

Analysis of the error sources of a Computer Tomography Machine

V. Andreu¹, B. Georgi², H. Lettenbauer², J.A. Yagüe³

¹*Iberprecis S.L., Spain;* ²*Carl Zeiss, Germany;* ³*Univ. of Zaragoza, Spain*

Abstract

Computer Tomography (CT) Metrology using X-rays is becoming a more and more used technology to measure both internal and external geometries simultaneously in a great variety of parts. Therefore, the CT is used not only as a simple inspection method but also as a measuring principle capable of providing accurate geometrical information. The Metrotom CT-machine together with Calypso software are able to provide also internal and external 3D modeling of the measured part. Nevertheless, studies of the measurement deviations caused by the complex influence factors affecting CT can hardly be found in literature. The objective of this paper is the study and analysis of these error sources. A thoughtful analysis and classification of the possible sources of error in CT-measuring machines has been carried out. This analysis has been experimentally validated by many tests in five different machines during several months and using several reference artefacts. The results of these experiments have allowed us to establish maximum permissible errors for four different specifications. In addition all this experimental work and the results have been very valuable for the development of the new VDI 2630 guideline.

1 Introduction

Accuracy and time exigencies are getting tighter and tighter in the field of manufacturing engineering. The evolution of the dimensional metrology has to be capable of meeting these demands. Thereby, apart from the optimization of traditional metrology equipments, new technologies based on new measuring concepts are being developed. One of these new concepts developed in the last years is the Computer Tomography (CT) Metrology using X-rays.

Computer Tomography is a well-known technology for its use in medical diagnostics since more than 30 years. In addition, it is also becoming a very interesting tool for industrial applications. Its more usual application in this field

is the detection of faults (cracks, etc) or material composition of a workpiece by non-destructive testing. However, the increasing demand of systems to quantitatively measure internal and external geometrical features has made CT gain importance as a system for dimensional metrology applications [1].

In this field, the Metrotom CT-machine was developed by Carl Zeiss for measuring both internal and external geometries simultaneously in a great variety of parts. Therefore, the CT is used not only as a simple inspection method but also as a measuring principle capable of providing accurate geometrical information. In addition, it allows the internal and external 3D modelling of the measured part.

Nevertheless, studies of the measurement deviations caused by the complex influence factors affecting CT can hardly be found in literature [2-4]. Many complex factors may influence the measurement and a deeper study of them must still be carried out in order to quantify this influence. This paper shows an intense study and analysis of those error sources through experiments carried out in five CT-machines for several months in order to study also reproducibility and stability. It also describes how calibrated reference artefacts are used to enhance their dimensional accuracy by correcting some of the systematic influences. Finally, it shows the use of those reference standards for their application in acceptance tests similar to the used in classical CMMs. Moreover, the preliminary results obtained from the work here presented were very valuable for the development of the technical guideline VDI/VDE 2630 "Computed tomography in dimensional measurement" [5], now available in draft version.

2 Metrotom CT-machine

CT machines and specifically the Metrotom CT-machine basically consist of (see Fig. 1) an X-ray source, a translational movable rotary table where the part to be scanned is placed, an X-ray detector and a processing unit (composed by 6 processors working together) to analyse and display the measurement results. Currently two different types of CT systems exist depending on the beam and detector types [2,3]: 2D-CT systems use a fan beam and a line detector, whereas 3D-CT systems utilise a cone beam and an area detector. In the case of the Metrotom CT-machine a 1024x1024 pixel (400x400 mm) in size area detector is used, so that 3D information can be measured with one revolution of the part.

During the measurement process the radiation not absorbed by the object is transmitted and recorded by the detector. For every angle rotated by the table a new projection is obtained. Once a complete revolution is given, the processing unit numerically reconstructs the measured object and provides a 3D graphical reconstruction. The primitive elements of the 3D data structure are called voxels (volumetric pixels). By identification of surfaces the CT-system is able to determine coordinates of the measured part. Therefore, it is able to perform dimensional measurements like CMMs.

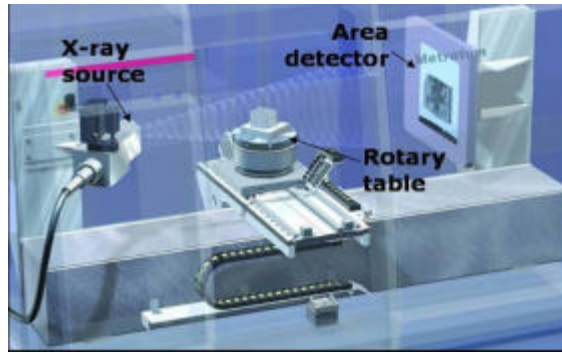


Figure 1: Metrotom CT-machine basic components

3 Analysis of the error sources

Due to the complexity of the process and the system the measurement uncertainties for 3D-CT systems have not been thoroughly determined yet. However, some studies about the error sources, resolution and repeatability aspects have been carried out as a first step for uncertainty determination [3]. From those studies and from the work carried out by the authors of this paper a classification of the influence factors affecting CT-machines is presented.

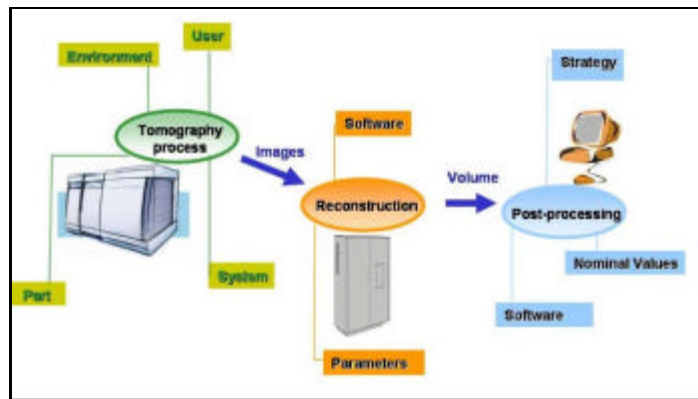


Figure 2: Main sources of error

3.1 Classification of error sources

Three steps have been established as the main steps of the measurement process by tomography. The possible error sources have been associated to those steps in the proposed classification (see Fig. 2).

3.1.1 Tomography process

It is the process where the parameters are adjusted, the tomographies taken in the CT-machine by rotating the part and the lineal attenuation coefficients of the measured body are stored.

In the tomography process the errors due to the structure of the machine itself are of special importance. The improvement of the CT-machine stability by using air bearings, linear drives, etc tries to limit its influence in the final error. In addition, the components of the machine have a remarkable importance in the final result:

The size (function of the intensity and voltage used) and shape of the X-ray focus is one of the main parameters to determine the resolution of the measurement: the smaller the focal spot is and the closer the object is positioned to the focus, the bigger the geometrical magnification achieved in the detector. In this case, the relative distances between the source and the object to be measured (“a” in Fig. 3) and the source and the detector (“b” in Fig. 3) are also very important, as well as the size of the voxel which is a function of the pixel size and the distance “a” and “b” (see Eq. 1). Evidently, the smaller the size of the object to be measured, the smaller the distance “a” may be. An excessive size of focus will provide a fuzzy zone. As a recommendation the use of a size of focus of 90% the size of voxel would be adequate.

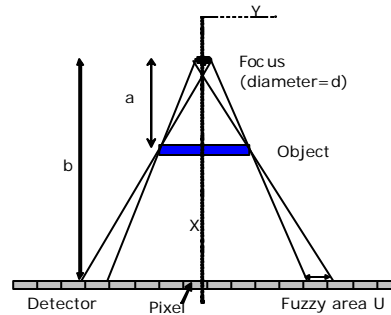


Figure 3: Influence of the distances between focus, object and detector

$$Size\ voxel = Size\ pixel \cdot \frac{a}{b} \quad (1)$$

Unexpected displacements of the focus along X or Y can happen. When the displacement in X happens, that implies an unexpected change in the distance “a” and the consequent scale error. A displacement along Y will imply a fuzzy 3D image and even double-edged. Both displacements are usual errors corrected by the calibration of the machine with ball artefacts (for the X case) or filaments (for the Y case).

Several sources of error can be associated to the detector properties, such as its lateral resolution, energy-dependent sensitivity (that can be regulated by a gain ratio parameter), signal-to-noise ratio, dynamics, etc. The main errors are due to failed pixels that can be detected by an adequate calibration of the

detector. In addition, as a general recommendation, the image of the object should be as centred as possible because the experiments carried out show that the central pixels show smaller deviations than the external ones.

Possible errors in the rotary table axis or due to the discrete sampling of CT projections are possible influences corrected by already developed correction techniques.

The part itself is an important source of error from different points of view. Initially it must be adequately tightened to the rotary table. The roughness and cleanness of the part are important issues. The thermal expansion coefficient and the temperature during the process must be taken into account in the compensation part of the measurement software. The geometry and the thickness of the part are an important influence in the quantity of radiation absorbed by the part, which can be different from the expected. The material composition will mainly determine the energy-dependent absorption (beam-hardening), obtaining better results for materials absorbing less radiation (ex. plastics). If the measured part is composed by a diversity of materials unexpected and important effects can be obtained.

The changes in the environmental conditions must be, of course, controlled and the system isolated from them as well as possible: vibrations, temperature changes, etc.

From the measurement of ten parts by three different users the influence of the manipulation of the part has shown to be inappreciable. However, the user must make some decisions that can greatly condition the results: the material chosen for attaching the part to the table must be stiff but has a low absorption index. The use of filters in front of the X-ray source can help to avoid some distortions or noises. The orientation where the part is placed is of great importance to expose the whole surface of the part to the X-rays, avoiding surfaces parallel to the radiation. A recommendation raised from the experiments carried out is to centre the part with respect to the detector. The orientation is also a key point in order to minimise the maximum thickness penetrated by the X-rays.

The user is also responsible for the determination of the adequate tomography process configuration parameters, including: focus intensity, focus voltage, detector gain factor, shot time and the number of projections. The adequate selection of these parameters will depend on the user experience helped by the application of the guidelines that are being currently developed [5].

3.1.2 Data reconstruction

The projections of the object are added and assembled by six processors able to provide a 3D image of the volume. The real information that this step provides is a 3D matrix 1024x1024x1024 voxels in size with the information of the gray levels (see Fig. 4).

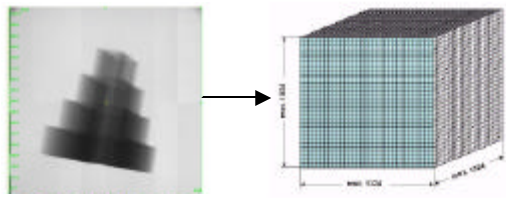


Figure 4: Data reconstruction

In this step the main errors can arise from systematic discrepancies between the values in the voxels and the attenuation coefficients of the object, obtaining elements in the image that are not really in the object. This effect is visible in this step but is mainly due to causes coming from the tomography process: beam-hardening, movements of the part, etc. In order to correct this kind of effects, the reconstruction softwares have being improved to compensate, for instance, the energy dependence of absorption or the effects of scattered radiation.

3.1.3 Data post-processing

In this phase the reconstructed voxel data are post-processed by software (Calypso in the case of the Metrotom) capable of translating the gray levels of the voxels into cloud of points. From that cloud of points the final 3D reconstruction and the measurement process are carried out (see Fig. 5).

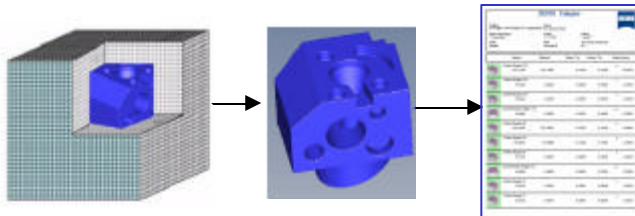


Figure 5: Data post-processing

In this step the two main processing happening influencing the final error are the threshold determination process and the scaling factor determination.

Firstly, the threshold value must be determined. This process is similar to the used in video image processing in order to carry out surface point detection by identification of edges inside the voxel by specifying the threshold value. Calypso provides the option of using a “dynamic threshold value” method for a more accurate and stable measuring process. Once the threshold value is known and applied, the output data form a triangulated data that can be fed into CAD analysis software (Calypso in this case).

Regarding the scale factor, an error in its determination can happen if, for example, an unexpected displacement along X has happened in the X-ray focus

(section 3.1.1.). Therefore, its adequate determination by calibration is essential in terms of accuracy.

3.2 Reference artefacts

As pointed out in section 3.1., many of the errors affecting CT-systems need an adequate calibration of the machine in order to reduce the systematic errors. The use of dedicated reference artefacts for the different parameters is the option applied in this work. The artefacts used are shown in Fig. 6.

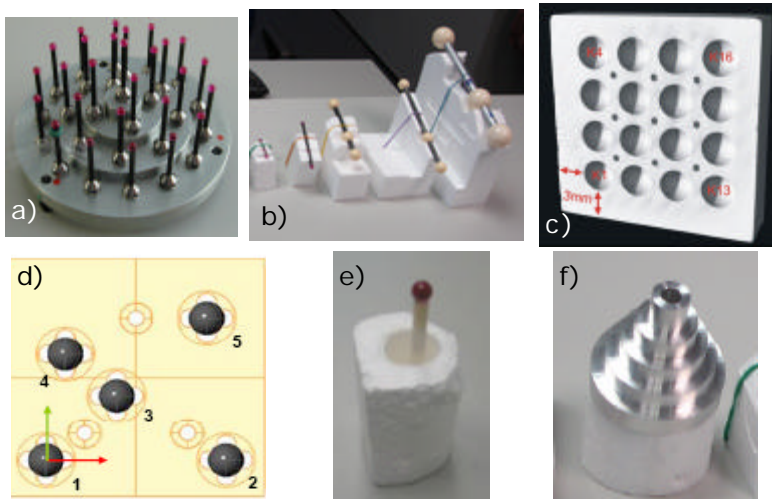


Figure 6: Reference artefacts used: a) Invar 27-sphere gauge (ruby spheres); b) Termofix ball bars (ruby and ceramic spheres); c) Zerodur sphere calotte plate; d) Zerodur ball plate; e) Ruby Spheres; f) Aluminium hollow stepped cylinder

Previous works carried out show the suitability of some of these artefacts for calibrate some systematic errors: one of the errors pointed out before was relative to the thickness of the object to be measured. To analyse material-specific absorption and for adjusting the measurement parameters, calibrated stepped cylinders (Fig. 6f) are usually utilised [3]. This artefact can be used, as well as hollow cylinders with calibrated inner and outer diameters, also to determine and enhance the threshold value determination [2]. Ball bars like the ones in Fig. 6b with almost null thermal expansion factor can be used for the determination of scaling factors, taking into account that the distance between the centres of the spheres is nearly independent of the threshold applied [2]. Zerodur sphere calotte plates (Fig. 6c) or cubes and Zerodur ball plates (Fig. 6d) are very suitable to determine several characteristics at the same time: sphere distance error, sphere error, probing error, etc. [3,4].

On the other hand, literature does not show extra results that can be obtaining by using those artefacts and an invar 27-sphere gauge (Fig. 6a). Those results are pointed out in the following sub-section.

3.3 Experimental analysis

The experiments here explained were carried out in five different Metrotom machines during 6 months in order to study the reproducibility and stability of the results. The repeatability was also studied by obtaining up to 50 data series for every measurement carried out.

After using the artefacts shown in section 3.2 to periodically carry out different calibration and corrections of the machine, they were also used to determine the expected limits of the final error in the measurements. Such determination implied the use of many different combinations of parameters (voltage, intensity, gain ratio, etc.) when measuring different artefacts in order to determine the error of different specifications according to DIN ISO EN 10360. Those specifications were: E (error in length or size), PS (probing error size), PF (probing error form) and GR (radius deviation), defined as the difference between measured and calibrated radius, either inner or outer. The errors associated to them that wanted to be determined (and minimized) where: MPE_E , $MPE_{(PF+PS)}$ and MPE_{GR} respectively.

The optimal parameters found for each of the artefacts tested are shown in Table 1.

Table 1: optimal parameters

	Sphere gauge	Ball bar L=300mm	Calotte ball plate	Ball plate	Stepped cylinder	Sphere d=7mm
Shot time (ms)	399	999	999	999	1500	1999
Voltage (kV)	180	150	200	200	200	80
Intensity (μA)	280	200	180	180	190	80
Number of projections	720	810	720	720	810	720
Gain ratio	0,5	0,5	0,5	0,5	0,5	0,5
Position of reference standard in machine X (mm)	777	1500	380	475	550	340

3.3.1 Size measurement error

Up to four of the artefacts were used to evaluate the size measurement error and its maximum permissible value. In Table 2 the results for the experiments carried out are summarised.

Table 2: MPE_E obtained from different artefacts

	Sphere gauge	Ball bar L=300mm	Calotte ball plate	Ball plate
MPE_E (μm)	5.5+L/50	8.0+L/50	3.0+L/50	6.0+L/50

The 27-sphere gauge showed to be a very suitable artefact to determine this specification because it was measured at different heights in Z and the error E showed to be independent on the position of the interest region on the detector.

From the experiments carried out it was finally determined a MPE_E for this specification of $MPE_E=9.0+L/50 \mu\text{m}$, as shown in Fig. 7.

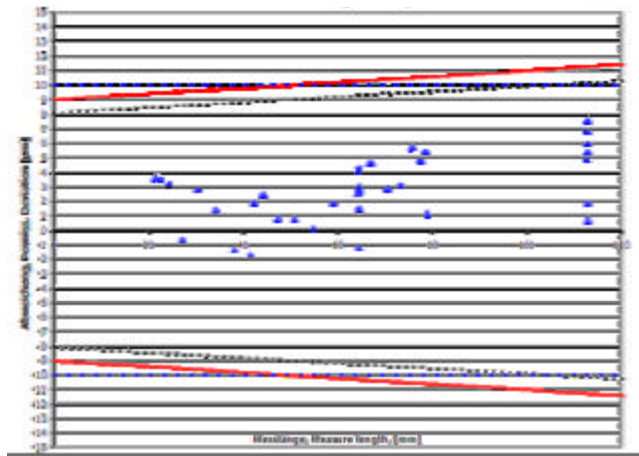


Figure 7: MPE_E finally determined for the Metrotom

3.3.2 Probing error

Probing errors (PF and PS) were determined by mean of a sphere as artefact. PF happened to be very dependent on the position on the detector (being the optimal the central one) and showed strong variations with undesired displacements of the focus in Y direction, forming a double-edged image. Therefore, PF could be used as an indicator of an undesired displacement along Y and, hence, of a lack of calibration of the system.

In addition, PS showed to be independent on the position on the detector and on the shot time, but strongly dependent on the threshold value and on the displacements of the focus along X. Thus, PS could be used as an indicator of an erroneous voxel size.

From the results of all the experiments a MPE for probing errors was determined, being: $MPE_{(PF+PS)}=7\mu\text{m}$.

3.3.3 Geometry error

The hollow stepped cylinder is the artefact used to define this specification by measuring the inner and outer diameter deviations with respect to the walls of the cylinder that contains them. The results show a $MPE_{GR}=5\mu\text{m}$.

4 Acceptance tests and VDI guideline

The results of these experiments have been used to elaborate several acceptance tests for Metrotom CT-machines by using 5 of the reference artefacts described. In addition, the results have also been taken into account in the development of

the new technical guideline VDI 2630 [5]: Computed tomography in dimensional measurement, now available in draft version. This guideline propose several acceptance tests for the CT-machine including several aspects such as: probing error (PF+PS), size measurement error (E) and material- and geometry-based influence (GR, GG and GF).

For the probing error, spheres or calotte artefacts and tests in two or more significantly different magnifications are recommended. For the size measurement error, parts with length size elements (sphere gauges, gauge blocks etc.) and test in two significantly different magnifications are recommended. For material and geometry errors, stepped cylinders made of a material dependent of customer's application are recommended.

5 Conclusions

A thoughtful analysis and classification of the possible sources of error in CT-measuring machines has been carried out. This analysis has been experimentally validated by many tests in five different machines during several months and using several reference artefacts. The results of these experiments have allowed us to establish maximum permissible errors for E, PF, PS and GR specifications. In addition all this experimental work and the results have been the validation for some of the recommendations presented in the new VDI 2630 guideline.

References

- [1] H. Schwenke, U. Neuschaefer-Rube, T. Pfeifer, H. Kunzmann, Optical Methods for Dimensional Metrology in Production Engineering, *Annals of the CIRP* 51 (2002) 685-699.
- [2] M. Bartscher, U. Neuschaefer-Rube, F. Wäldele, Computed Tomography – A highly potential tool for industrial quality control and production near measurements, *VDI-Berichte* 1860 (2004) 477-482.
- [3] M. Bartscher, U. Hilpert, J. Goebbels G. Weidemann, Enhancement and Proof of Accuracy of Industrial Computed Tomography (CT) Measurements, *Annals of the CIRP* 56 (2007) 495-498.
- [4] U. Neuschaefer-Rube, M. Neugebauer, W. Ehrig, M Bartscher, U. Hilpert, Tactile and optical microsensors: test procedures and standards, *Measurement Science and Technology* 19 (2008) 1-5.
- [5] Technical guideline (draft) VDI/VDE 2630, Computed tomography in dimensional measurement, Part 1.1. Basics and definitions (2007), Part 1.2. Influencing variables on measurement results and recommendations for computed tomography dimensional measurements (2008) and Part 1.4. Measuring procedure and comparability (2008).