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Use of reference objects for correction of measuring errors in X-ray computed tomography

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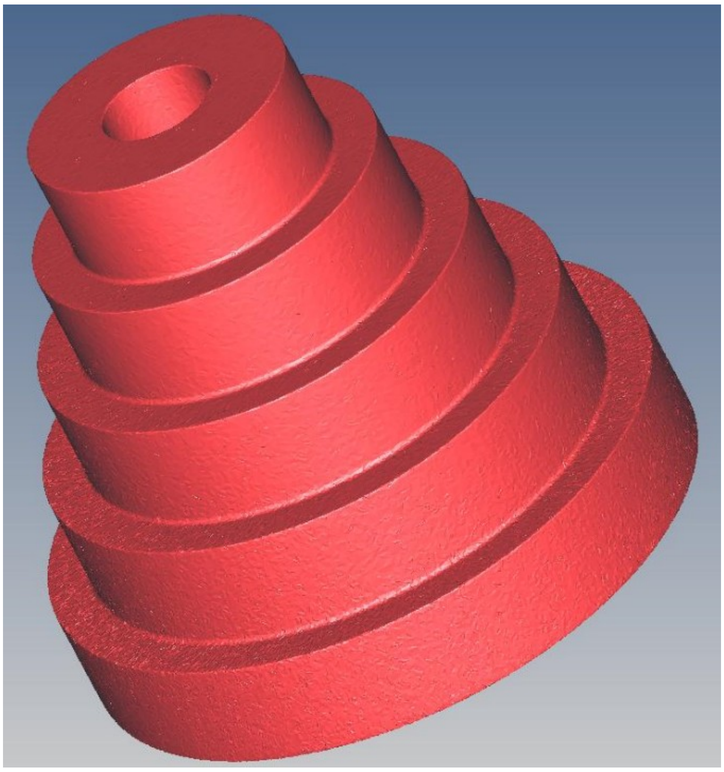

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Preface

Computed tomography (CT) has entered into the industrial world around thirty years ago. Working in the field of CT for coordinate metrology brings about many challenges. One of the biggest challenge is an establishment of traceability and calculation of uncertainty. Uncertainty calculation is a rather difficult task due to many influence factors. Also, due to the fact that guidelines and standards dealing with the assessment of measurement uncertainty are still under development, this document presents current possibilities of expression of the measurement uncertainty for CT applications. Mainly, this is done through the use of reference objects, a method for uncertainty assessment which is adapted from coordinate metrology for tactile measurements. This document presents state of the art with reference objects and their use for correction or elimination of error sources in CT. This report also describes a manufacture of a reference object - an aluminum step cylinder - following a German standard VDI/VDE 2630 - Part 1.3. At the end of this report, few ideas on manufacture of new reference objects are presented.

This report has been written during the first year of a PhD study at DTU. Development of reference objects for different kinds of investigation in CT, both for characterisation or correction of error sources, is still ongoing.

Chapter 1

Introduction

Computed tomography (CT) has recently become a powerful tool in the field of coordinate metrology. This is mainly due to its advantages compared to, e.g., tactile and even optical measuring devices. Namely, with CT, not only external but also internal geometries can be easily measured with high accuracy. Using CT, a complete 3D model of a scanned part is obtained in a few minutes, resulting in high density information. However, due to many complex influence quantities, establishment of an equation for uncertainty calculation is a challenging task. Calculation of the uncertainty is very important due to traceability reasons. According to VIM [1], traceability is defined as: "the property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons, all having stated uncertainties." This means that to make CT systems traceable measuring instruments, the measurement results obtained from CT have to be traceable to the SI units through chains of calibrations, as it is schematically shown in Figure 1.1.

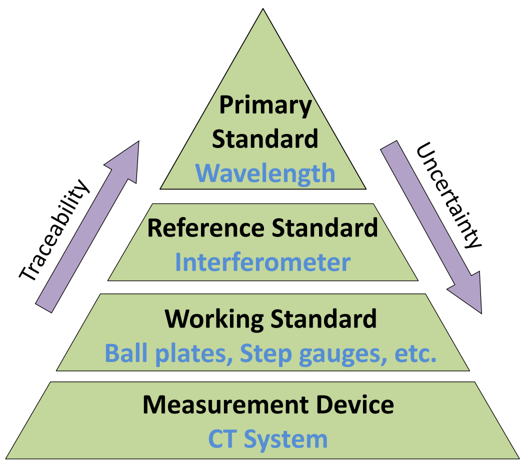


Figure 1.1: Traceability pyramid.

Uncertainty in CT can be assessed using the following methods:

- Uncertainty budget - GUM method (JCGM 100:2008) [2];
- Simplified budget - PUMA method [3];
- Computer simulation - Suppl. 1 to GUM (JCGM 101:2008) [4, 5];

- Empirical methods - Use of calibrated workpieces [6], multiple positions measurement [7];
- Use of specifications - VDI/VDE 2617-11 draft.

Few steps leading to achievement of traceability in CT scanning can be summarized as following:

- Development of reference standards (e.g. for correction parameter assessment, task specific measurement uncertainty assessment, etc.)
- Understanding of influence factors
- Empirical studies of measurement uncertainty
- Assessing methods for measurement uncertainty

As in CT many factors influence the whole process chain, not all the components of the task-specific uncertainty of CT measurements can be thoroughly quantified. Therefore, analytical uncertainty budgeting is not a valid approach. However, the overall uncertainty may be evaluated through the substitution method, adapting the approach described in ISO/TS 15530 part 3 [6]. Since the substitution method is based on the use of calibrated workpieces, traceability of measurements can be established only by comparison with calibration results obtained from a more accurate measuring system (such as tactile CMM) [8]. Therefore, a comparison of CT dimensional measurements with tactile CMM measurements is of fundamental importance. This is due to traceability and due to the fact that mechanical CMMs are very widespread and recognized measuring machines in industry. Therefore, comparability of results is crucial for acceptance of CT scanning as a valid metrological tool [9].

Chapter 2

Characteristics and correction of error sources

The importance of reference objects in CT has been described in chapter 1. This chapter presents a state of the art (literature review) of error sources and their correction using reference objects. Due to a big number of influence factors in CT, as discussed in previous chapter, not all of them can be corrected using reference objects. Methods describing principles of the use of reference objects for correction of the error sources are described in this chapter.

2.1 Threshold determination

A threshold value, using reference objects, is evaluated by simultaneous measurement of internal and external features. The dimensions of inner and outer features depend on changing threshold in opposite way. As the threshold value increases, dimensions of inner features increase, while dimensions of outer features decrease. Using a calibrated reference object, the correct threshold value is determined as the value that minimizes the maximum between: (i) deviation of inner dimension with respect to its calibrated value, and (ii) deviation of outer dimension with respect to its calibrated value (both deviations taken in absolute values). Therefore, assessment of the correct threshold value is an important factor for surface determination and thus accuracy of dimensional measurements.

Table 2.1: Threshold.

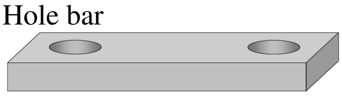
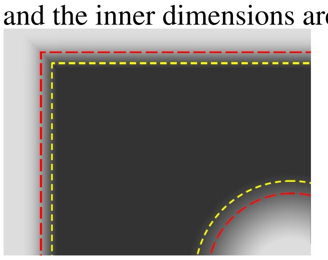
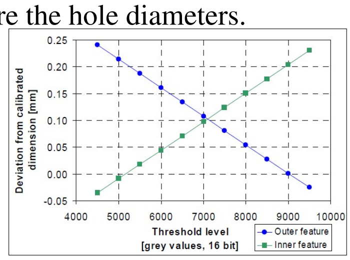
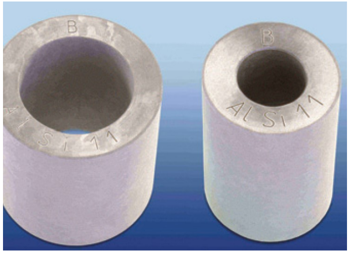
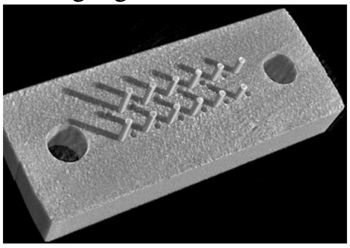
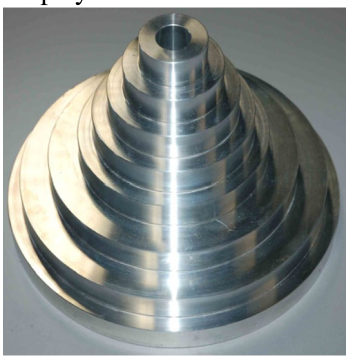
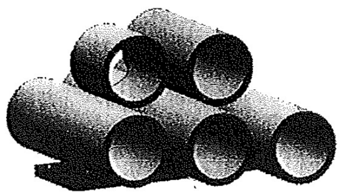
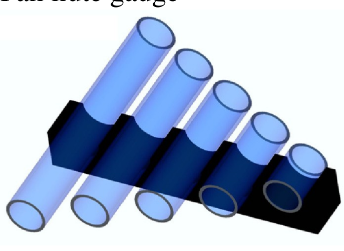
Threshold		
Reference object	Method	Reference
Hole bar 	The outer dimensions are the width and length of the bar and the inner dimensions are the hole diameters.  	[8]
Continued . . .		

Table 2.1: Threshold (continued)

Threshold (continued)		
Hollow cylinders 	The outer dimension is the outer cylinder and the inner dimension is the inner cylinder.	[10–12]
Fibre gauge 	The outer dimensions are the fibres and the inner dimensions are inner cylinders on the multi-hole ferrule.	[9]
Step cylinder with bore hole 	The inner dimension is the inner bore hole and outer dimensions are the cylinders at different heights.	
Olympic gauge 	The outer dimensions are the outer tubes and the inner dimensions are the inner tubes.	[13]
Pan flute gauge 	The outer dimensions are the outer tubes and the inner dimensions are the inner tubes.	[14]

2.2 Scale errors

Determination of scale errors in all space directions is achieved through measurement of distance between balls centers (e.g., ball bar) or holes axes (e.g., hole bar), respectively. The distance measured with CT, L_M, is compared to the calibrated distance L_R, measured with a reference instrument, for example tactile coordinate measuring machine (CMM). The distance between spheres centers or holes axes, respectively, measured on CT systems is nearly independent from the threshold applied. This makes the evaluation of scaling factors very robust and independent from threshold determination [8]. The correction factor, ΔV, is based on correcting the original voxel size (V_0) using the reference object. The *CF* is calculated as:

$$\Delta V = \frac{L_R}{L_M} \tag{2.1}$$

After that, the new voxel size, V_C, is calculated as follows:

$$V_C = V_0 \cdot \Delta V \tag{2.2}$$

Table 2.2: Scale errors.

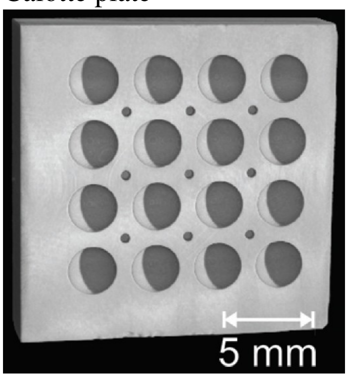
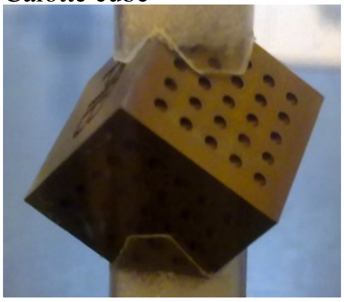
Scale errors		
Reference object	Method	Reference
Ball bar (ceramics balls) 	Measurement of the distance between the spheres centers and comparison with calibrated values.	[11]
Ball bar (ruby balls)	Measurement of the distance between the spheres centers and comparison with calibrated values.	
Hole bar 	Measurement of the distance between the holes axes and comparison with calibrated values.	[8]
Calotte plate 	Measurement of the distance between the calottes centers and comparison with calibrated values.	[10, 15–17]
Continued . . .		

Table 2.2: Scale errors (continued)

Scale errors (continued)		
Calotte cube 	Measurement of the distance between the calottes centers on all cube sides and comparison with calibrated values.	[14]
Invar 27 sphere gauge 	Measurement of the distance between the spheres centers and comparison with calibrated values.	[18]

2.3 Beam hardening

Polychromatic X-ray beams with lowest energies are preferentially absorbed when travelling through a matter, as a linear attenuation coefficient generally decreases with increasing energy. As a consequence of this, only those X-rays with higher energies remain in the beam when passing the matter. These X-rays are less likely to be attenuated. Also, the longer the X-ray paths through the object, the more low energy photons are absorbed, resulting in a more penetrating beam. In other words, the beam becomes harder, i.e. its mean energy increases, which explains why this is called "beam hardening". Hence, for polychromatic radiation, the total attenuation, given by the logarithm of the ratio of the incoming and the attenuated X-ray beam, is no longer a linear function of objects thickness. If this non-linear beam hardening effect is not compensated, the reconstructed images in X-ray CT will be corrupted by artifacts. There are few methods to reduce beam hardening effect, two of them, using the reference objects, are presented below.

Typical characteristic curves for monochromatic and polychromatic radiation can be seen in Figure 2.1. It can be noticed that the intensity change is linear when monochromatic radiation propagates through the matter while the curve is non-linear for polychromatic radiation.

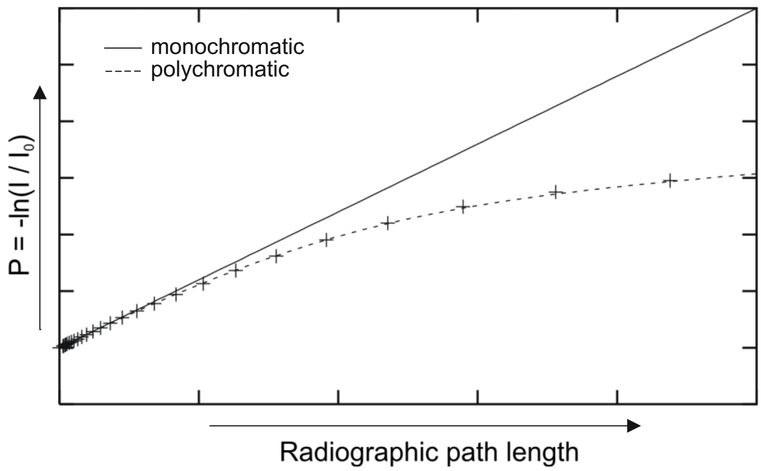


Figure 2.1: Mono- and polychromatic radiation curve [19].

Table 2.3: Beam hardening.

Beam hardening		
Linearization Linearization is based on the estimation of the relation between a propagated path length within the specimen and measured weakened intensity by means of various estimation algorithms, in other words linearization uses a correction function to transform polyenergetic to monoenergetic projection data. The resulting characteristic line can be used to compute beam hardening corrected intensity values which allow the reconstruction of an artifact free CT image. The characteristic line can be determined by performing a reference measurement of a reference object. This reference object has to be composed of the same material as the specimen.		
Reference object	Method	Reference
Continued ...		

Table 2.3: Beam hardening (continued)

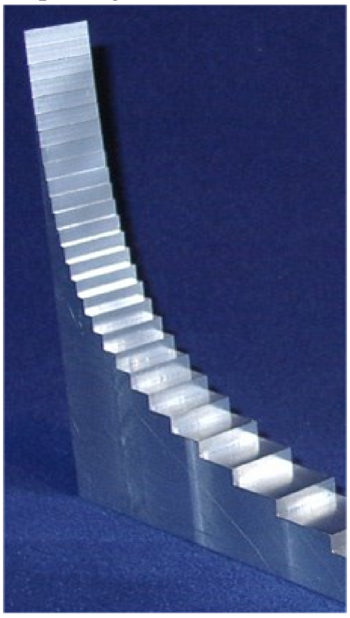
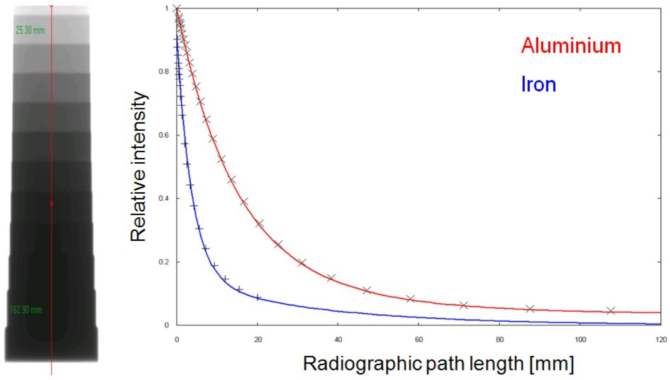
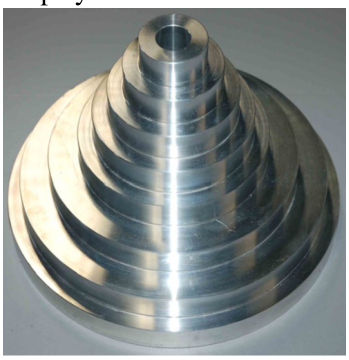
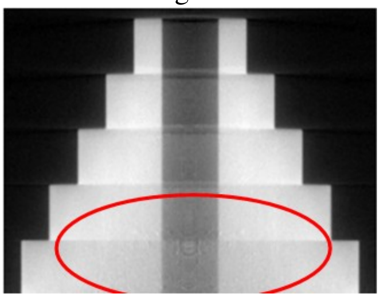
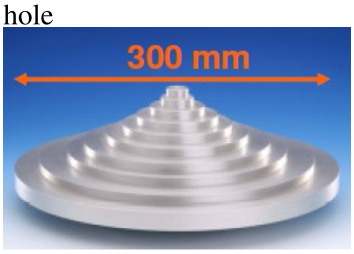
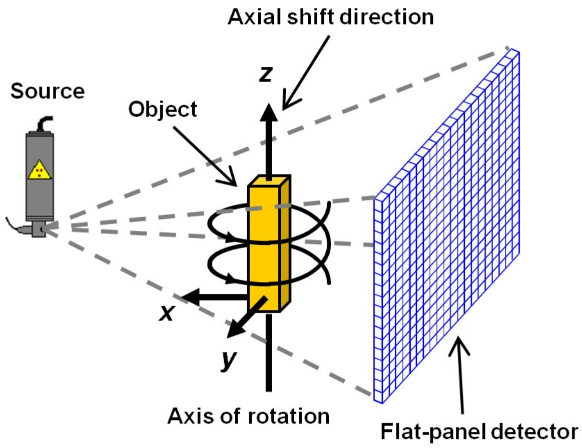
Beam hardening (continued)		
Step wedge 	The idea of using this reference object is to determine a path length in order to obtain a correction function from the object itself. This method can be however only applied for measurement using one source spectrum and one material type. 	[20]
Step cylinder with bore hole 	Due to the increasing wall thickness in the lower rings of this reference object, artefacts affect the dataset so that it is difficult to distinguish between material and air in the bore hole. With this object, the limitations of a CT concerning geometrical and dimensional measurements are shown. Red circle in the figure below shows above mentioned beam hardening effect. 	[18, 21, 22]
Step cylinder without bore hole 	A strong gradient of the form deviation measured at different heights of the step cylinder indicates the maximum material thickness that can be measured with a give CT system.	[10]
Continued . . .		

Table 2.3: Beam hardening (continued)

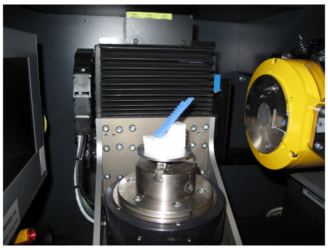
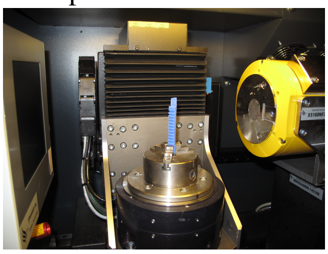
Beam hardening (continued)
Helical geometry of a CT scanner Using the helical scan geometry, an object rotation in one plane is replaced through a helical rotation. The object is shifted vertically every rotational step. 

2.4 Orientation

Orientation of the measured object with respect to to the rotation axis has influence on the length of the way the rays have to pass through the object and variation of this length during the rotation while the object is measured. If the length changes significantly, there is a possibility that in projection images with shorter lengths the object is outshined, while in projection images with greater lengths of X-rays parts of the image are too dense and the remaining intensity is too weak for proper reconstruction. The object has to be positioned in such a way so that the length the rays travel through the object is, if possible, equally distributed along all angle positions.

There is no specific reference object for correction of the orientation influence. However, Table 2.4 presents a reference object - Step gauge - used for the investigation regarding the influence of the orientation.

Table 2.4: Orientation.

Orientation		
Reference object	Method	Reference
Step gauge 	It was investigated that by positioning the step gauge at 45°, the error for indication of length measurement, *E*, can be improved by more than 50% with respect to the vertical position. This is due to a significant reduction of border noise on the flat surfaces of the steps.  	[23]

2.5 Spatial distribution of errors

Measuring errors can be characterized inside of the CT volume using reference objects with known (calibrated) lengths. Such objects are shown in the table below. The main principle relies upon comparison of lengths measured by CT and by reference instrument (e.g., CMM). The difference then highlights error of the CT scanner. These objects are CT scanned under different orientations and at different positions within the scanner in order to be able to monitor the error distribution.

Table 2.5: Spatial distribution of errors.

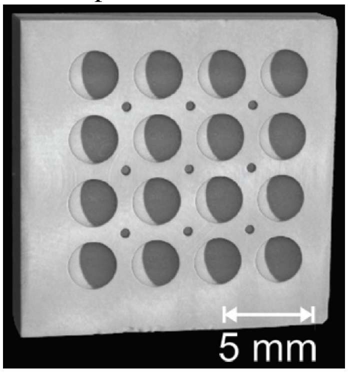
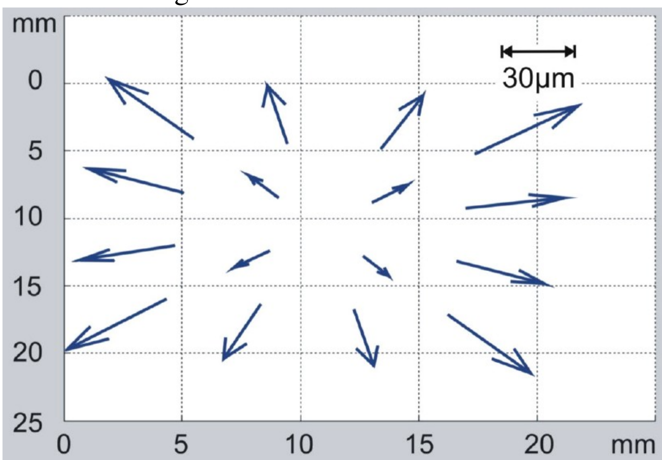
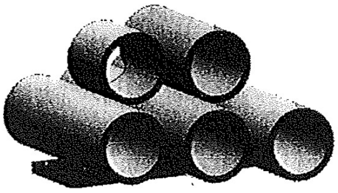
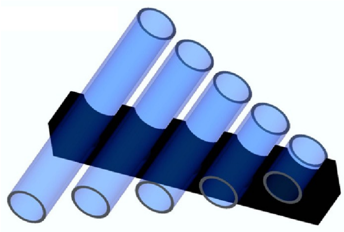
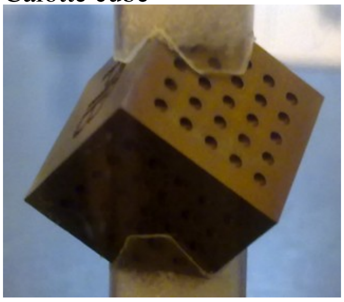
Spatial distribution of errors		
Reference object	Method	Reference
Calotte plate 	The reference object is measured several times in the whole measurement volume. Difference vectors between calibrated center positions and CT measured positions are shown in the figure below. 	[10, 15–17]
Olympic gauge 	Repeated measurement of tube lengths and diameters in the whole measurement volume. Differences from the calibrated values determine the spatial distribution of errors.	[13]
Pan flute gauge 	Repeated measurement of tube lengths and diameters in the whole measurement volume. Differences from the calibrated values determine the spatial distribution of errors.	[14]
Continued . . .		

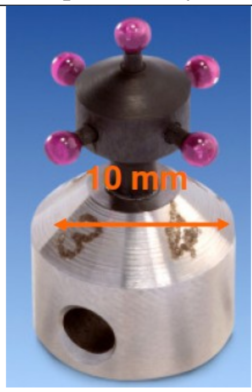
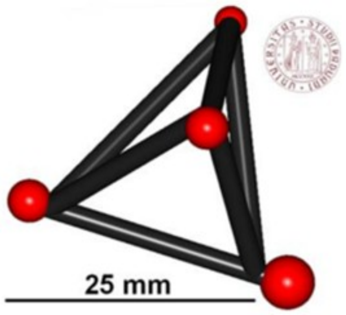
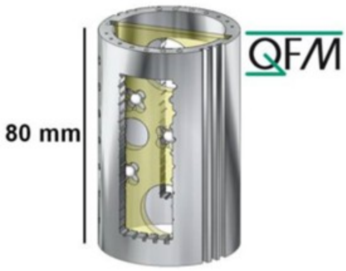
Table 2.5: Spatial distribution of errors (continued)

Spatial distribution of errors (continued)		
Calotte cube 	Measurement of distances between centers of calottes and comparison of these measurements with calibrated values.	[14]

2.6 Other reference objects

Other reference objects have been also developed (see Table 2.6). CT tetrahedron and QFM cylinder have been for example used during the First international intercomparison of industrial CT scanners, organized by University of Padova.

Table 2.6: Other reference objects.

Other reference objects	
Micro tetrahedron (ruby) [24]	Mini probe (ruby) [24]
	
CT tetrahedron [14]	QFM cylinder (titanium + epoxy resin + sapphire) [14]
	

Chapter 3

Correlations and redundancies

State of the art of reference objects for correction of errors and determination of characteristics in CT has been presented in chapter 2. This chapter focuses on analysis of correlations and redundancies of these reference objects and proposes a systematic approach for designing new reference objects.

Before the design stage, an identification of the particular error source has to be clarified. Then, material, size and geometry of such a reference object has to be considered. The proposed, so called "3-directional approach", is schematically shown in Figure 3.1.

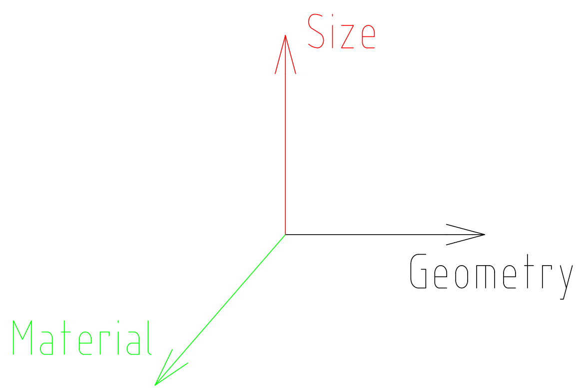


Figure 3.1: Proposed model for development of new reference objects.

An example of the use of this approach is presented for threshold value determination:

- Geometry: Two features, one inner and one outer, are needed to determine an optimal threshold value.
- Material: Material of the reference object should be the same or similar to the material under investigation.
- Size: Depending on what kind of CT scanner (micro CT or macro CT) is used for scanning of real workpieces, the size of the reference object is an important parameter.

Table 3.1 presents an overview of reference objects and their overall use for error source correction and characteristic determination. It can be noticed that some of the reference objects are used to correct more than one error source or determine more than one characteristic.

Table 3.2 is than a logical output of Table 3.1, i.e. Table 3.2 presents an overview of possible reference objects that have not yet been developed for particular correction of error sources or determination of characteristics.

However, the relevance of the use of reference objects is highlighted by symbols, where the meaning is specified below the table. The assessment of relevance of these reference objects is based on the authors short experience with CT.

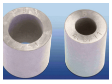
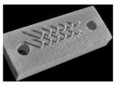
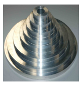
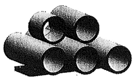
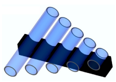
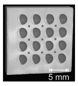
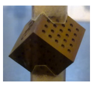
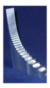
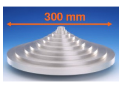
One of the criteria for development of reference objects is size. By *size* here is meant the size of the object with respect to the measuring volume inside of the CT scanner. This is further connected to achievable resolution in terms of voxel size (i.e., dependent on the magnification factor) and maximum power applied to scan the sample.

It should be noted that the development of reference objects from a specific material is dependent on a particular error source. This means, for instance, that error sources A, C and E and characteristics F, G and H, according to the nomenclature of Table 3.1, should be corrected by reference objects made out of the same or similar material as is the material of real scanned object. On the other hand, scale errors (correction of the original voxel size) do not need to include various materials. Scale errors are generally corrected using reference objects consisted of balls (ball bars) made of ruby, steel or ceramic material, where measurements of the balls (spheres) center to center distance is the most robust procedure. The only question may arise: "What is the influence of using different ball bar lengths with respect to the size of scanned object?". The quantification of the effect of different ball bar lengths will be investigation by the author during the PhD study.

Due to the big number of error sources in CT, the list of reference objects in Table 3.1 is not finished and development of new reference objects is necessary. Other materials from materials included in Table 3.1 should be considered, since the ones presented in the table do not cover the whole range of materials being scanned by CT.

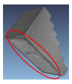
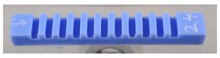
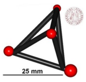
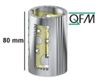
New reference objects should however be designed and developed since the error sources described in Table 3.1 do not cover the whole range of error sources. Several suggestions for development of these reference objects is described in chapter 5. These include, e.g., investigation of the influence of the cone bean effect..

Table 3.1: Use of reference objects (color-filled cells) in CT for error sources correction and determination of characteristics. A: Threshold, B: Scale factor, C: Beam hardening, D: Orientation, E: Spatial distr. of errors, F: Error for indication of length measurement, G: Probing error size, H: Probing error form.

			Error source							
Reference object	Material	Size	A	B	C	D	E	F	G	H
										
	Aluminum									
	Glass fibre	Micro								
	Aluminum	Macro								
	Borosilicate glass [1] + Carbon fibre [2]	Micro								
	Borosilicate glass + Carbon fibre [3]	Micro								
	General ceramics	Macro								
	Zerodur	Micro								
	Titanium alloy (Ti6Al4V) [4]	Micro								
	Aluminum, Iron	Macro								
	Aluminum	Macro								
Continued . . .										

[1]Chemical composition: 72% SiO_2, 12% B_2O_3, 7% Al_2O_3, 6% Na_2O, 2% K_2O, 1% CaO
[2]Carbon fibre is only used as a support.
[3]Carbon fibre is only used as a support.
[4]Chemical composition: 90% Ti, 6% Al, 4% V, max 0.25% Fe, max 0.2% O

Table 3.1: Use of reference objects in CT scanning for error sources correction and determination of characteristics (continued).

			Error source							
Reference object	Material	Size	A	B	C	D	E	F	G	H
	Aluminum	Macro								
		Macro								
	Plastics	Micro								
	Ruby (Al_2O_3)	Macro								
	Ruby (Al_2O_3)	Micro								
	Ruby (Al_2O_3)	Micro								
	Ruby (Al_2O_3) + Carbon fibre [5]	Micro								
 [6]	Titanium grade 4 [7] + epoxy resin + sapphire	Macro								

Gray color: Use of reference objects based on literature review, Yellow color: Possible use of reference objects based on the author knowledge.

[5]Carbon fibre rods are only used to support the ruby balls.

[6]This reference object can also be possibly used for determination of the resolution of the CT scanner and for characterization of multiple materials.

[7]Chemical composition: 99% Ti, max 0.1% C, max 0.5% Fe, max 0.15% H, max 0.05% N, max 0.4% O

Table 3.2: Relevance of development/manufacture of new reference objects, considering their size, material and geometry. A: Threshold, B: Scale factor, C: Beam hardening, D: Orientation, E: Spatial distr. of errors, F: Error for indication of length measurement, G: Probing error size, H: Probing error form.

		Error source							
Size	Material	A	B	C	D	E	F	G	H
Micro	Aluminum	●	○	⦸	○	●	⦸	⦸	⦸
	Zerodur	⦸		⦸	○		⦸		
	Robax	⦸	○	⦸	○	⦸	⦸	⦸	⦸
	Macor [8]	⦸	○	⦸	○	⦸	⦸	⦸	⦸
	Borosilicate glass		○	⦸	○			⦸	⦸
	PMMA (HDPE)	●	○	●		●		⦸	⦸
	Titanium	⦸		⦸	○		⦸	⦸	⦸
	Ruby	○		⦶		⦶			
	Copper	⦸	○	⦸	○	⦸	⦸	⦸	⦸
	Lead	⦸	○	⦸	○	⦸	⦸	⦸	⦸
Macro	Aluminum				○	●	⦸	⦸	⦸
	Zerodur	⦸	○	⦶	○	⦶	⦶	⦶	⦶
	Robax	⦸	○	⦸	○	⦸	⦸	⦸	⦸
	Macor	⦸	○	⦸	○	⦸	⦸	⦸	⦸
	Borosilicate glass	⦸	○	⦸	○	⦸	⦸	⦸	⦸
	PMMA (HDPE)	⦶	○	⦸	○	⦸	⦸	⦸	⦸
	Titanium			⦸	○	⦸			
	Ruby	○		⦶	⦸				
	Copper	⦸	○	⦸	○	⦶	⦶	⦶	⦶
	Lead	⦸	○	⦸	○	⦶	⦶	⦶	⦶

● Highly relevant ⦸ Relevant ⦶ Less relevant ○ Not relevant

Chapter 4

Manufacture of a step cylinder

Reference objects, in general, can be divided into the following three groups:

1. Performance evaluation,
2. Image processing,
3. Reference objects near real-workpiece.

In the following, design for use, manufacture and calibration will be presented for a reference object - Step cylinder - following a draft version of a German standard VDI/VDE 2630 - Part 1.3.

4.1 Step cylinder

An example of the reference object used for performance evaluation is an aluminum 5-step cylinder (Figure 4.1) manufactured at DTU facilities according to a German standard VDI/VDE 2630 - Part 1.3 (DRAFT) [25]. In this chapter, design for use, design requirement, design for manufacture and design for calibration are described. Due to the fact, that this reference object is axis symmetric, this reference object was modified and a fixture was manufactured allowing alignment in 3 dimensions.

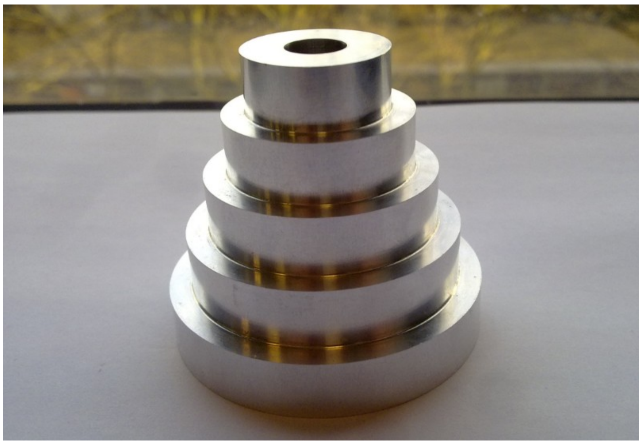


Figure 4.1: 5-step cylinder.

4.1.1 Use

5-step cylinder allows classification of different inner and outer diameters at different wall thicknesses. Due to the increasing wall thickness in the lower rings (steps), artefacts (e.g. beam hardening) affect the dataset so that it is difficult to distinguish between material and air in the bore hole. With this reference object, the limitations of a CT concerning geometric and dimensional measurement are shown. Red circle in Figure 4.2 shows above mentioned beam hardening effect.

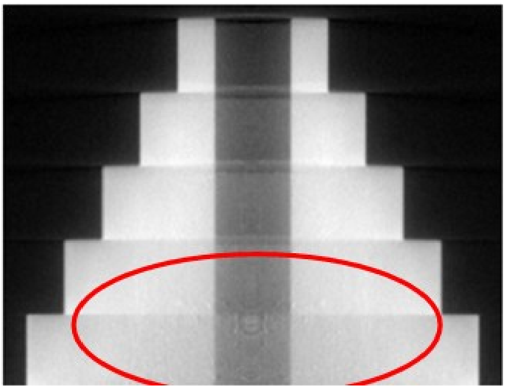


Figure 4.2: CT scan of the step cylinder [21]. The cross-section of the step cylinder shows increasing artefacts in the center reamed hole when wall thicknesses are increasing.

Step cylinder can be also used for determination of characteristics, i.e. probing error size, probing error form and straightness of the bore hole axis.

Probing error size
Probing error for size measurement, GS, is defined as deviation of measured inner diameter of the bore hole and corresponding outer diameter, D_{m}, from the calibrated diameters, D_{m}. The parameter GS is indicated for each level for inner as well as for the outer diameter. Probing error size is mathematically expressed in Equation 4.1 and can be graphically seen in Figure 4.3(a).

$$GS = D_{\mathrm{m}} - D_{\mathrm{r}} \tag{4.1}$$

Probing error form
Probing error form, GF, is defined as the range of the radial error between the maximum and minimum measured points and compared to calibrated values. Probing error form is mathematically expressed in Equation 4.2 and can be graphically seen in Figure 4.3(b).

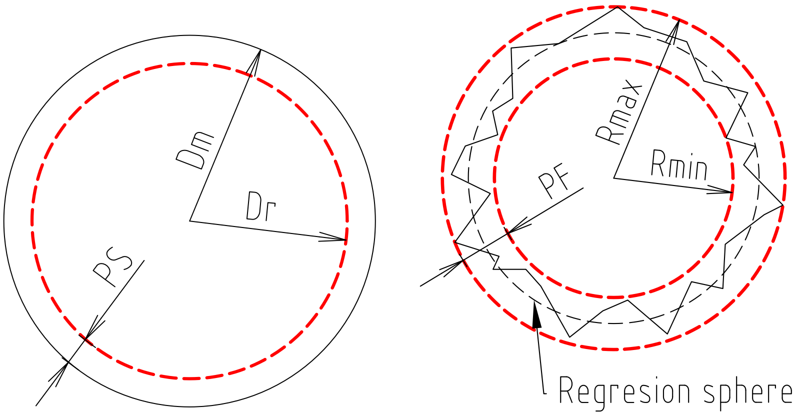
$$GF = R_{\mathrm{max}} - R_{\mathrm{min}} \tag{4.2}$$

Both above mentioned characteristics are based on Gaussian fitting algorithm.

Straightness of the bore hole axis
The determination of the evaluating geometry's elements can be conducted following two different methods:

1. Method about the global workpiece coordinate system - Method A

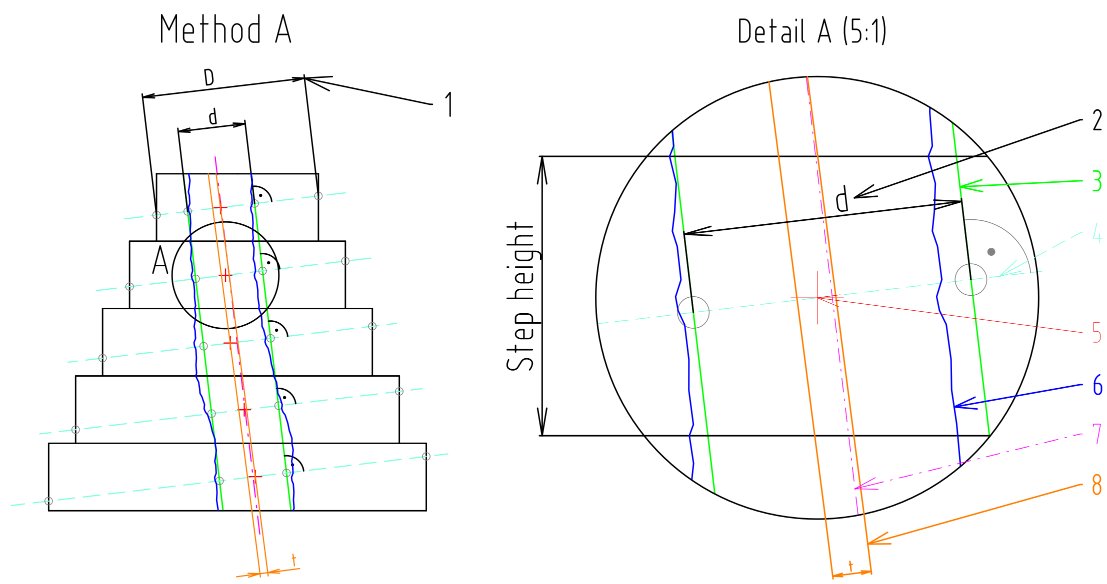
2. Method about the local workpiece coordinate system - Method B



(a) Probing error size. (b) Probing error form.

Figure 4.3: Definition of geometrical characteristics, probing error size and probing error form, according to [25].

Description of both above mentioned methods is in details written in [25] and schematically shown in Figure 4.4 and in Figure 4.5. The main difference between these two methods is in the evaluation of the straightness of the bore hole axis.



(a) Full size sketch. (b) Detail.

Figure 4.4: Definition of straightness of the bore hole axis evaluation - Method A according to [25]. 1-Outer measured diameter, 2-Inner measured diameter, 3-Gaussian fitted cylinder along the step cylinder height, 4-Slice perpendicular to the cylinder axis, 5-Middle point measured at each step height, 6-Real contour of the bore hole, 7-Axis of the fitted cylinder, 8-Straightness tolerance.

Moreover, this reference object can be used for threshold determination. This is achieved by simultaneous measurement of inner and outer diameters of cylinders at different heights.

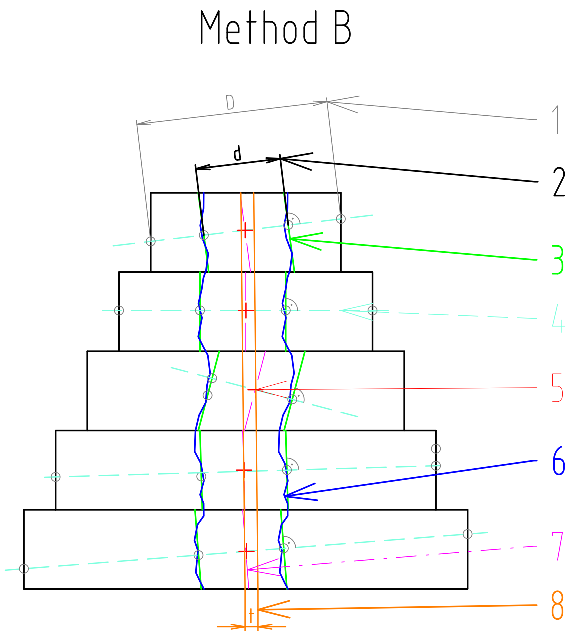


Figure 4.5: Definition of straightness of the bore hole axis evaluation - Method B according to [25]. 1-Outer measured diameter, 2-Inner measured diameter, 3-Gaussian fitted cylinder along the step cylinder height, 4-Slice perpendicular to the cylinder axis, 5-Middle point measured at each step height, 6-Real contour of the bore hole, 7-Axis of the fitted cylinder, 8-Straightness tolerance.

4.1.2 Design requirement

Figure 4.6 shows requirements for a design of the proposed 5-step cylinder according to [25]. Following this standard, the number of steps should be at least 5 and maximum 10. The dimensions of the manufactured step cylinder can be seen in Table 4.1.

Table 4.1: Dimensional specifications of a step cylinder.

Step	Height, h [mm]	Outer diameter, D [mm]	Inner diameter, d [mm]
1	10	24	10
2	10	32	10
3	10	40	10
4	10	48	10
5	10	56	10

The key design issues are:

- Due to a big thickness of the step cylinder, some problems with scanning using Nanotom CT scanner (Novo Nordisk) were encountered a so this object will be scanned using Metrotom CT scanner (Technological Institute).
- The material has to be sufficiently penetrable for the X-rays. According to [26], the maximum penetrable length of the X-rays is 120 mm for Al and its alloys.
- No special precautions related to the weight of the object need to be applied since the maximum load applied on the rotary table is 500 N.

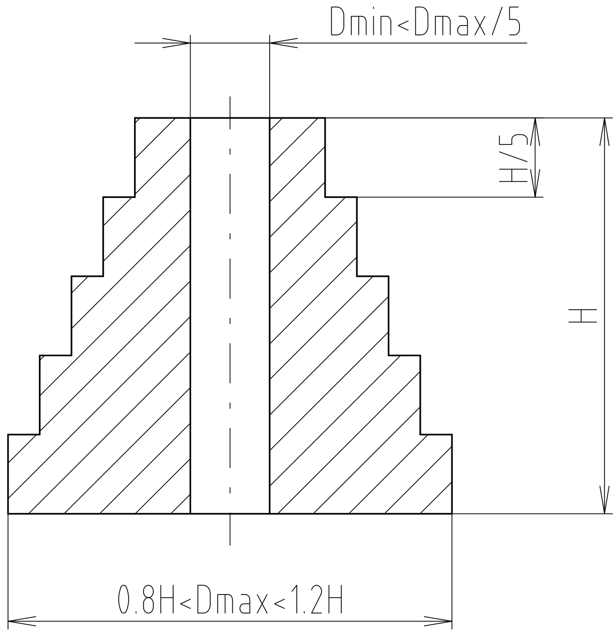


Figure 4.6: 5-step cylinder - definition according to a German standard VDI/VDE 2630 part 1.3.

- No special precautions related to the height of the object need to be applied due to big dimensions of the flat panel detector (410 x 410 mm).

4.1.3 Manufacture

- According to [25], the material of the step cylinder should be the same or similar to test pieces. Due to the fact, that aluminum and aluminum alloys are among the most machinable of the common metals used in industry, the material of the step cylinder is an aluminum alloy (EN AW-2011). Typical physical and mechanical properties of aluminum alloys are shown in Table 4.2 and material composition of this specific aluminum alloy is shown in Table 4.3.

- Taking into account a machine design of the Metrotom CT scanner and dimensions of the step cylinder, the best achievable resolution is between 50 to 90 μm. Then, geometrical tolerances, in our case cylindricity, should approx. be 5-10 times better than the resolution value. This means that calibration values for cylindricity should be less than 20 μm when taking into account specifications of the CT scanner (i.e. size of the flat panel detector, pixel size, maximum achievable magnification, etc.).

- Roughness of the item should be negligible.

The individual steps are machined on the lathe by turning. The cutting conditions were chosen in order to obtain high geometrical accuracy specified on the drawing. The inner bore hole of the step cylinder are drilled and reamed.

4.1.4 Fixture

Due to the fact that step cylinder is an axis symmetric item, a specially designed fixture (see Figure 4.7.) was manufactured allowing assessment of a coordinate system in 3 dimensions. Additional two holes were machined into the step cylinder from the bottom face for assembling of the step cylinder with the fixture (see Figure 4.8) via connecting pins with h6 tolerance.

Table 4.2: Typical physical and mechanical properties of aluminum alloys.

Physical and mechanical properties of aluminum alloys		
Density	2600-2800	kg/m^3
Melting Point	660	°C
Elastic Modulus	70-79	GPa
Poisson's Ratio	0.33	
Tensile Strength	230-570	MPa
Yield Strength	215-505	MPa
Elongation	10-25	%
Thermal properties		
Thermal Expansion Coefficient	$20.4 - 25.0 \times 10^{-6}$	1/K

Table 4.3: Material composition of a 5-step cylinder made of aluminum alloy EN AW-2011.

Element	**Mass [%]**	**Element**	**Mass [%]**
Al	90.46-92.15	Bi	0.2-0.6
Si	0.4	Pb	0.2-0.39
Fe	1.7	Zn	0.3
Cu	5.0-6.0	Other	0.05-0.15

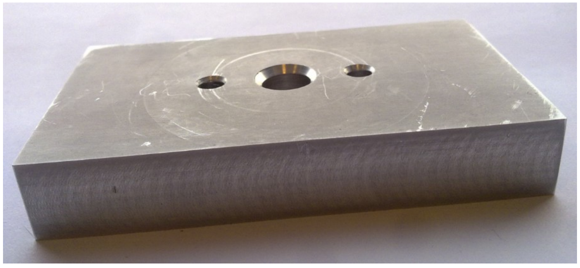


Figure 4.7: Specially designed fixture.

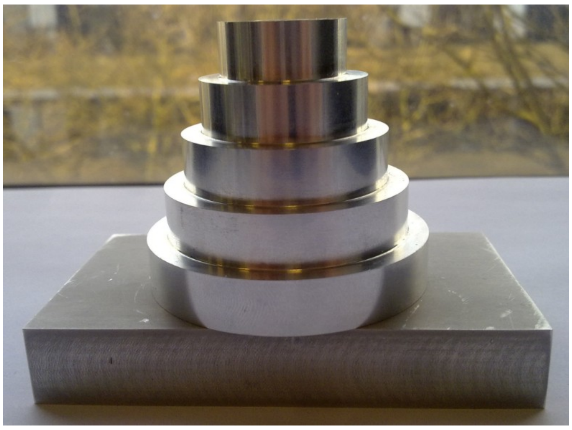


Figure 4.8: Step cylinder assembled on the fixture.

4.1.5 Calibration

Design for calibration includes measurements performed using a tactile CMM, OMC 850 from Zeiss, with MPE=(2.5±L/300) μm (L in mm) and a styli with 3 mm diameter probe. Measurements were performed in a temperature controlled laboratory with temperature of 20±0.5 °C. Firstly, the fixture was fixed on the CMM table (Figure 4.9(a)).

The alignment was done in the following way:

1. 8 points were probed on the top surface of the fixture.
2. 4 points were probed inside the hole for connecting pin 1.
3. 4 points were probed inside the hole for connecting pin 2.

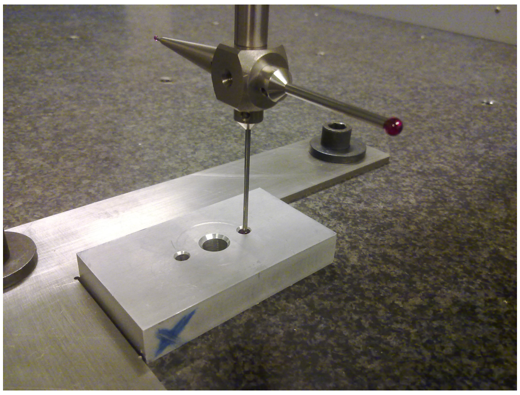
The connecting pins were placed in the fixture (Figure 4.9(b)) and the step cylinder was put and attached to it (Figure 4.9(c)). Then, alignment on the step cylinder was done in the following way:

1. 8 points were probed on the top surface of the step cylinder (Top Plane).
2. 8 points were probed inside the bore hole of nominal diameter 10 mm at 5 levels (-5, -15, -25, -35 and 45 mm) (Cylinder Datum A).
3. Intersection between Top Plane and Cylinder Datum A is created (Intersection 1).

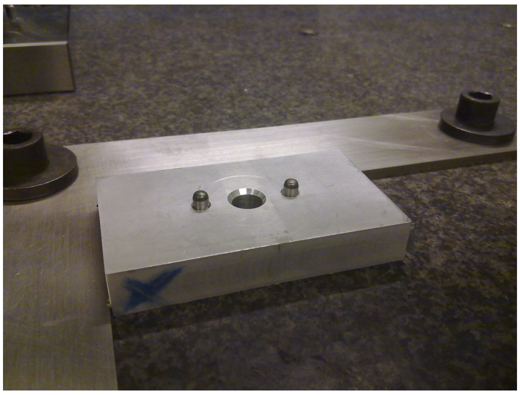
Furthermore, 8 points were probed on the top surface of each step (Plane Step i, i = 2-5) and another 8 points on the outer dimensions of the step cylinder (i.e. 24, 32, 40, 48 and 56 mm) at 3 levels for each step (i.e. -2.5, -5.0 and -7.5 mm) from the nominal height (Cylinder Step i, i = 1-5).

The following measurands were defined:

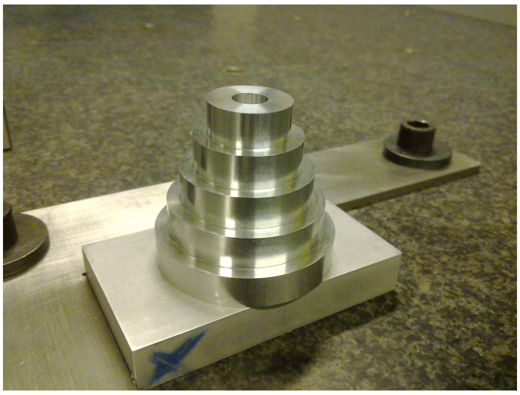
- Cylindricity of the bore hole (Cylindricity Datum A).
- Diameter of the bore hole calculated as an average diameter at 5 levels (Diameter Cylinder Datum A).
- Perpendicularity of the axis of the bore hole with respect to the top plane (Perpendicularity 1).
- Actual Z position of each step height calculated as an average of 8 points (Z value Plane Step i, i = 2-5).
- Diameter of the outer cylinder measured at each step and calculated as an average diameter at 3 levels (Diameter Cylinder Step i, i = 1-5),
- Cylindricity of the outer cylinder at each step (Cylindricity Cylinder Step i, i = 1-5).
- Coaxiality between the outer cylinder with respect to the bore hole measured at each step (Coaxiality Cylinder Step i, i = 1-5).



(a) Setup for the fixture.



(b) Pins inserted into the fixture for connection with the step cylinder.



(c) Setup for measurements of the step cylinder, attached to the fixture by pins.

Figure 4.9: Measuring setup for calibration of the step cylinder.

Chapter 5

Proposals for new reference objects

In this chapter, proposal for manufacture of a new reference object is presented. Hand drawings of the object along with descriptions (purpose, material) are described below.

5.1 Ball plate

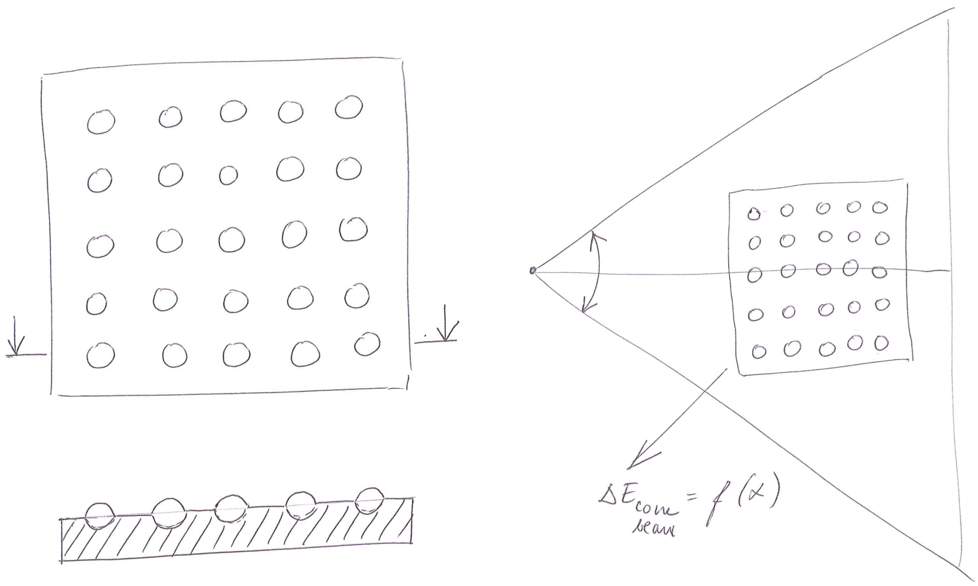
The geometry of the object will enable (see Figure 5.1) to use this object for performance testing of industrial CT scanners and for characterization of errors inside of the CT volume.

Description:
25 balls of diameter 5 mm are glued in 25 pre-manufactured calottes in the plate. The evaluation will be carried out only on the upper-spherical surfaces of the balls due to a possibility of imperfections and thus resulting noise occurrence in the lower parts of the spheres.

Purpose:
CT volume characterization, influence of the error of the cone beam in the CT system, through evaluating the scale error in vertical direction, determination of probing error for size measurement and probing error form.

Material:
Spheres: Ruby
Plate: Carbon fibre

Manufacture requirements:
Well chosen glue has to be used for proper attachment of the balls to the plate.



(a) Schematic drawing. (b) Ball plate in the CT volume.

Figure 5.1: Ball plate.

Chapter 6

Conclusions

A state of the art of reference objects in computed tomography was presented in this report. The use of reference objects in CT is one of the requirements for achieving traceability. Reference objects are used to correct measurement errors (systematic errors) in CT. It was documented that one reference object can be used to correct several parameters (errors) at the same time. Correlations and redundancies in the development of the reference objects was discussed and new reference objects were proposed. These are mainly connected with performance testing of industrial CT systems and correction of e.g. scaling errors.

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