Measurement of shape and dimensions of forgings

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AND **INDUSTRIAL DESIGN**

CONTENTS

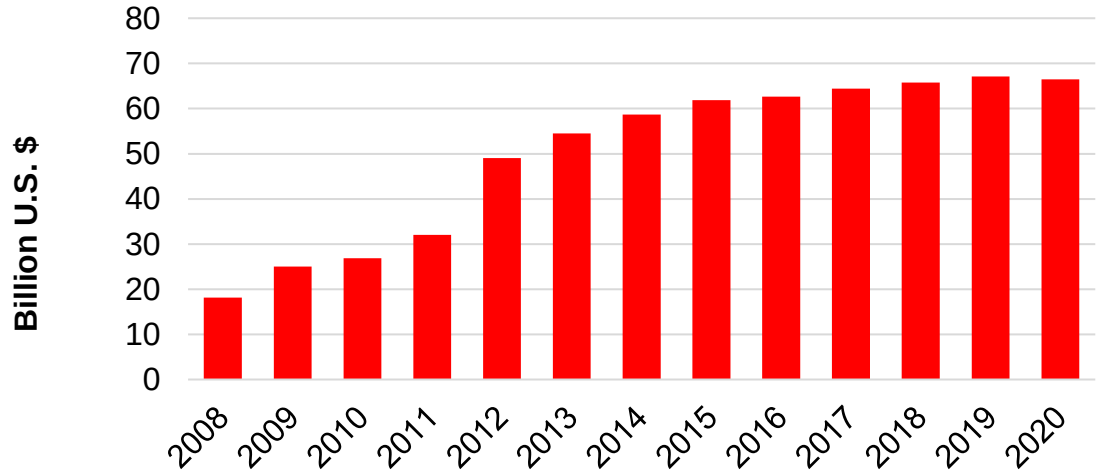
- Introduction
- State of the art
- Aims of the thesis
- **Camera calibration**
- **Edge detection**
- **Accuracy improvement**
- Conclusion

Heavy forging (simufact.com)

INTRODUCTION

HEAVY FORGINGS

- Energy, petrochemical, shipbuilding industry
- Various shafts – basic shapes
- Dimensions in meters, weight in tons
- Forging temperatures 800 – 1250 ºC
- China – 11 million tons (39 % of production)



Revenue of forging manufacture in China (statista.com)

Material for heavy forging

Heavy forging blanks

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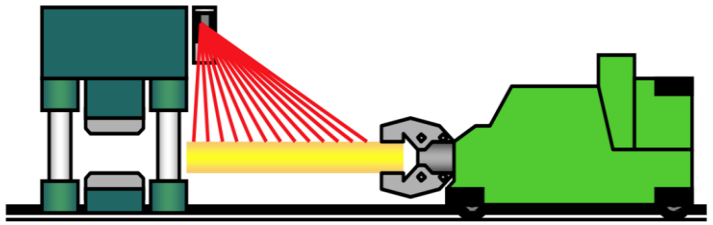
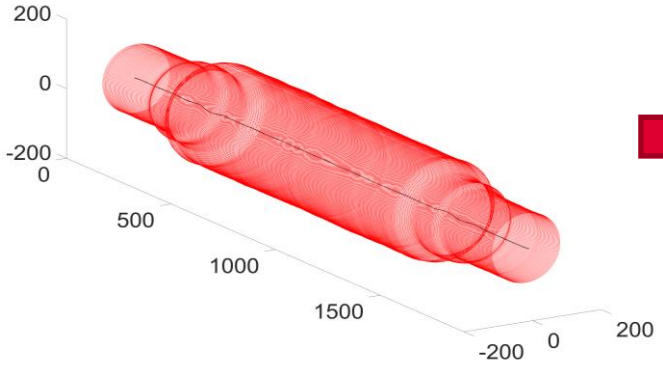
INTRODUCTION

MOTIVATION

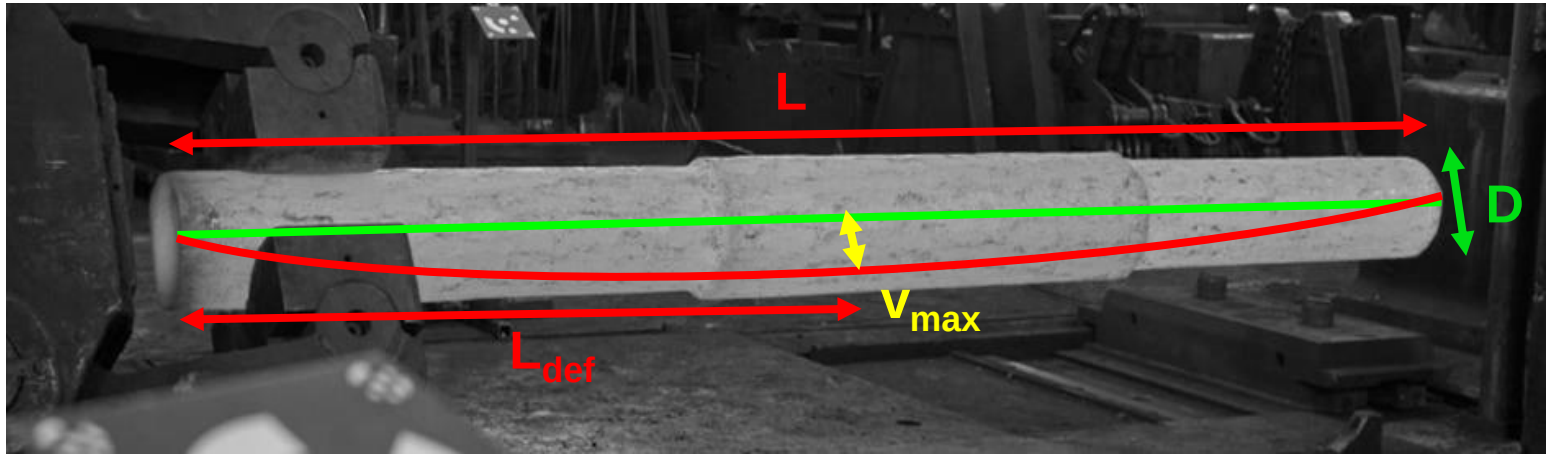
- **Inaccurate manufacturing**
- Machining allowances – 20 % of material
- Feedback - straightness, diam.



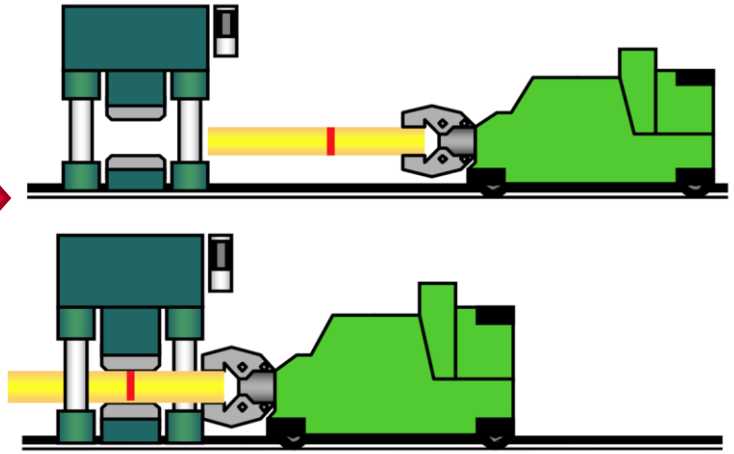
Forging measurement and shape correction (Minteq, ed.)



Forging geometry (Hurník et al.,2022)



Sample forging measurement result



Forging measurement and shape correction (Minteq, ed.)

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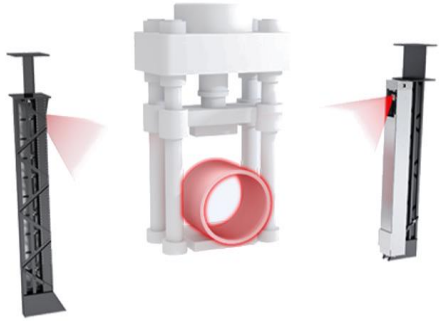
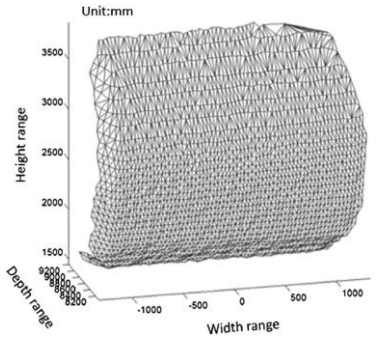
STATE OF THE ART – Approaches

Laser scanning

- Commercial systems
- **High mesurement times**

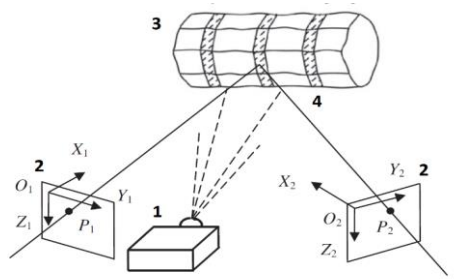


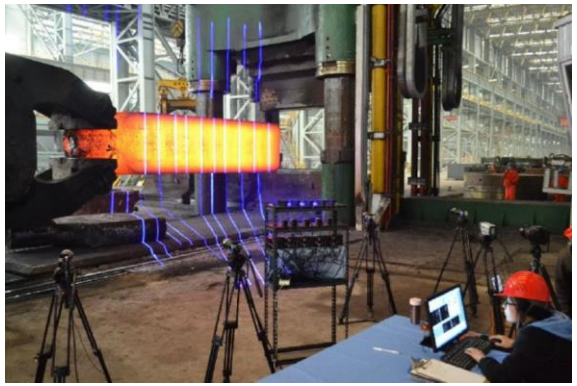


Laser scanning for forging measurement (MERMEC Group, Du et al., 2016)

Active photogrammetry

- Suppressing the influence
- **SNR – limited measurement volume**

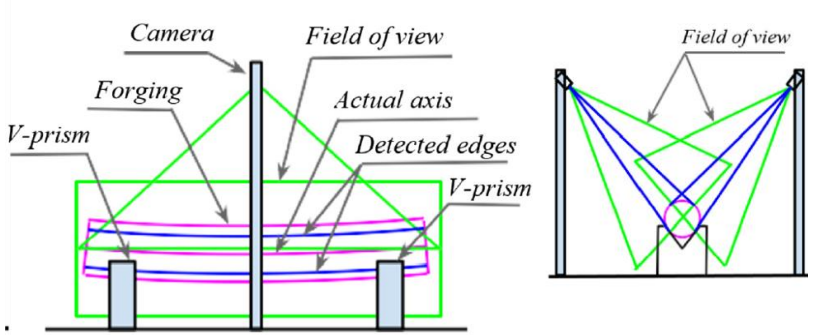


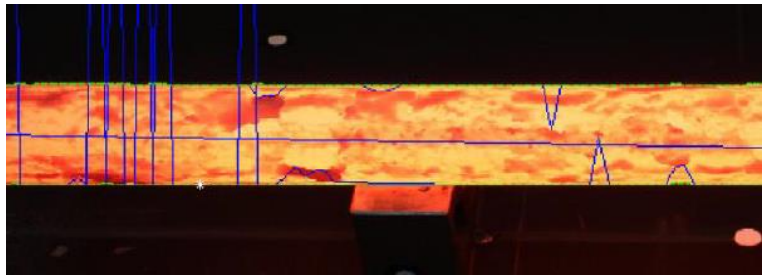


Active stereo measurement system (Jia et al.,2015)

Passive photogrammetry

- Radiation - silhouettes
- **Not developed - opportunity?**





Passive 3D forging measurement (Zatočilová et al., 2014, 2016, ed.)

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STATE OF THE ART – Challenges

Camera calibration

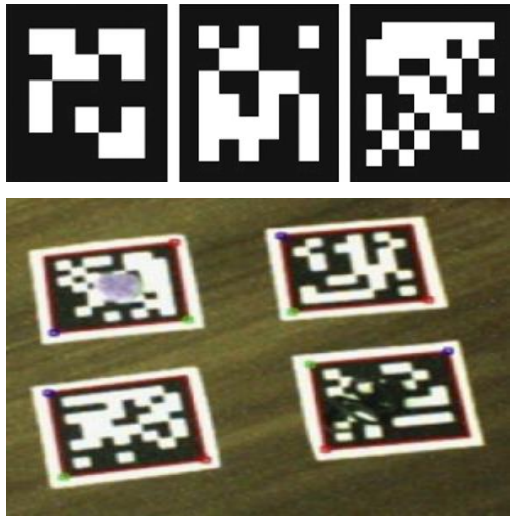
Hu et al. 2012

- Large meas. volume
- Space resection

Space resection – calibration image

Garrido-Jurado et al. 2014

- Non-metrological calib.
- Error correction

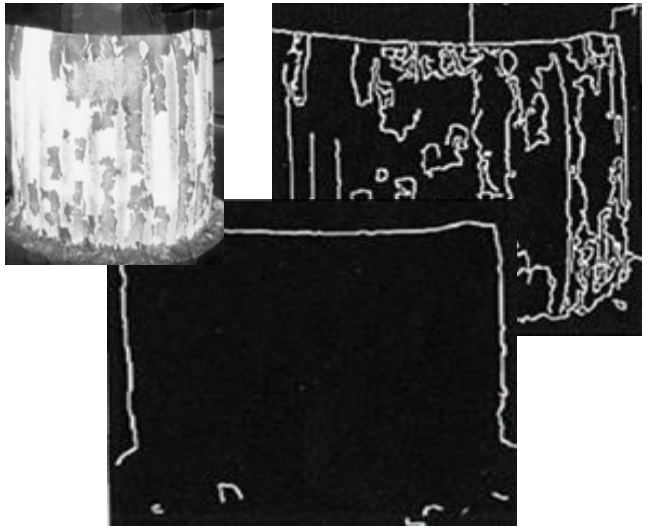


ArUco target system

Thermal radiation

Hu et al. 2009

- Canny-based detector
- Pixel precision

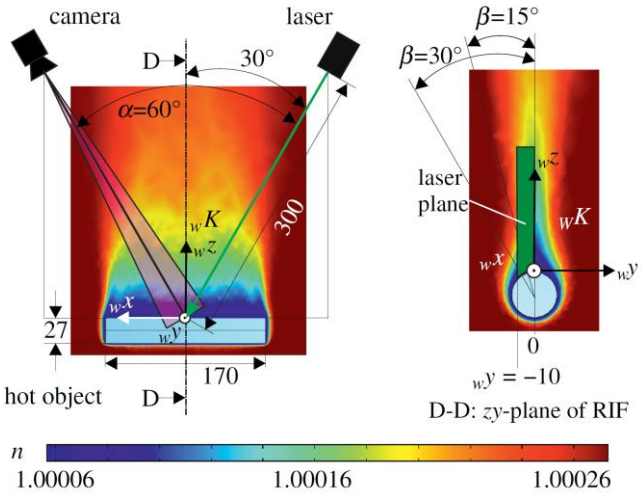


Specialized edge detection method

Air lens

Beermann et al. 2018

- Simulation + ray tracing
- Boundary conditions problem



Simulated active forging measurement

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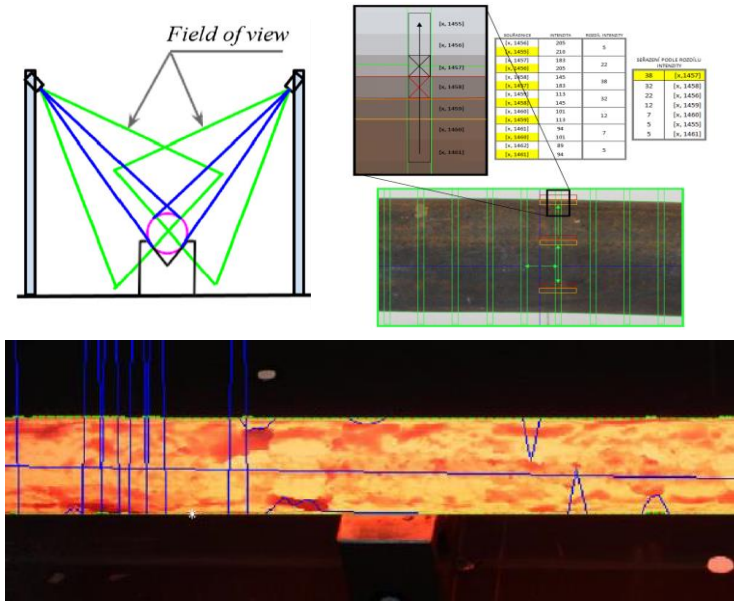
STATE OF THE ART – Silhouettes measurement

2016 | 2018 | 2020

Zatočilová et al.

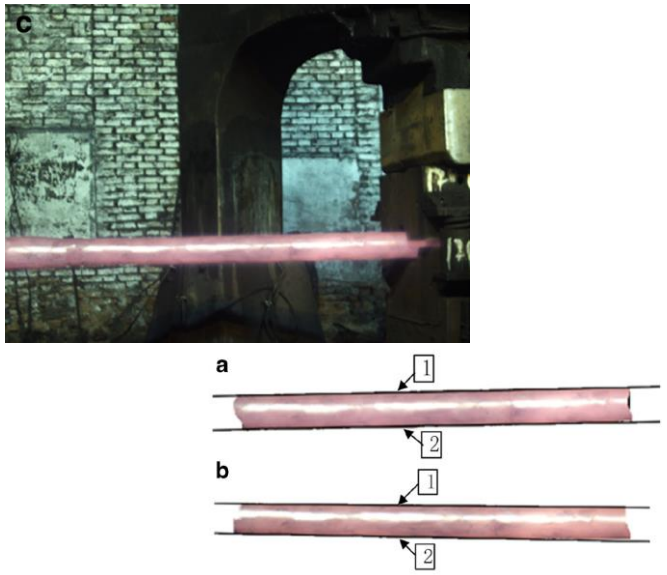
- 3D meas., smoothing, error 2%
- **Laboratory, pixel precision**



3D forging measurement

Zhou et al.

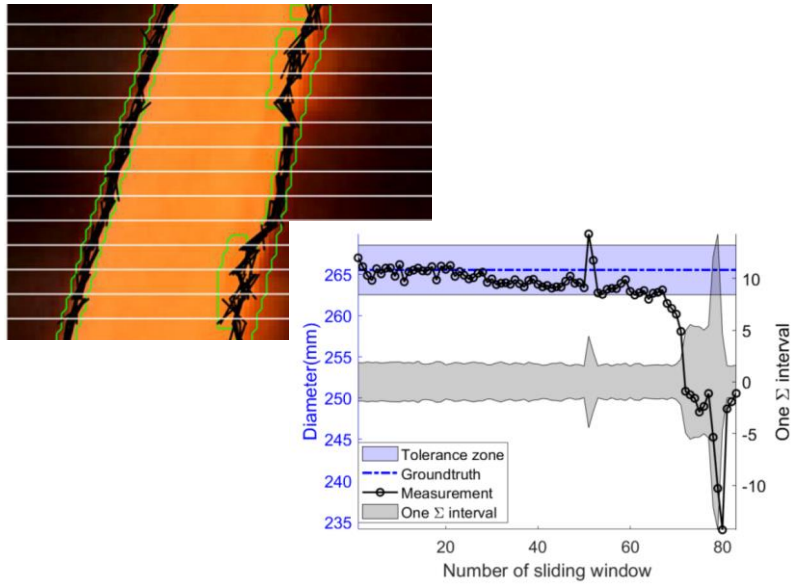
- Triangulation of lines, error 0.79 %
- **No axis-straightness**



Forging diameter measurement

Wang et al.

- Level of trust – diam. deviation, ROI
- **Deleting observations**



Rolled bar width measurement

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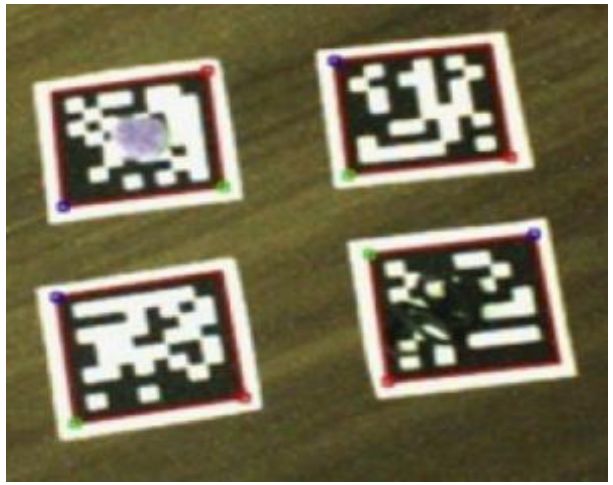
STATE OF THE ART – Analysis

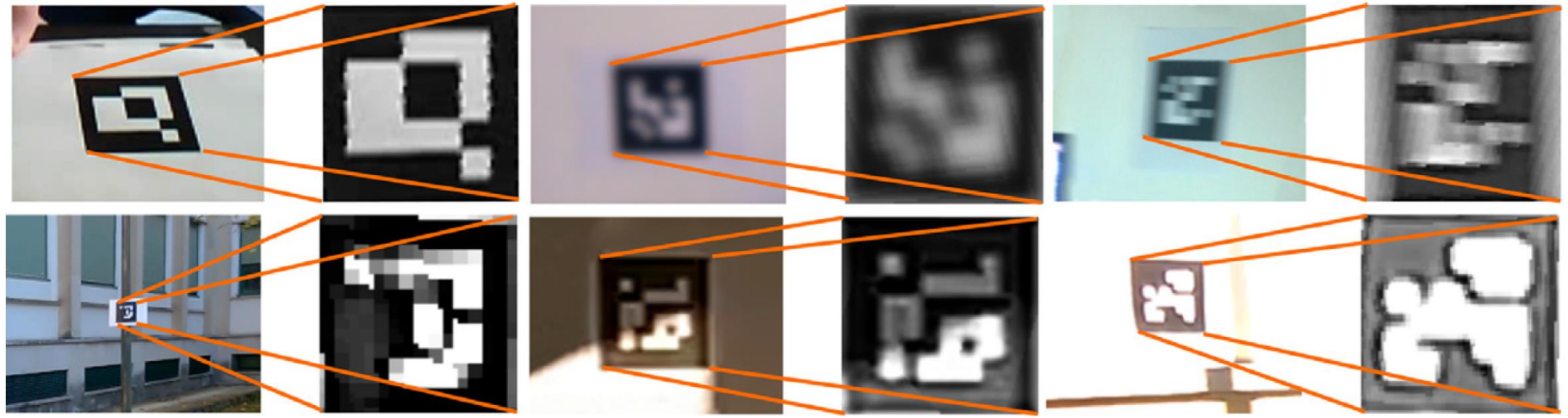
BLANK SPOTS

- On-line calibration - **robust photogrammetric targets**?
- Advantage of **sub-pixel accuracy**?
- **Limits in industrial environment**?

→ *No cicr. coded targets with error correction.*



ArUco target system performance (Garrido-Jurado et al., 2014)

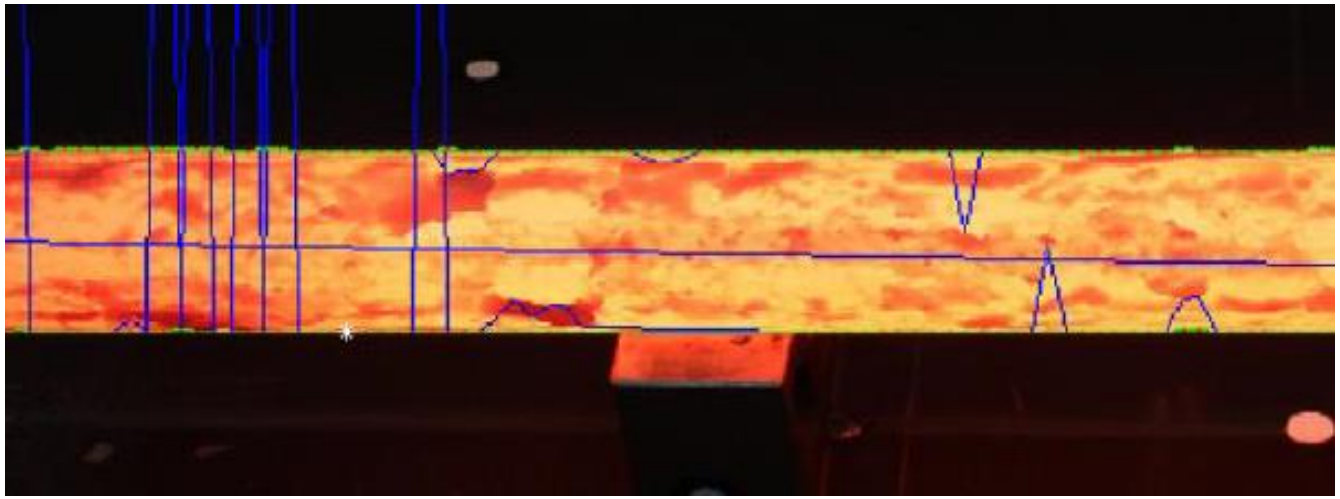


ArUco target system markers under extreme conditions (Mondéjar-Guerra et al., 2017)

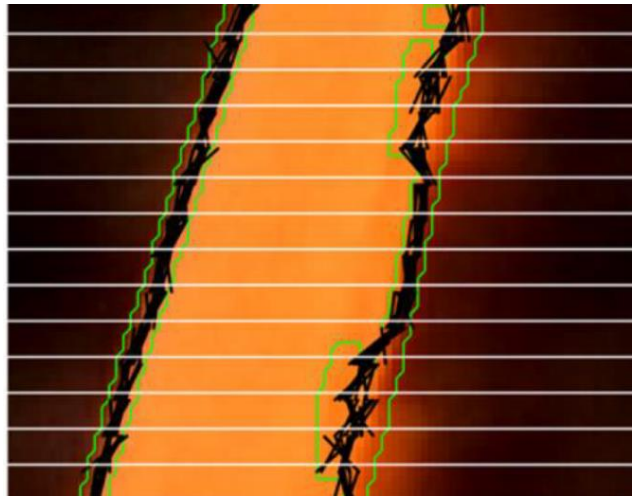
STATE OF THE ART – Analysis

BLANK SPOTS

- On-line calibration - **robust photogrammetric targets**?
- Advantage of **sub-pixel accuracy**? ➡
  - *Dominated by interfering effects?*
  - *Edge quality indicator?*
- **Limits in industrial environment**?



Edge detection (Zatočilová et al., 2016, ed.)

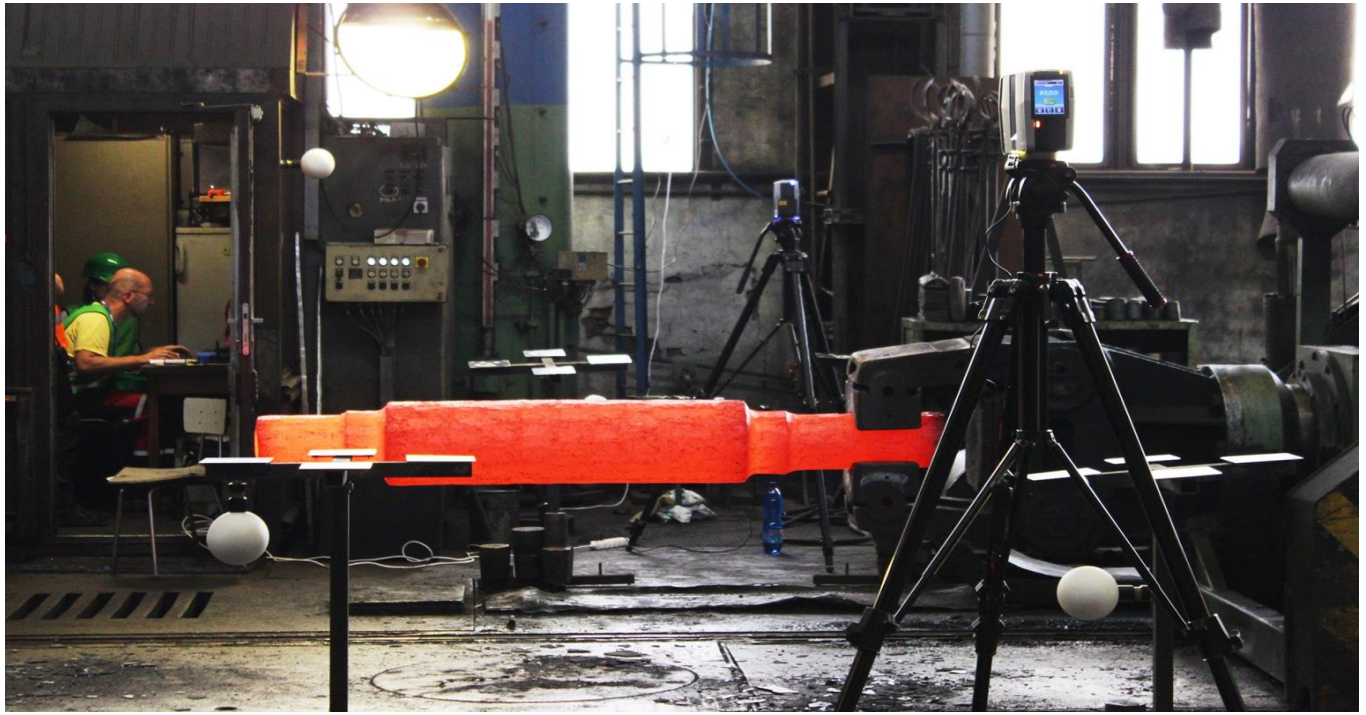


Edge quality indicators (Wang et al., 2020)

STATE OF THE ART – Analysis

BLANK SPOTS

- On-line calibration - **robust photogrammetric targets**?
- Advantage of **sub-pixel accuracy**?
- **Limits in industrial environment**? ➡
  - *Was never done before.*

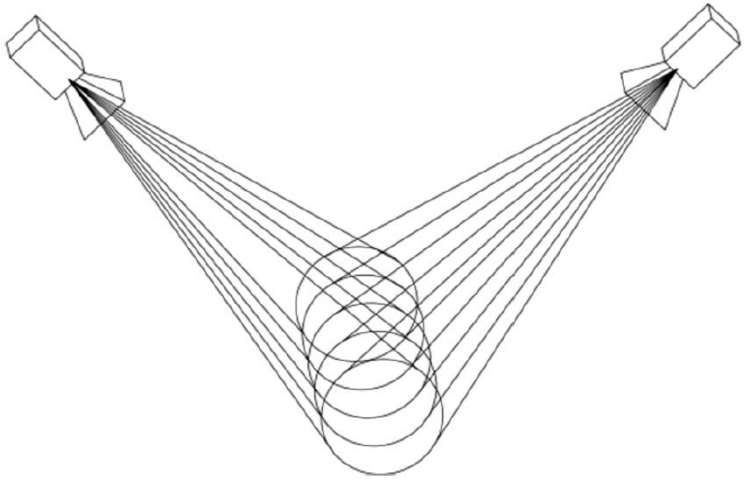


Forging measurement

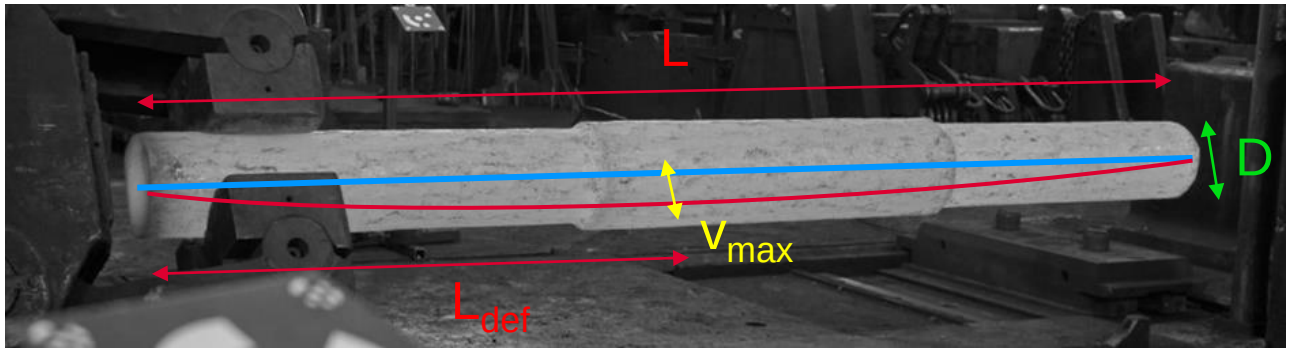
AIMS OF THE THESIS

GOAL, OBJECTIVES

- **To examine the limits of forging measurement based on object silhouettes.**
- Novelty: description of interferring effects, original methods
- **O1:** Camera calibration
- **O2:** Edge detection method
- **O3:** Demonstration of feasibility



General measurement principle (Hurník et al., 2022)



Desired Forging Characteristics

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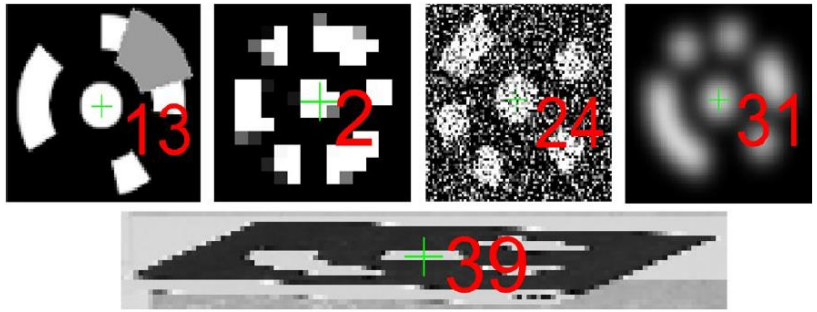
AIMS OF THE THESIS – scientific questions

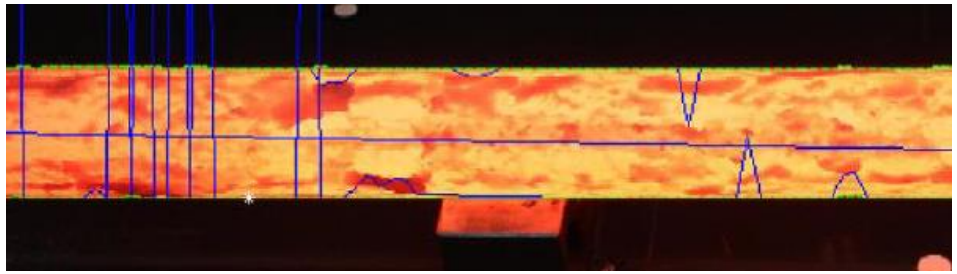
SCIENTIFIC QUESTIONS

- **Q1:** How to implement error correction method in target cyclic codes decoding for **robust camera calibration**?
- **H1:** The error correction method could use optimized target code library and a rotation-invariant distance with certain tolerance.



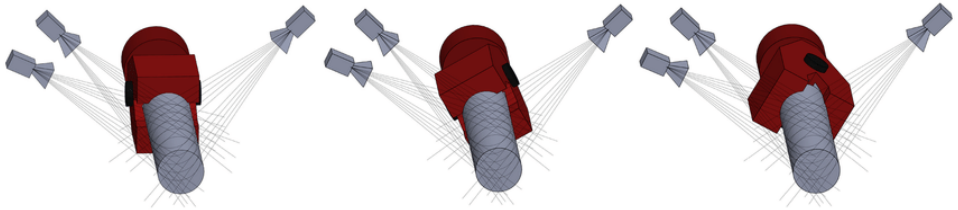
Coded targets with error correction (Hurník et al., 2021)

- **Q2:** How to suppress corrupted edges during **edge detection**?
- **H2:** The true and false edges could be distinguished based on edge gradient magnitude and its direction.



Corrupted edges of forging (Zatočilová et al., 2016)

- **Q3:** Could be **more measurements** used to achieve higher accuracy?
- **H3:** The errors obtained by changing angle viewpoints are random.

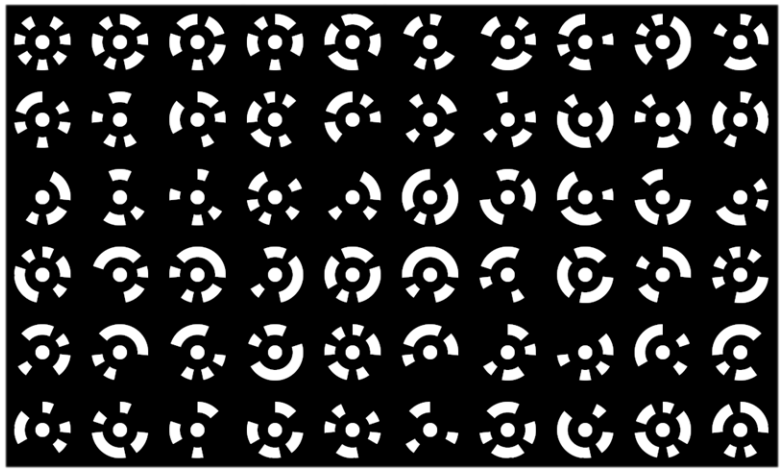


Multi-view measurement system idea (Hurník et al., 2022)

CAMERA CALIBRATION

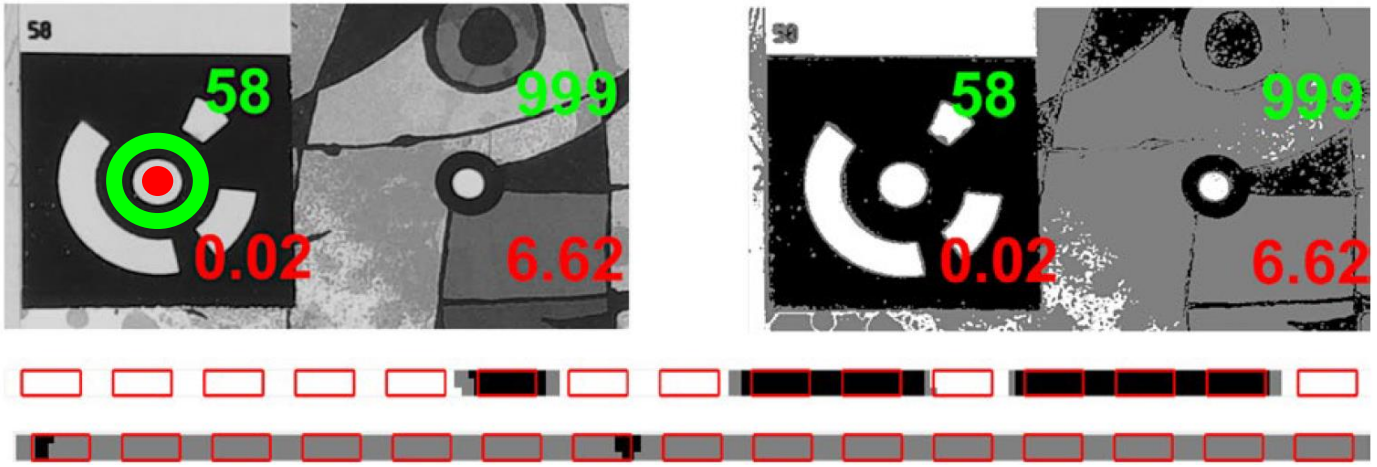
Q1: How to implement error correction method in target cyclic codes decoding for **robust camera calibration**?

H1: The error correction method could use **optimized target code library** and a **rotation-invariant distance**. Idea: **similarity condition**.



Sixty 15-bit targets

ArUco (Garrido-Jurado et al. 2014, ed.)



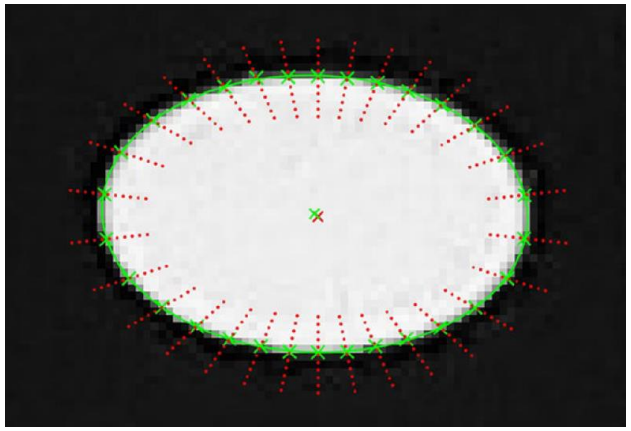
Quantization using similarity condition, scanned target code (Hurník et al., 2021)

TP1: Higher recall, similar precision (confusion rate).

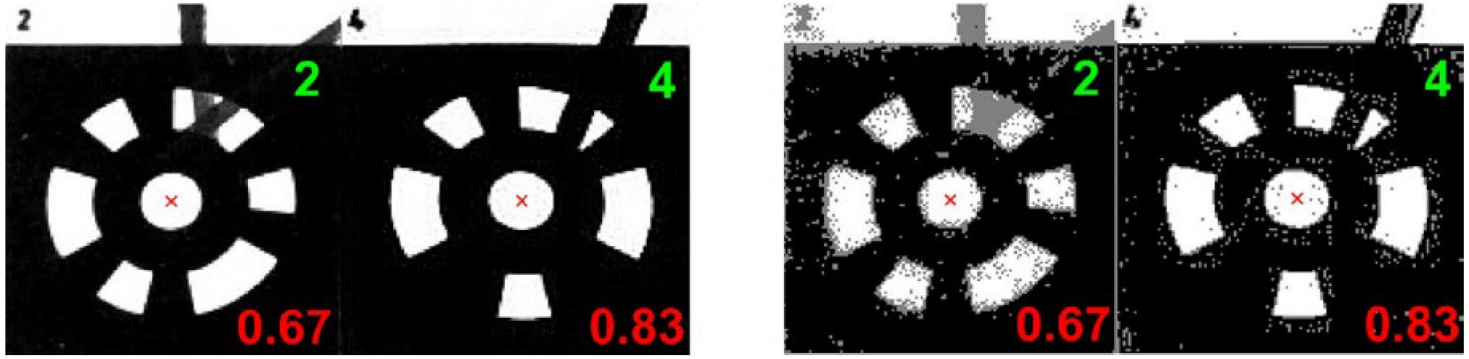
CAMERA CALIBRATION

METHODS

- Sixty 15-bit targets
- **Up to 1 bit changed, 2 bits occluded**
- Canny, ellipse fitting
- Star ellipse operator
- Probability code scanning
- Rotation invariant distance



Star ellipse operator (Hurník et al., 2021)



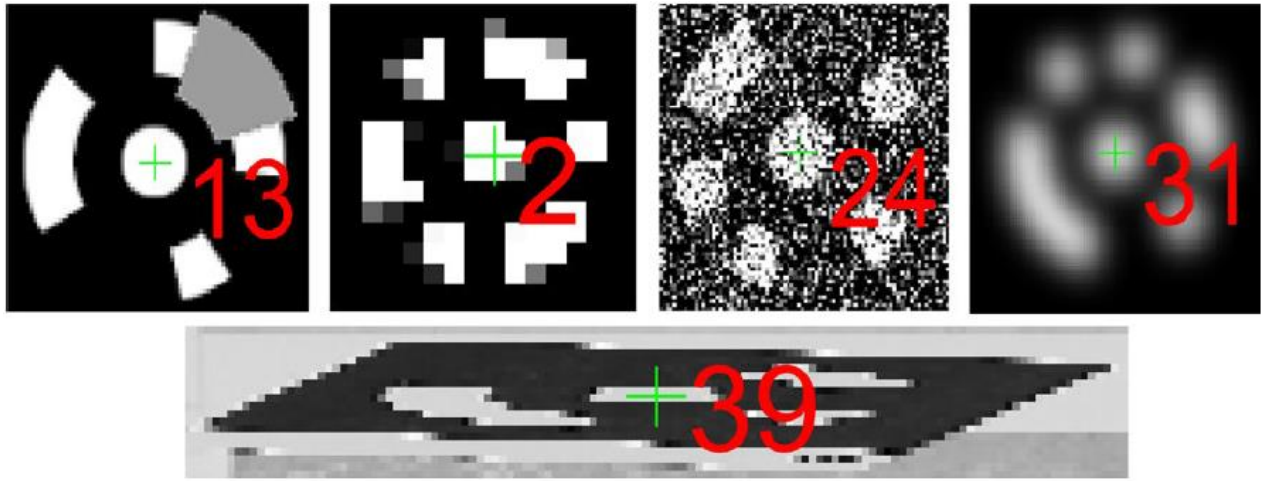
Effect of the similarity condition (Hurník et al., 2021)

- **Q1:** How to implement error correction method in target cyclic codes decoding for robust camera calibration?

CAMERA CALIBRATION


RESULTS AND DISCUSSION

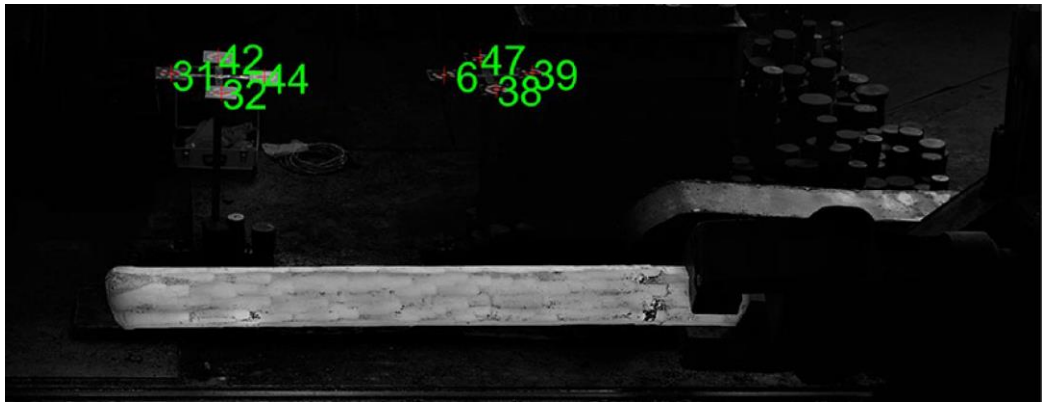
- Benchmark - overall best performance
- 35 % better performance (occlusion)
- **No sig. decrease of precision**
- **H1 not falsified**
- Validated in practice



Example of succesfully recognized targets (Hurník et al., 2021)

	ICCT	SA	TRITOP	ArUco
Occlus.	0.930 **1st**	0.732	0.721	0.868 **2nd**
Scale	0.934 **1st**	0.418	0.870	0.928 **2nd**
Angle	0.939 **2nd**	0.701	0.775	0.962 **1st**
Blur	0.620 **2nd**	0.609	0.772 **1st**	0.400
Noise	0.839 **1st**	0.730 **2nd**	0.118	0.487

Target systems performace (Hurník et al., 2021)



Target system during forging measurement (Hurník et al., 2021)

- **Q1:** How to implement error correction method in target cyclic codes decoding for robust camera calibration?

CAMERA CALIBRATION

RESULTS AND DI

- Benchmark - overall best
- 35 % better performance
- **No sig. decrease of prec**
- **H1 not falsified**
- Validated in practice

Machine Vision and Applications (2021) 32:39
https://doi.org/10.1007/s00138-020-01159-1

ORIGINAL PAPER

Check for updates

Circular coded target system for industrial applications

Jakub Hurník[1] · Aneta Zatočilová[1] · David Paloušek[1]

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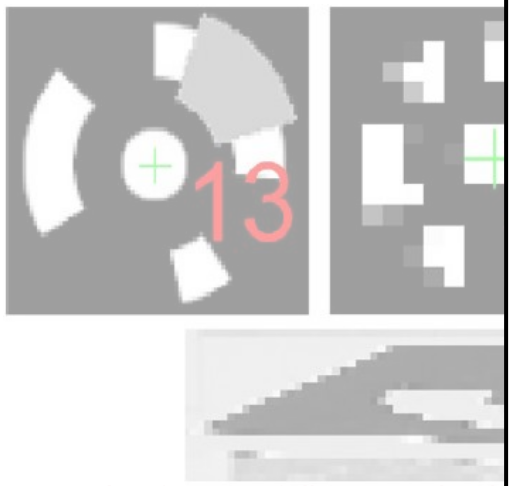
Abstract
Coded targets are used as reference targets with a known location during camera calibration, for robust searching of corresponding features between images during various applications of machine vision like object tracking, robot navigation or 3D measurement. In this paper, a target system for industrial photogrammetric applications is outlined. The methods which have been chosen emphasize maximum robustness, along with accuracy at the expense of computational efficiency, since photogrammetric measurements are mainly evaluated offline. The outlined system combines widely used photogrammetric circular coded target design with an automatic library generator. It also utilizes robust methods of target detection and recognition with error correction (in case of 60 15-bit targets, up to 1 bit confused or 2 bits occluded) along with preserving the low false-positive or confusion rate. Any error correction method for this type of targets was not introduced before. The solution also allows for the creation of versatile target libraries or to work with the existing target libraries of a number of commercial photogrammetric systems. The properties of the target system were tested under challenging conditions (including heavy noise, blur, occlusion and geometrical image transformations) and compared to state-of-the-art systems, e.g. TRITOP (GOM), or ArUco, which it outperforms. The target system is already used for the camera calibration of a specialized photogrammetric system utilized in the heavy industry environment.

Keywords Circular coded target · CCT · Coded target · Fiducial marker · Camera calibration · Photogrammetry

	TRITOP	ArUco
	0.721	0.868 2nd
	0.870	0.928 2nd
	0.775	0.962 1st
	0.772 1st	0.400
2nd	0.118	0.487

al., 2021)



Example of succesfully recognized

ment (Hurník et al., 2021)

- **Q1:** How to implement error correction method in target cyclic codes decoding for robust camera calibration?

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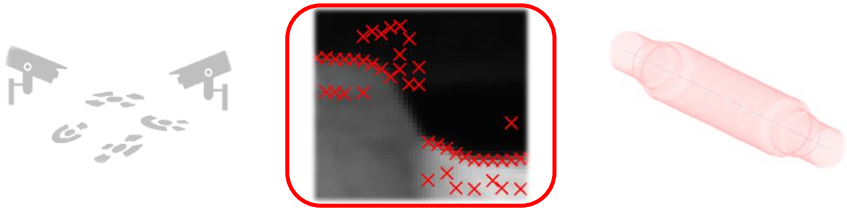
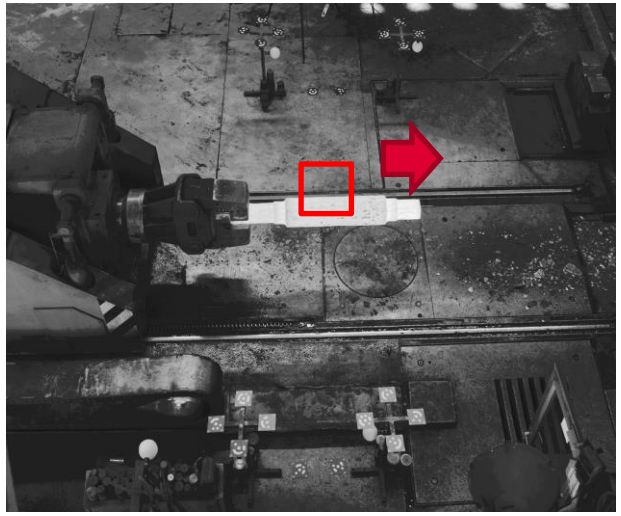
EDGE DETECTION

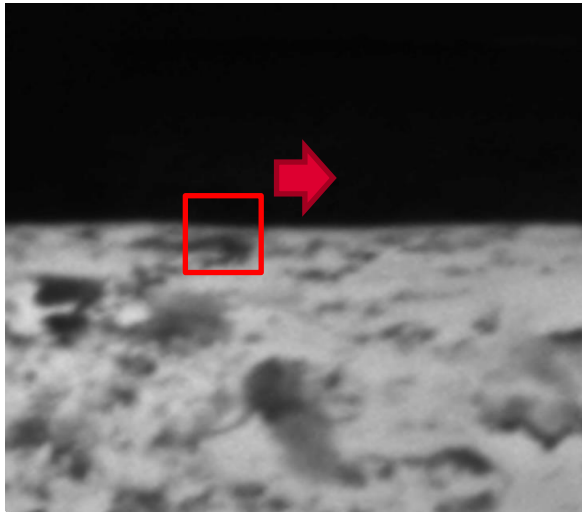


Q2: How to suppress corrupted edges during **edge detection**?

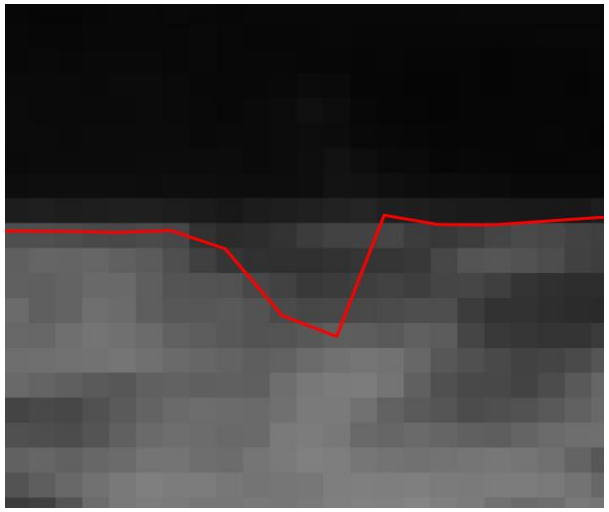
H2: The true and false edges could be distinguished based on **edge gradient magnitude and its direction**.



Measurement image (Hurník et al., 2022, ed.)



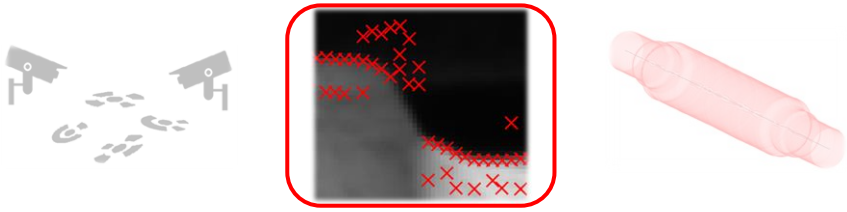
Corrupted edges of forging



Edge detection failure (Hurník et al., 2022, ed.)

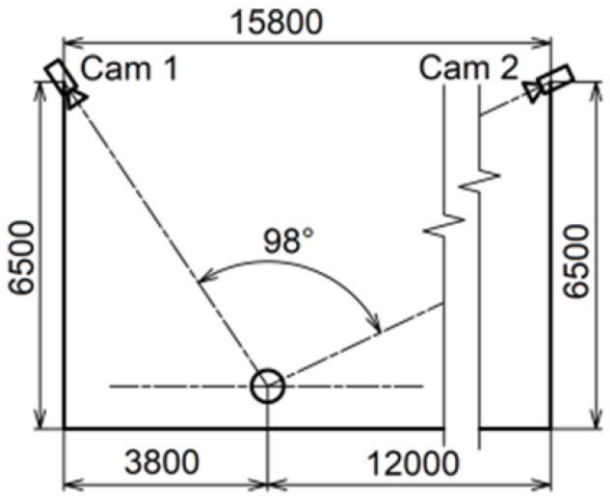
TP2: Weighted edge smoothing, lower measurement repeatability error.

EDGE DETECTION



METHODS – HARDWARE

- Volume approx. 6 × 6 × 2 m
- 16 MPx cameras
- Red colour filters (630 – 730 nm)

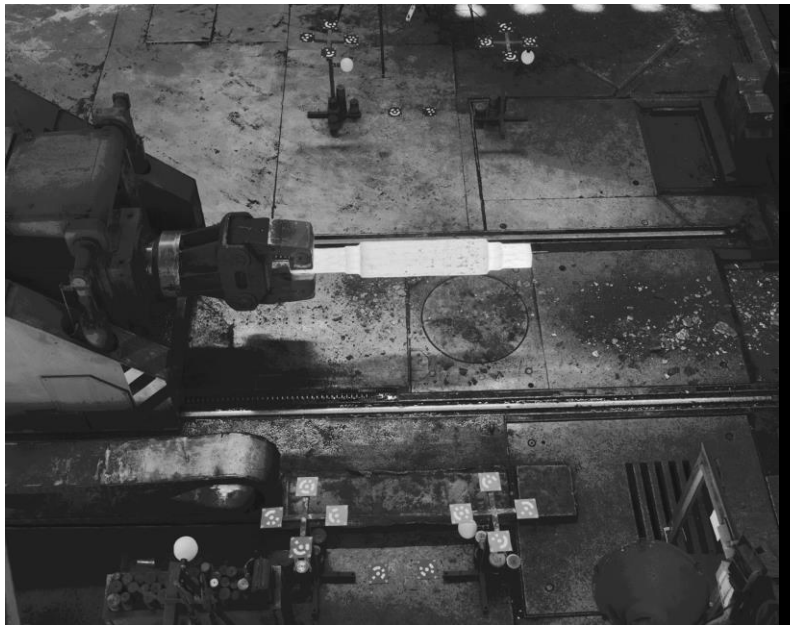


Hardware layout (Hurník et al., 2022)

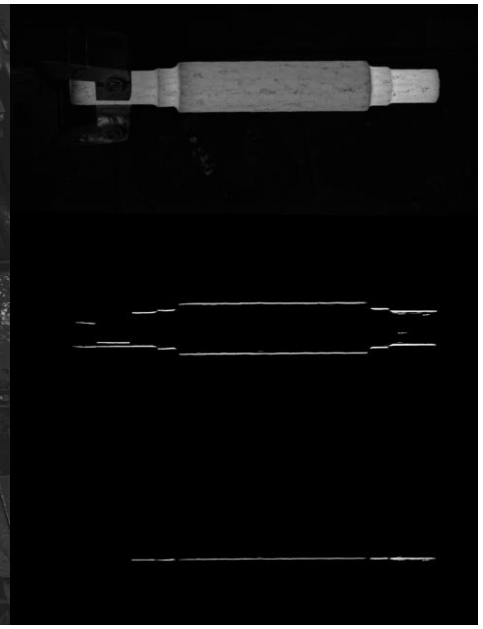
Thermo-regulated camera cover

METHODS – IMAGE PROC.

- Robust segmentation
- Zero-crossing edge detection
- Weighted smoothing



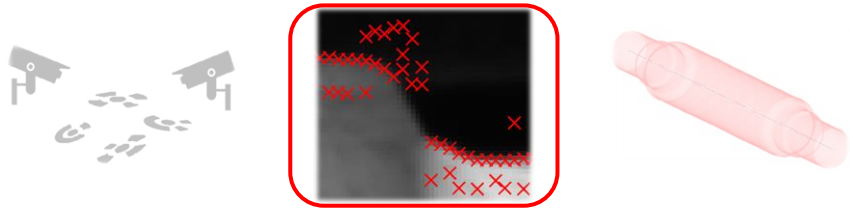
Measurement image (Hurník et al., 2022, ed.)



Segmentation method (Hurník et al., 2022, ed.)

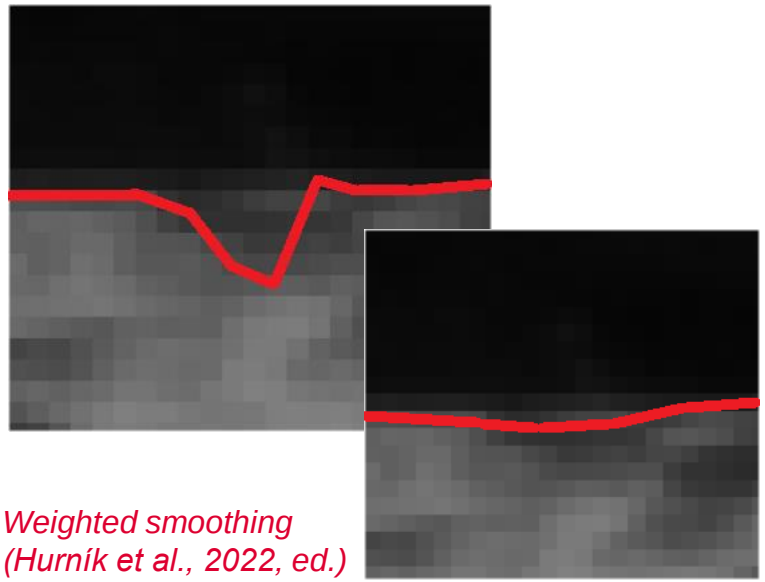
- **Q2:** How to suppress corrupted edges during **edge detection**?

EDGE DETECTION

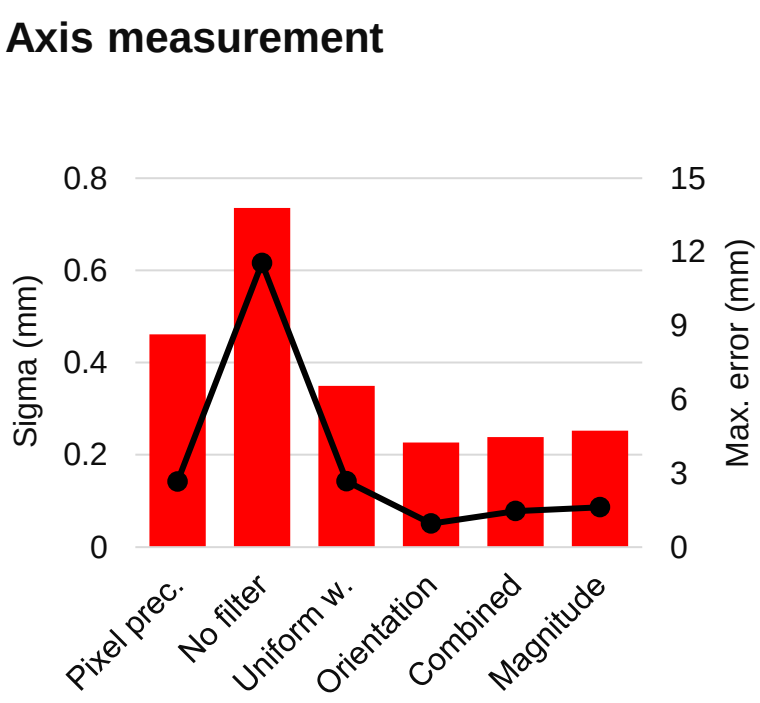


RESULTS AND DISCUSSION

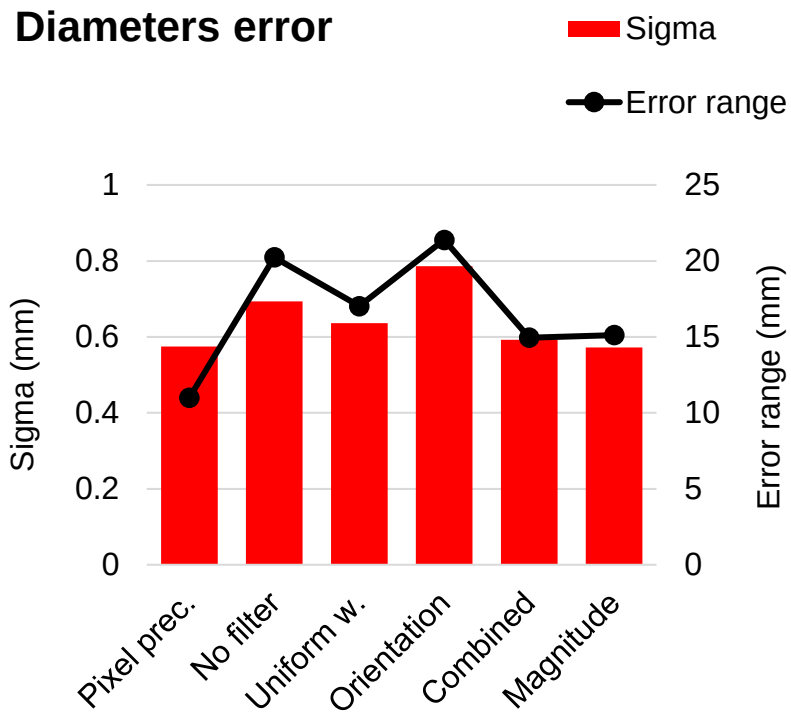
- Sub-pixel edge detection 50 % better
- **Axis** - edge gradient better by 30 %
- **H2 not falsified**
- Error ±0.5 mm (axis) and ±1 mm (diam.)



Weighted smoothing (Hurník et al., 2022, ed.)



Axis measurement error (Hurník et al., 2022)



Diameter measurement error (Hurník et al., 2022)

- **Q2:** How to suppress corrupted edges during **edge detection**?

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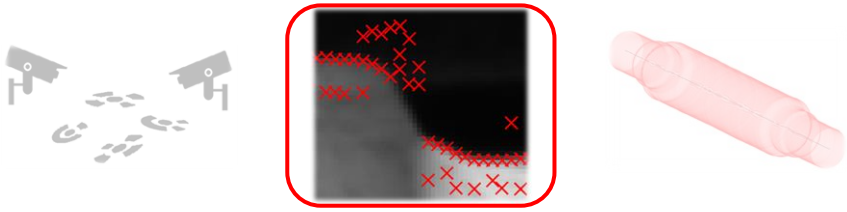
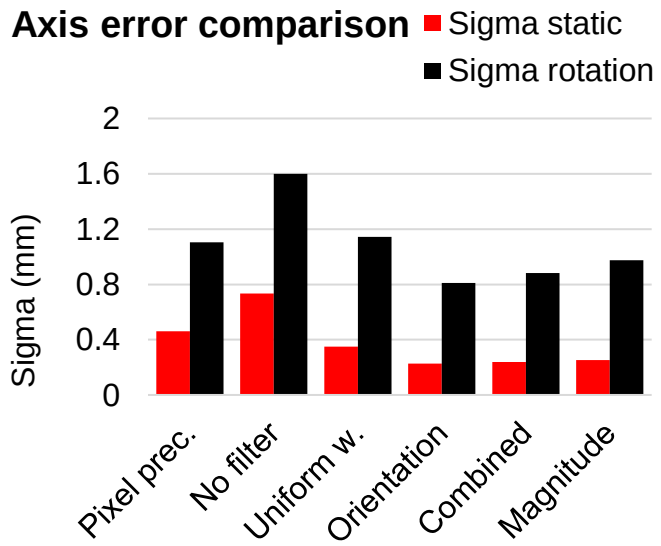
EDGE DETECTION

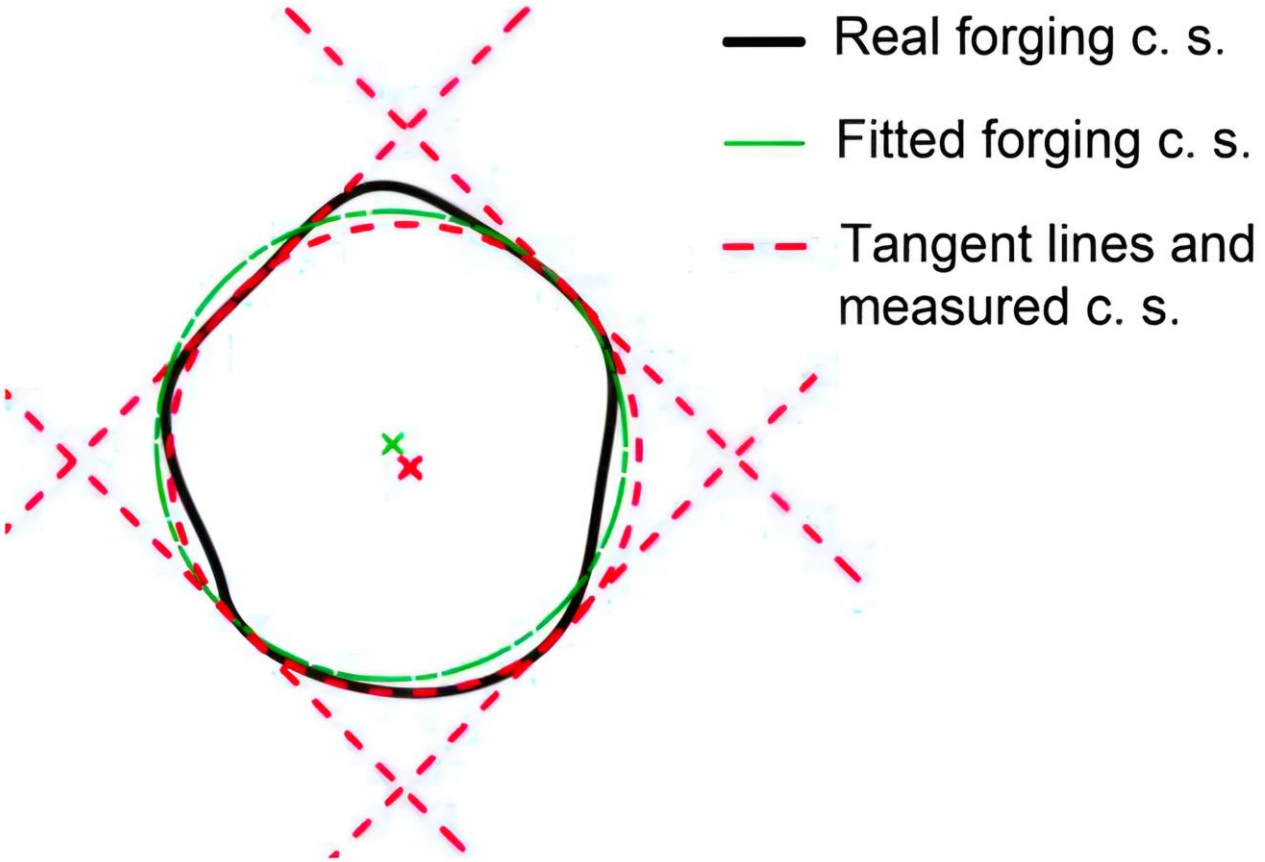


RESULTS AND DISCUSSION

- Sub-pixel edge detection 50 % better
- **Axis** - edge gradient better by 30 %
- **H2 not falsified**
- Error ±0.5 mm (axis) and ±1 mm (diam.)
- **3 × worse for meas. from different viewpoints!**



Diameter measurement (Hurník et al., 2022)



Effect of irregular forging c.s (Hurník et al., 2022, ed.).

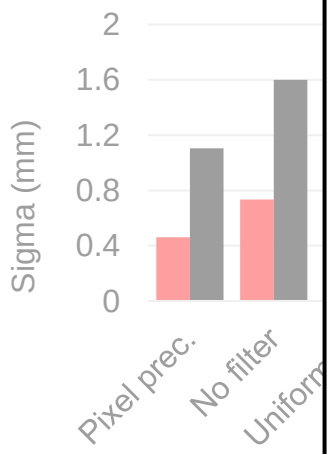
- **Q2:** How to suppress corrupted edges during **edge detection**?

EDGE DETECTION

RESULTS AND

- Sub-pixel edge detec
- **Axis** - edge gradient
- **H2 not falsified**
- Error ±0.5 mm (axis)
- **3 × worse for meas.**

Axis error compa



Diameter measurement (Hurník et al., 2022)

Measurement 194 (2022) 111059

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Enhancing the accuracy of forging measurement using silhouettes in images

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ARTICLE INFO

Keywords:
Forging
Measurement
Edge detection
Silhouettes
Axis straightness
Image analysis

ABSTRACT

In this study, a new passive camera system for heavy cylindrical forging measurement, based on silhouettes in images, is developed. New methods for making such a system more resistant to the negative effects of the industrial environment have been proposed. This includes weighted edge filtering based on complementary information about the edge quality in an image. The recorded measurement median errors were ±0.12 mm and ±0.14 mm. Moreover, the 95% confidence intervals were ±0.5 mm and ±1 mm for the forging axis and diameter measurements, respectively. Both results were achieved in a measurement volume of 6 × 6 × 2 m during the measurement of glowing hot forgings in industrial conditions. The results surpass those of the state-of-the-art method, mainly in the case of axis straightness measurement, by approximately 50%. The measurement is fast, and it provides feedback about the axis straightness for its subsequent correction.

Effect of irregular forging c.s (Hurník et al., 2022, ed.).

- **Q2:** How to suppress corrupted edges during **edge detection**?

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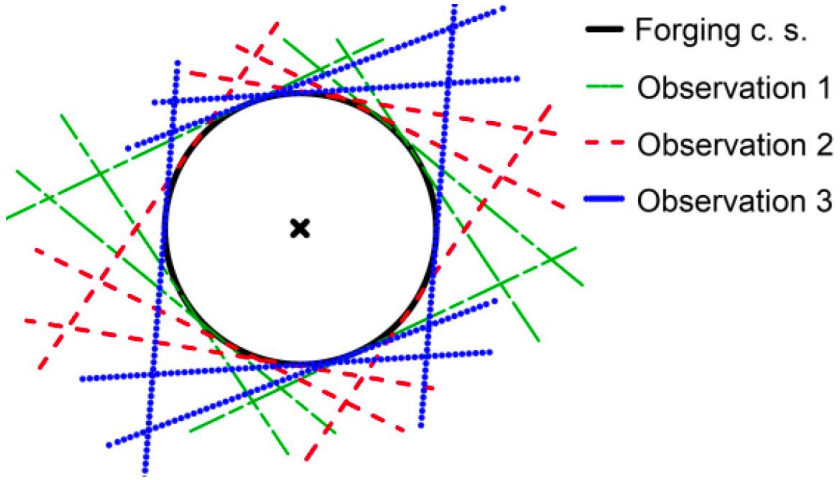
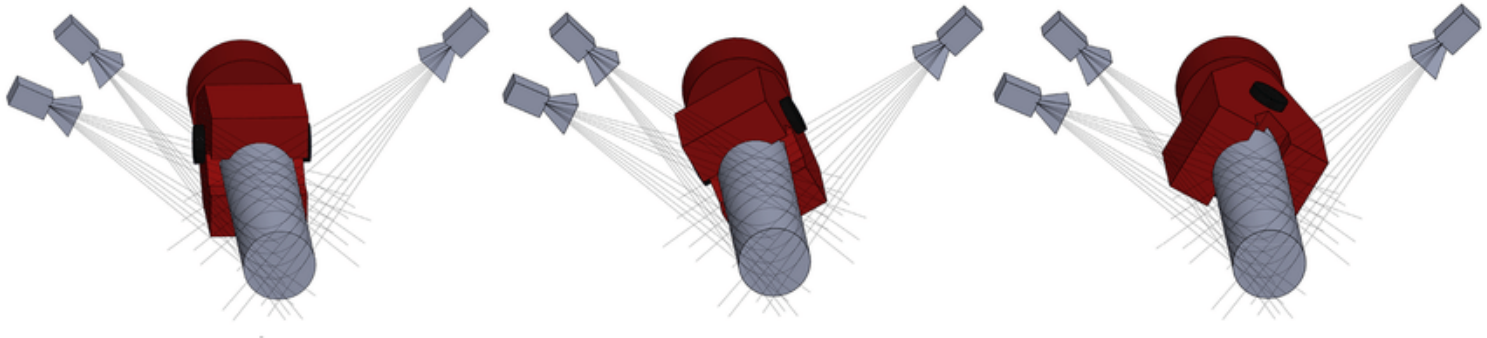
MULTI-VIEW SOLUTION

Q3: Could be **more measurements** used to achieve better precision?

H2: The errors of measured geometry from different angle viewpoints are random.



Overdetermined cross-section (Hurník et al., 2022)



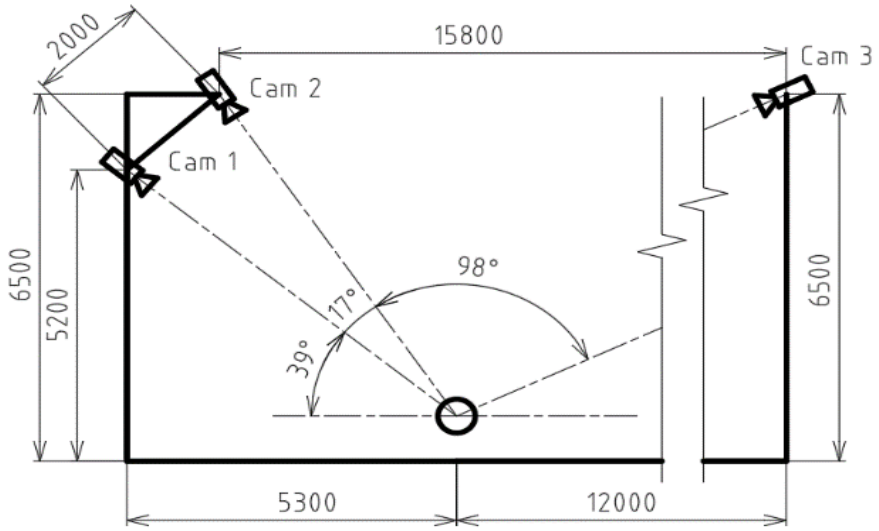
Utilization of forging positioning system (Hurník et al., 2022)

TP3: Error of mean geometry based on multiple observations decreases approx. with $\sqrt{n}$

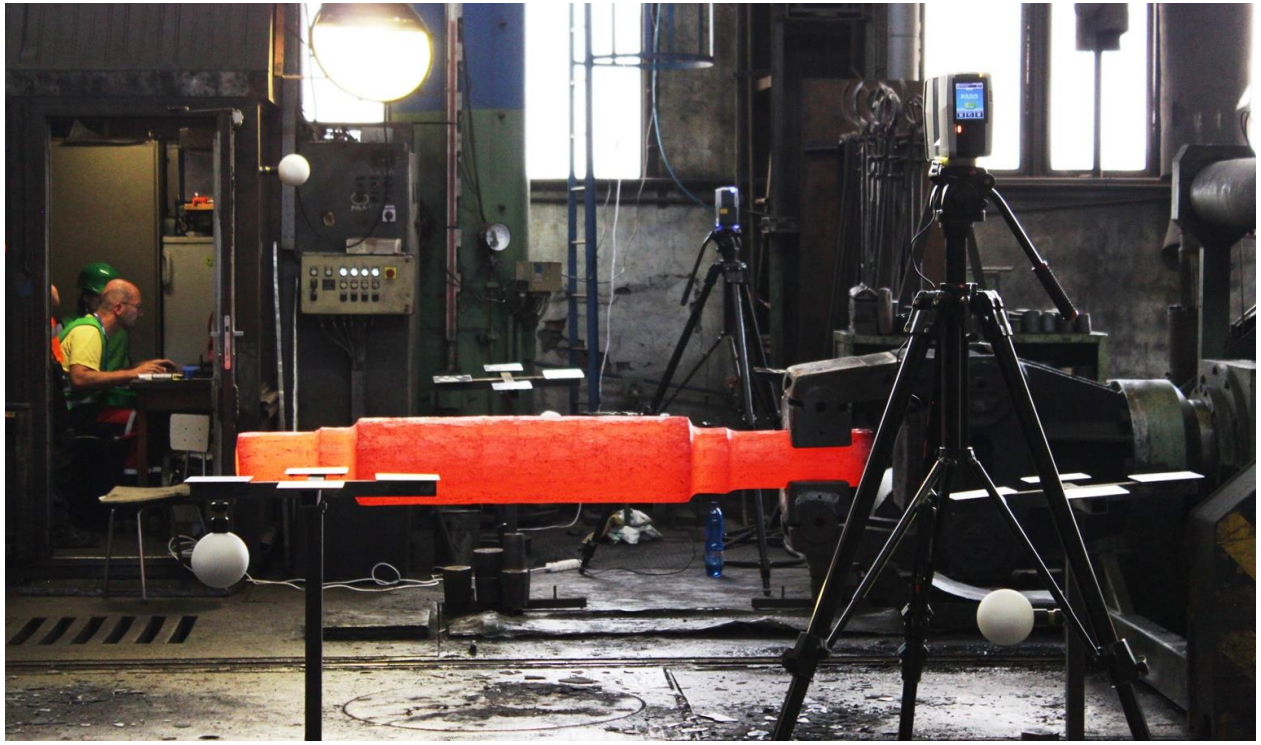
MULTI-VIEW SOLUTION

METHODS

- Third camera
- Manipulator accuracy ± 0.5°, rotation by 30°
- 2 × FARO laser scanners for comparison



Three camera layout (Hurník et al., 2022)



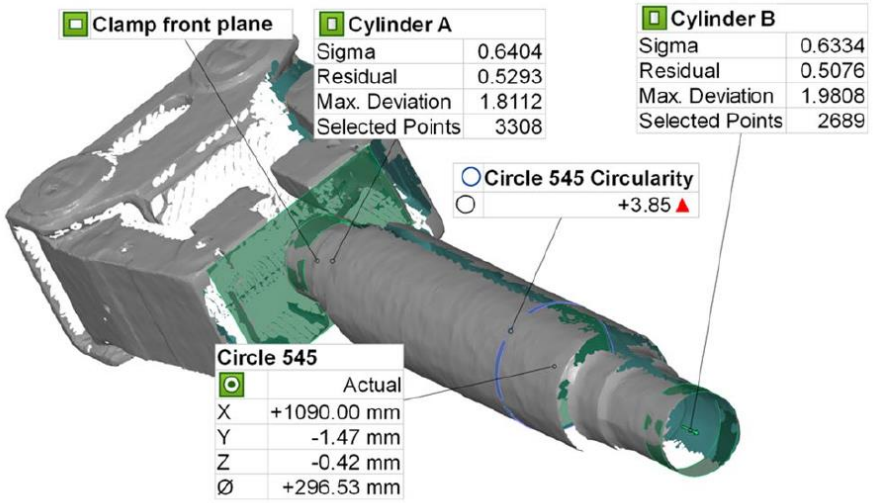
Comparative measurement system

- **Q3:** Could be more measurements used to achieve higher accuracy?

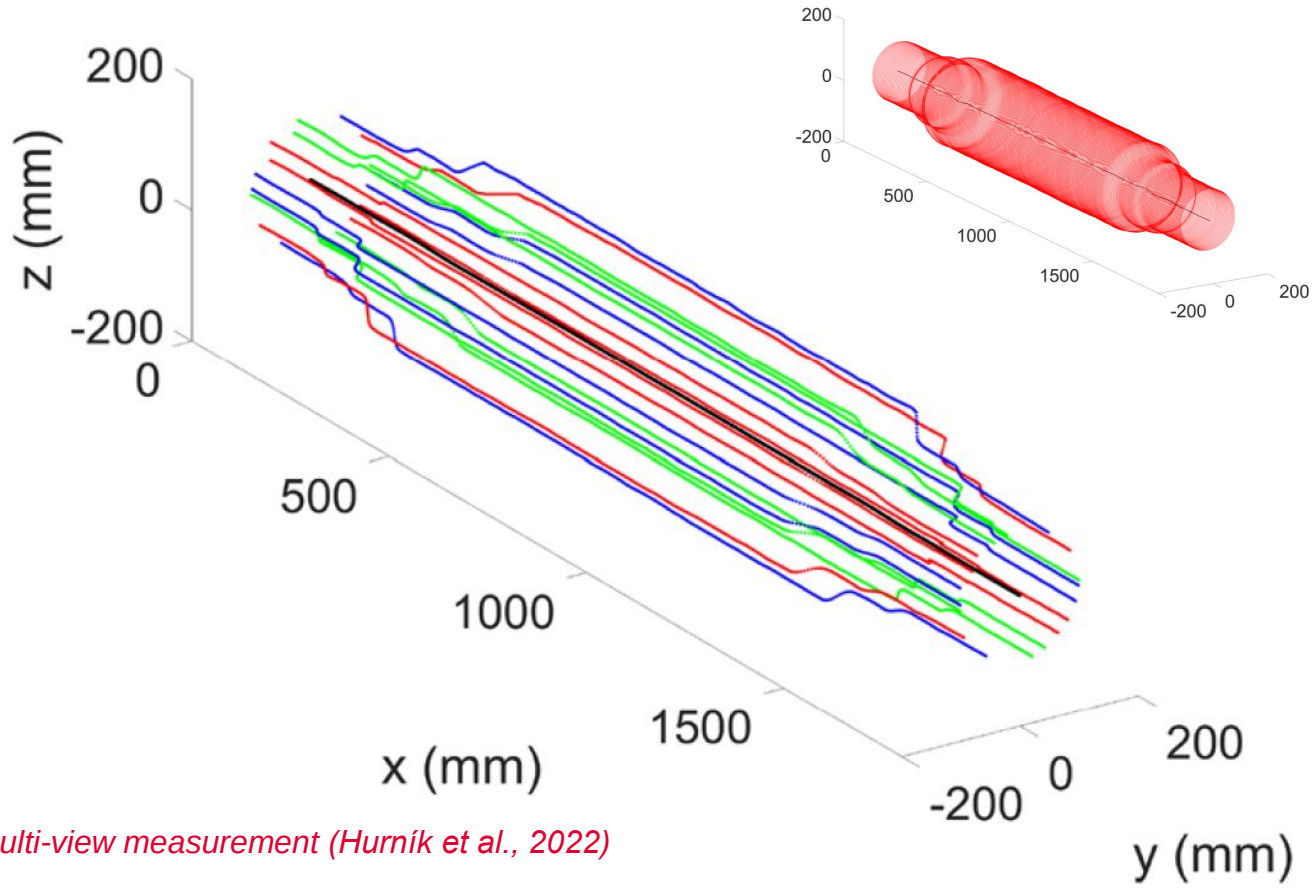
MULTI-VIEW SOLUTION

RESULTS, DISCUSSION

- Good agreement with reference
- 10 % outliers (diam., circ.)
- Irregular convergence = **H3 falsified**
- **Regular distribution of observations needed**
- **Axis and diam. ±0.5 mm, circularity 1.379 mm**



Laser scanning result (Hurník et al., 2022)



Multi-view measurement (Hurník et al., 2022)

- **Q3:** Could be more measurements used to achieve higher accuracy?

MULTI-VIEW SOLUTION

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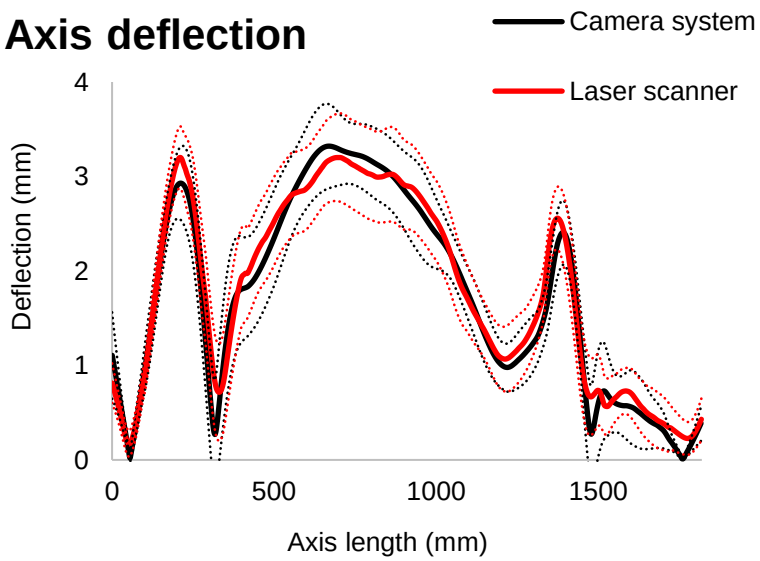
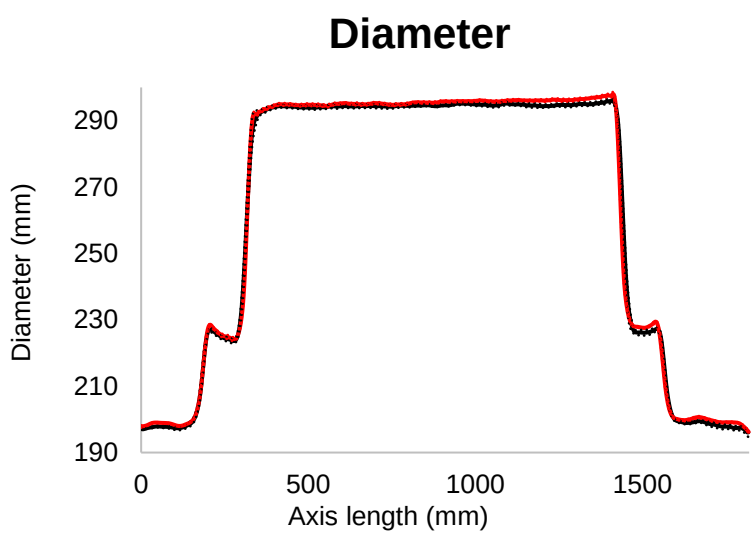
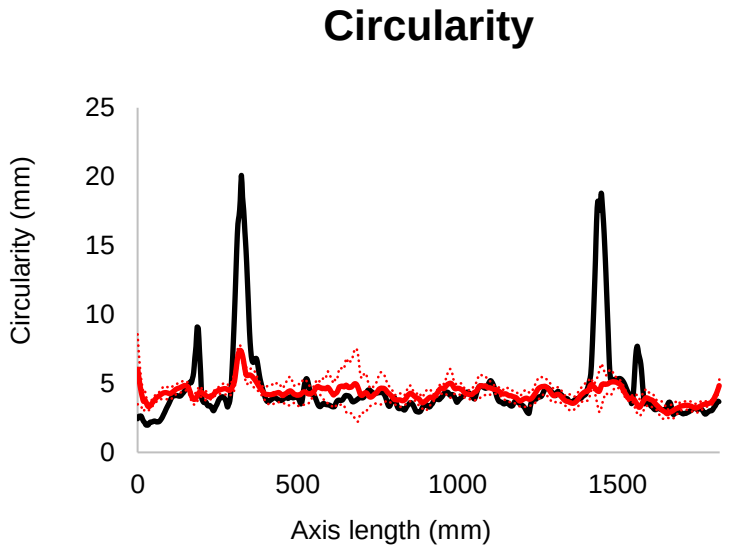
Forging measurement image (Hurník et al., 2022, ed.)







Forging measurement – comparison with laser scanning – Axis deflection, Diameter, Circularity (Hurník et al., 2022)

- **Q3:** Could be more measurements used to achieve higher accuracy?

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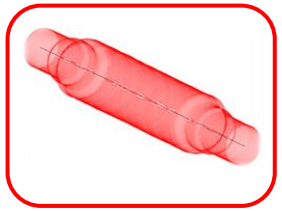
MULTI-VIEW SOLUTION





RESULTS, DISCUSSION

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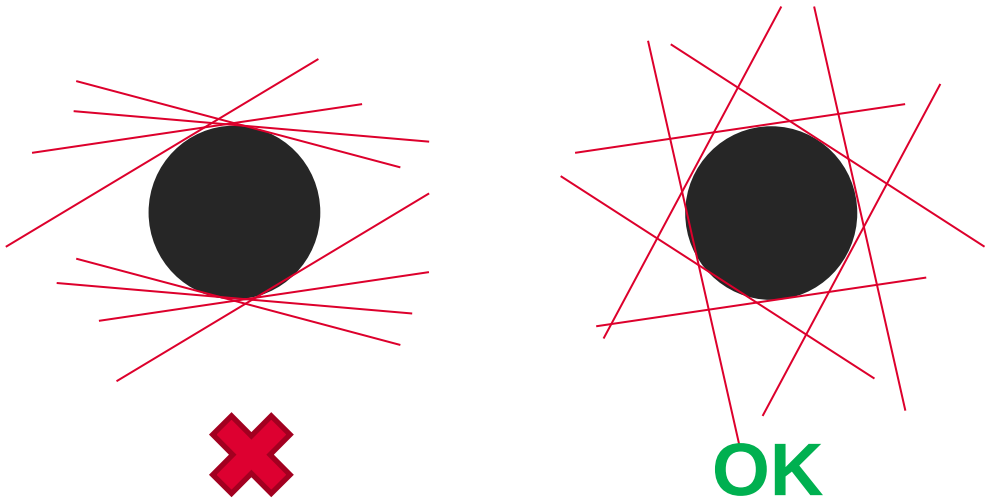
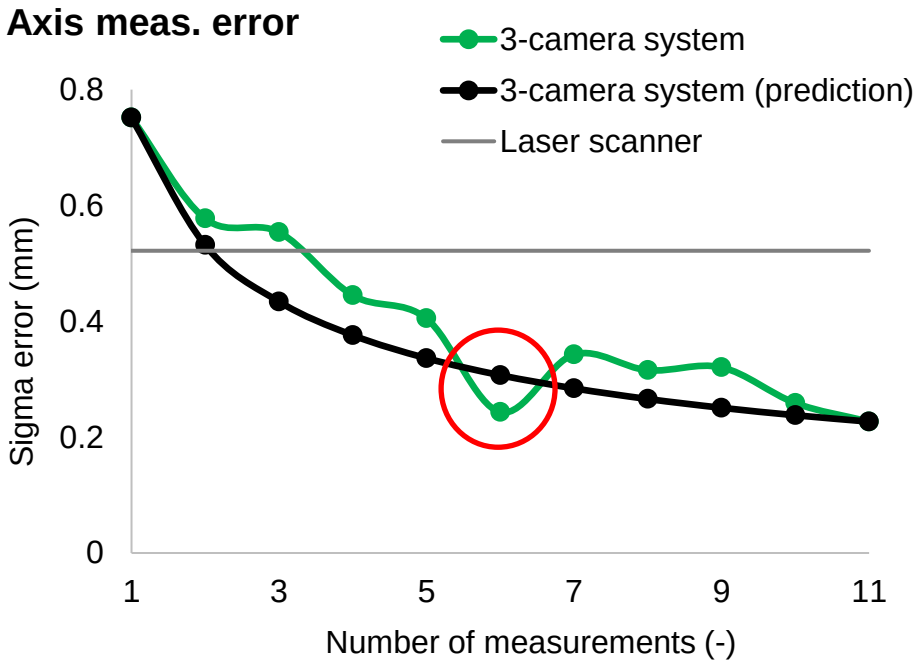
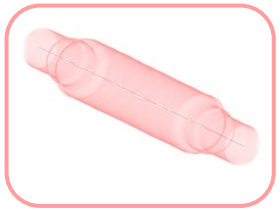




Multi-view measurement – prediction and reality (Hurník, 2022)

- **Q3:** Could be more measurements used to achieve higher accuracy?

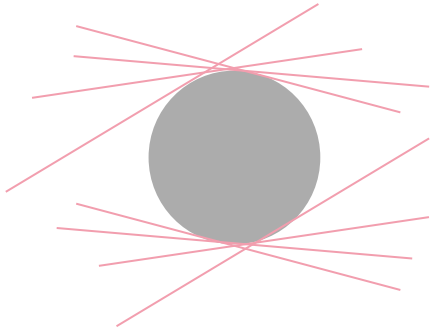
MULTI-VIEW SOLUTION



RESULTS, DISCU

- Good agreement with r
- 10 % outliers (diam., ci
- Irregular convergence =
- **Regular distribution o**
- **Axis and diam. ±0.5 m**

ediction)



The International Journal of Advanced Manufacturing Technology (2022) 121:7295–7310
https://doi.org/10.1007/s00170-022-09809-6

ORIGINAL ARTICLE

Check for updates

Multi-view camera system for measurement of heavy forgings

Jakub Hurník[1] · Aneta Zatočilová[1] · Tereza Konečná[1] · Pavel Štarha[1] · Daniel Koutný[1]

Received: 4 March 2022 / Accepted: 18 July 2022 / Published online: 27 July 2022

Abstract
Open-die forging is used to manufacture heavy durable parts such as shafts. In-process measurements are required for shape correction. The passive 3D measurement method is based on forging silhouettes in images and has demonstrated its advantages in this application. However, when using two cameras, only four tangents are available to determine the cross-section. In this paper, we propose a novel multi-camera multi-observation method for forging measurements; it increases the number of tangent lines used to determine the forging cross-section. The results suggest a decrease in measurement error proportional to the square root of the observation number. The six-observation precision is ±0.5 mm in a measurement volume of 6×6×2 m for axis straightness and diameter measurements (95% confidence interval). However, many outliers remain in case of diameter measurement. In addition, the forging circularity can be measured. The proposed system shows good agreement with the laser scanning measurement method. Overall, the system has considerable potential for forging manufacturing applications.

Keywords Axis · Diameter · Edge detection · Forging · Measurement · Laser scanner · Silhouettes

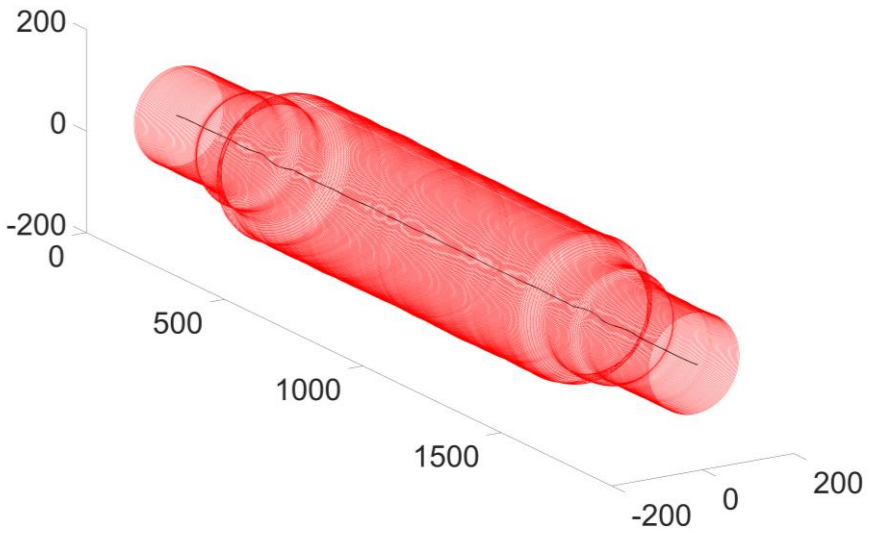
11

- **Q3:** Could be more measurements used to achieve higher accuracy?

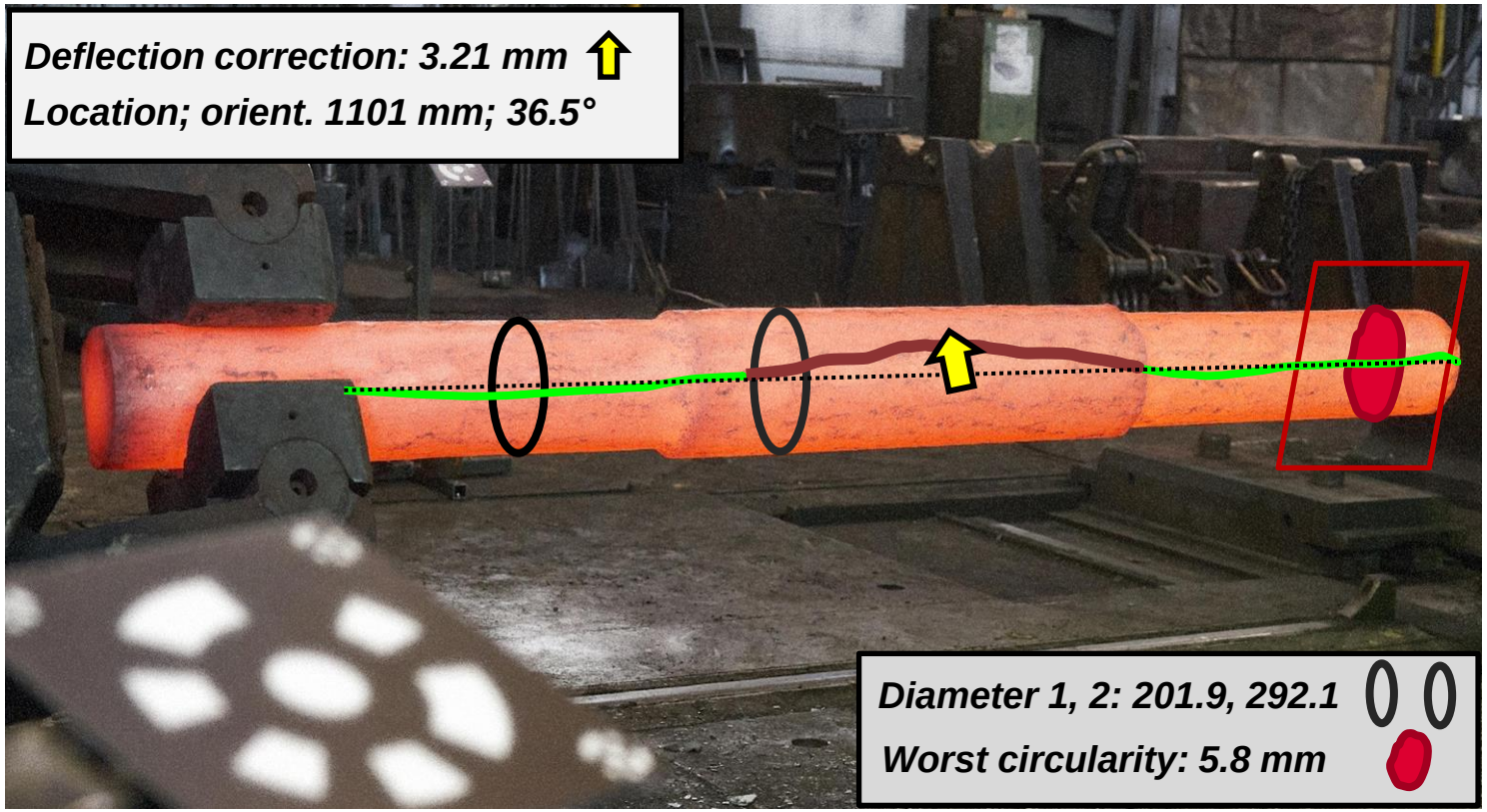
CONCLUSIONS

CONCLUSIONS

- TRL 4 → TRL 5-6
- Description of problems, specilized methods
- **Meas. error 0.5-2 % → 0.02 %**
- **Geometric characteristics**



Reconstructed geometry (Hurník et al. 2022)



Sample result

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LIST OF PUBLICATIONS

Journal papers with IF	**HURNÍK, J.**, A. ZATOČILOVÁ and D. PALOUŠEK. Circular coded target system for industrial applications. *Machine Vision and Applications*. 2021, 32(1), 1–14. ISSN 14321769. Available at: doi:10.1007/s00138-020- 01159-1 ***(IF 2.983; Q2)*** **HURNÍK, J.**, A. ZATOČILOVÁ, D. KOUTNÝ and D. PALOUŠEK. Enhancing the accuracy of forging measurement using silhouettes in images. *Measurement*. 2022, 194, 111059. ISSN 02632241. Available at: doi:10.1016/j.measurement.2022.111059 ***(IF 5.131; Q1)*** **HURNÍK, J.**, A. ZATOČILOVÁ, T. KONEČNÁ and P. ŠTARHA. Multi-view camera system for measurement of heavy forgings. *The International Journal of Advanced Manufacturing Technology*. 2022, ISSN 02683768. Available at: doi:10.1007/s00170-022-09809-6 ***(IF 3.563; Q2)*** MICHALEC, M., V. POLNICKÝ, J. FOLTÝN, P. SVOBODA, P. ŠPERKA and **J. HURNÍK**. The prediction of large-scale hydrostatic bearing pad misalignment error and its compensation using compliant support. Precision Engineering. 2022, 75, 67–79. ISSN 01416359. Available at: doi:10.1016/j.precisioneng.2022.01.011 ***(IF 3.315; Q2)*** MICHALEC, M., **J. HURNÍK**, J. FOLTÝN and P. SVOBODA. Contactless measurement of hydrostatic bearing lubricating film using optical point tracking method. Proceedings of the Institution of Mechanical Engineers Part J-Journal of Engineering Tribology. 2022, ISSN 13506501. Available at: doi:10.1177/13506501221108138 ***(IF 1.818, Q3)***
Conference papers	**HURNÍK, J.**, A. ZATOČILOVÁ and D. PALOUŠEK. Camera calibration method of optical system for large field measurement of hot forgings in heavy industry. In: *Opt. Meas. Syst. Ind. Inspect. XI, Proc. SPIE*. 2019, p. 11056. Available at: doi:10.1117/12.2527693 ***(Indexed in WoS)*** VRÁNA, R., VAVERKA, O., ČERVINEK, O., PANTĚLEJEV, L., **HURNÍK, J.**, KOUTNÝ, D., PALOUŠEK, D. Heat treatment of the SLM processed lattice structure made of AlSi10Mg and its effect on the impact energy absorption. In: Euro PM2019 Proceedings. 2019. ***(Indexed in Scopus)***

THANK YOU FOR YOUR ATTENTION

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