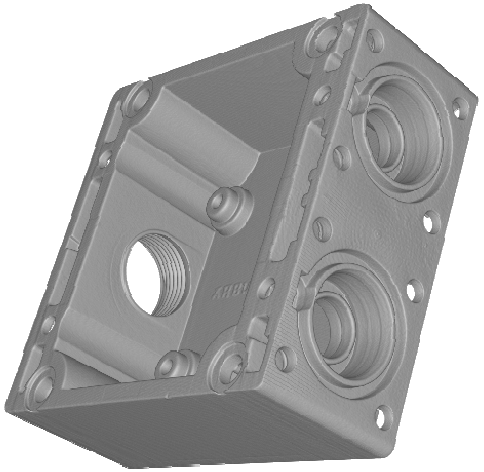


Improving the Production using X-Ray Computed Tomography - Potentials and Challenges

National conference on CT scanning - Application of CT Scanning in Industry

Danish Technological Institute Taastrup, May 31st 2011

Prof. Dr.-Ing. Robert Schmitt,
Dipl.-Ing. Christian Niggemann

RWTH Aachen University,

Chair of Metrology and Quality Management

Outline

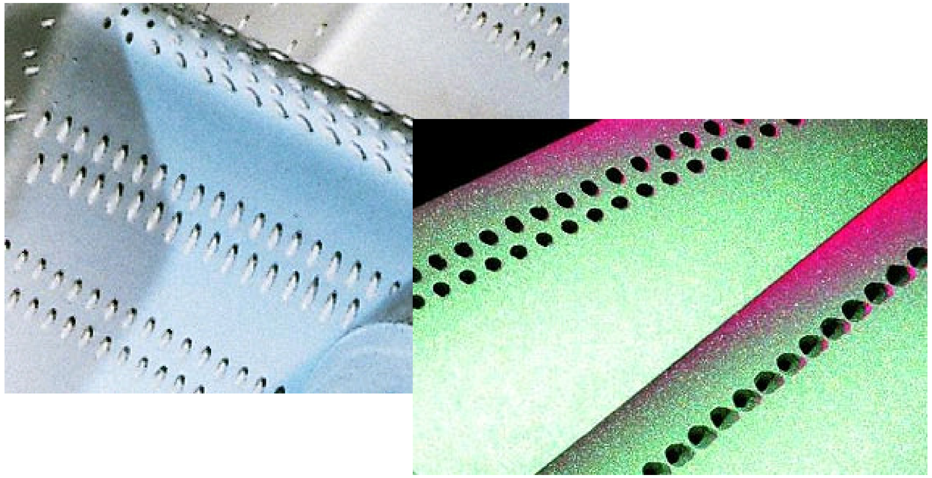
1 X-Ray Computed Tomography as inspection technology

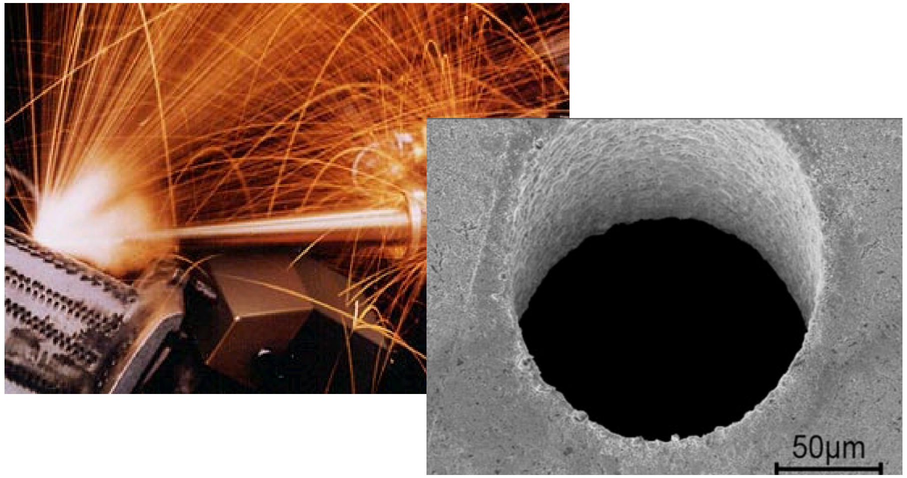
2 Technological challenges

3 Integration and planning aspects

4 Application aspects

More complex High-Tech-Products conquer the market
Production processes reach technological limits





Laser Drilling:

- Focusing of laser beam onto the surface of a turbine blade
- The high energy density of the laser beam leads to a local melting of the blade material
- Drilling of cylindrical bore holes through several short laser pulses on the same spot

Challenge:

- Bore holes have to be through holes
- But structures behind the bore holes must not be damaged by the laser beam

➡ How can the conformity of the inner and outer geometry of such a part be proved non-destructively to assure the quality of the production process?

Image sources: Courtesy of MTU, GFH GmbH

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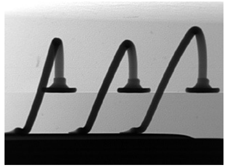
State of the art for inspection of work pieces with complex geometry

- For the first sample release a lot of features have to be checked
- Some features are inaccessible for tactile or light-optical sensors
- This could mean elaborate additional destructive testing
- Some of these features cannot even be acquired with adequate uncertainty by destructive testing, e.g. not embodied features
- Currently, the 100%-control of the all relevant geometric features is technologically and economically not feasible

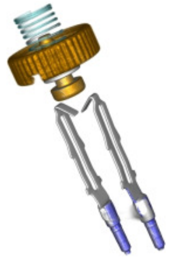
➔ X-Ray Computed Tomography can be an answer to the inspection of inaccessible features and holistic acquisition of the work piece geometry

Basic developments for the X-Ray Inspection technology

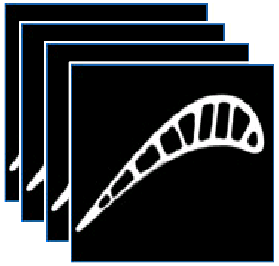
First commercial X-Ray source with micro focus for industrial applications



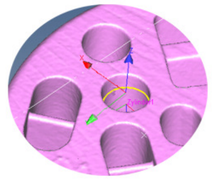
Volumetric acquisition of the work piece with 3D CT



Inspection of interior features for turbine blades with 2D CT



Measurement of geometric features by enhanced system concepts

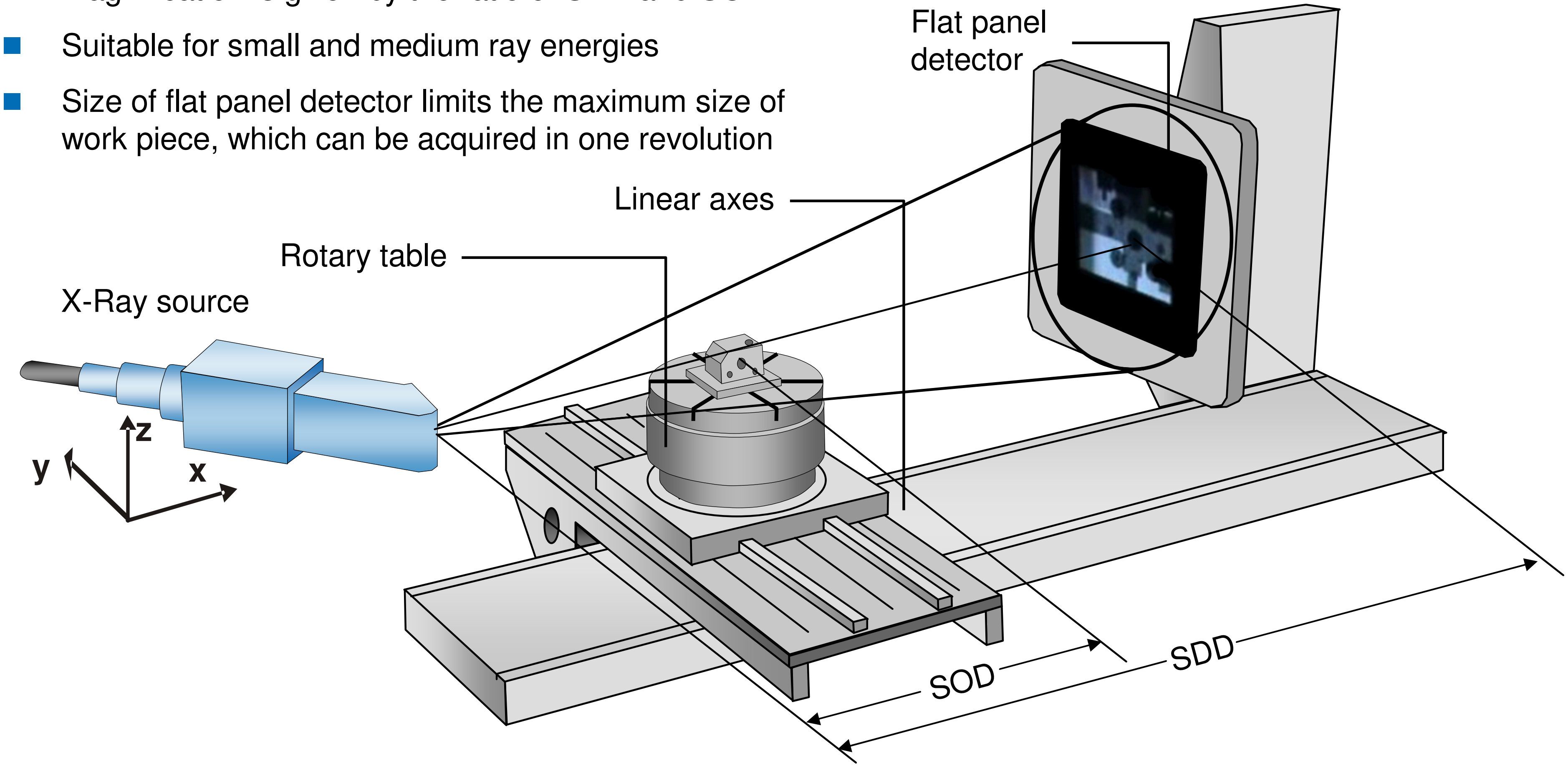


1980 | 1990 | 2000

Image sources: Courtesy of Nordson Dage, Pratt & Whitney, WZL

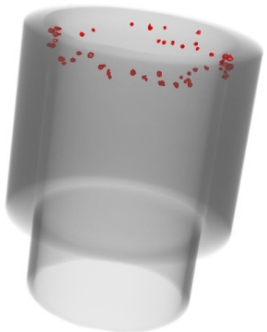
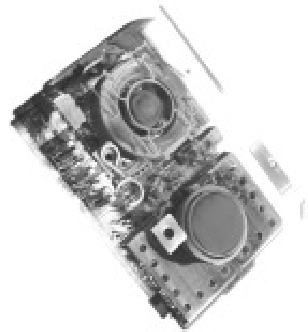
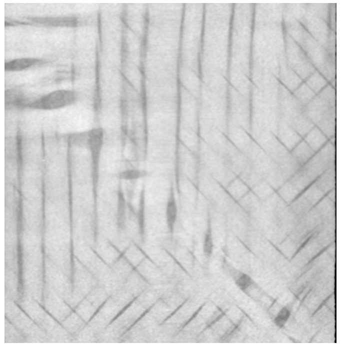
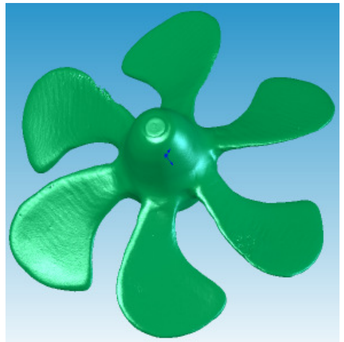
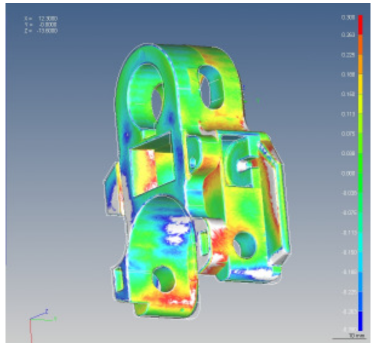
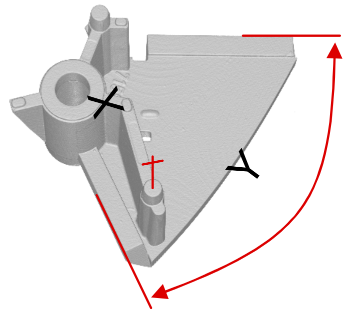
Set-up of a typical industrial CT scanner with cone-beam

- Volumetric acquisition of the work piece
- Magnification is given by the ratio of SDD and SOD
- Suitable for small and medium ray energies
- Size of flat panel detector limits the maximum size of work piece, which can be acquired in one revolution



Tasks that can be performed by CT

- Detection of voids and inclusions
- Mounting control of assemblies
- Damage analysis
- Additional analysis of destructive tests, e.g. analysis of failure mechanisms for Fiber-Reinforced Plastic Parts
- Reverse Engineering
- Dimensional Measurements
  - CAD-to-Part-Comparison – Comparison to nominal geometry (CAD-Model)
  - Part-to-Part-Comparison – Comparison to reference measurement, e.g. tactile, optical or other CT-measurement)
  - Measurement of features according to inspection plan (Fitting of regular geometries)
  - Wall thickness analysis, e.g. casted parts

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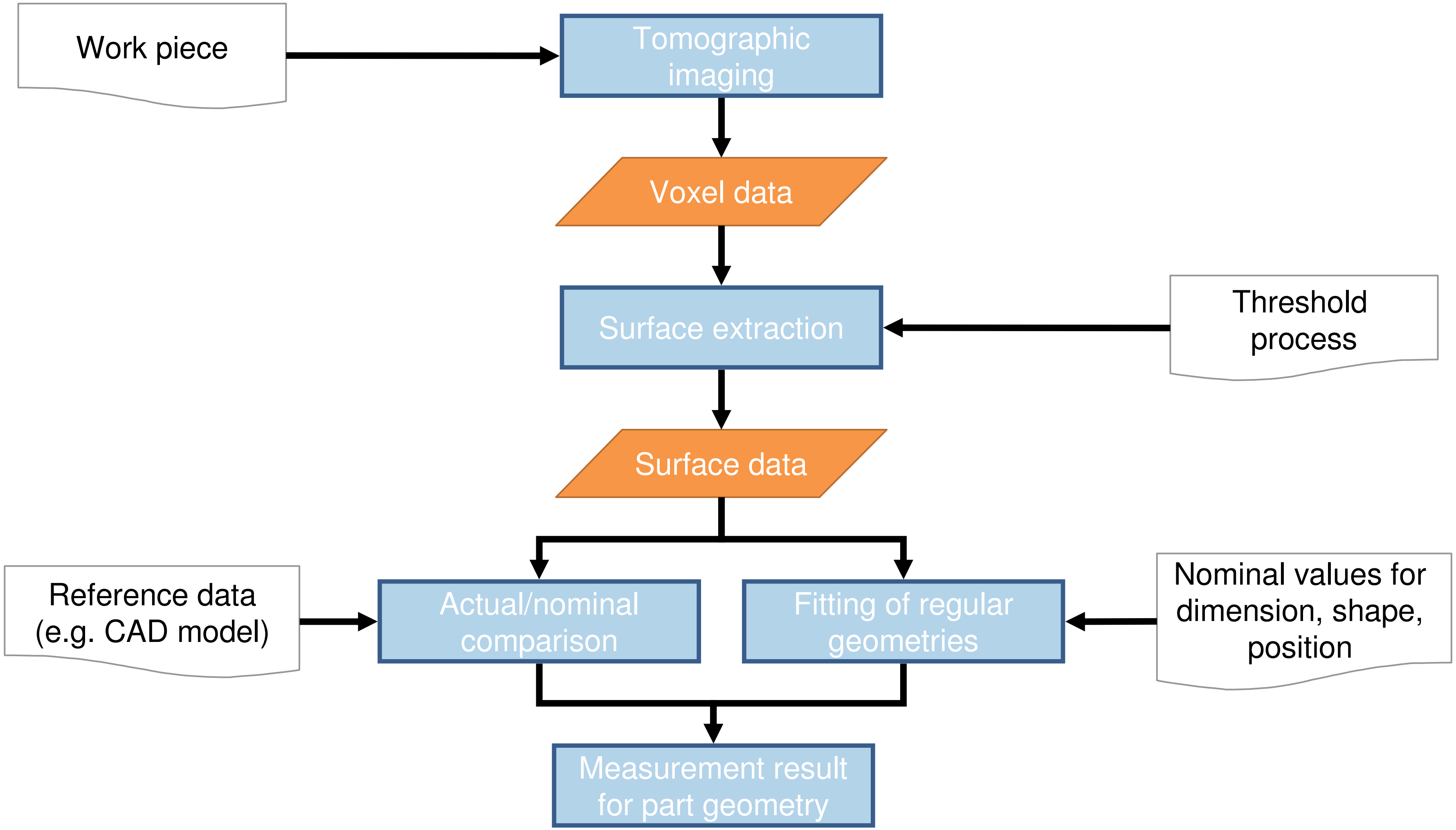
CT measurement process



Why not using well-established medical CT systems also for metrology purposes?

- Medical CT-systems are designed for spatial and time-resolution imaging
- Most measurement tasks in production metrology aim for dimensional features ➔ spatial resolution is important
- A lot of measurement tasks have tolerances in a range of a few microns
- Industrial CT-systems achieve a higher spatial resolution than medical CT-systems
- This is the base for capable and controlled measurement processes

For metrology applications the traceability to the national length standard is essential

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Advantages and disadvantages of X-Ray Computed Tomography

+

- Very high point density
- Holistic 3D image of work piece possible
- Non-destructive acquisition of exterior and interior features
- Multiple tasks can be performed with one device

-

- New measurement technology for production
- Complex technology with many influencing factors
- Uncertainty in measurement for most tasks unknown
- Relatively long acquisition time

Challenges occur for technological, organizational and application aspects

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1 X-Ray Computed Tomography as inspection technology

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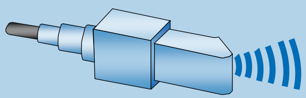
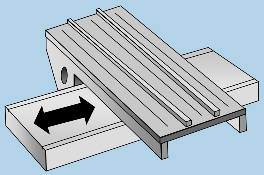
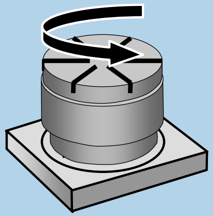
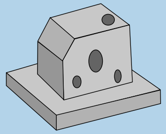
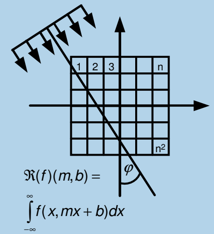
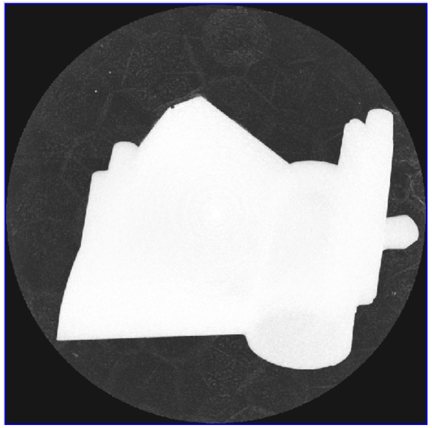
How can the effect of hardware and software algorithms on the CT measurement process be reduced?

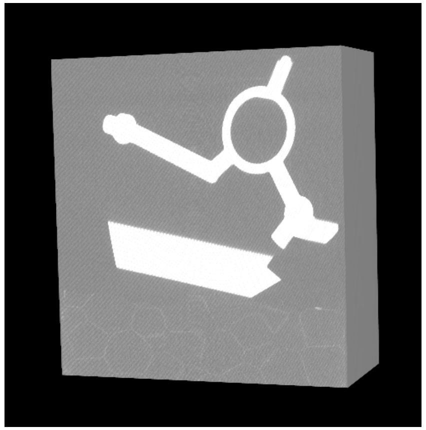
X-ray tube	Axes	Turn table and clamping	Work piece	X-ray detector	Evaluation (algorithm)
					

- X-Ray tube: reduction of focal spot diameter, reduction of emitted spectrum band width, rotation target ➔ improved sampling, less blurring, less beam-hardening artifacts, higher power
- Linear axis: accuracy of linear axis is already at an elevated level ➔ sufficient accuracy achieved
- Turn table: accuracy of turn table is already high ➔ sufficient accuracy achieved
- Clamping: utilization of foamed materials with few standard geometries ➔ reduction in set-up time
- Work piece: aim is the tomography also of hybrid parts, bigger work pieces and less cooperative materials, e.g. alloyed steel ➔ more challenging parts
- X-ray detector: higher resolution, increase in efficiency ➔ lower exposure times per projection
- Evaluation: analytic reconstruction and adaptive thresholds for segmentation ➔ reduction of artifacts

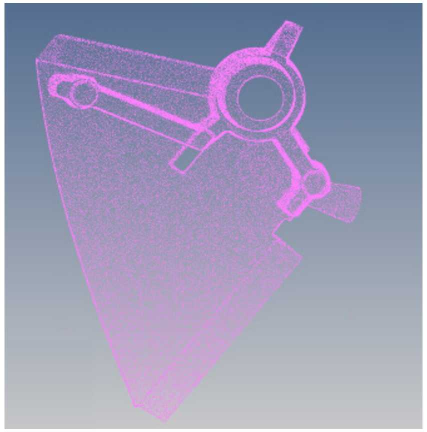
From the voxel model to the point cloud



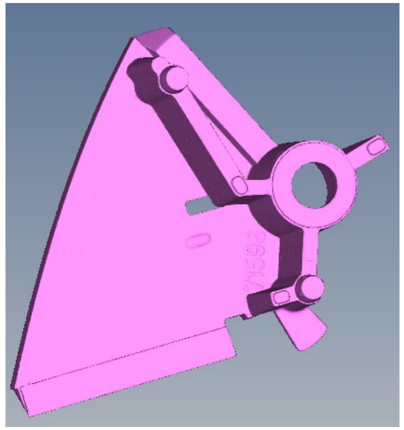
Import of voxel model



Before segmentation



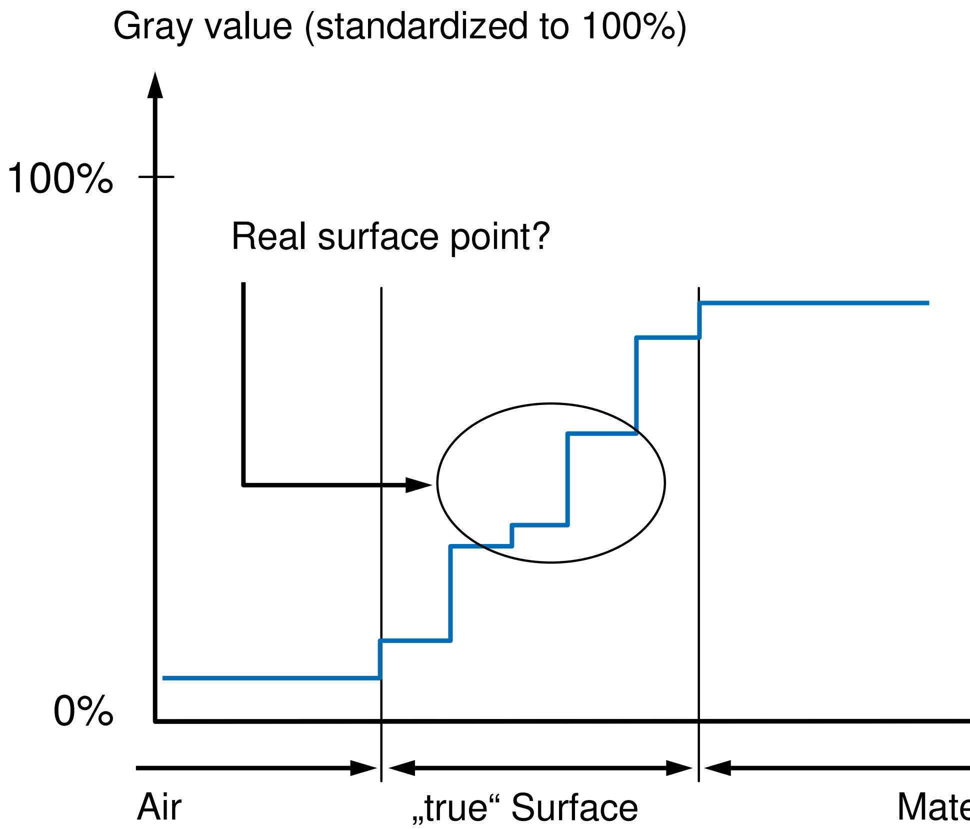
Visualization of point cloud

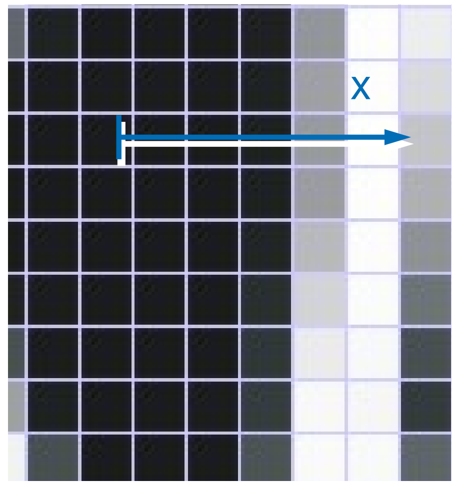


Interpolated surface model

- Voxel model contains representation of work piece + clamping + air
- Segmentation separates the work piece from the clamping device and the air
- Extraction of the work piece surface
- **Segmentation is a crucial step at it affects the geometry to be measured**

Finding the true surface of the work piece





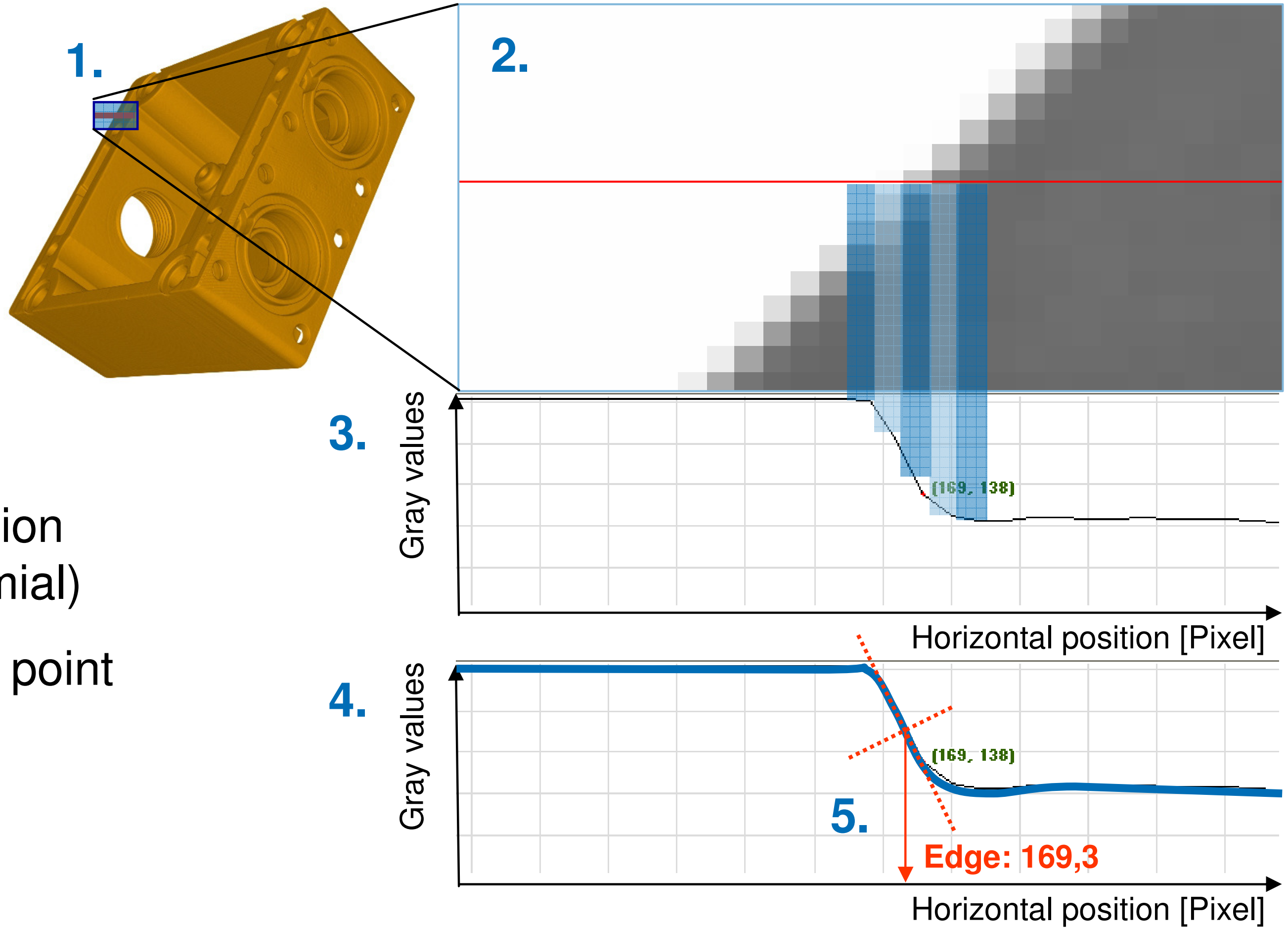
Extract from voxel model

- Disturbance variables and parameter values change the gray value distribution in the voxel model
- The chosen threshold must not affect the position of the boundary surface

Detection of object contour with subvoxel accuracy

Procedure

1. Voxel model
2. Neighborhood
3. Horizontal profile
4. Interpolation of a function (e.g. 5th grade polynomial)
5. Determination of edge point (e.g. Turning point)



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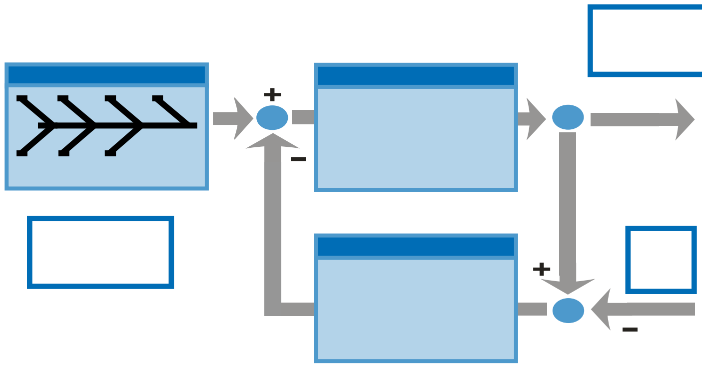
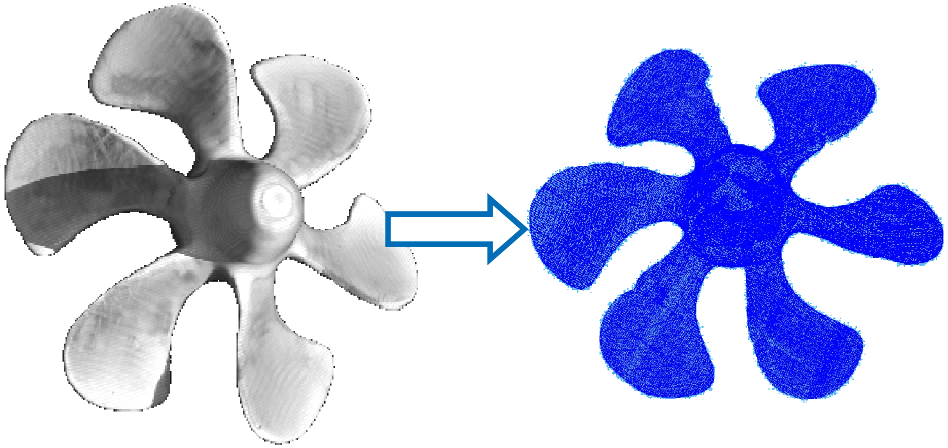
For which purposes can I can utilize X-Ray Computed Tomography in production?

- Quality assurance
  - Control of the start of production
  - Control of the serial production with random sample testing
  - Long-term control of production via Statistical Process Control (SPC)
  - Adaptation of manufacturing processes based on CT data



- Digitalization of surfaces
  - Holistic acquisition of non digitalized surfaces as first step for reverse engineering
  - Acquisition of the actual work piece geometry for modeling and simulation purposes



Which production domains are affected by the step from tactile Coordinate Measuring Metrology to CT Metrology?

Adaptation of established production network structures

- Geometric Product Specification
- Process planning
- Inspection planning
- Interpretation and use of Results
- Worker skills and training
- IT-Network

- New measurement technology for production
- Complex technology with many influencing factors
- Uncertainty in measurement for most tasks unknown
- Relatively long acquisition time

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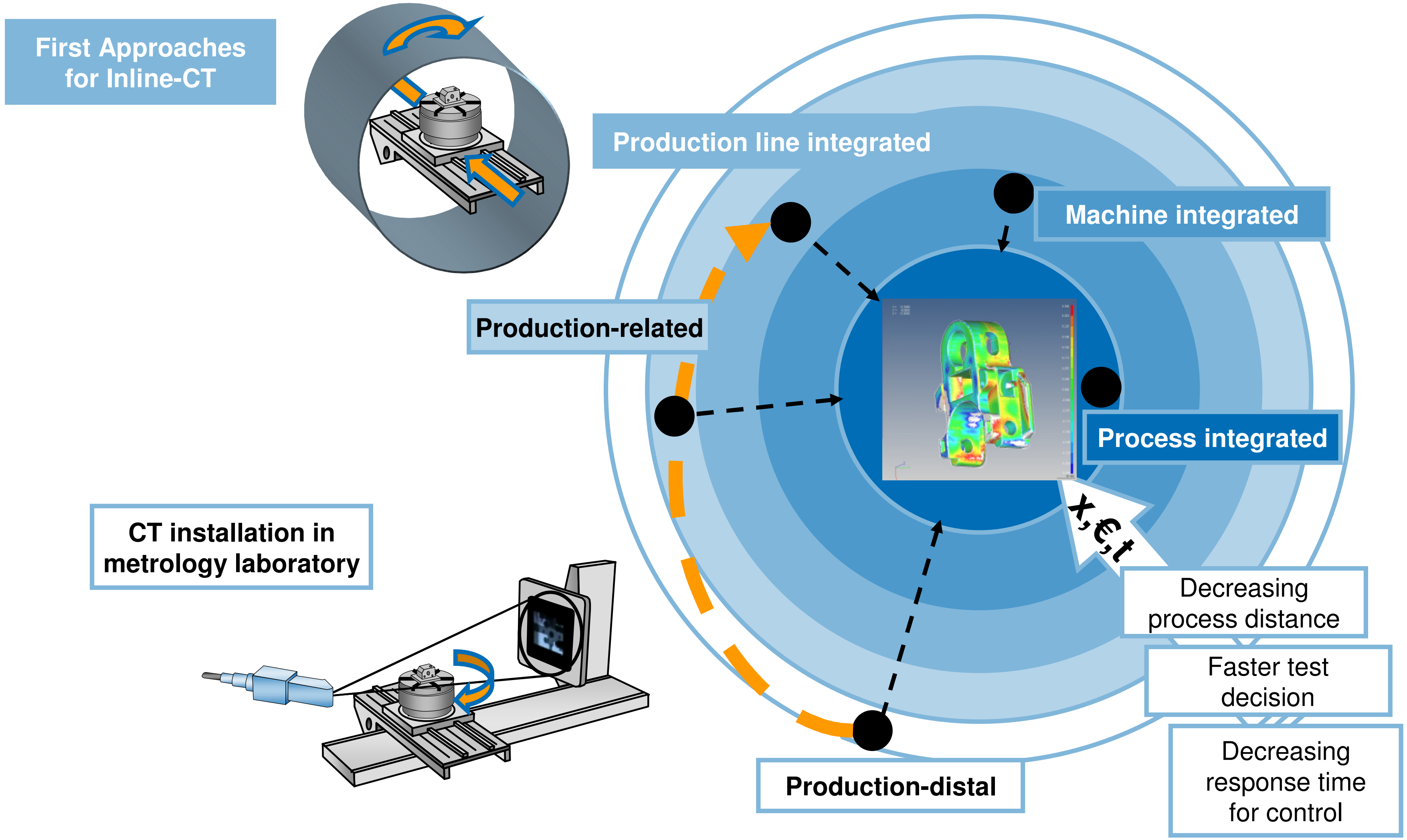
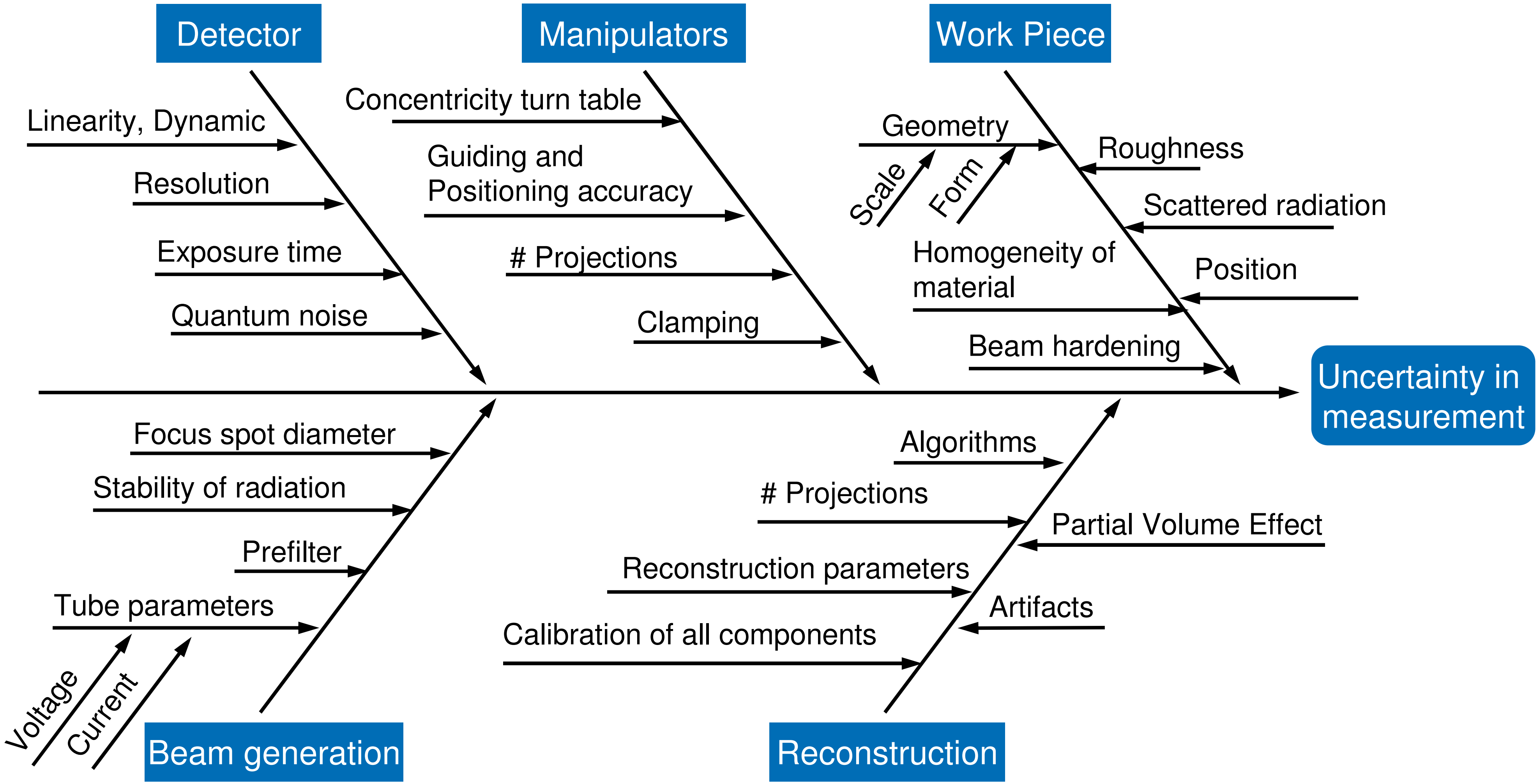
Current degree of integration for industrial CT scanners



Disturbance variables for the CT measurement process

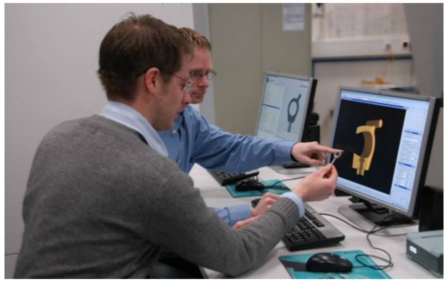


According to Guideline VDI/VDE 2630 Sheet 1.2

Influence of the operator and the work piece onto the CT measurement

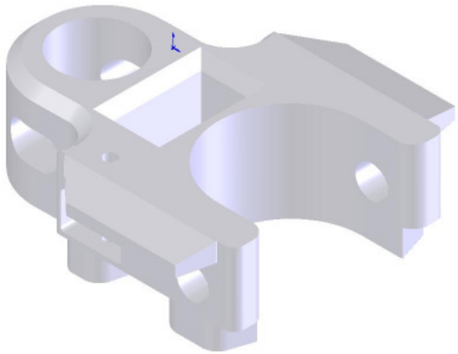
Set-up by the Operator

- Tube current and voltage
- Pre-filter
- Number of projections
- Magnification
- Exposure time and feedback capacitance of detector
- Reconstruction filter und Interpolation method
- Registration of work piece in measurement program
- Measurement strategy

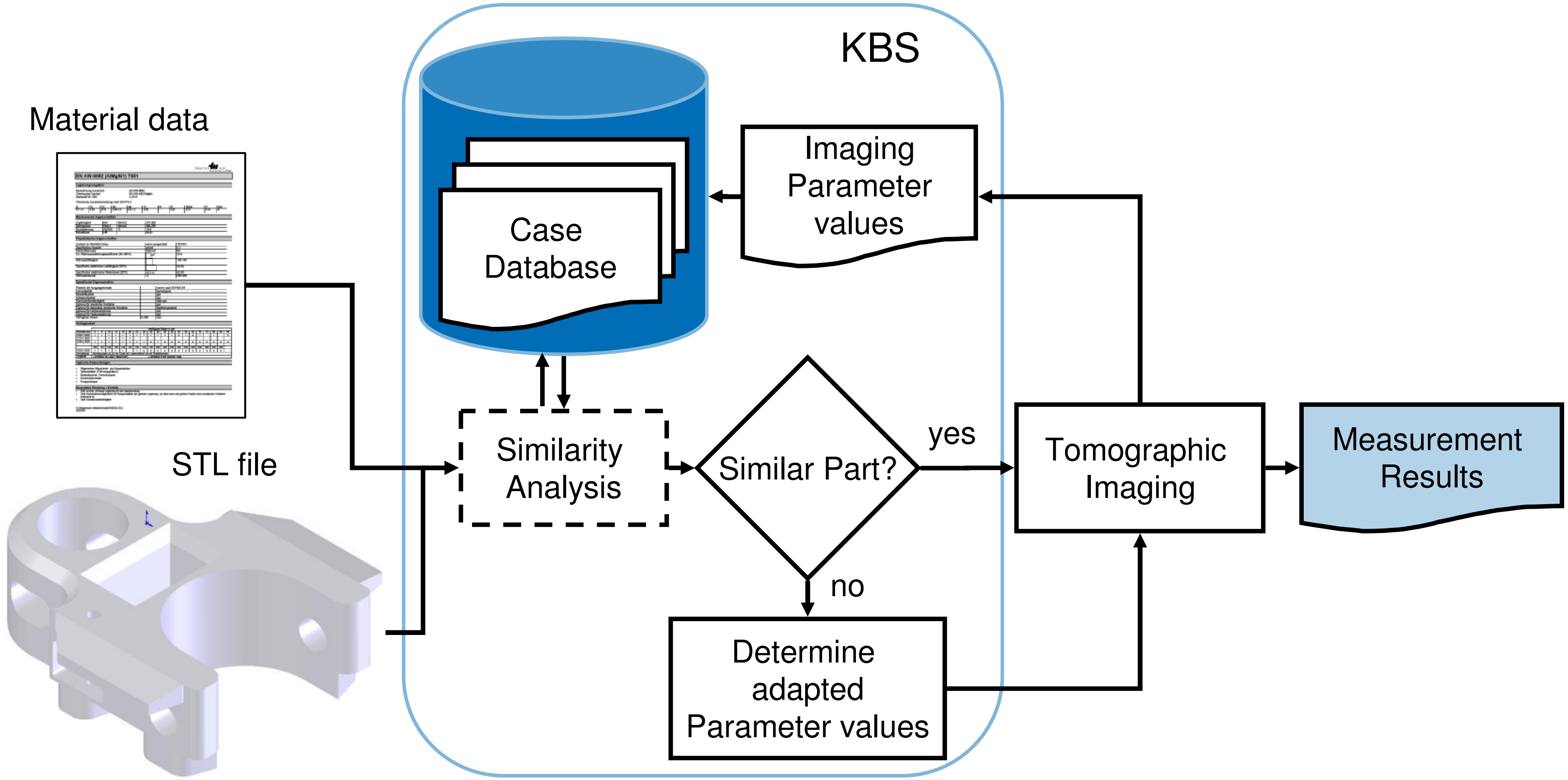


Work piece

- Material (density, elements)
- Penetration lengths
- Work piece orientation



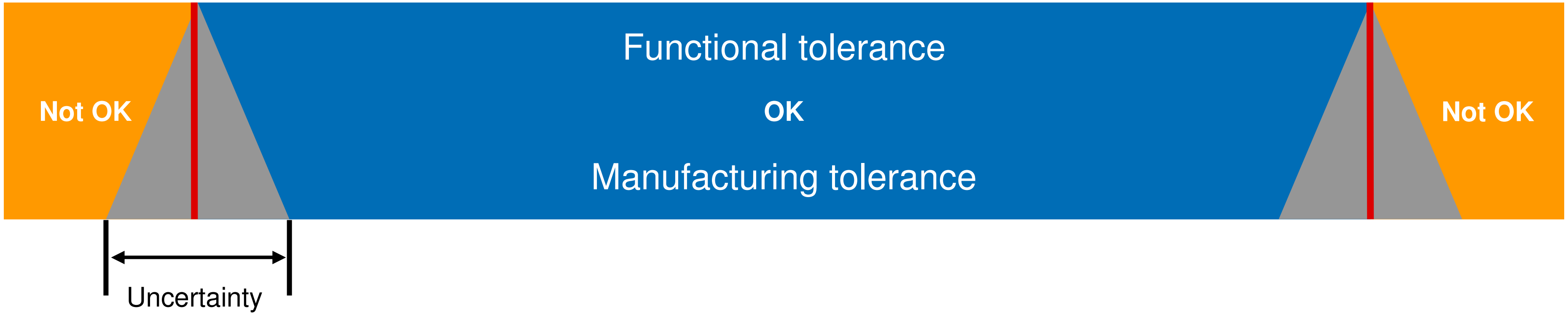
Cognitive methods to reduce the user influence on CT measurements for a proper acquisition of the control variable work piece geometry



KBS: Knowledge-Based System

How valid and reliable can CT acquire the part geometry?

Uncertainty in measurement constrains the tolerance for the manufacturing processes
➔ False decisions can occur at the specification boundaries



- Reduced manufacturing tolerance requires more accurate machines thus increasing costs
- Economic production demands capable testing processes.
- The testing process suitability for CT measurements the relationship of the uncertainty in measurement and the feature tolerances has to be assessed

Estimation of uncertainty in measurement for CT using calibrated work pieces according to ISO/TS 15530-3

$$U = k \cdot \sqrt{u_{cal}^2 + u_p^2 + u_w^2 + |b|^2}$$

$$u_{cal} = \frac{U_{cal}}{k}$$

$$u_p = \sqrt{\frac{1}{n-1} \cdot \sum_{i=1}^{n} (y_i - \bar{y})^2}$$

$$b = \bar{y} - x_{cal}$$

- Empiric approach using repetitive measurements
- Single factors cannot be separated from each other
- Results can be transferred to similar parts
- u_{cal}: standard uncertainty from calibration (method B)
  - **Difficult for non-accessible features**

  → Additional destructive testing and measurement of reference features before and after the destruction
- u_p: standard unc. from measurement process (method A)
- u_w: standard uncertainty from material and production scattering, e.g. roughness, form (method A or B)
  - **Founded estimation of work piece influence difficult**

  → Use of simulation
- b: systematic deviation from calibrated value (method A)

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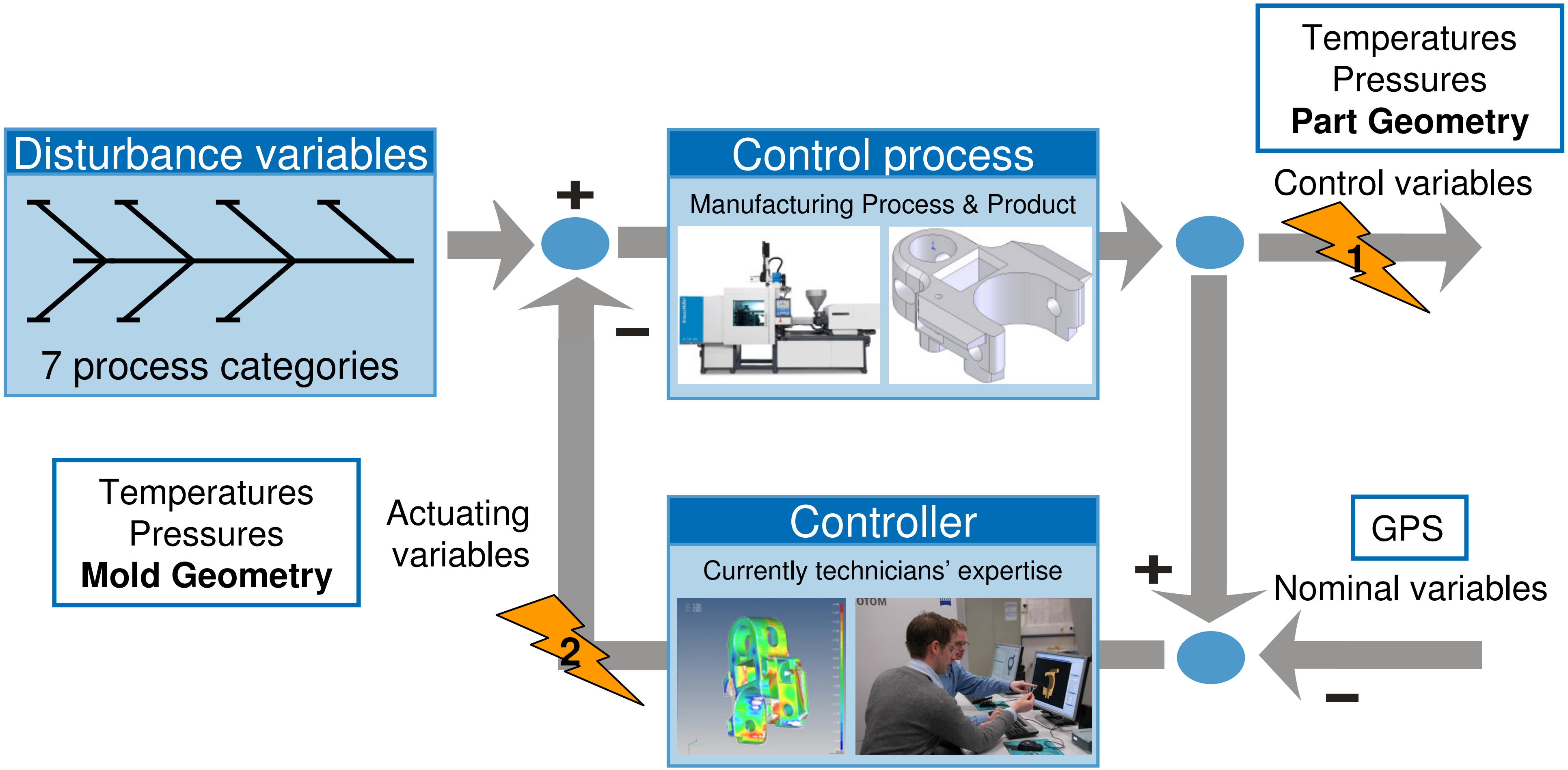
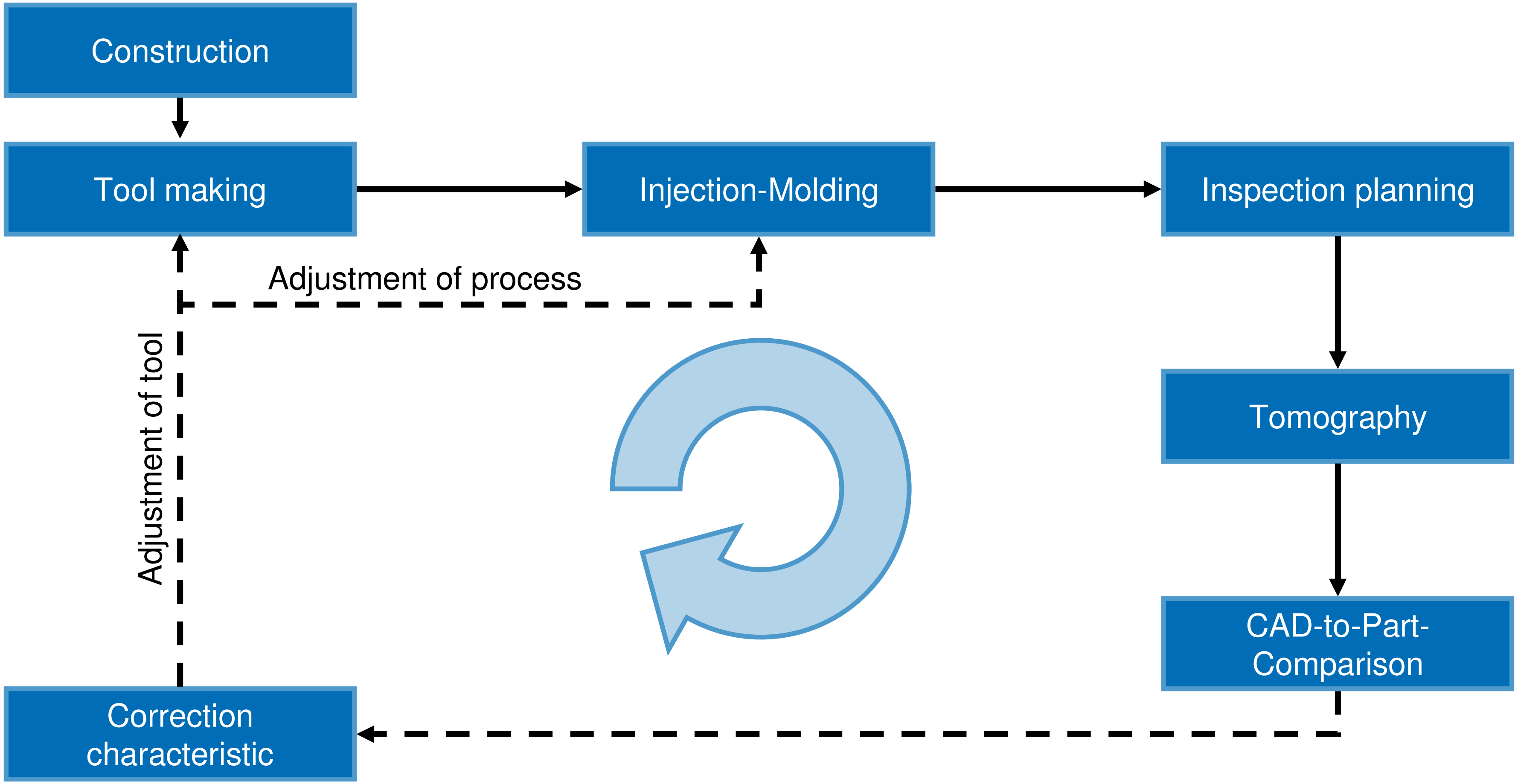
Closed-loop-control for the production of injection-molded parts using CT

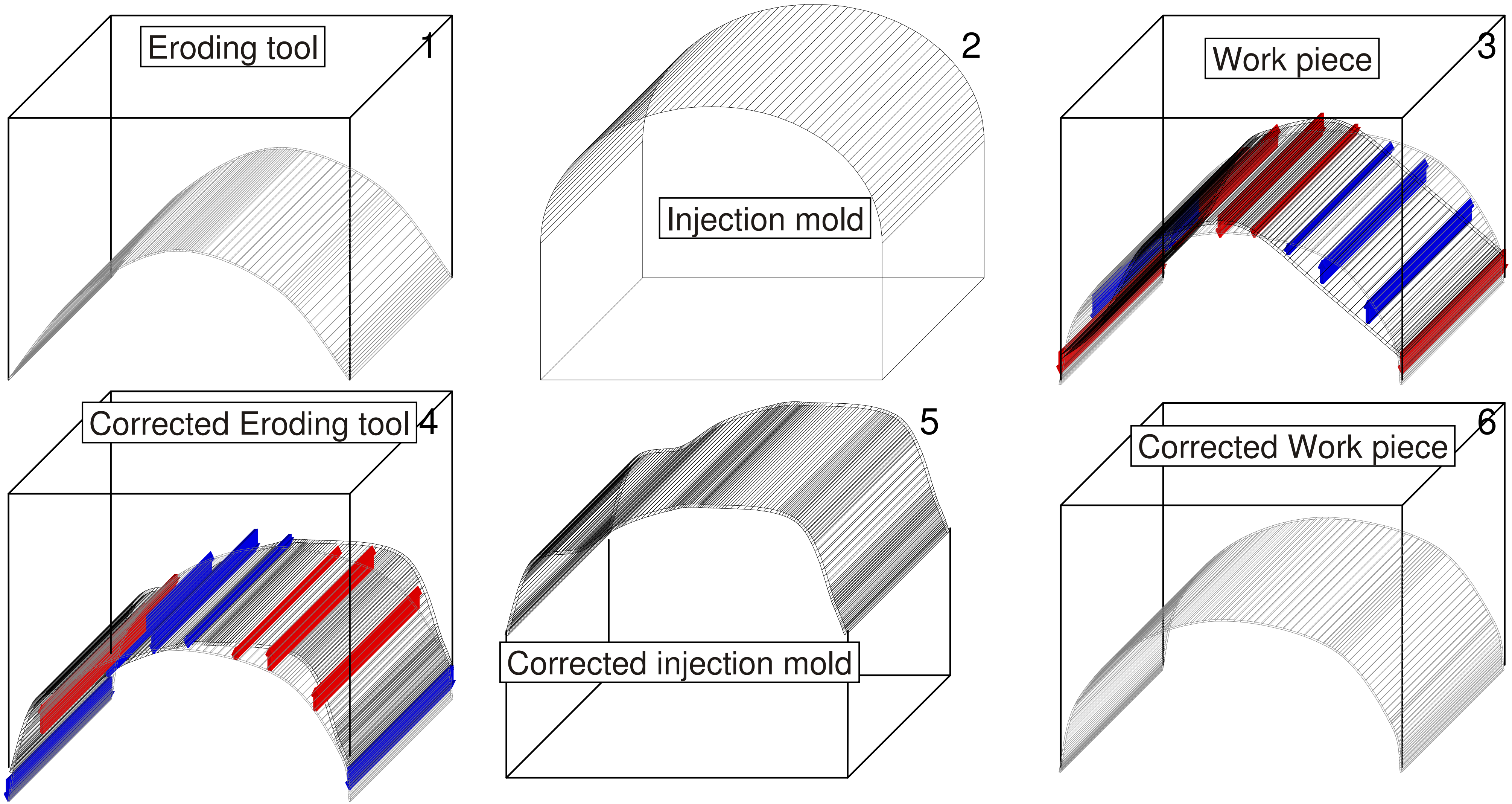


GPS: Geometric Product Specification, Image of injection-molding machine courtesy of KraussMaffei Technologies GmbH

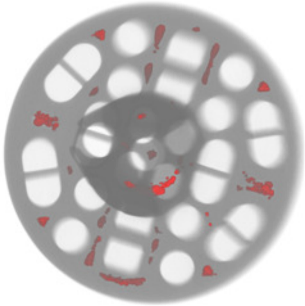
Adjustment of the injection-molding process based on the CAD-to-Part-Comparison

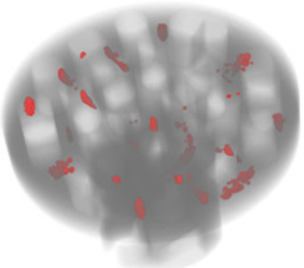


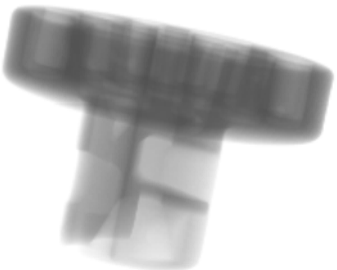
Correction of the eroding tool based on CT data



Summary and Outlook







- CT offers new possibilities for the assessment of enhanced manufacturing processes
- CT provides volumetric data useable for various inspection tasks
- CT enables the step from feature-based evaluation to the high resolution holistic evaluation
- Main tasks for the future:
  - traceability of metrological CT to the national length standard and uncertainty models ➔ federal metrology institutes
  - Reduction of user influence onto the measurement ➔ research institutes and industry
  - Improvement of X-Ray tube, detector and algorithms for reconstruction, segmentation and registration ➔ system manufacturers, research institutes
  - Establish control-loops for the production based on CT data ➔ research institutes and industry


Thank you for your attention!

CIRP Keynote on CT

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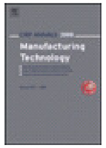

Computed Tomography for Dimensional Metrology

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Abstract: The paper gives a survey of the upcoming use of X-ray Computed Tomography (CT) for dimensional quality control purposes: i.e. for traceable measurement of dimensions of technical (mechanical) components and for tolerance verification of such components. It describes the basic principles of CT metrology, putting emphasis on issues as accuracy, traceability to the unit of length (the meter) and measurement uncertainty. It provides a state of the art (anno 2011) and application examples, showing the aptitude of CT metrology to: i) check internal dimensions that cannot be measured using traditional coordinate measuring machines, ii) combine dimensional quality control with material quality control in one single quality inspection run.

Keywords: Quality control, Metrology, X-ray Computed Tomography (CT)

1. Introduction

Today X-ray computed tomography (CT) finds applications in three major fields. CT scanners for **medical imaging** go back to the early 1970's [1, 50]: 1st scanner built by Nobel Prize winner Hounsfield in 1969 and 1st patient brain scan performed at the Atkinson Morley Hospital, Wimbledon, UK, in October 1971. Since 1980, CT became popular for **material analysis** and non-destructive testing (NDT) [71]: e.g. for observing the inner structure of materials (e.g. fiber-reinforced plastics) and detecting material defects. The cabinets of material testing CT devices are often small and aimed at hosting samples cut out from larger objects. More recently, CT technology entered the application field of **dimensional metrology**, as an alternative to tactile or optical 3D coordinate measuring machines, measuring arms, fringe projection systems, etc. (fig. 1). The first attempts to perform dimensional measurement using existing CT scanners appeared around 1991 [11, 20, 65, 100] but accuracy was not better material components (e.g. 2K injection molded plastic parts or plastic parts with metallic inserts): fig. 2a and b. The advent of those production methods favoring the trend for more part feature integration and yielding parts with complex internal geometries or multi-material components, is a major incentive that boosts the demand for dimensional CT metrology: industry can no longer accept that intricate components produced by additive manufacturing or multi-material injection molding escape any geometrical and tolerance quality control for the only reason that

a) CT scanner for dimensional metrology

there is no non-destructive method to measure the inner or internal geometry. Dimensional CT metrology is also interesting for quality control of assemblies in assembled states, since the geometry and dimensions of components may differ in unassembled and assembled state: an assembly may fail geometrically, even if all individual elements of the assembly meet the tolerances when unassembled. CT being a non-contact measuring technique, it also might become a competitor to other novel non-contact quality inspection methods, like fringe projection, laser scanners, etc.

Another major advantage of industrial CT technology is that it allows performing dimensional quality control and material quality control simultaneously. In fig. 2a CT measurement was not only used to check geometrical tolerances, but at the same time glass weld quality and porosity in bulb and socket have been checked. For further examples, see fig. 12, 33, 34.

Although the three fields of application (medical, material analysis, dimensional metrology) rest on the same physical and mathematical principles, the devices and procedures are quite different as they have to fulfill diverse requirements: see fig. 1. In medical applications the doses of radiation and hence power have to be limited to protect the patient. The object (patient) cannot be rotated the same way as material samples or mechanical workpieces in technical CT scanners. Moreover, requirements on accuracy and spatial resolution are usually relatively low for medical scanners. Dimensional CT metrology lies at the other end of the specification scale: it often calls for high penetration power as there is a demand for measuring ever larger and thicker workpieces made of more absorbing materials (e.g. metals). Furthermore dimensional quality control requires high spatial resolution and **accuracy** in respect of the rules of measurement uncertainty [43, 44] and traceability to the SI unit of measurement (the meter). Even though CT has been developed and applied in medical and material sciences for several decades, its application to dimensional metrology is therefore far from trivial and still requires substantial developments to bring it to maturity.

This paper summarizes the relevant general and specific principles of CT technology for dimensional metrology. It further gives the state of the art of dimensional CT metrology.

2. Basic principles

Fig. 3 illustrates the setup of a tomograph. A source generates X-rays. As the X-rays propagate through the workpiece material, the X-rays are attenuated due to absorption or scattering (see §5.3). The amount of attenuation is determined by the length traveled in the absorbing material, by the material composition and its density (i.e. attenuation coefficient μ) and by the energy of the X-rays. Measuring this attenuation allows to detect the presence of material (even of various materials in case of multi-material workpieces), as well as the lengths traveled inside the various materials: see 3D reconstruction in §3.4. The attenuation

Figure 2. Typical part calling for CT metrology: a. Measuring squareness and electrode distance in multi-material lamp bulb; b. Multi-material assemblies/mechanisms (watch and connectors); c. Measuring drug eluting cavities in stent; d. Layered manufactured nozzle with complex internal channels; e. Measuring beam thickness in medical bone scaffold.

3. Technical systems and components

HARDWARE

3.1 X-ray sources

The X-ray tube (vacuum tube) typically consists of an electron beam gun containing a cathode filament emitting electrons, an anode accelerating the electrons, a Wehnelt grid electrode for control of the electron beam (convergence and intensity of beam) and magnetic deflectors and lenses to focus the electron beam onto a target that will generate X-rays (fig. 4). When hitting the target, the fast electrons are decelerated very suddenly, causing