

## Obtaining dimensional information by industrial CT scanning – present and prospective process chain

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### Abstract<sup>©</sup>

In a joint project the foundry company Rautenbach Aluminium Technologie GmbH in Wernigerode, Germany, as a user of industrial computed tomography (CT) scanning, and the Coordinate Metrology Department of the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig, Germany, are investigating the dimensional measurement capabilities of CT. The dimensional measurement capability of industrial CT systems critically depends on the process chain used to obtain dimensions from the set-up of the system to the final presentation protocol. So this paper deals with the existing process chain [1,2,3] which has been further developed and improved within the scope of the above project. The work presented is based on the comparison of CT-measured dimensions of reference objects with dimensions obtained by tactile measurements with coordinate measuring machines (CMMs). The first initial sample approval for a cast product part of Rautenbach in 2002 with the process chain developed in this project is one important result. Further steps to improve process control and raise higher confidence are discussed.

### Introduction

Computed tomography (CT) using x-rays has become an important tool in industry for certain tasks. Industrial-type CT scanners applied here are a spin-off of the well known medical CT systems. During the last few years the field of application has shifted. In the beginning of its industrial use, CT is mainly applied for defect analysis. But for some time now the dimensional measurement of products has also gained in importance. Dimensional measurements using CT are now performed at several industrial facilities with different frequency. Due to the short time CT is applied in dimensional measurements and also due to the complex nature of the associated process engineering, the traceability of the measurements is not yet assured. Only partial studies exist [1,2,3].

Therefore the foundry company Rautenbach Aluminium Technologie GmbH in Wernigerode, Germany, as a user of industrial CT scanning, and the Coordinate Metrology Department of the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig, Germany, started a joint project to investigate the dimensional measurement capabilities of industrial computed tomography (CT). The company Rautenbach AG is the second largest gravity die casting foundry in Germany (> 25.000 t of aluminium / year) (Rautenbach Aluminium Technologie GmbH is the engineering branch of Rautenbach AG). The products are mainly intended for the automotive industry and range from cylinder heads (1,8 million heads / year) to crankcases and frame parts to motor cycle frames. Main customers are (in alphabetical order) Audi, BMW, Daimler-

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Chrysler, Porsche, Skoda and Volkswagen. Rautenbach was the first German foundry using CT scanning for the dimensional measurement of cast products and uses a dedicated industrial 2D CT system to perform measurements and to analyze its products. The Rautenbach CT system will be described in the following.

#### Parameters of the Rautenbach CT system:

Type:	2D CT scanner 450kV
Manufacturer:	Bio-Imaging Research, Inc., Lincolnshire IL, USA
X-ray tube:	Seifert ISOVOLT 450/5 (double focus) (1,5mm / 0,8mm focus width, IEC336)
Max. current:	5 mA / 2 mA depending on selected focus
Detector:	CdWO <sub>4</sub> line detector (16 bit effective dynamics, 1024 channels)
Max. part cross section:	400mm
Max. part height:	1000mm
Max. dimensional measurement penetration:	200mm aluminum (differs from max. penetration values possible for defect analysis and related tasks)
Beam hardening correction for aluminum parts	

In contrast to other existing CT systems, this CT scanner is mainly used for dimensional analysis tasks. Defect analysis is performed only for selected products. While this CT system has some advantages for dimensional measurements, the CT scanning speed is only moderate. The complete scan of a cylinder head of 500mm height takes 20-25h to run standard parameters.

#### Objectives of the PTB — Rautenbach research activities

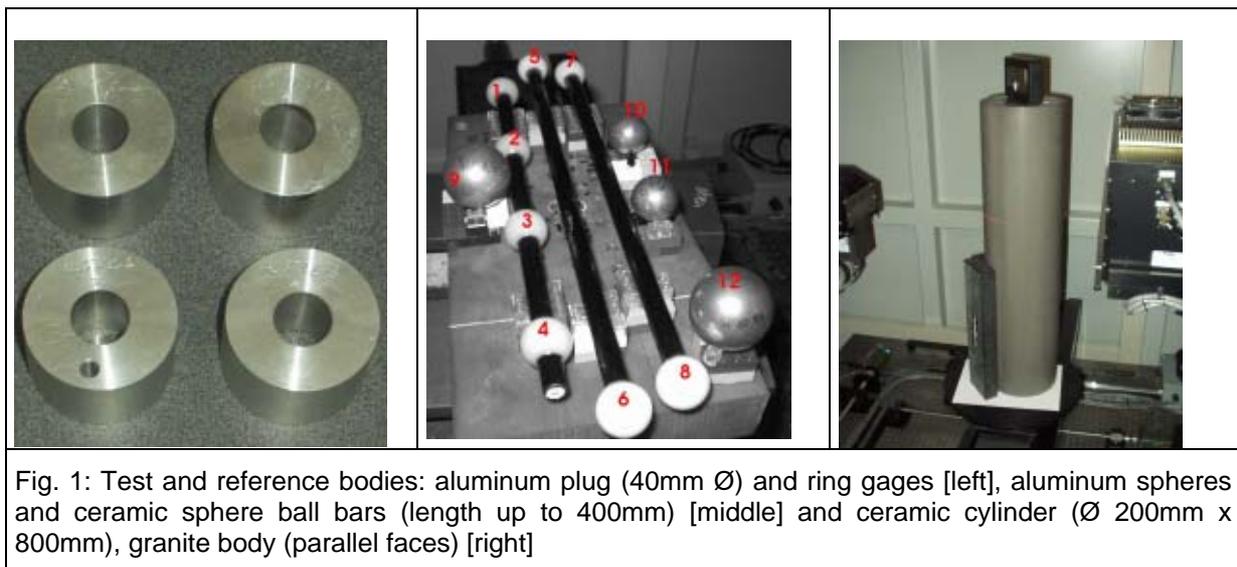
- (1) Metrological study of CT in the field of dimensional measurement and experimental analysis of measurement uncertainty for selected measurement tasks.
- (2) Principal objectives:
  - Study of feasibility of CT initial sample approval and quality assurance.
  - Study of CT measurement uncertainty contributions.
  - Development of test bodies to quantify the dimensional measurement capabilities of CT systems.

The main activities of the project are concentrated on the application of one specific 2D CT scanner. The findings are to be analyzed to find out whether principles exist which are also valid for other CT scanners and CT scanner types. Of special importance is the exclusive use of tactile reference data, as these can be obtained in a traceable and well known way.

### Previous process chain (-2001; before launch of PTB-Rautenbach project)

After system qualification according to the manufacturer's specifications including detector alignment, detector gain calibration, detector offset calibration, wedge calibration and central ray calibration, the (aluminum) part under study and a dimensional reference cylinder with calibrated outer diameter (aluminum plug gage) are scanned by the CT system. The reconstructed CT slices (stack of grey value images) are converted by a threshold process (performed by the CT scanner software ACTIS) into surface data (in STL format<sup>1</sup>). The diameter of the plug gage is analyzed with a CAD software (e.g. METRIS). A cylinder is matched to the measured data. The diameter of this fitted cylinder is compared to the known calibrated value. By iteratively varying the threshold, the diameter of the measured cylinder is (after sequential export to the STL format) matched to the calibrated value. With the threshold so defined, the full CT data set of the part under study is converted into the surface STL data format. STL data reduction is applied depending on the size of the part under study. Further analysis of the part is performed with the STL data so obtained.

Within this project a set of reference and test bodies is used to qualify the dimensional measurement properties of the CT system (Fig. 1).



For the evaluation of the CT running the process chain described above, a combined aluminum plug and ring gage is scanned (Fig. 1; left image, ring bottom left). The gage features a calibrated 40mm outer diameter and two calibrated inner diameters (4,5mm and 15,2mm).

<sup>1</sup> The STL data file format contains the coordinates of the extracted surface points and information about the meshing of the data points.

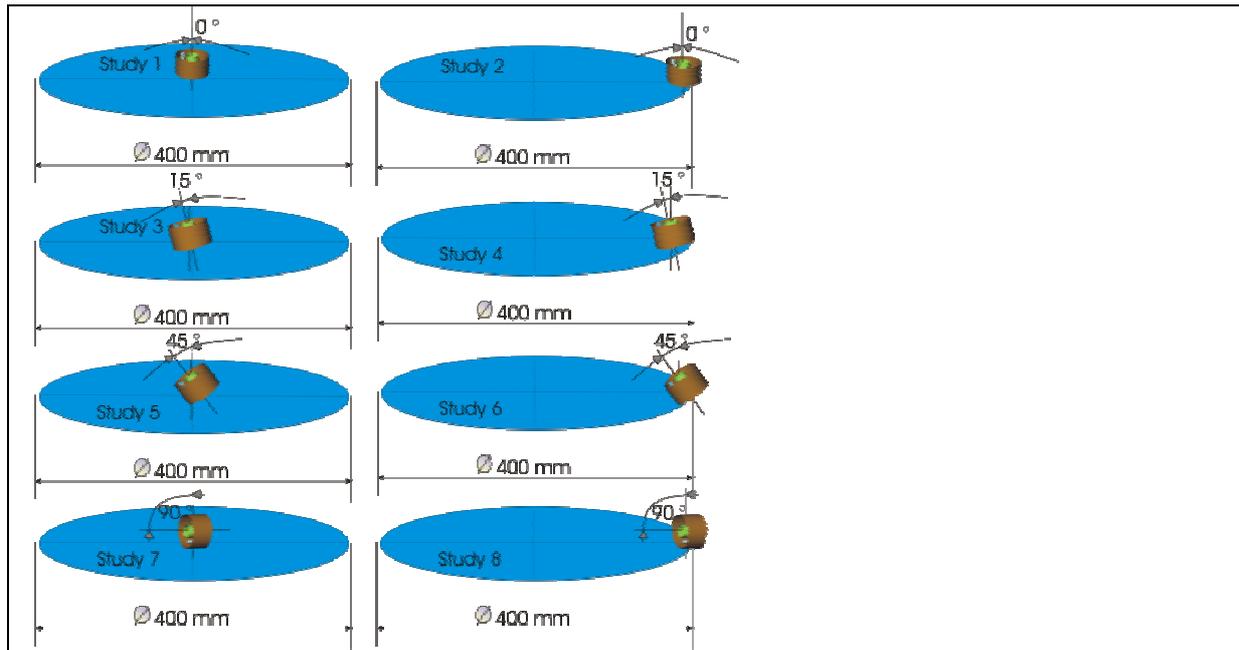


Fig. 2: Measurement set-up for a series of 8 independent measurements of a combined aluminum plug and ring gage.

Fig. 2 shows the measurement set-up of 8 independent CT measurements (studies 1-8). Scan parameters are selected to simulate the measurement of an aluminum cylinder head. This is, of course, a rough approximation as the CT measurement properties depend significantly on the object to be analyzed. Here principal dependencies are to be studied, therefore this test can furnish useful information as will be shown.

The threshold for surface generation is adjusted for study 1 to match the measured outer diameter (40mm nominal) to the calibrated value to some  $\mu\text{m}$ . The threshold so defined is used for all other studies and surfaces of this test. The analysis is focused on the deviation of the measured from the calibrated diameters and on form deviations (Tab. 1.)

	Outer diameter (40mm nominal)	Inner diameter I (15,2mm nominal)	Inner diameter II (4,5mm nominal)
Deviation of CT-measured diameter from calibrated diameter	-48 $\mu\text{m}$ — +6 $\mu\text{m}$	-100 $\mu\text{m}$ — +50 $\mu\text{m}$	<b>- 275<math>\mu\text{m}</math></b> — +19 $\mu\text{m}$
Form deviation of CT-measured data	245 $\mu\text{m}$ — 320 $\mu\text{m}$	120 $\mu\text{m}$ — 235 $\mu\text{m}$	105 $\mu\text{m}$ – 195 $\mu\text{m}$
Form deviation as measured by CMM	4 $\mu\text{m}$	5 $\mu\text{m}$	85 $\mu\text{m}$

Tab. 1: Comparison of CT-measured dimensional features and of calibrated properties. The ranges of deviations given indicate the variation between the 8 studies. CT-measured dimensions are calculated from the STL representation of the gage under study.

Two additional observations have to be noted here for the analysis of results given in Tab. 1.

1. The measured diameters depend strongly on the export threshold.
2. The inner and outer diameter dimensions depend on changing threshold in the opposite way (Fig. 3).

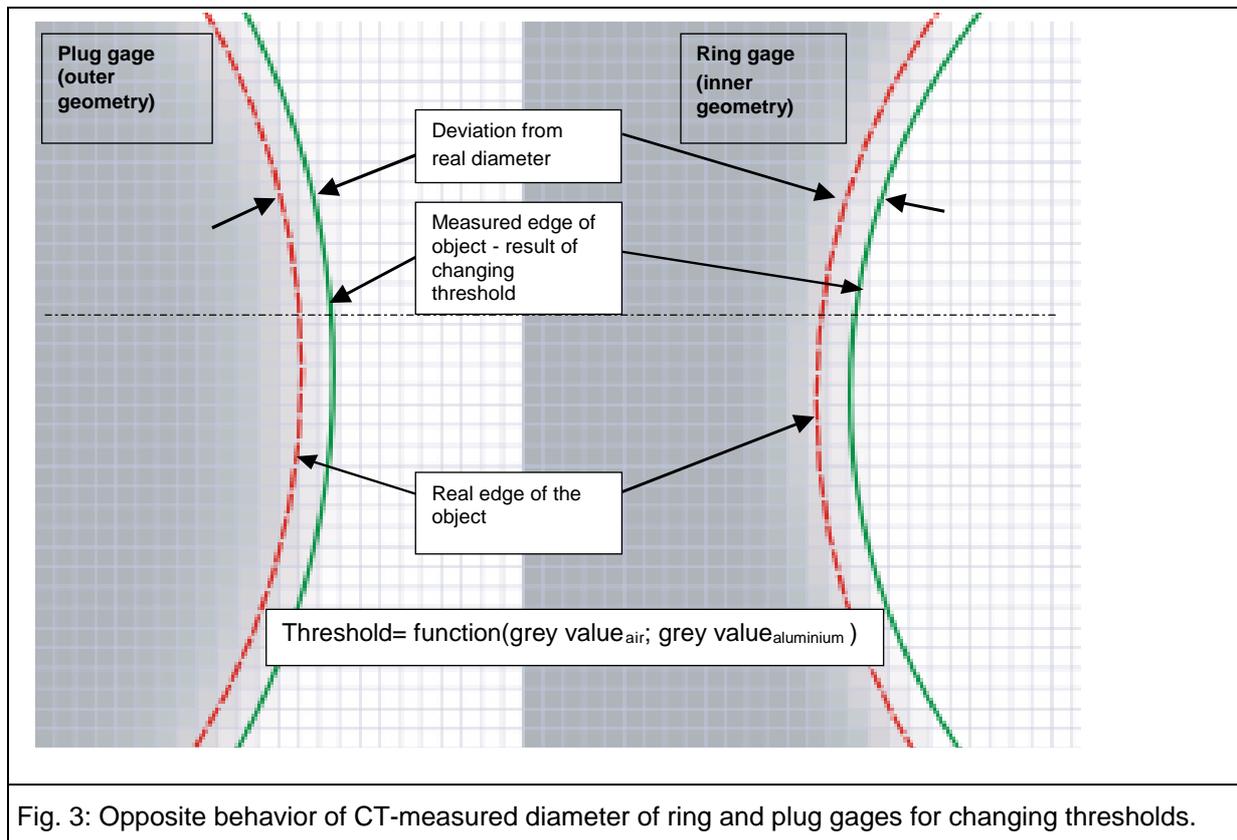
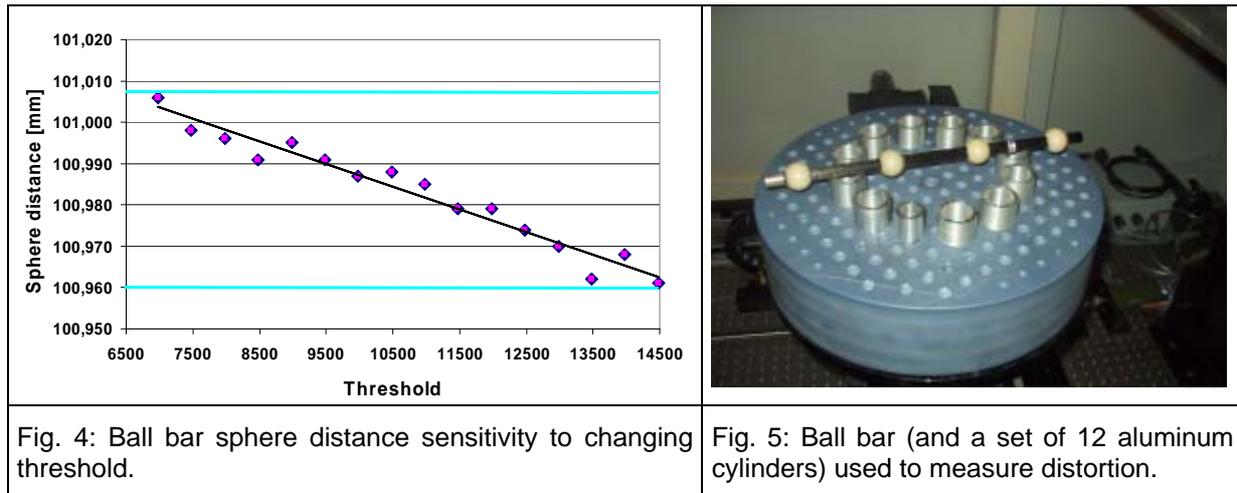


Fig. 3: Opposite behavior of CT-measured diameter of ring and plug gages for changing thresholds.

Both observations have important consequences: With the presence of a global distortion of the dimensions, it is in principle impossible to tune the diameter of the inner and outer geometries to also match the calibrated value. This case can be observed in the present series of measurements. While the deviations of the “adjusted” outer diameter are relatively small, the inner diameters reach deviations which are greater than the maximum diameter deviations of the outer cylinder by up to a factor of 5,7. This is a strong indication that a global dimensional distortion is present.

The magnitude of the distortion has to be measured by a method which is relatively independent of the threshold chosen. Therefore a series of measurements on a ball bar has been made. A ball bar consists of a (carbon fiber) rod used to mount two or more precision balls made from ceramics (Fig. 5). The ball bar distances are affected by the threshold choice only to a small extent (Fig. 4). The remaining slope (Fig. 4) is due to second-order effects like the partial registration of the spheres due to the rod used to mount the assembly. The sensitivity to threshold variations is less than e.g. ring gage diameters by about a factor of 20, therefore the sphere distances of a ball bar are well suited for measuring geometric deviations.



The geometric distortion has been analyzed to be mainly a constant scaling of the dimensions. The scaling factor is about 1,009 for the setting analyzed here (Fig. 4, Fig. 5). The factor depends strongly on the CT mode used, the CT measurement parameters, the CT configuration and finally also on the CT system applied. The geometric deviation affects x,y-plane only (CT-plane) (no need for correction in the z-direction) for the CT scanner under study. This known systematic deviation is to be corrected in an adapted process chain as described in the following.

#### Current process chain (2002/2003)

After system qualification according to the manufacturer's specifications, the (aluminum) part under study and a dimensional reference ball bar are scanned by the CT system. The reconstructed CT slices (stack of grey value images) are converted to surface data (in the STL format) by a threshold process (performed by the CT scanner software) on the basis of an estimated threshold. The spheres of the ball bar are analyzed with a CAD software (e.g. METRIS). Each sphere surface point cloud is Gauss fitted by an ideal sphere. The distances of the fitted spheres are compared to the known calibrated value. The ratio of the measured and the calibrated distances is used to correct the STL data given by the CT scanner software. Correction is applied with ACCESS database software in the x,y-plane only (result valid for the CT system under study). STL data reduction is applied depending on the size of the part under study. Further analysis of the part under study is performed with the STL data so obtained.

Fig. 6 shows how the ball bars are applied in standard measurements of cast products. It turned out that the short-term stability of calculated scaling factors is sufficient but that the factors change on a time scale of weeks and months. Observed variations are able to change dimensions of bigger parts to undesired values (e.g. 0,4mm on a length of 400mm in the x,y-plane). Therefore the scaling factor is assessed for every measurement for which the knowledge of the dimensions is of importance, i.e. for the majority of measurements with the CT scanner under study.

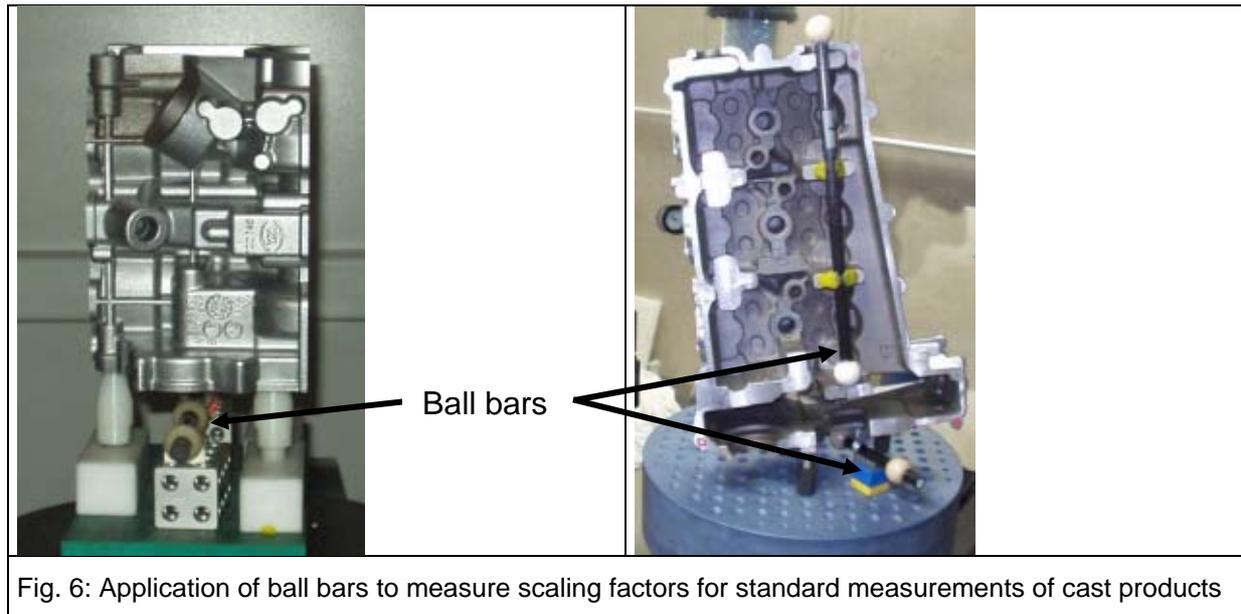


Fig. 6: Application of ball bars to measure scaling factors for standard measurements of cast products

#### Test measurements with adapted process chain

A ball bar, tactilely calibrated by CMM, has been measured by CT with the adapted process chain. The obtained STL data representation of the ball bar is compared with a “tactilely calibrated” CAD model of the ball bar. The “tactilely calibrated” CAD model is a model of the ball bar in which the relative positions of the spheres are set to their calibrated values as measured by a CMM. The replacement of the real spheres by mathematically ideal spheres is allowed as the form deviation of the ceramic spheres used to make the ball bar is of the order of  $0,1\mu\text{m}$ - $0,3\mu\text{m}$  and can therefore be neglected in the following. Fig. 7 shows a graphical representation of the comparison. The maximum deviations observed are  $\pm 0,15\text{mm}$ , a value which is quite satisfactory for the given voxel size ( $0,39\text{mm} \times 0,39\text{mm} \times 0,5\text{mm}$ ).

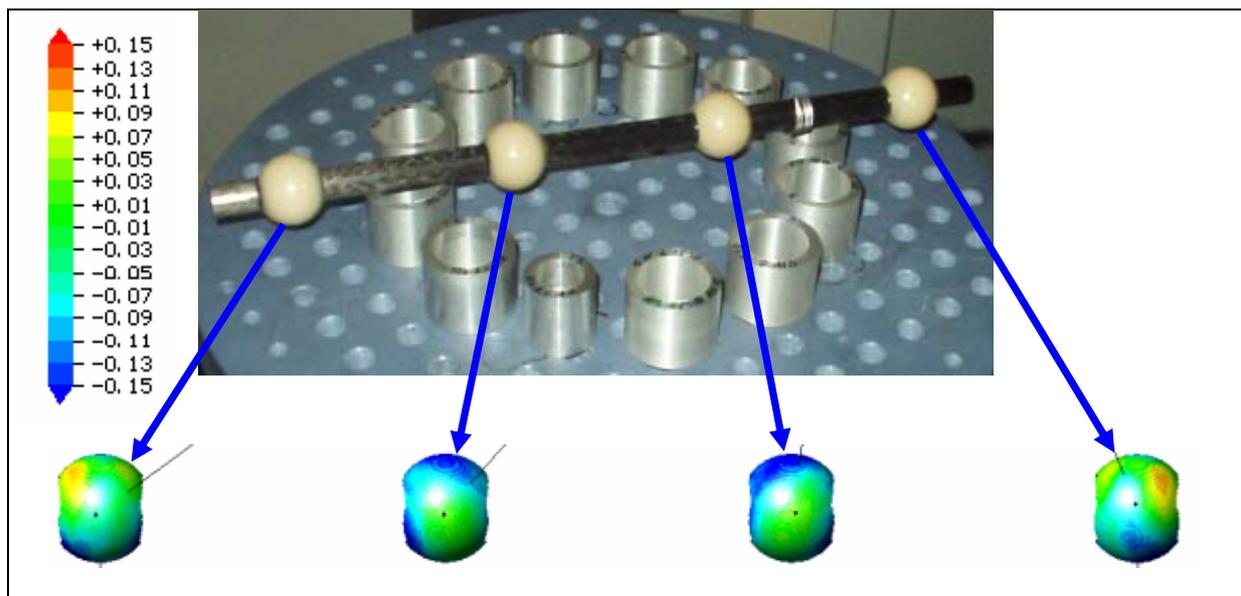


Fig. 7: Ball bar CT data compared with „tactilely calibrated“ CAD data model. CT measurements have been performed with the current process chain. The scaling factor of the CT measurement has been calculated from a measurement run before. The color map presented here indicates the full range of deviations. The comparison has been made with the METRIS software. Similar software packages can

yield comparable results.

A similar result was achieved for the measurement of a homogeneous aluminum body of dimensions 90mm x 80mm x 120mm featuring prismatic faces (planes, cylinders, cones) — a body usually used for CMM training purposes. Here the observed deviations compared to correlated data points achieved by tactile CMM scanning<sup>2</sup> are also  $\pm 0,15\text{mm}$ .

It is to be noted that the roughness values of the ball bar spheres and of the aluminum test body are relatively small compared to the roughness encountered in cast products. The surface roughness leads to an additional uncertainty when the surface is measured. This is valid for tactile and for CT measurements. For certain tactile measurements applying single-point probing, the measurement uncertainty contribution for each assessed point can be approximated by  $R_z/2$  for a known roughness parameter  $R_z$  [4]. The uncertainty contribution of roughness in CT measurements, especially for the greater roughness of cast products, is a point for further studies.

Measurements with the adapted process chain as shown offer the possibility to carry out certain measurement tasks with  $\pm 0,15\text{mm}$  deviation from the real geometry with the given CT scanner. It is to be noted that deviations from the real geometry smaller than the cubic root of the voxel volume can be obtained. This can be understood by the fact that the location of any edge in space is mapped with CT by a set of voxels. A local plane element, which mathematically fits the location of the edge, is furnished by the information present in all edge-near voxels (sub-voxeling).

Before adapting the process chain, the deviation was in various cases higher by about a factor of 2 and more. This is an important step towards qualifying the CT system as a measurement tool (like CMMs) for the casting industry.

#### Further development of the CT process chain

Due to the experience gained on the present process chain, several possibilities of further improving dimensional CT measurements arise. It seems to be necessary to perform quick checks of the grey picture quality at the beginning, in the course and after the end of the CT run, as the grey level greatly influences the resulting dimension after STL export. Critical influences of non-constant detector temperatures have also shown the importance of this step. Measurements show that the grey level and also the noise are functions of the thickness of the material penetrated. Further steps of development are required here to get correct evaluations of the dimensional measurements. The design of the quick test body has to avoid geometric problems with the part under study. A solution, which will be followed, is to mount the quick test body directly on the CT axis and to use it as a mounting base for the part under study.

#### Prospective process chain (2003-)

One of the next work packages of the PTB-Rautenbach project will be the development of a refined process chain as described in the following. After system qualification as described above, a quick check of the CT system is performed. The quick test body is permanently mounted on the CT axis and features geometry, MTF<sup>3</sup> analysis

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<sup>2</sup> The CMM scanning of a surface causes additional measurement uncertainty contributions. These contributions are here of the order of some  $\mu\text{m}$ . Therefore they can be neglected for the comparison.

<sup>3</sup> MTF is the modulation transfer function of the CT system.

and density contrast information. The (aluminum) part under study is scanned together with a dimensional reference body (ball bar or metrology frame) and a composition reference object. After 1/3, 2/3 and after the end of the CT scan, an interim check is performed. The repetition of the quick test mentioned above is a possible choice here. The reconstructed CT slices (stack of grey value images) are converted into surface data (in STL format) by a threshold process (performed by the CT scanner software) on the basis of a first estimated threshold. The dimensional reference body STL data is analyzed by a CAD software to obtain geometry scaling information, while the composition reference body STL data is analyzed to get a better estimate for the correct surface export threshold. Finally, the data of the part under study is exported for STL surface representation using the refined threshold. The part STL data obtained is now scaled with the geometry factor calculated before. STL data reduction is applied depending on the size of the part under study. Further analysis of the part under study is performed with the STL data so obtained.

### Summary and outlook

The authors hold the view that industrial computed tomography has the potential to become one of the most versatile and powerful non-destructive evaluation techniques both for defect analysis (as already known) and for dimensional measurements. The present examinations show that CT systems will in future be increasingly used for dimensional measurement tasks – like CMMs today. The first initial sample approval for a cast product part of Rautenbach in 2002 with the process chain developed in this project is a clear indication of this.

The development of the process chain has been shown for one sample CT system used to measure dimensions of cast aluminum parts [5]. It is very likely that different CT systems might require customized process chains. The present process chains need to be further adapted to ensure results of dimensional CT measurements of higher traceability. The results available up to now indicate the suitability of the CT system under study for certain dimensional measurement tasks in casting industry. Further work is focused on CT acceptance tests and on the determination of the measurement uncertainty of selected measurement tasks in accordance with ISO 15530-3.

### Literature

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