Friedrich-Alexander-Universität
Technische Fakultät

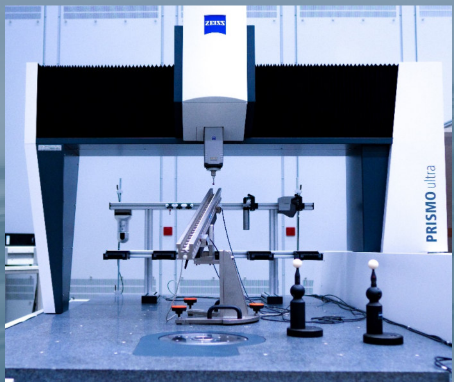
FMT LEHRSTUHL FÜR FERTIGUNGSMESSTECHNIK

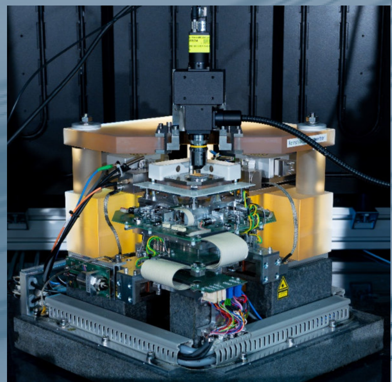
FAU

Numerical measurement uncertainty estimation for industrial computed tomography - from basic qualified software for X-ray radiographic simulation tools to numerical measurement uncertainty estimation using a virtual CT system

T. Hausotte

Keynote on **2nd International Workshop on Metrology for Virtual Measuring Instruments (VirtMet2025)**, Online, 03.12.2025





Overview

1 Motivation for the CTSimU project series and fundamentals

2 CTSimU1: Motivation, objectives, and results

3 CTSimU2: Motivation, objectives, and results

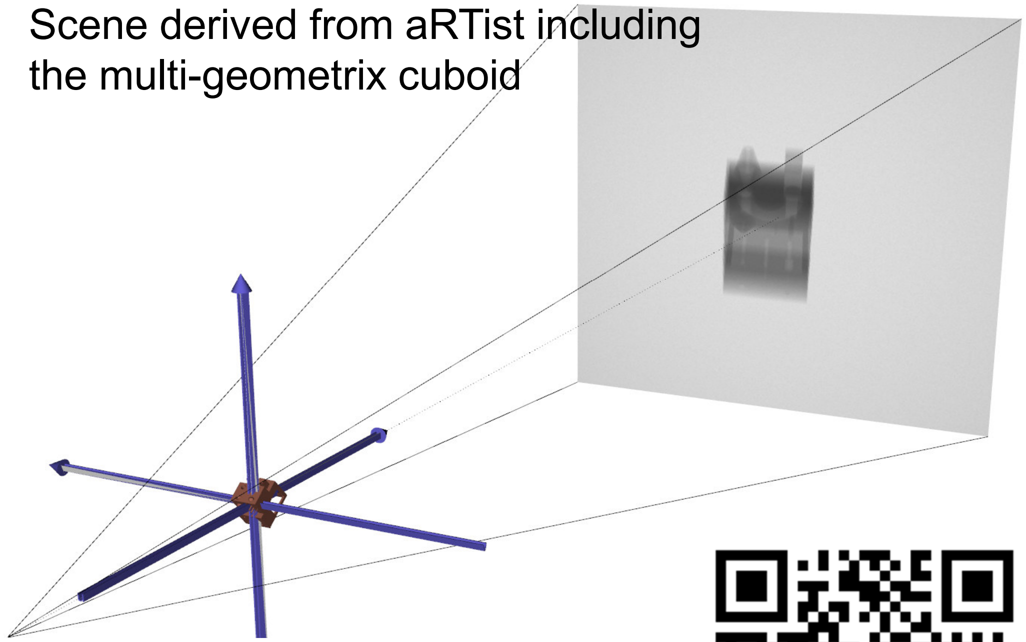
4 CTSimU3: Motivation, objectives, and approach

5 Application of Monte Carlo simulation results for conformity or non-conformity assessment

6 Impact of the project series on standardization

7 Summary

Scene derived from aRTist including the multi-geometrix cuboid



https://www.ctsimu.forschung.fau.de/

Motivation for the CTSimU project series and fundamentals

Introduction and motivation

Increasing use of industrial computed tomography (CT) for coordinate metrology

↓

Demand on accurate and reliable measurements with CT to gain acceptance of CT measurements

↓

Traceability to the metre is the key for accuracy and reliability

↓

Measurement uncertainty determination necessary

How could measurement uncertainty (MU) in industrial CT be determined in principle?

- ↓ Evaluation of measurement uncertainty with calibrated workpieces
- ↓ Evaluation of measurement uncertainty using measurement uncertainty budgets
- ↓ Evaluation of measurement uncertainty through simulation

Standards, guidelines and technical specifications

Relevant standards, guidelines and technical specifications for evaluation of measurement uncertainty

Publications of Joint Committee for Guides in Metrology (JCGM): Guides in Metrology

JCGM 100:2008(E) – in English
Evaluation of measurement data - Guide to the expression of uncertainty in measurement (2008)

JCGM 101:2008
Supplement 1 to the “Guide to the expression of uncertainty in measurement” - Propagation of distributions using a Monte Carlo method (2008)

JCGM 102:2011
Supplement 2 to the “Guide to the expression of uncertainty in measurement” - Extension to any number of output quantities (2011)

JCGM 106:2012
The role of measurement uncertainty in conformity assessment (2012)

JCGM GUM-1:2023
Guide to the expression of uncertainty in measurement - Part 1: Introduction (2023)

JCGM GUM-6:2020
Guide to the expression of uncertainty in measurement - Part 6: Developing and using measurement models (2020)

https://www.bipm.org/en/committees/jc/jcgm/publications

Standards, guidelines and technical specifications

Relevant standards, guidelines and technical specifications for evaluation of measurement uncertainty

ISO GPS standards

ISO 14253-2 “Geometrical product specifications (GPS) - Inspection by measurement of workpieces and measuring equipment - Part 2: Guidance for the estimation of uncertainty in GPS measurement, in calibration of measuring equipment and in product verification”

ISO 15530-3 “Geometrical product specifications (GPS) - Coordinate measuring machines (CMM): Technique for determining the uncertainty of measurement - Part 3: Use of calibrated workpieces or measurement standards”

ISO/TS 15530-4 “Geometrical product specifications (GPS). Coordinate measuring machines (CMM). Technique for determining the uncertainty of measurement. Evaluating task-specific measurement uncertainty using simulation”

VDI/VDE standards

VDI/VDE 2617 Part 7 “Accuracy of coordinate measuring machines - Parameters and their checking - Estimation of measurement uncertainty of coordinate measuring machines by means of simulation”

VDI/VDE 2617 Part 11: “Accuracy of coordinate measuring machines - Characteristics and their checking - Determination of the uncertainty of measurement for coordinate measuring machines using uncertainty budgets”

VDI/VDE 2630 Part 2.1 “Computed tomography in dimensional measurement - Determination of the uncertainty of measurement and the test process suitability of coordinate measurement systems with CT sensors”

Only VDI/VDE 2630 Part 2.1 is related to CT!

Motivation for the CTSimU project series

There are various standards, guidelines and technical specifications for evaluation of the measurement uncertainty, but they

- ➡ cannot be implemented due to the complexity of CT,
- ➡ do not take into account the special features of CT measurements,
- ➡ are time-consuming and resource-intensive (e.g. VDI/VDE 2630 Part 2.1)

Task-specific measurement uncertainty evaluation according to GUM Supplement 1 – Use of the Monte Carlo method

Resource and cost-saving?

No standardised procedure for

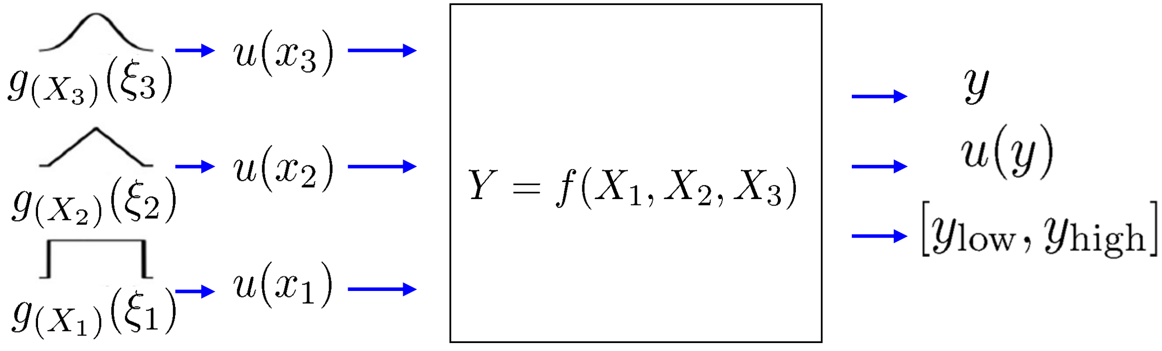
- qualifying simulation software,
- qualifying digital models and
- performing a dimensional measurement with uncertainty specification.

Motivation for the CTSimU project series

Evaluation of measurement uncertainty according to GUM Supplement 1

Measurement uncertainty (GUM standard procedure):

- propagation of the uncertainty values of the influencing factors through an analytical model of the measurement
- central limit theorem and assumption of normal distribution

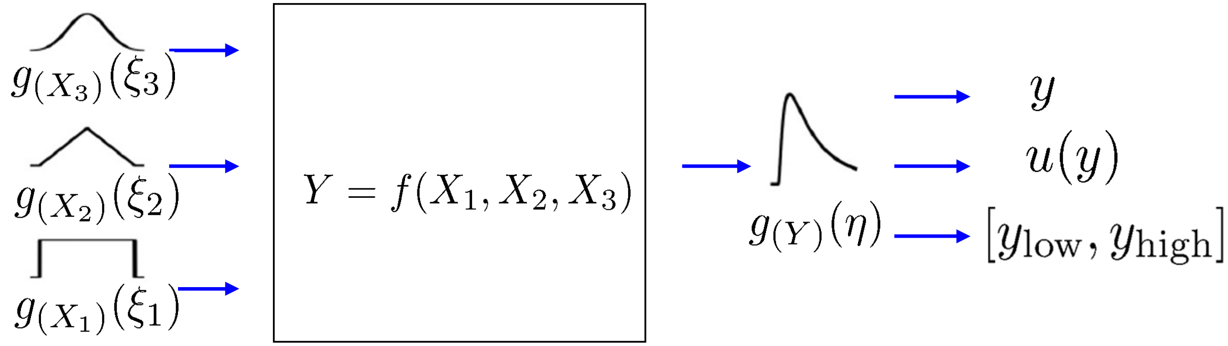


[JCGM 101:2008 Supplement 1]

Measurement uncertainty using the Monte Carlo method:

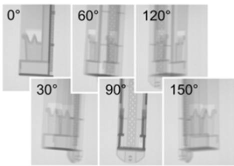
- propagation of distributions through an analytical or **numerical** model of the measurement

→ numerical approximation to the distribution function

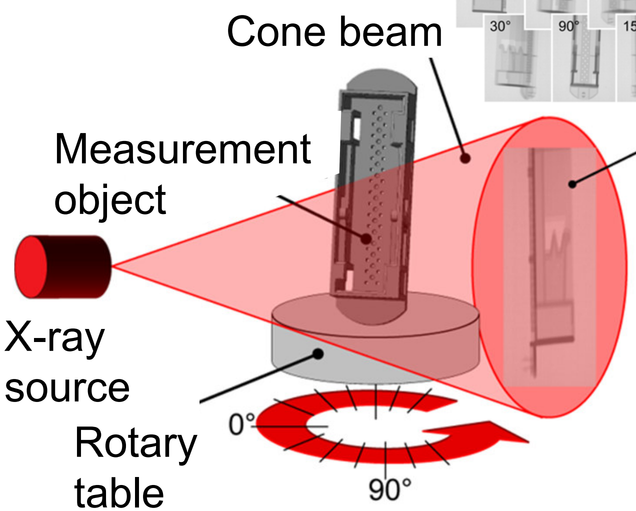


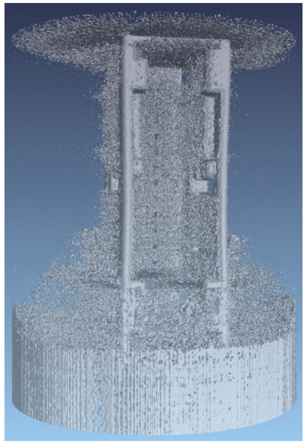
Workflow of dimensional CT measurements

CT measurement → Image stack → Recon-struction → Volumetric model → Surface estimation → Surface model → ISO GPS geometry evaluation / Actual/nominal comparison

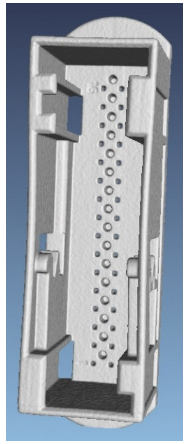


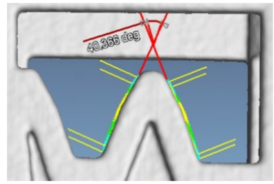
e.g. filtered back-projection

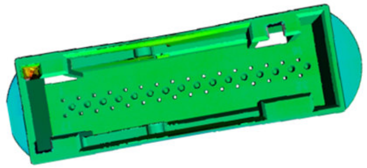




thresholding:
- ISO50
- local adaptive





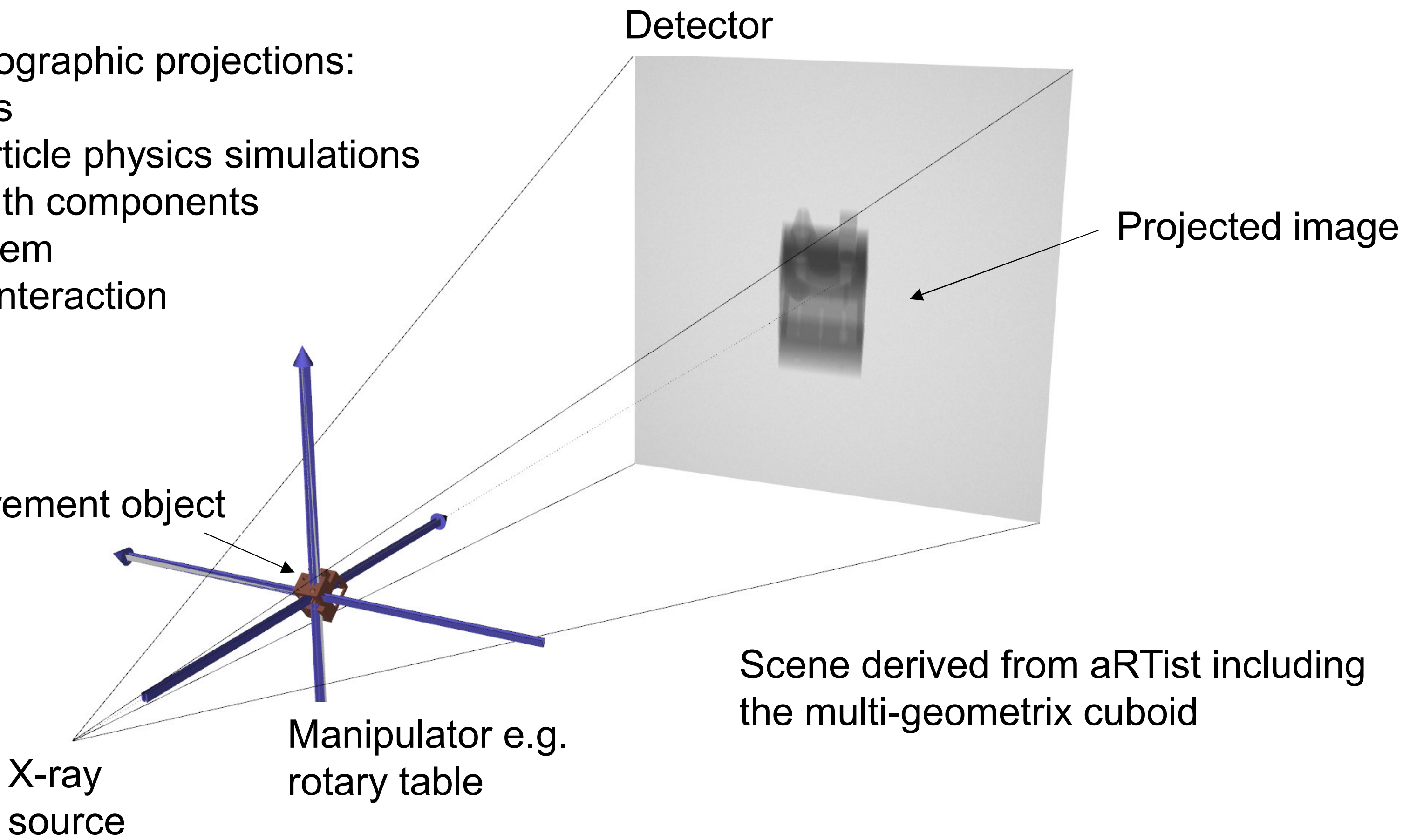


Software → direct useable for a digital metrological twin (D-MT)

CT system = Hardware → Process must be simulated using a realistic parametrised simulation software

How simulation software works

- Methods for simulating radiographic projections:
  - Ray casting simulations
  - Monte Carlo-based particle physics simulations
- Modelling a virtual scene with components analogous to a real CT system
- Modelling radiation-matter interaction



Scene derived from aRTist including the multi-geometrix cuboid

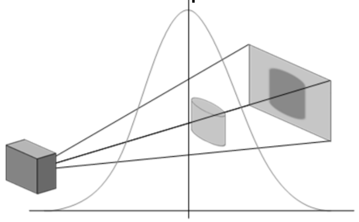
Structure of the CTSimU project series

WIPANO – Wissens- und Technologietransfer durch Patente und Normen

https://www.ptj.de/projektfoerderung/wipano-wissens-und-technologietransfer-durch-patente-und-normen

CTSimU1

Step 1: Test framework for testing the simulation software with regard to the correct reproduction of relevant physical effects and functionalities



✓

CTSimU2

Step 2: Toolbox for creating a digital model of a CT system and test for verification

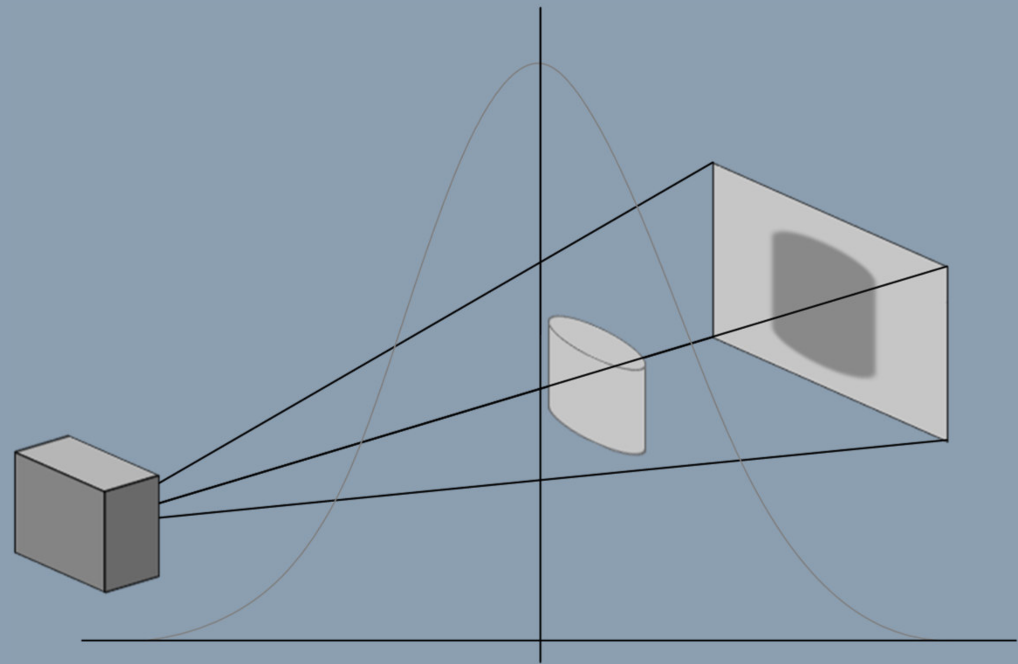
✓

CTSimU3

Step 3: Evaluation of the task-specific or measurement-specific measurement uncertainty (MU) by means of simulation using the Monte Carlo method

started

CTSimU1

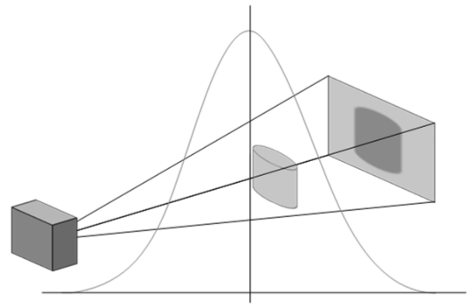


CTSimU1

Motivation and objectivs

Radiographic simulation for determining measurement uncertainty when measuring geometric features using X-ray computed tomography – basic qualification of simulation software

Consortium: 4 research partners, 5 industrial partners, 1 associated partner



Test framework for testing radiographic simulation software → Basic qualification of the radiographic simulation software

Draft of a standard for VDI/VDE 2630 series ‘Computed tomography in dimensional measurement’ → Submission to VDI/VDE-GMA Technical Committee 4.33 ‘Computed tomography in dimensional measurement’ for finalisation

Does simulation software adequately model the relevant physical laws of radiation, radiation-matter interaction and functionalities of CT scans?

CTSimU1

Requirements

Sections regarding:

(1) Detector of the CT system

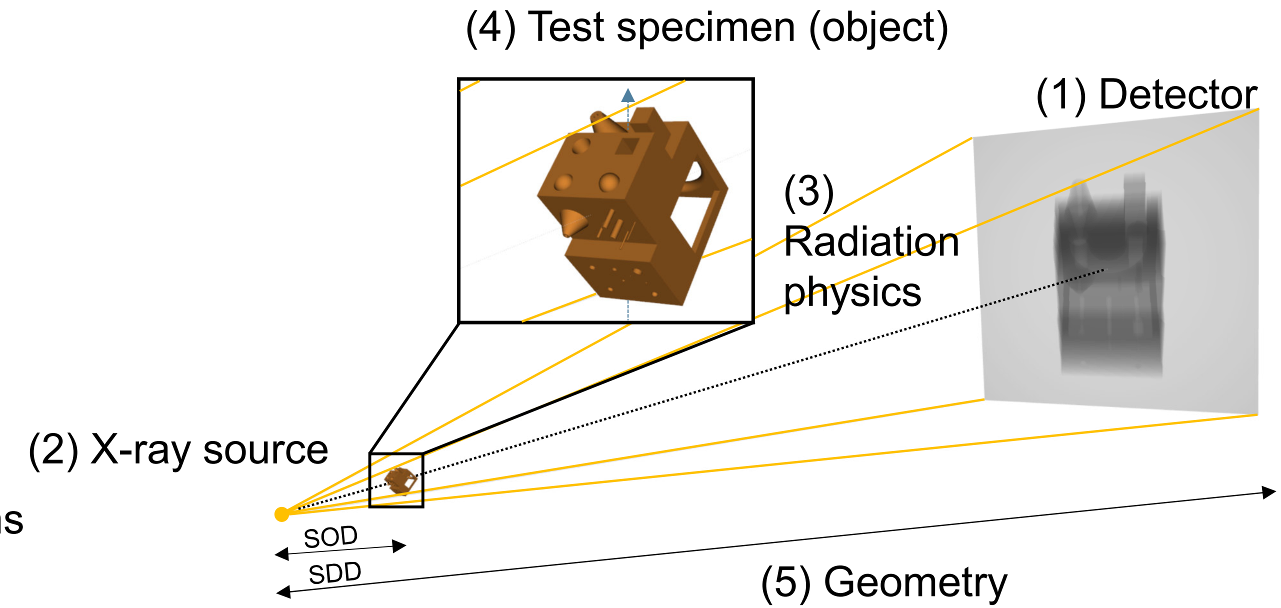
(2) X-ray source of the CT system

(3) Radiation physics

(4) Test specimen (object)

(5) Geometry of the CT system

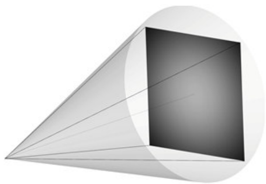
(6) Parameters for complete CT scans

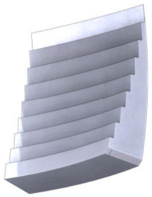


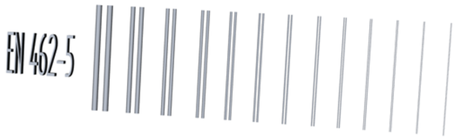
Objective: definition of requirements that are essential to conduct a dimensional measurement with a X-ray CT system

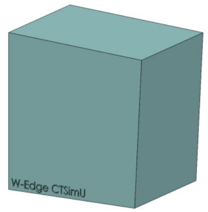
CTSimU1

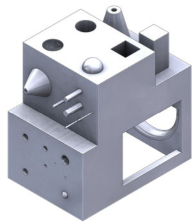
Virtual reference standards and test objectives











Free-beam (FB)

- Image noise
- Intensity profile

Conical hole sheet (HS)

- Position and orientation
  - Object
  - Detector

Spherical step wedge (SW)

- Material penetration length
- Extinction law, radiation-matter interaction
- Spectral filtering, beam hardening
- Scintillator characteristics
- Adjacent surfaces
- Scattered radiation

Duplex wire (DW)

- Detector unsharpness

Inclined Tungsten edge (WE)

- Partially covered pixels
- Focal spot size

Multi-geometry cuboid (3D test)

- 3D test involving all steps of the chain

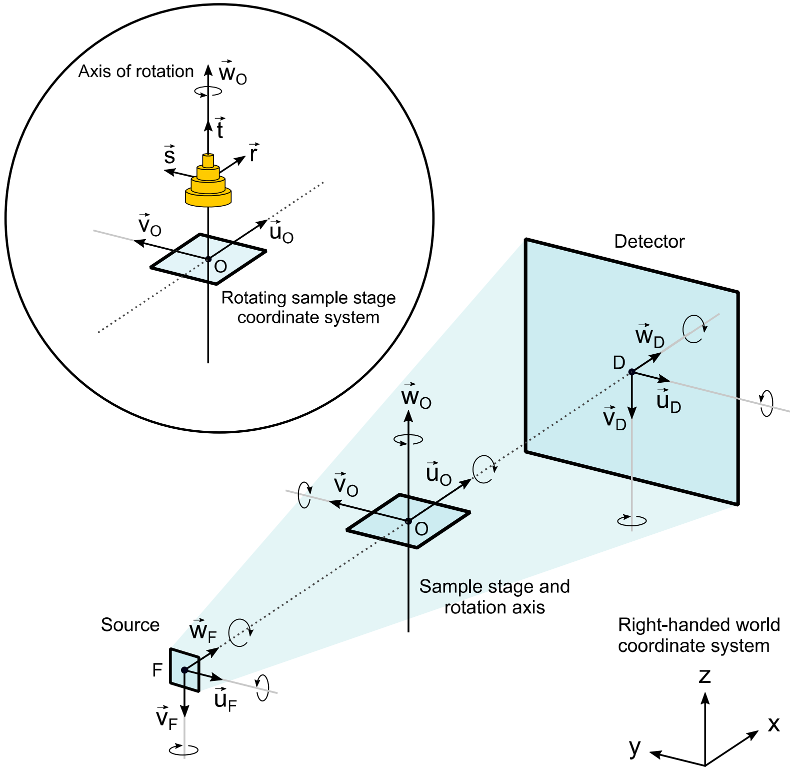
CTSimU1

Generalised file interface

- JSON (Java Script Object Notation) – file interface
- Serves as standardised specification for a complete CT scan:
  - Material
  - CT geometry with variations and deviation
  - X-ray source
  - Detector
  - Scan parameter
  - Test specimen (object)


```
"geometry":
{
    "detector":
    {
        "centre": {
            "x": {"value": 400, "unit": "mm", "uncertainty": {"value": 0, "unit": "mm"}, "drift": null},
            "y": {"value":   0, "unit": "mm", "uncertainty": {"value": 0, "unit": "mm"}, "drift": null},
            "z": {"value":   0, "unit": "mm", "uncertainty": {"value": 0, "unit": "mm"}, "drift": null}
        },

        "vector_u": {
            "x": {"value":  0, "drift": null},
            "y": {"value": -1, "drift": null},
            "z": {"value":  0, "drift": null}
```

CTSimU1

2D test example – Projection noise

SNR 150

↓ Simulation

Projections

↓ Evaluation (Evaluation Toolbox)

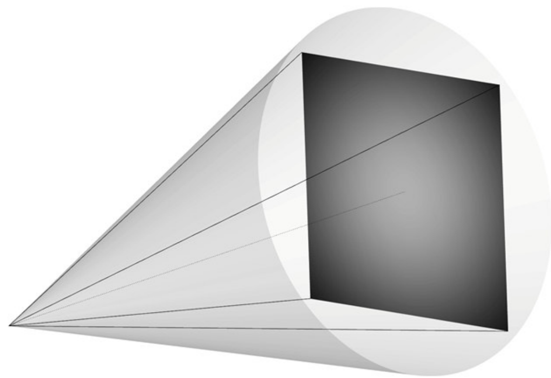
Result

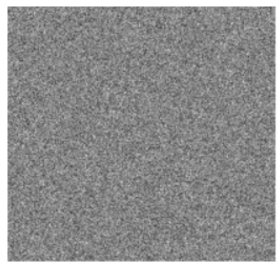
↓

Decision

Given: spectrum, SDD, detector geometry

Simulated SNR within the given interval?





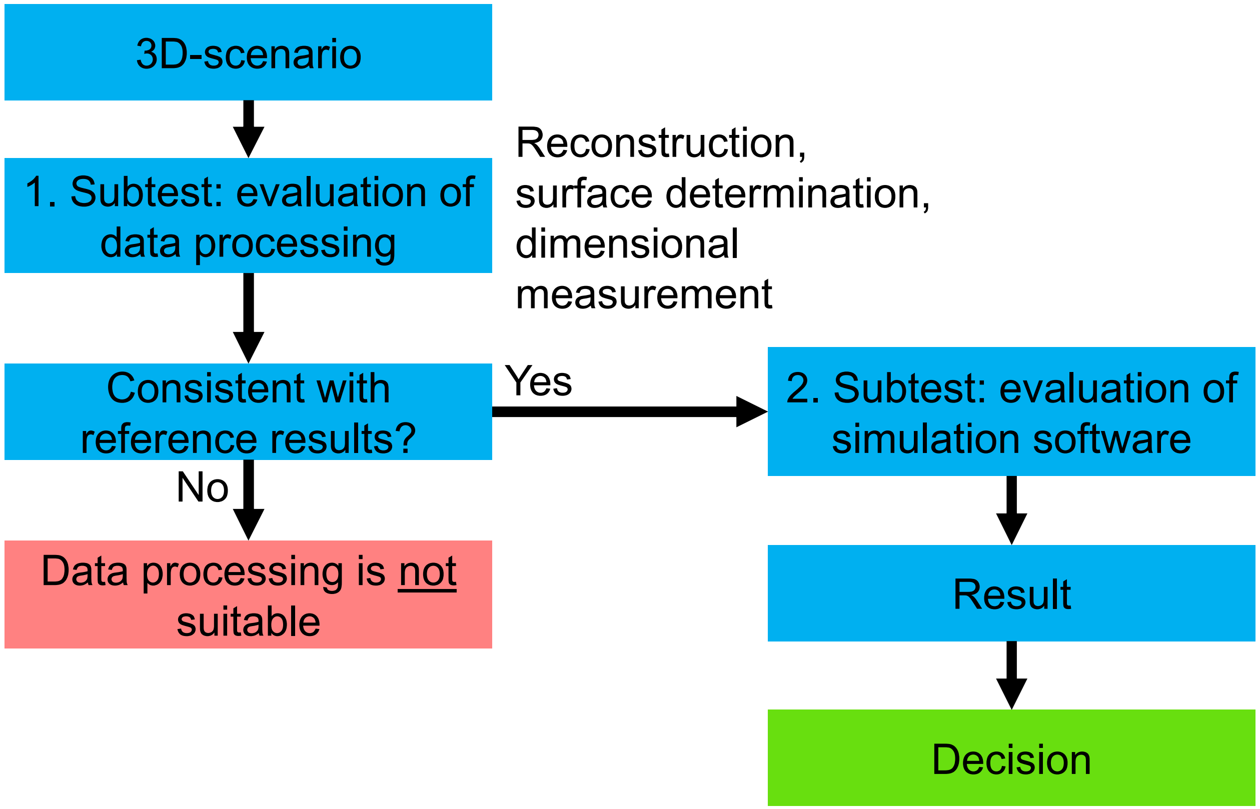
SNR 150 at max. intensity

Intervals for acceptable test results: Derived from parameter variations of a 3D scenario

Borges de Oliveira, F.; Reuter, T.; Plotzki, D.; Wohlgemuth, F.; Bartscher, M.; Bellon, C.; Kasperl, S.: Assessment of 2D-based tests for the qualification of simulation software for dXCT 34 (2023) 064005 (12 pp.), DOI 10.1088/1361-6501/acc1f9

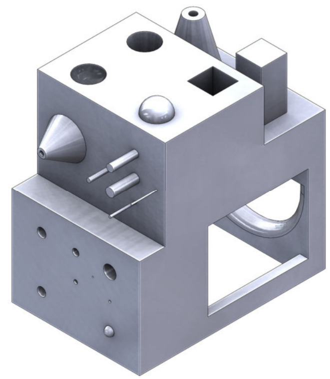
CTSimU1

3D test – process chain



Aim:

- Test of measurement chain
- Test of entire CT Scan
- Test regarding different challenges e.g. noise; detector unsharpness …



Multi-geometry cuboid

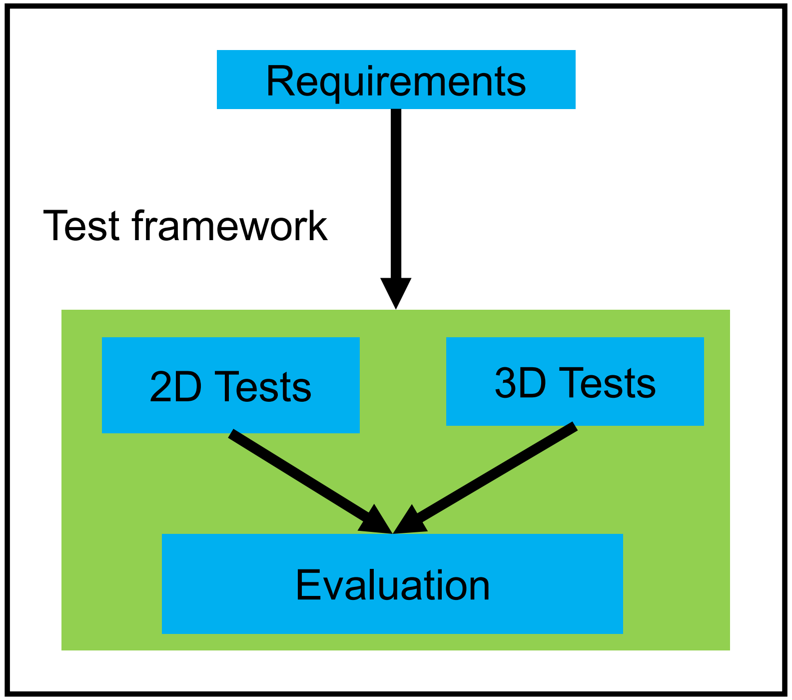
CTSimU1

Results

Simulation file interface (JSON)

New test specimens (virtual)

Image Processing Toolbox



Result: **Draft of a standard for VDI/VDE 2630 series**

<u>2D Tests</u>:
- 10 scenarios
- 4 different test specimens (virtual)

<u>3D Tests</u>:
- 2 Tests
- 1 test specimen (virtual)

<u>CTSimU evaluation toolbox:</u>
- Reference implementation for 2D tests
- Automated evaluation of 2D tests
- Based on Python

<u>VDI/VDE 2630 Part 2.2:2026-01</u>
Computed tomography in dimensional measurement - Determination of measurement uncertainty by simulation - Basic qualification of software for radiation simulation

CTSimU2

CTSimU2

Motivation and objectives

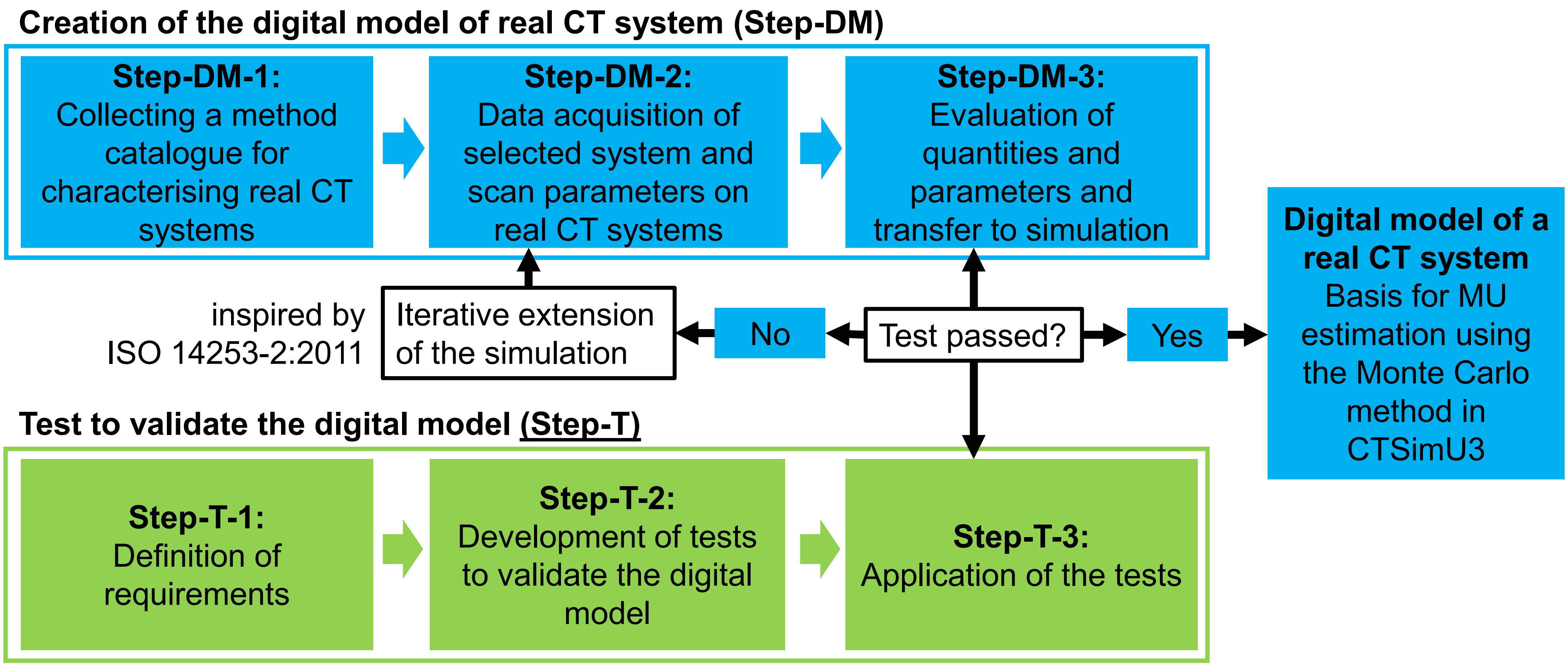
Realistic simulation of real X-ray computed tomography systems with basic simulation software

Consortium: 4 research partners, 7 industrial partners, 1 associated partner

Toolbox with methods for characterising a real CT system and modelling or parameterisation in simulation software	Parameterised digital model of a real CT system
Test to verify whether the digital model accurately reflects the dimensional measurements	Basic qualification of the digital model of a real CT system
Draft of a standard for VDI/VDE 2630 series 'Computed tomography in dimensional measurement'	Submission to VDI/VDE-GMA Technical Committee 4.33 'Computed tomography in dimensional measurement' for finalisation

CTSimU2

Procedure



CTSimU2

Procedure

Requirements for and testing of the digital model

- Definition of minimum requirements for the digital model (derived from the defined JSON interface from CTSimU1)
- Test concept based on modified metrological compatibility of repeated measurements on calibrated material standards

- Comparison of the results of the digital model with real measurement results in terms of metrological compatibility
- Identification of suitable deviation limits
- Documentation of the defined minimum requirements
- Examination of the test concept with regard to borderline cases/failures/external influences
- Definition of the test procedure

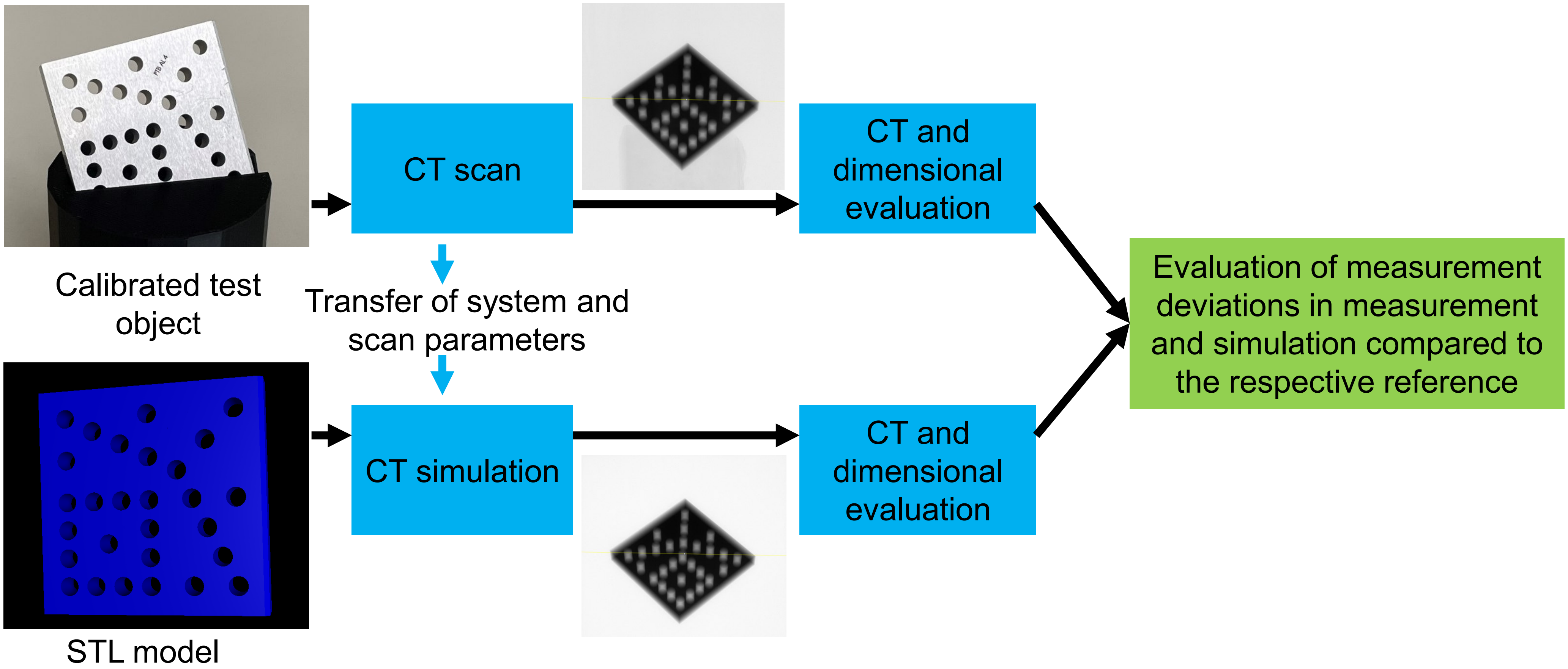
CTSimU2

Overview for system and scan parameters modelled in simulation

	Effects	Model
X-ray source	Spot size	✓
	Intensity distribution	✓/×
	Spectrum	✓
	Spot drift	×
Detector	Detector geometry (pixel size, number)	✓
	Scintillator thickness	✓
	Scintillator material	✓
	Noise	✓
	Back scattering	×
	Unsharpness	✓
System geometry	Modelling of the measurement trajectory (calibration, manipulator translations)	✓
	Dynamic deviations of the rotary table	✓/×
	Positioning accuracy of manipulator (translation)	×
Test object	Positioning of the test object	✓
	Manufacturing deviations of the actual test object	×
	Scattered radiation	✓

CTSimU2

Modelling of a measurement



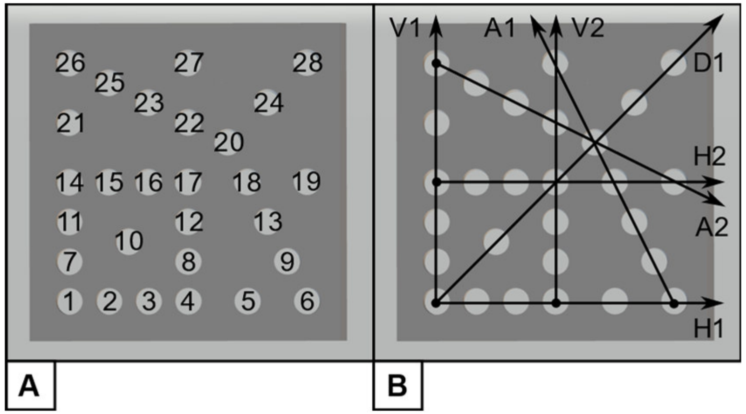
CTSimU2

Performing measurements on calibrated workpiece
Repeated measurement of calibrated aluminium hole plate

Example: Repeated measurements of calibrated aluminium hole plate (10 repeated measurements)

Scan parameters:

Acceleration voltage	150 kV
Tube current	180 µA
Exposure time	2 s
Number of projections	2050
Magnification	4.9
Voxel size	40.7 µm
Pre-filter	0.5 mm Copper



Source: Felix Binder *et al* 2022 *Meas. Sci. Technol.* **33** 104002

Size: 48 x 48 x 8 mm³

Quantities:

- 28 Hole diameters
- 35 Centre-to-centre distances

CTSimU2

Parameterisation and characterization
Measurement model in the simulation

X-ray source

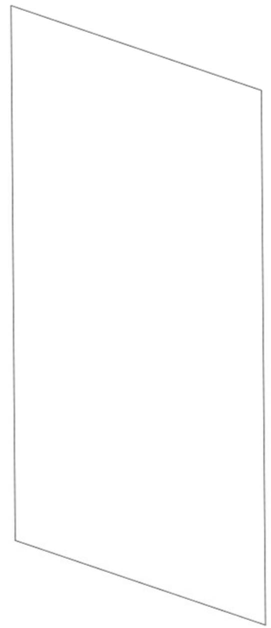
- **Calculated polychromatic spectrum** (Target type, Tube geometry, Source filter, Tube voltage)
- **Gaussian spot** (power)

Scan geometry and workpiece

- **Calibrated trajectory**
- **Digital workpiece model with nominal geometry and aluminium alloy according to data sheet**
- **Orientation of the workpiece in the measuring volume derived from actual measurement**
- **Scattered radiation**

Detector and image

- **Detector characteristic curve** (scintillator material and thickness)
- **Linear energy to grey value characteristic**
- **Noise** (SNR at maximum grey value)
- **Blurring** (iSrb and long range unsharpness)



All input parameters were assumed to be static nominal values
→ Variance in measurement values results only from noise and scattered radiation

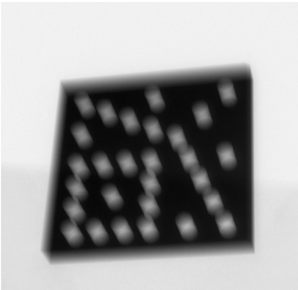
CTSimU2

Evaluation - Workflow

Repeated measurements of a calibrated aluminium hole plate

Real Measurements

METROTOM 1500
(Zeiss)



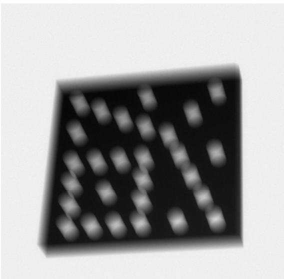
METROTOM OS
(Zeiss)

METROTOM OS
(Zeiss)

VG Studio Max
(Volume Graphics)

Projection acquisition → Bright and dark image correction → FDK-Reconstruction → Surface determination and measurement strategy

Simulated Measurements



MATLAB
(The Math Works, Inc.)

CERA
(Siemens Healthcare)

VG Studio Max
(Volume Graphics)

aRTist
(BAM)

CTSimU2

Dimensional evaluation of the measured variables

$$e_{\bar{x}} = \bar{x} - x_{\text{ref}}$$

- Measurement: tactile calibration
- Simulation: value of digital component representation

$e_{\bar{x}}$: mean measurement error
$\bar{x}$: averaged measured value
x_{ref}: reference value

Actual measurement is subject to external influences (e.g. calibration, temperature) → Uncertainty analysis

Measurement:
Measurement uncertainty based on VDI 2630 Part 2.1 (adapted for repeated measurements)

$$U_{\text{meas}}(\bar{x}_{\text{meas}}) = k \cdot \sqrt{u_{\text{cal}}^2 + \left(\frac{u_{\text{p,meas}}}{\sqrt{n}}\right)^2 + u_{\text{b}}^2}$$

Simulation:
Uncertainty due to noise and scattered radiation

$$U_{\text{sim}}(\bar{x}_{\text{sim}}) = k \cdot \frac{u_{\text{p,sim}}}{\sqrt{n}}$$

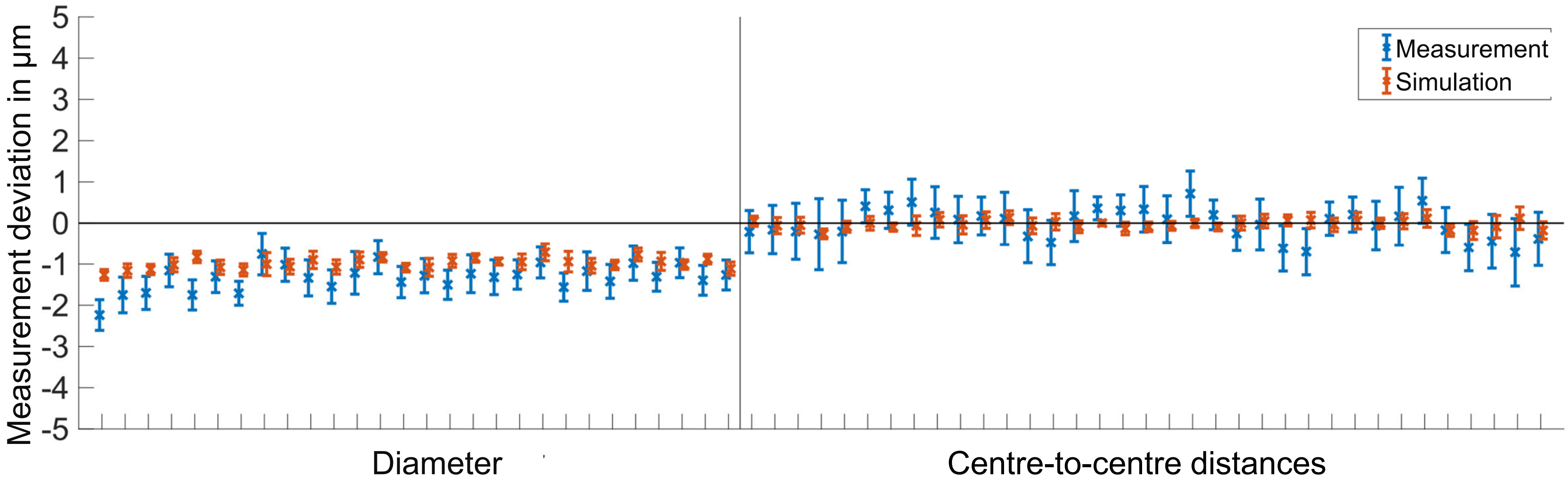
For a detailed description of the procedure shown here, see also:
M. Braun *et. al.*, „Simulation of a real dimensional CT measurement study using a calibrated aluminum specimen“, doi: 10.58286/31414

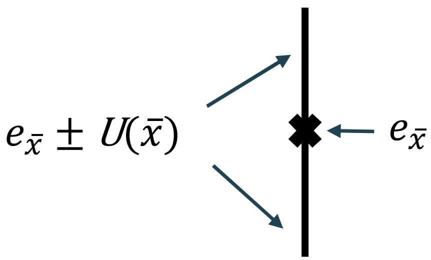
$U(\bar{x})$: expanded measurement uncertainty for the mean value $\bar{x}$
u_{p}: standard deviation of repeated CT measurements
u_{cal}: standard calibration uncertainty
u_{b}: uncertainty of the correction of the systematic error (here: only temperature!)
n: number of repeated meausurement
k: coverage factor

CTSimU2

Measurement results

Repeated measurement of calibrated aluminium hole plate





$$e_{\bar{x}} = \bar{x} - x_{\text{ref}}$$

$$U_{\text{meas}}(\bar{x}_{\text{meas}}) = k \cdot \sqrt{u_{\text{cal}}^2 + \left(\frac{u_{p,\text{meas}}}{\sqrt{n}}\right)^2 + u_{\text{b}}^2}$$

$$U_{\text{sim}}(\bar{x}_{\text{sim}}) = k \cdot \frac{u_{\text{p,sim}}}{\sqrt{n}}$$

Sufficient agreement between measurement and simulation?

CTSimU2

Testing the digital model
Metrological compatibility

Test criterion: Adapted approach for the E_n value according to (DIN EN ISO/IEC 17043:2023)

$$E_\mathrm{n,DM} = \frac{(\bar{x}_\mathrm{sim} - x_\mathrm{ref,sim}) - (\bar{x}_\mathrm{meas} - x_\mathrm{ref,meas})}{\sqrt{U^2_\mathrm{sim}(\bar{x}_\mathrm{sim}) + U^2_\mathrm{meas}(\bar{x}_\mathrm{meas})}}$$

$E_\mathrm{n,DM}$: normalized error of the digital model
$\bar{x}$: mean measured value
x_ref: reference value

$$\left|E_\mathrm{n,DM}\right| \leq 1$$

→ The difference between the simulated and measured mean values of the systematic measurement deviation is smaller than the associated uncertainty of this difference.

$$\left|E_\mathrm{n,DM}\right| \leq \sqrt{n}$$

→ A digital model does not require the implementation of distributions of relevant influencing factors. Depending on the application, it may be sufficient for the digital model to meet a weaker requirement. (no direct mathematical interpretation of the limit value)

Adaptation of the E_n value demands boundary conditions in order to maintain the significance of the parameter

CTSimU2

Testing the digital model
Boundary conditions

Boundary conditions

1. The calibration uncertainty must be sufficiently smaller than the standard deviation of the CT repeated measurements.

a) $q_{\text{cal}} = \frac{u_{\text{cal}}}{u_{\text{p,meas}}} \leq q_{\text{l,cal}}$

2. The standard deviation of the simulated measurement must not exceed a certain level relative to the standard deviation of the actual CT measurement.

b) $q_{\text{sim}} = \frac{u_{\text{p,sim}}}{u_{\text{p,meas}}} \leq q_{\text{l,sim}}$

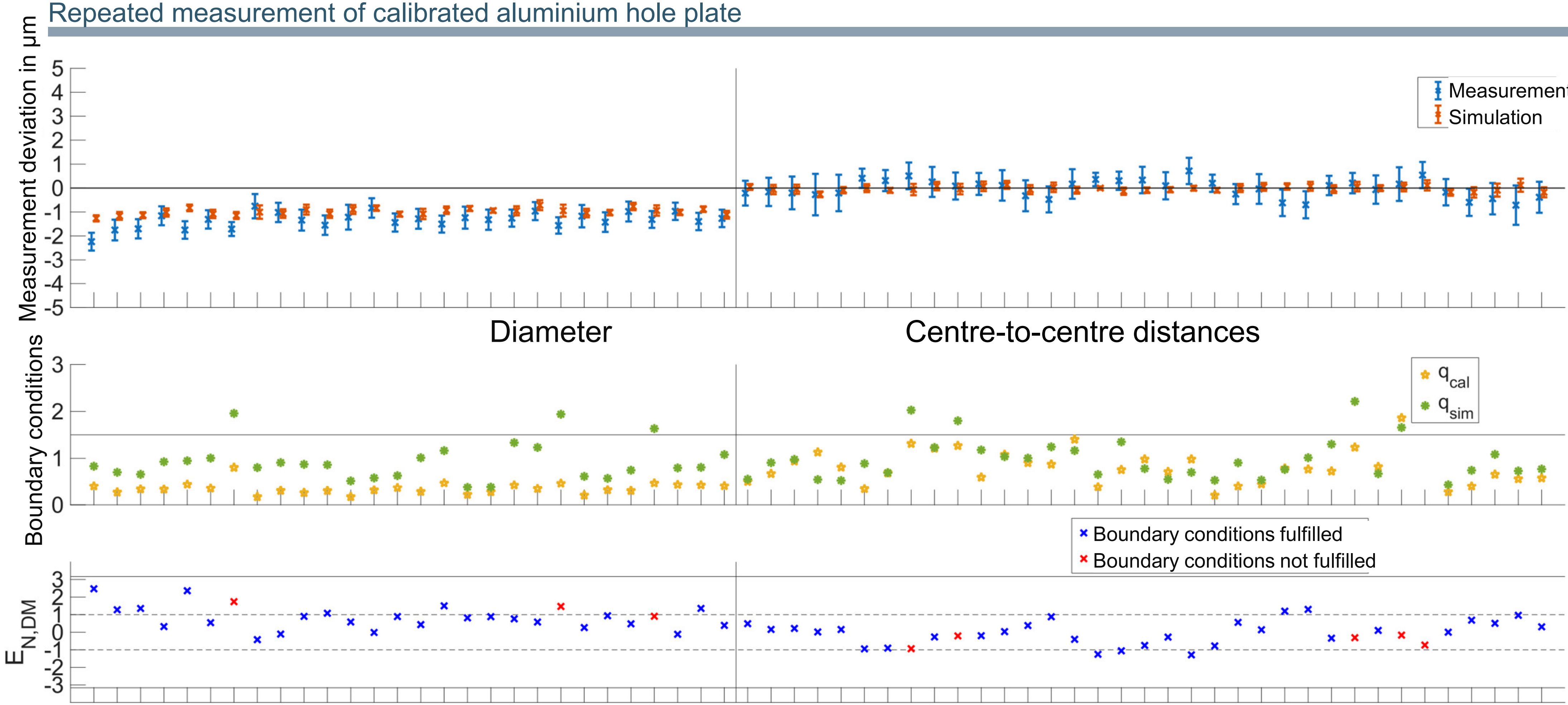
u_{p} : Standard deviation of repeated CT measurements
u_{cal} : Standard calibration uncertainty
$q_{\text{l,cal}}$: Maximum ratio

For $q_{\text{l,cal}}$ and $q_{\text{l,sim}}$, for example, 1.5 can be selected in each case.

CTSimU2

Test results

Repeated measurement of calibrated aluminium hole plate



CTSimU2

Results

Comprehensive literature review and systematisation of methods for obtaining parameters	Review article about the methods for characterising a real CT system is currently being drafted
Parameter acquisition from real CT systems, modelling and parameter evaluation as well as parameter conversion for simulation software	Improvement and extension of the simulation file interface (JSON)
Development of the test to verify whether the digital model accurately reflects the dimensional measurements	Further improvement and extension of the image processing toolbox and application of the test with various calibrated material standards (https://bamresearch.github.io/ctsimu-toolbox/)

Result: **Draft of a standard for VDI/VDE 2630 series**

Submission to VDI/VDE-GMA Technical Committee 4.33 ‘Computed tomography in dimensional measurement’ for finalisation

CTSimU3

CTSimU3

Motivation and objectivs

Evaluation of the uncertainty of X-ray computed tomography measurements of geometric features through simulation

Consortium: 4 research partners, 7 industrial partners, 5 associated partners

Evaluation of MU: Identification and prioritisation of the key influences on MU in CT, evaluation of influence factor distributions (how and which influence factors vary on which time scales), toolbox for Monte Carlo simulation and evaluation (discrete distributions, estimated values of measured quantities and coverage intervals), identification of simulation termination criteria, verification.

Verification that the evaluated MU is stable and reliable according to the state of the art and that it accurately reflects the real uncertainty.

Draft of a standard for VDI/VDE 2630 series ‘Computed tomography in dimensional measurement’

→ Submission to VDI/VDE-GMA Technical Committee 4.33 ‘Computed tomography in dimensional measurement’ for finalisation

CTSimU3

Determination of the uncertainty of X-ray computed tomography measurements of geometric features by simulation

Starting point from CTSimU2: Sufficiently accurate digital model

Evaluation of the distribution of influencing quantities of relevant scan and CT system parameters

Implementation of influencing factor distributions and simulation
→ Monte Carlo method

Identification of suitable termination criteria
→ Reduction in the number of simulations required

Verification of the determined MU by comparison with experimental MU according to VDI/VDE 2630 Part 2.1:2015-06

Result:
Method for the evaluation of the numerical, task- or measurement-specific MU of CT measurements

Application of Monte Carlo simulation results for conformity or non-conformity assessment

Application of Monte Carlo simulation result

Possible overall process for conformity and non-conformity assessment

Measurement uncertainty / discrete representation of the distribution from Monte Carlo simulation (see JCGM 101:2008)

Fitting the underlying distribution function
→ Distribution parameters and goodness of fit

Test with conformity and non-conformity probabilities (see JCGM 106:2008 Chapter 7)

Calculation of the **probability of conformity or non-conformity** using the distribution function / sorted discrete representation of the distribution and specification limits (Y_{LSL}, Y_{USL}, or both)

Comparison with the limits of conformity and non-conformity probability (p_{AL} und p_{RL})

Test with guard bands and acceptance and rejection limits (see JCGM 106:2008 Chapter 8)

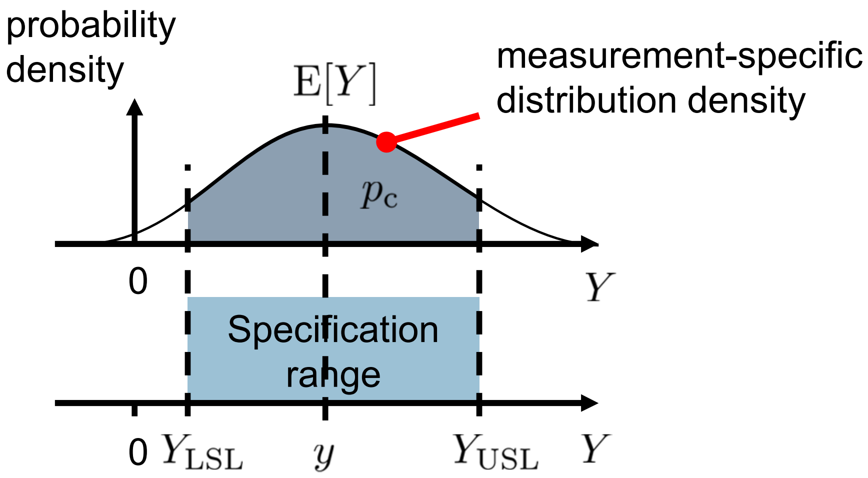
Calculation of **guard bands** for conformity or non-conformity with the distribution function / sorted discrete representation of the distribution and specification limits (Y_{LSL}, Y_{USL}, or both)

Comparison of measurement results with acceptance and rejection limits calculated from specification limits and guard bands

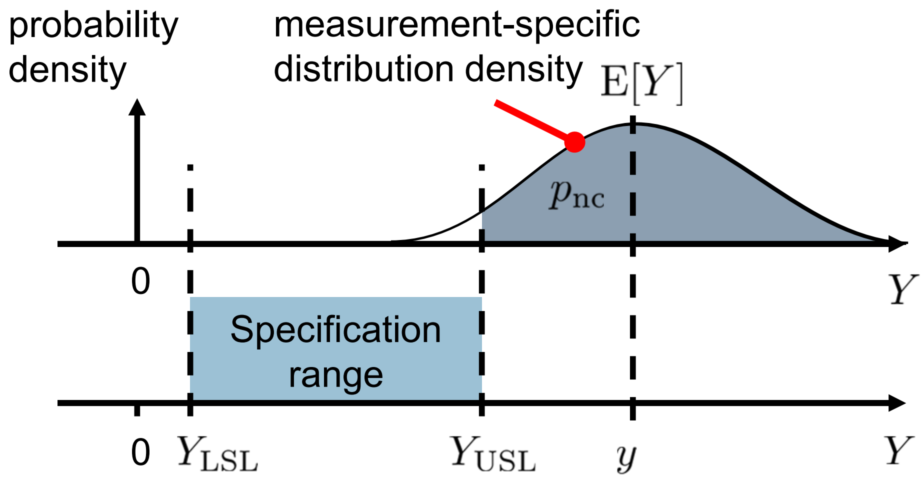
Conformity and non-conformity assessment

Test with conformity and non-conformity probabilities (see JCGM 10:2008 Chapter 7)

Conformity assessment



Non-conformity assessment



Y measurand and *y* measured value

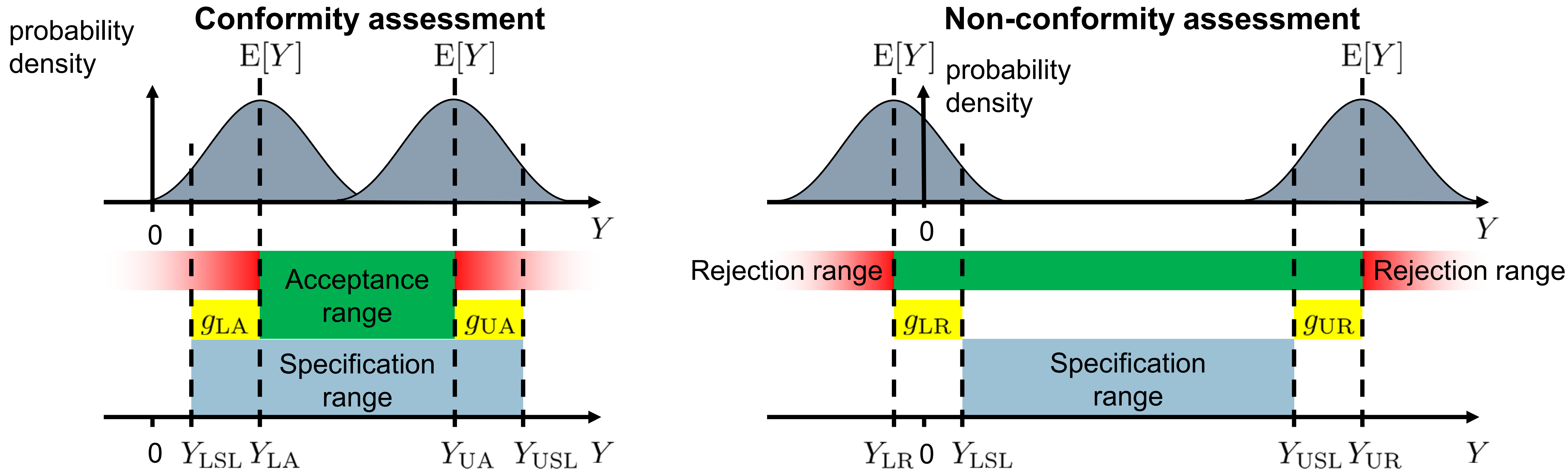
Y_{LSL} and Y_{USL} lower and upper specification limits

p_c and p_{nc} Probability of conformity and probability of non-conformity

p_{AL} and p_{RL} Limits of conformity probability and non-conformity probability

Conformity and non-conformity assessment

Test with guard bands and acceptance and rejection limits (see JCGM 106:2008 Chapter 8)



Y measurand

g_{LA} and g_{UA} guard bands

Y_{LA} and Y_{UA} smallest and largest measured value for which conformity can be confirmed

Y_{LSL} and Y_{USL} lower and upper specification limits

g_{LR} and g_{UR} guard bands

Y_{LR} and Y_{UR} smallest and largest measured value for which non-conformity can be confirmed

Impact of the project series on standardization

Impact of the project series on standardization

The work in the project series directly or indirectly influences standardisation work in the following committees:

- VDI/VDE-GMA Technical Committee 4.33 “Computed tomography in dimensional measurement”
- VDI/VDE-GMA Technical Committee 4.31 / DIN NA 152-03-02-12 GUA “Coordinate measuring technology”
- ISO/TC 213 Dimensional and geometrical product specifications and verification
  - WG 10 Coordinate measuring machines (German mirror committee: DIN NA 152-03-02-12 GUA “Coordinate measuring technology”)
- VDI/VDE-GMA Technical Committee 1.12 “Measurement uncertainty and test process suitability”
- German Society for Non-Destructive Testing (Deutsche Gesellschaft für Zerstörungsfreie Prüfung, DGZfP) Subcommittee (UA) CT
- ISO/TC 213 Dimensional and geometrical product specifications and verification
  - WG 4 Uncertainty of measurement and decision rules (German mirror committee: DIN NA 152-03-02 AA CEN/ISO “Geometric product specification and verification”

Summary

Summary and Outlook

Summary

- Motivation for the CTSimU project series and fundamentals
- Motivation, objectives, and results for the projects CTSimU1 and CTSimU2
- Motivation, objectives, and approach for the started project CTSimU3
- Application of Monte Carlo simulation results for conformity or non-conformity assessment
- Impact of the project series on standardisation

Outlook

- Upon completion of the CTSimU3 project, the results of the project series will hopefully lead to better acceptance of CT for dimensional measurements and to optimisation of CT measurements.

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FMT LEHRSTUHL FÜR FERTIGUNGSMESSTECHNIK

FAU

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Thank you

for your attention!

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