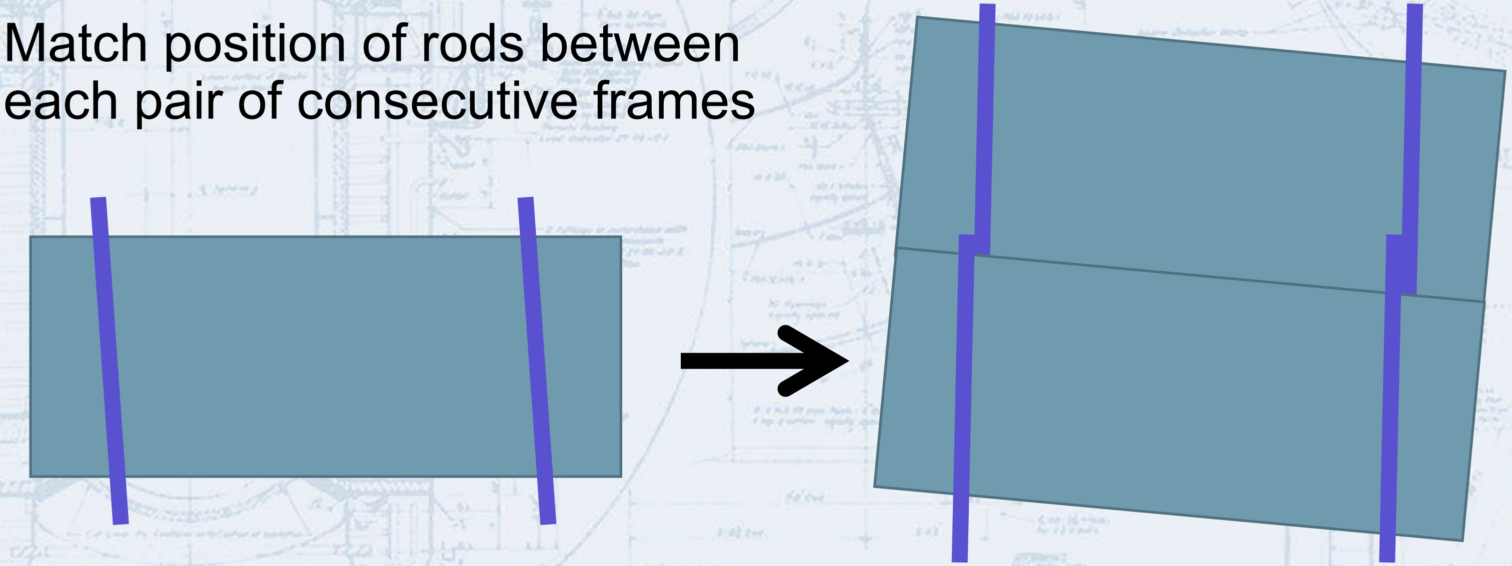
Computed values split to:

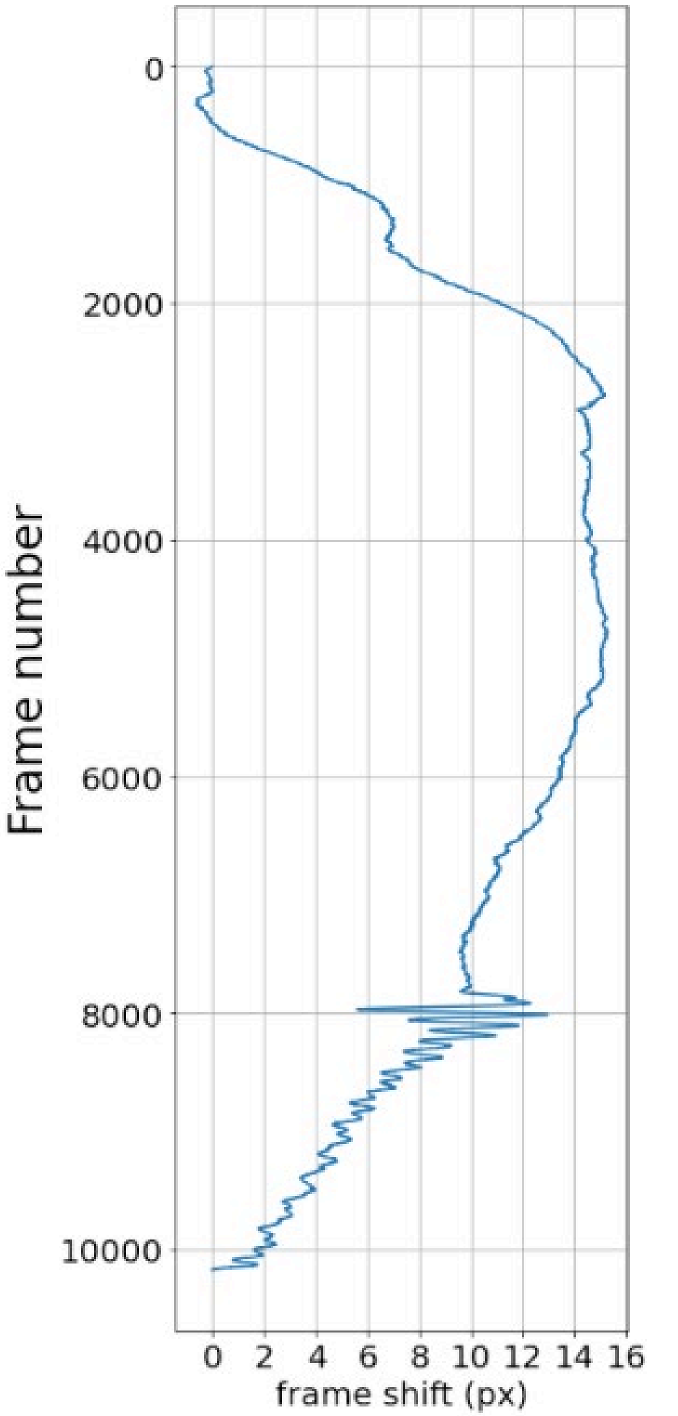
- Camera lean – the mean value of computed angles – **we want to remove this**
- Fuel assembly deformation - low frequency angle changes – **we want to keep this in image**
- High frequency vibrations – camera / FA movement – **we want to remove this**



X-shift compensation

Match position of rods between each pair of consecutive frames





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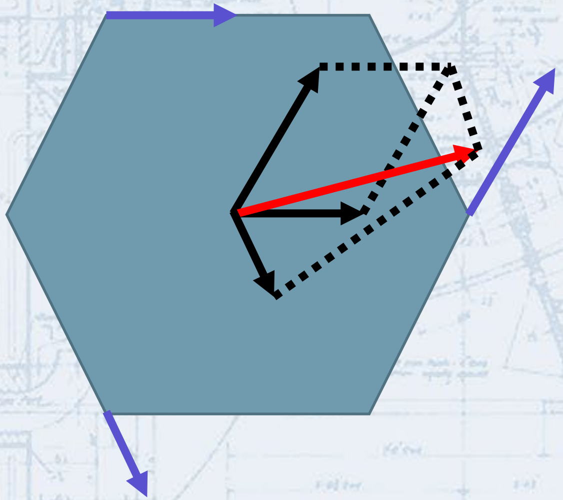
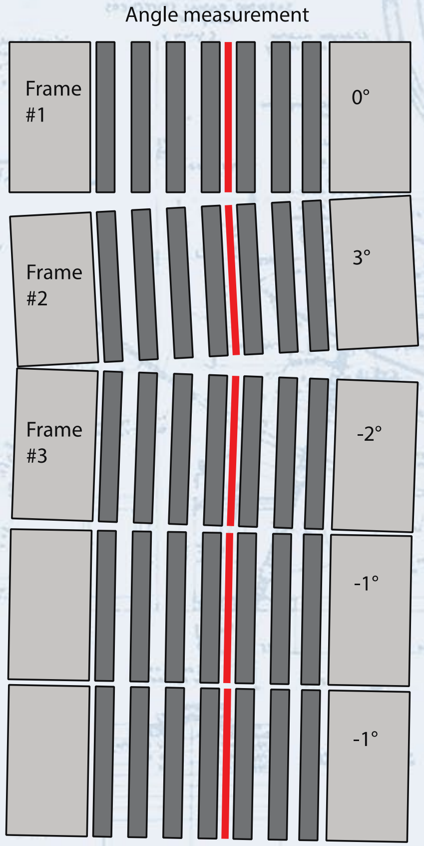
One image overview – side products

Directions of rods in each frame & X-shift compensation ➔ FA bow estimate



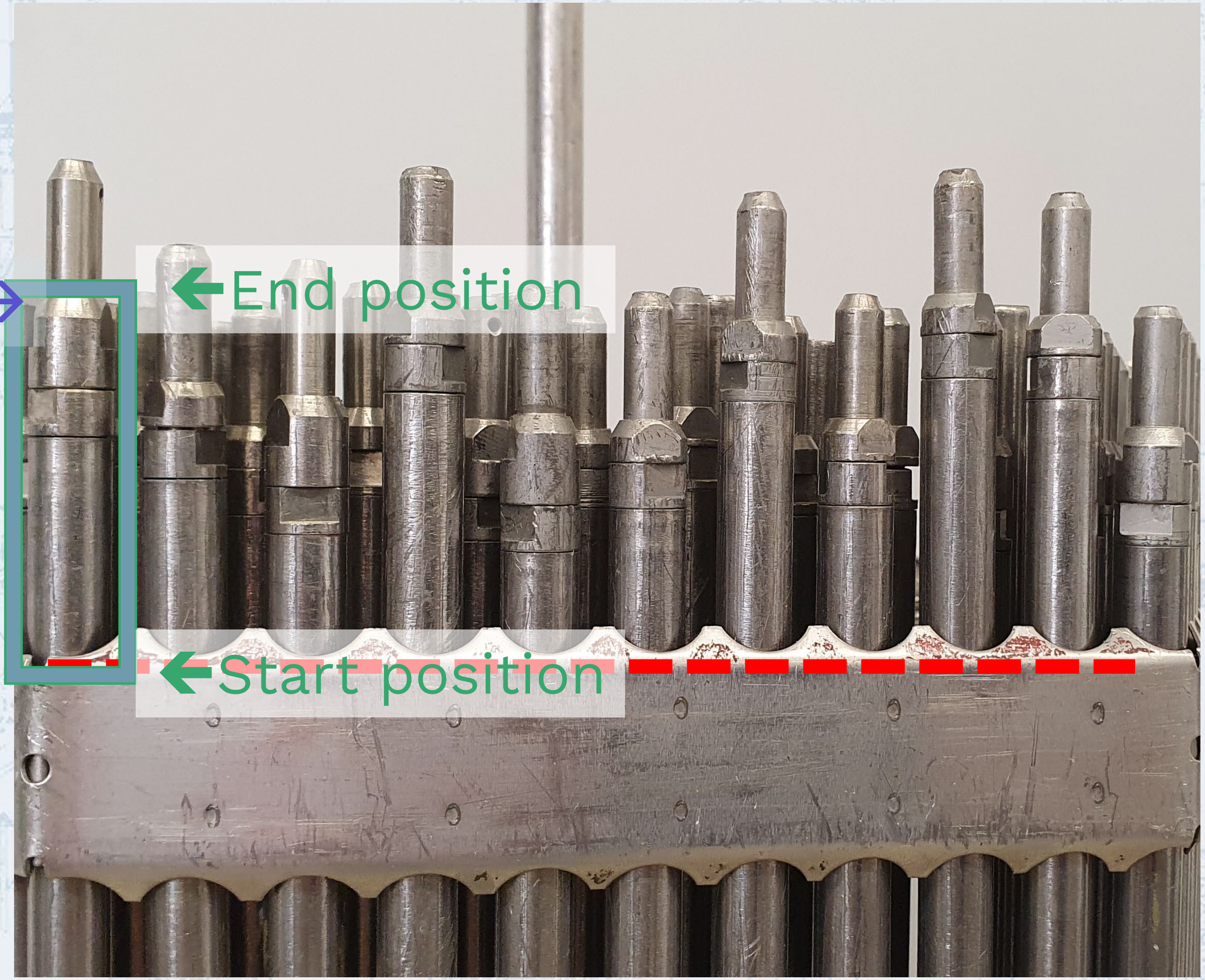
!!! Applicable only when FA is fixed



Digital image processing and geometry measurements

Relative Rod Growth

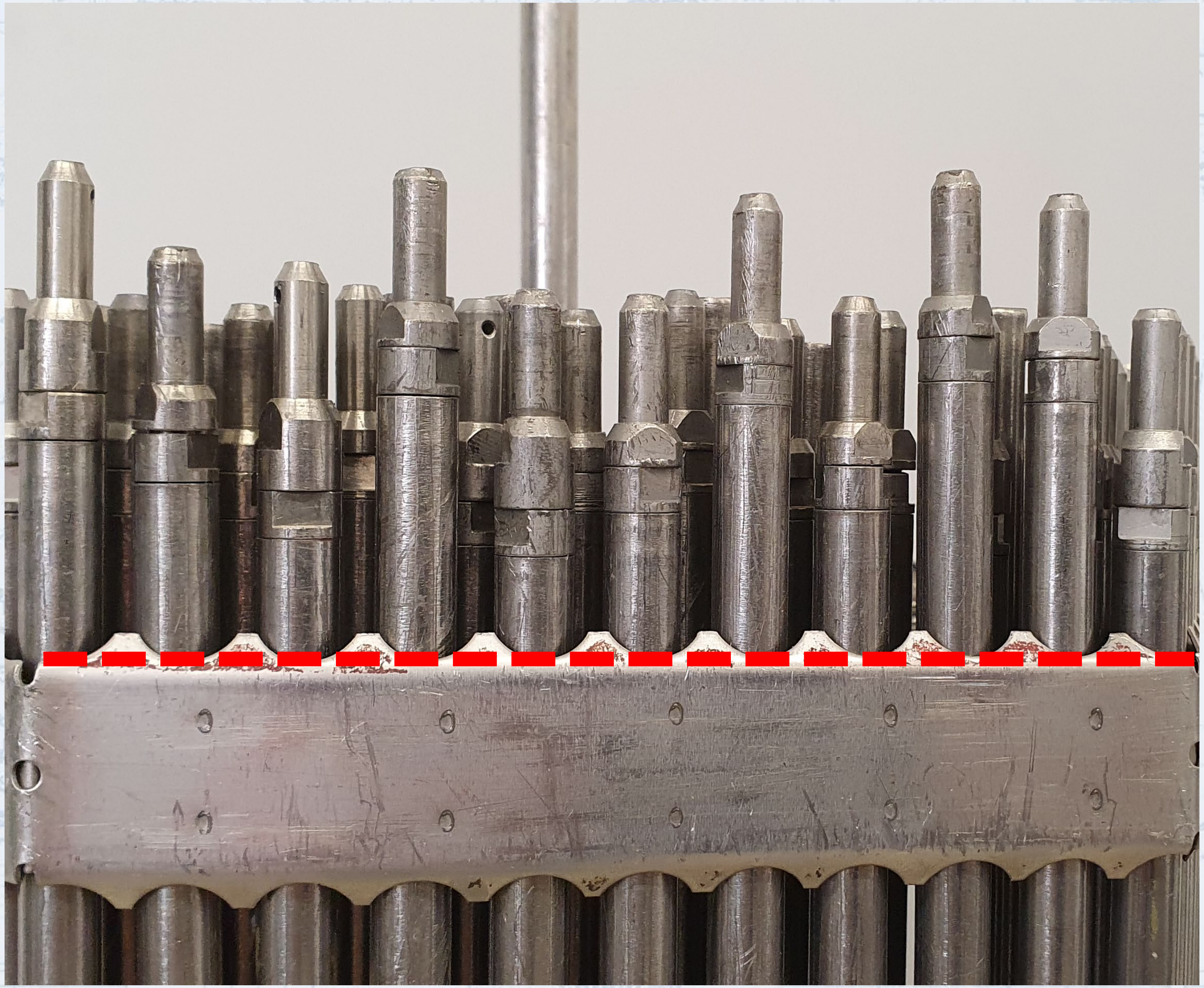
Correct position →



Relative Rod Growth spacer grid detection

The ligthest row in area of the grid

$$\boldsymbol{Y} = \underset{y \in \{y_1, \ldots, y_2\}}{\operatorname{argmax}} \sum_{x=0}^{width} I(x, y)$$

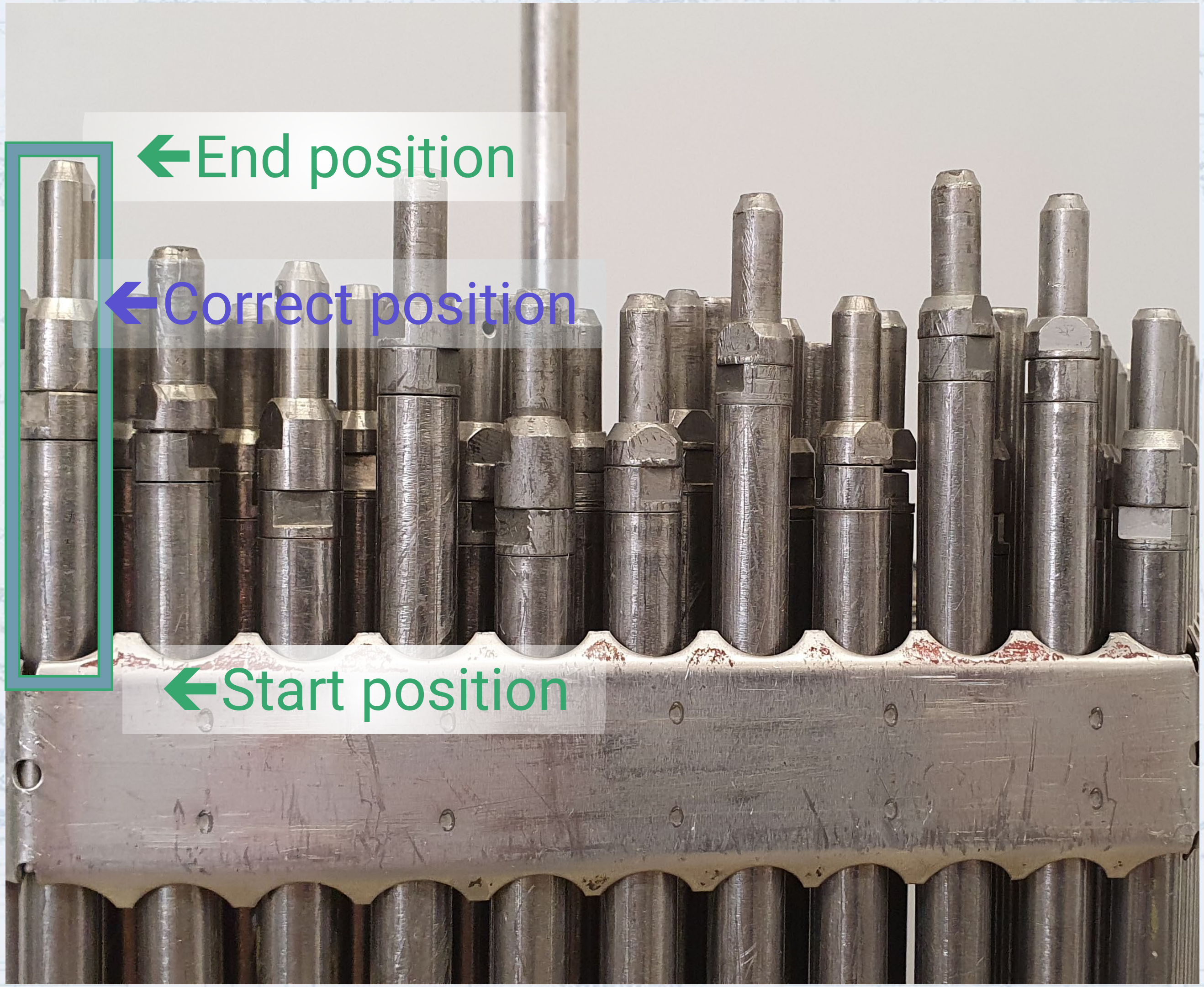


Relative Rod Growth weld position

A line with the highest sum intensity:

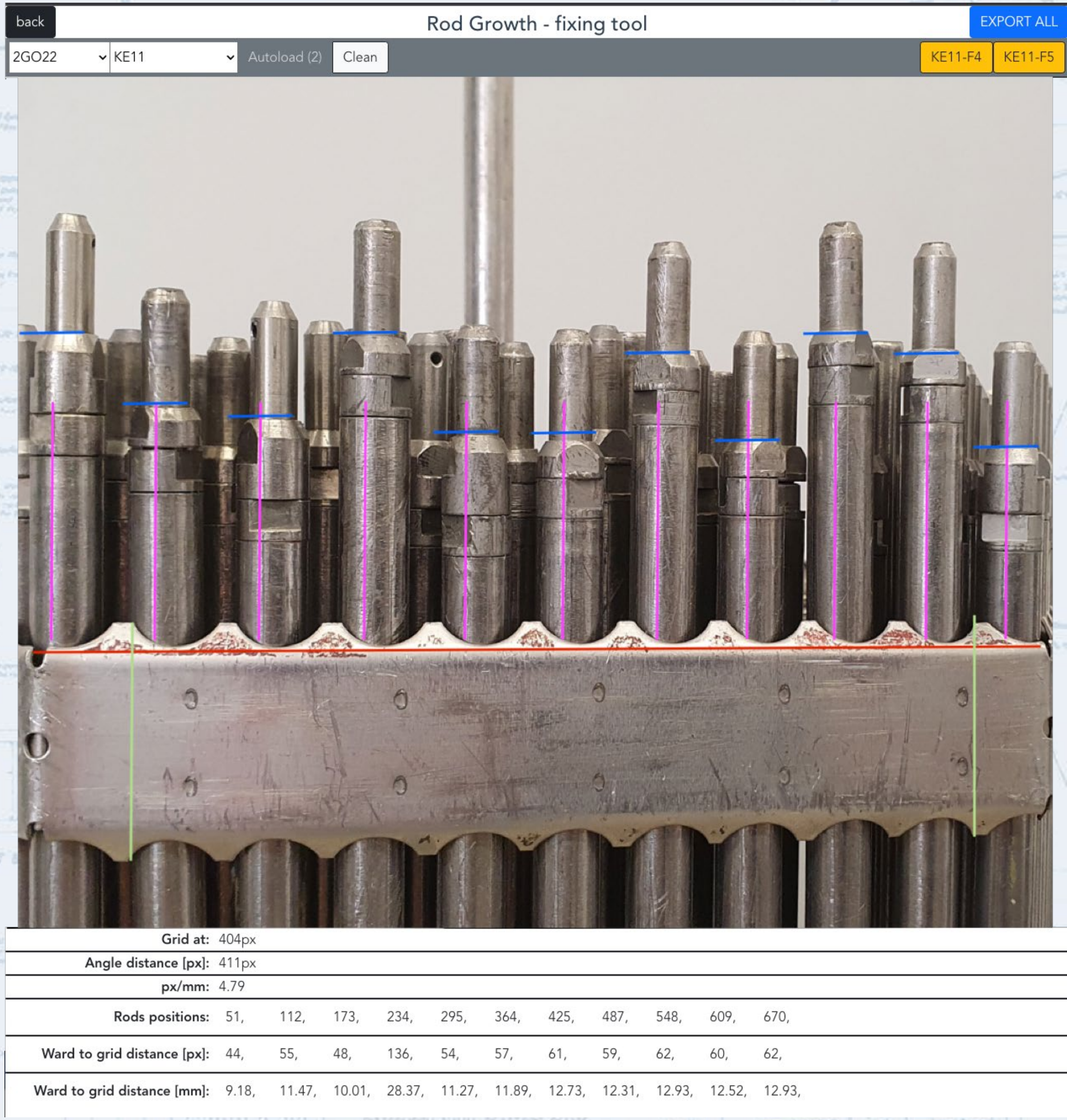
$$h = \max_{y} \sum_{x=0}^{rod\_width} I(x,y)$$

New approach based on convolutional neural network in progress...



Relative Rod Growth summary

- 87% of images correctly processed
- >> 90% of overall rods correctly detected
- → GUI for manual correction



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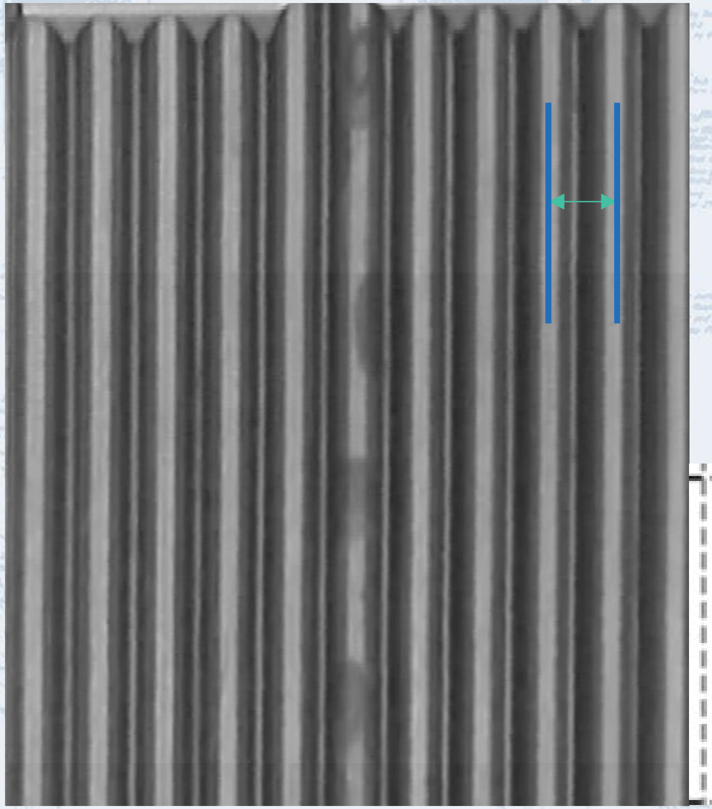
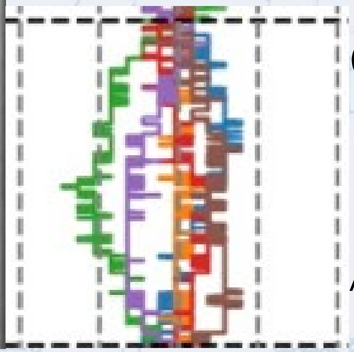
Rod bow measurement

… a DIP approach





Rod center to rod center measurements

- Track rod center positions
- Measure distance between rods
- Develop UI for fixing the errors

Calibration

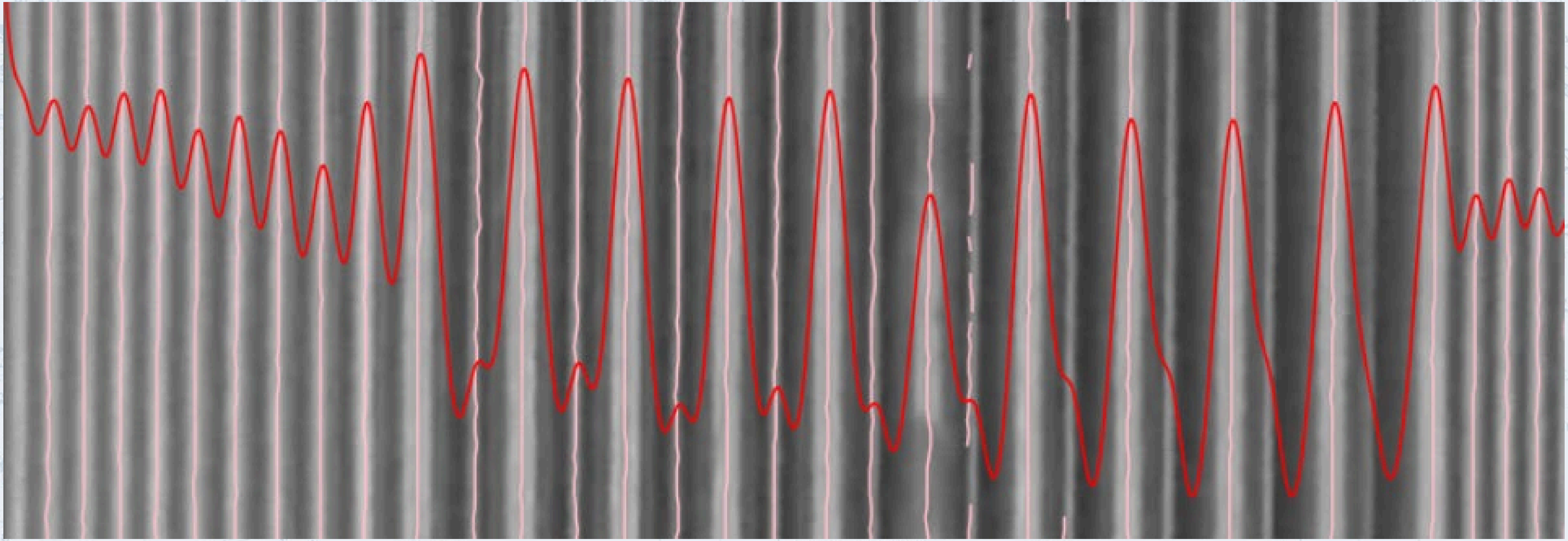
- Average of all measured distances = default distance

Alerting

- Customized e.g., less than 1mm

Rod Bow

The rod center detection



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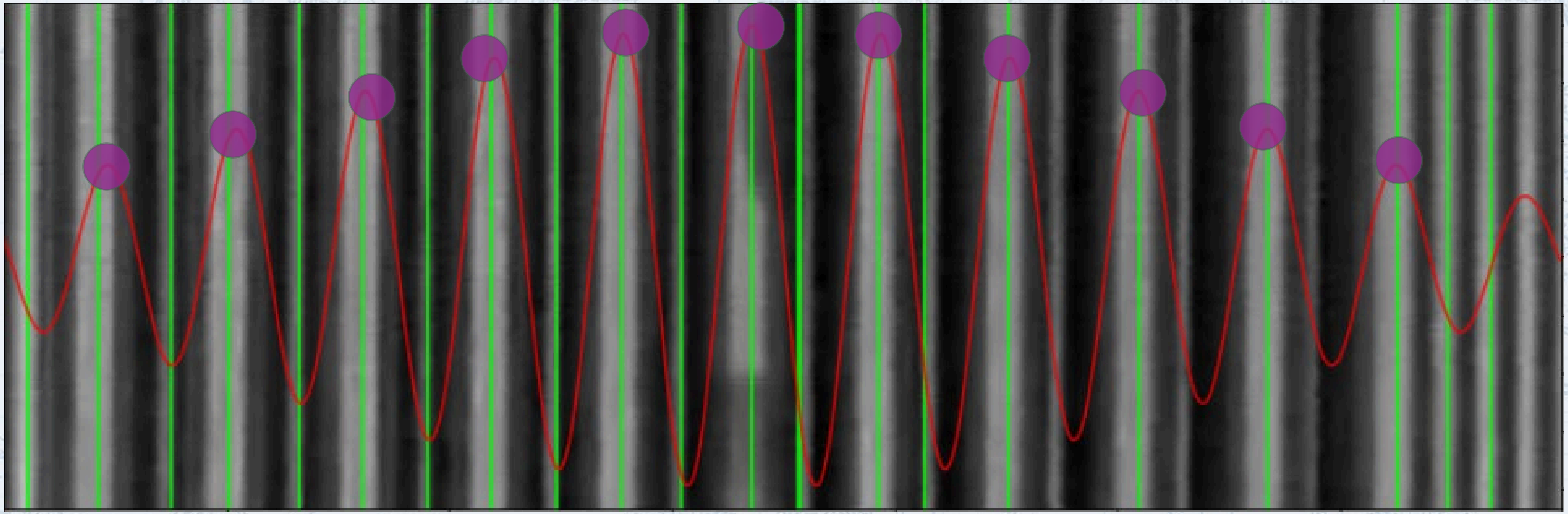
Rod Bow

The rod center detection



$$\underset{S,\bar{x},\sigma,d}{\operatorname{argmax}} \sum_{s}^{S} \cos(ds(x))\, \mathrm{pdf}_{\sigma}\big(s(x)\big)$$

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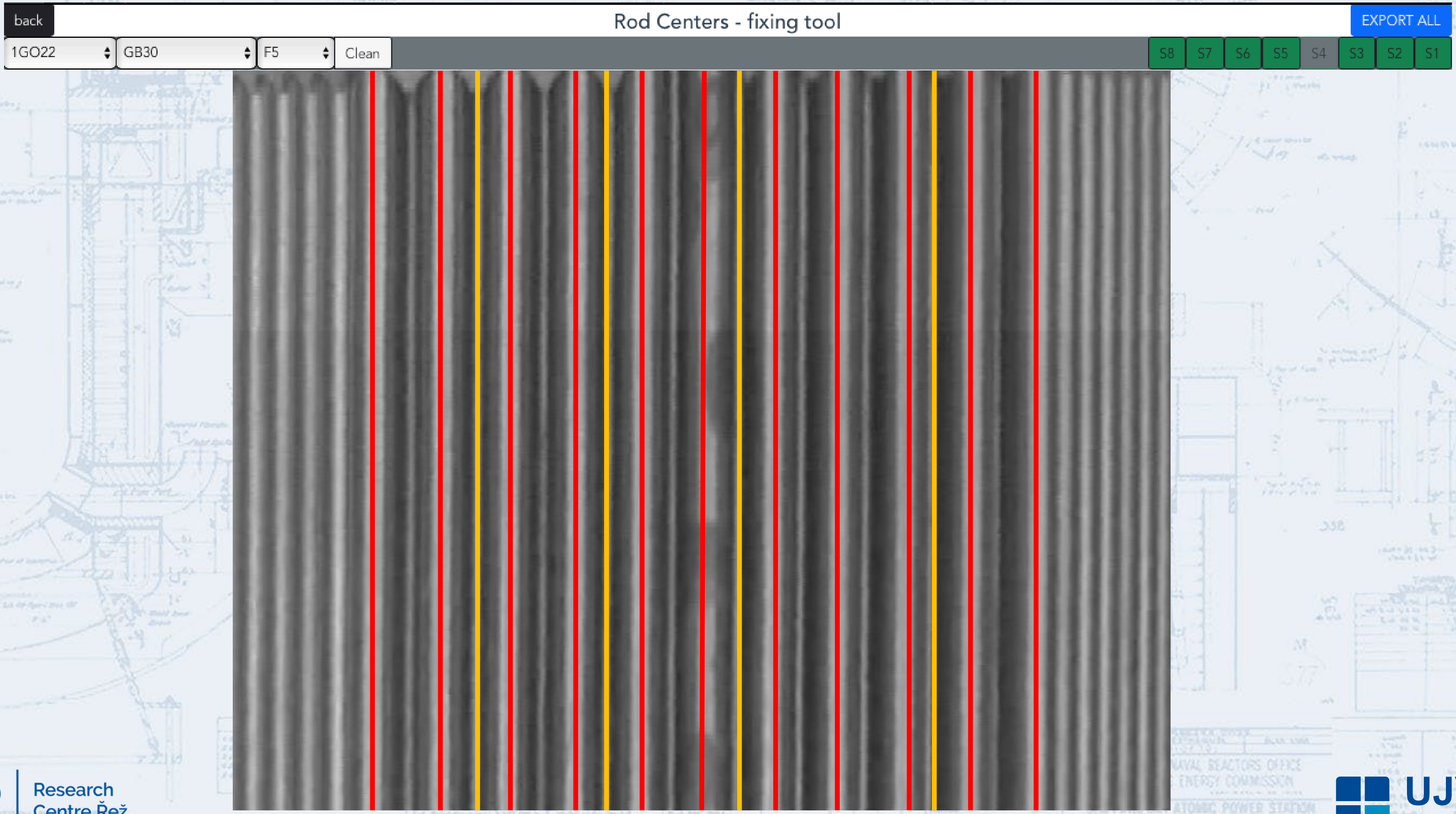
Rod bow – GUI for fixing errors



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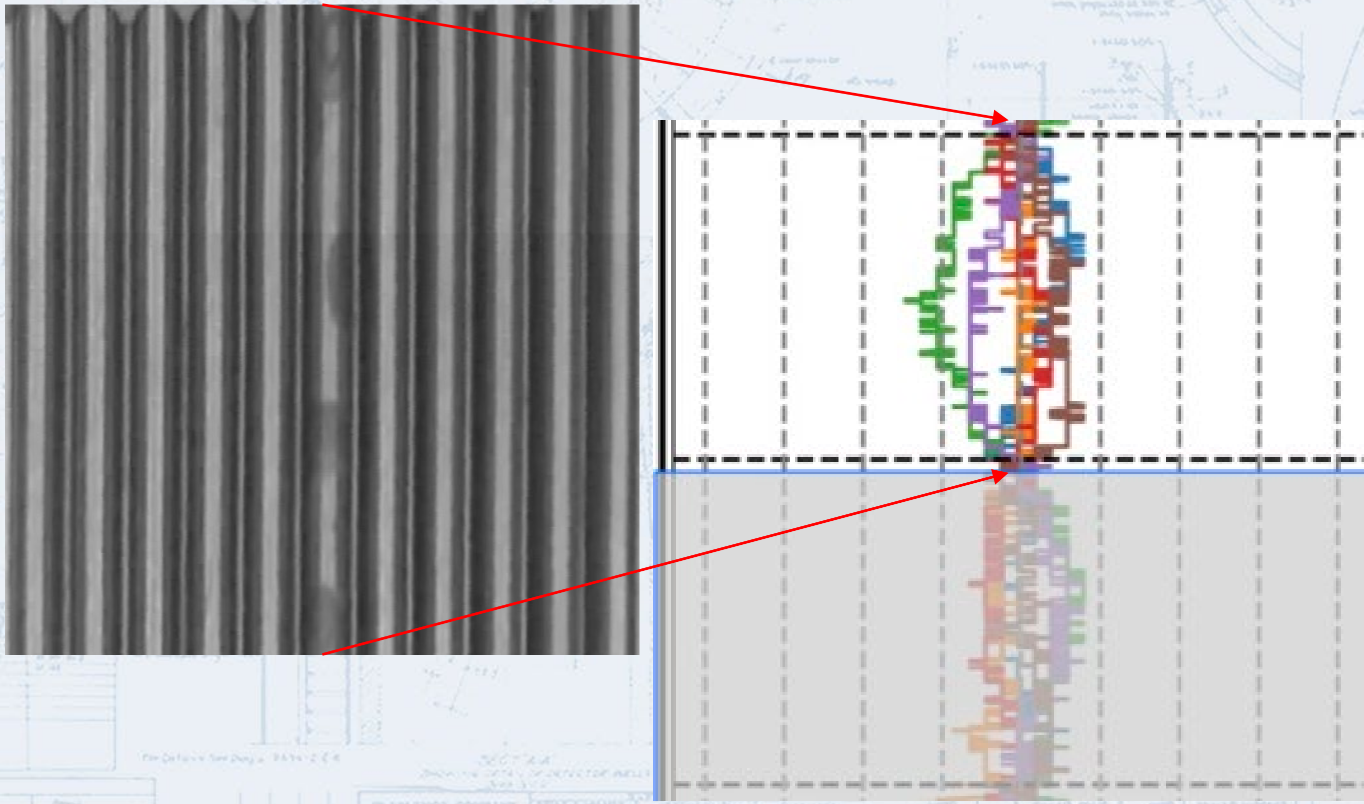
Rod Bow
our achievements

- Precision >90%
- Recall >99%
- Reports according to customer requests



Spacer Grid segmentation
Motivation

- Unlock of automation for grid / rod processing
- Filtration of SG images by shape variance

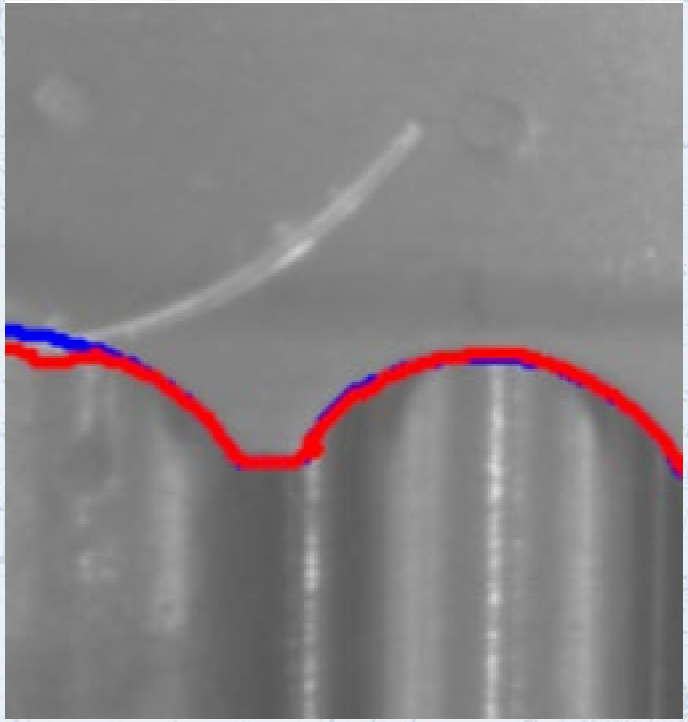
SG segmentation

Focus on the shape of the boundary

1. Mechanism of boundary detection
2. Definition of a normal shape
3. Computation of boundary divergence

SG segmentation

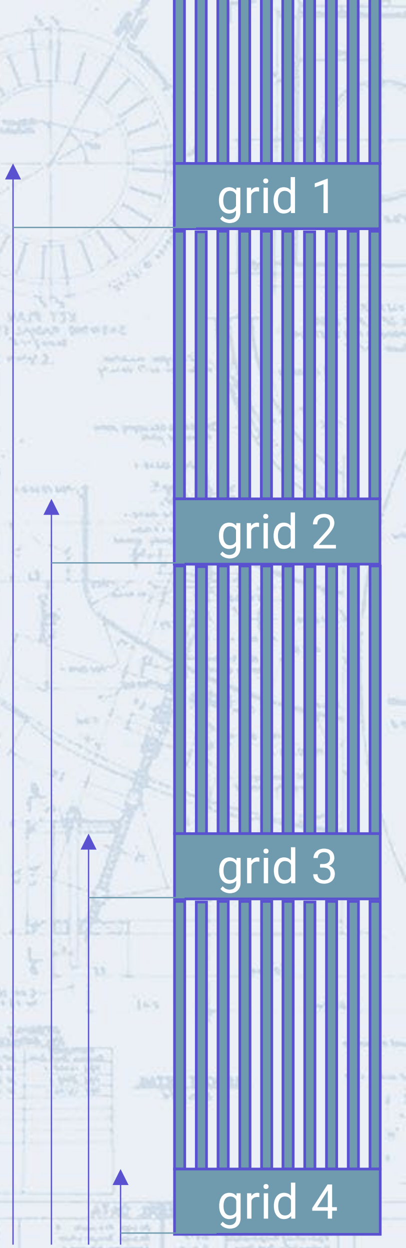
- ResU-Net
- + Manual labeling
- Own error metrics (line distance)



Skeleton measurement

Based on camera speed

campaign	fuel	side	grid 1	grid 2	grid 3	grid 4	grid 5	grid 6	...
2023	XY-01	face 1	4000	3600	3200	2800	2400	2000	...
		face 2	4002	...					
		face 3	3999						
		face 4	...						
		average	4000	3592.3	...				
	standard deviation		± 2.6	± 3.2	± 1.5	...			



Changes in a screening procedure

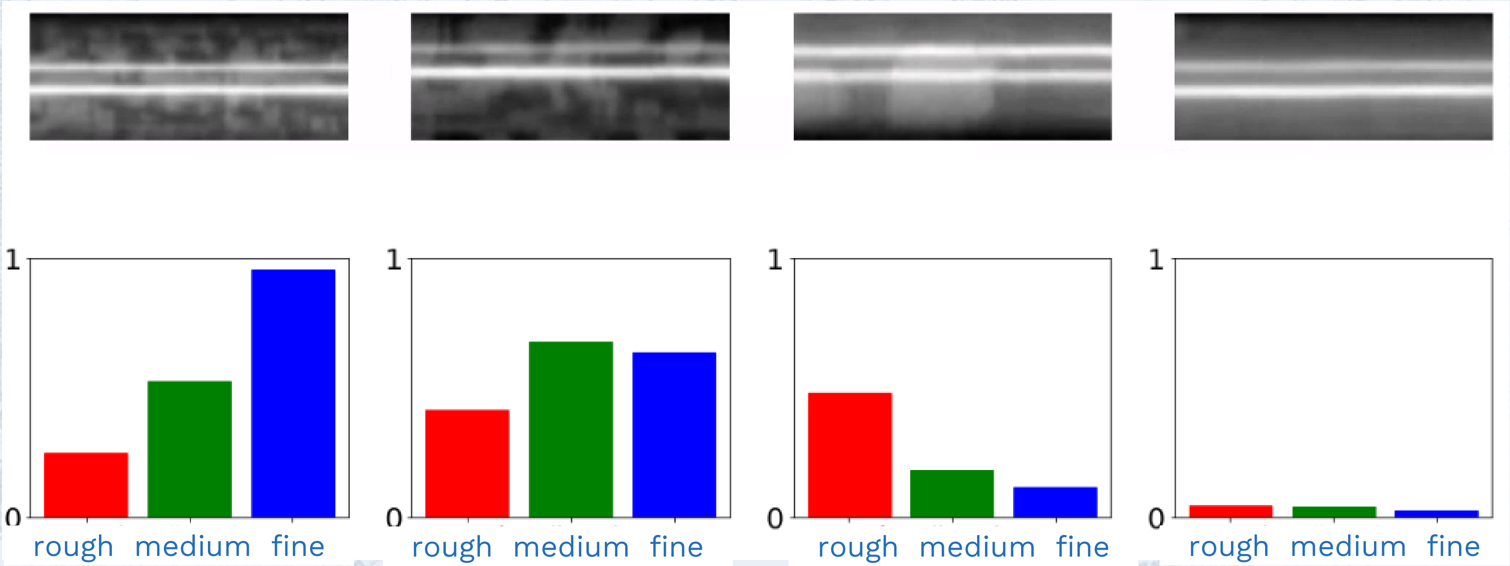
Fixed camera speed
- Recording only when camera speed is stable
- No stopping
- No PTZ
- No changes in the procedure during whole
  PP outage

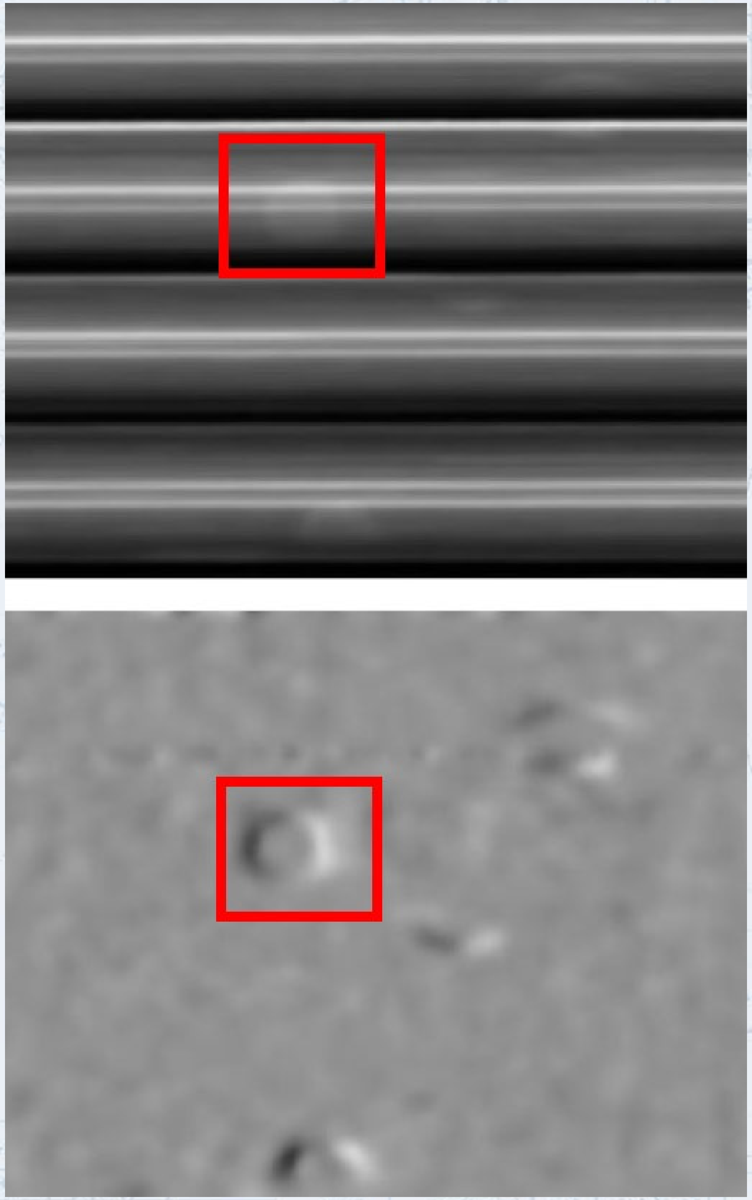
Video sequence beginning/end extension
- Start of recording above FA and end of recording below
- Camera speed must be stable
- Merged pixels must be in center of the frame

Lens setup
- Fixed for whole outage
- Calibration before screening
  - All peripheral rods must be in view during recording

Analytics

Data in unified format enables deeper insight





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DIP incorporation – summary

- Automated processing, reproducibility
  - Normalization of video acquisition process
  - … across power plants
- Unlock for non-biased monitoring

Thank you