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Procedia CIRP 43 (2016) 345 – 350

www.elsevier.com/locate/procedia

14th CIRP Conference on Computer Aided Tolerancing (CAT)

Impact of the Threshold on the Performance Verification of Computerized Tomography Scanners

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Abstract

Computerized tomography is an emerging technology for geometric inspection. Its capability of easily scanning internal and undercut surfaces, as well as micro components, makes it the only possible choice for several measurement tasks. However, traceability is still a relevant issue, due to the lack of well-established procedures for testing CT scanners: several international standards about the application of computerized tomography for geometric inspection are still under development.

In this work, we will propose the results we obtained in the application of the VDI/VDE 2617 part 13 standard on two computerized tomography scanners. In particular, we will show the impact of the choice of the threshold on the results of the test.

Peer-review under responsibility of the organizing committee of the 14th CIRP Conference on Computer Aided Tolerancing
Keywords: Computerized Tomography; Performance Verification; Threshold.

1. Computerized Tomography in Industry

Computerized Tomography (CT) is a very diffused diagnostic technique in medicine due to its ability of distinguishing the various organs of the human body and representing them in three dimensions thorough a voxel representation of the X-ray absorption (which is approximately proportional to the local density) of the measuring volume. This is obtained by taking several X-ray images of the body, or body part, from different points of view, and then reconstructing them by means of a “back projection” algorithm [1]. In recent years, this same technique has begun to spread in the industrial field as well [2,3]. There are several reasons for this success. With the use of CT metrologists are finally allowed to inspect the inside of parts. In fact there are a lot of mechanical components whose functionality is guaranteed by inner cavities. Traditional coordinate measuring systems rely on contact probes: in most situations, it is impossible to access these cavities without physically cut the component, which usually turns into a destructive test of the part. Even when non-contact sensors are adopted the need for an access from the exterior of the component is apparent. The use of CT solves this problem: as what is really measured is the absorption of X-rays within the measuring volume, it is sufficient the interior is filled with a material characterized by a different X-ray absorption (e.g. air) with respect to the component. CT can solve also other issues in metrology: for example, it is not affected by the presence of undercut surfaces, which can be impossible to reach even if external. Finally, with the introduction of micro- and nano-focus X-ray sources, it has become suitable even for the measurement of micro mechanical components.

However, the use of CT scanners in geometric metrology still proposes many challenges. The current maximum power of X-ray sources limits the maximum thickness of components made of dense materials (e.g. steel, copper) to few millimeters. The minimum focal spot size of current CT scanners limits the resolution to a minimum value of around 1 μm , if the thickness of the object is not particularly thin. Reconstruction artifacts, like e.g. those due to beam hardening, can badly affect the measurement accuracy.

In this work, we will focus on one of these challenges, the choice of the threshold, and its impact on the performance verification of CT systems. The problem of threshold is related to what is actually the primary output of a CT scan: a map of the X-ray absorption, related to the density of the material of the scanned object. In general, it is impossible to directly extract dimensional and geometrical measurements from this kind of representation: the scan must first be “segmented”, i.e. based on the density one must define the boundary (usually represented by a triangulated cloud of points) between the component and the environment (usually the surrounding air). this is done defining a “threshold”, i.e. the gray value of the voxels

Peer-review under responsibility of the organizing committee of the 14th CIRP Conference on Computer Aided Tolerancing
doi:10.1016/j.procir.2016.02.082

that distinguishes a component from the surrounding air in the voxel representation of the measuring volume. This step would be obvious, if the transition from the air to the component was sharp in the voxel representation. But actually this is not the case, in most situations the transition passes through several density value, due to the limitations of the reconstruction. Besides, the presence of artifacts like beam hardening can make the measured density of the component inhomogeneous. And finally, even the real density can be inhomogeneous. Well, the choice of the wrong threshold leads to an over or underestimation of the size of a component. This in general acts as a bias in the measurement. When this happens during the application of a performance test, the results of the test itself can be misleading. This effect will be discussed in this work when the VDI/VDE 2617 part 13 standard [4] is applied for testing a CT scanner. We will give evidence that the wrong choice of the threshold can lead to stating that the scanner is not conforming, while actually the problem should be looked for only in the elaboration of the scan results.

2. Traceability of CT scanners

The problem of the traceability of CT scanners has been addressed by several authors. Kruth *et al.*in their discussion about the the use of CT for dimensional metrology [2] gave a good review of these approaches. Here we will try to update this review; for anything else, the reader is addressed to the cited paper.

Two main streams of research deal with traceability of CT scanners: research on CT measurement uncertainty, and research on CT scanners performance verification and calibration.

The approach considering the measurement uncertainty evaluation is the most direct one, as it neglects whether the CT scanner is behaving correctly or not, but just tries to evaluate the uncertainty itself as parameter allowing the verification of the compatibility of measurements. In this field, Hiller and Reindl [5] propose computer simulation as approach for the evaluation of the uncertainty. They developed a “Virtual CT” model to simulate the acquisition of CT scans, which includes as inaccuracy sources both the unsharpness of the images and the noise. The Virtual CT then performs a Montecarlo simulation of CT scans, from which the measurement uncertainty is derived. The authors claim this allows the identification of the systematic effects, and can help the machine calibration and inspection planning. This approach can be further improved by the introduction of a bootstrap method in the simulation planning [6]. Dewulf *et al.*[7] propose instead a more traditional approach, trying to identify and quantify the various uncertainty sources in a CT dimensional measurement, and then combine them according to the GUM [8]. The uncertainty contributors are considered directly at the voxel level (uncertainty on voxel size and impact of the number of voxels). A study of the uncertainty sources has also been carried out by Hiller *et al.*[9]. Another different approach is proposed by Müller *et al.*[10], based on the substitution method. In practice, a reference calibrated geometric master is measured at least twenty times in the standard operating conditions, and then the repeatability of the measurement result, together with other uncertainty contributions, is propagated to any other measurement performed in similar conditions. This is a generalization of the methodology proposed in the ISO 15530-3 standard [11] to the case of CT dimensional measurements. A few inter-laboratory comparisons were also conducted in order to verify traceability of measurements [12,13].

Testing the performance of CT scanners and calibrating them tries instead to solve in part the traceability problem a priori by demonstrating that the measurements are traceable at least on one or more reference artifacts. In practice, procedures are developed to set the geometric parameters of the CT scanner, and for verifying the global accuracy of the system. In the last years, several authors proposed novel artifacts and procedures for the calibration of various CT scan parameters. For example, Lifton *et al.*[14,15] proposed a reference workpiece for the voxel size correction, which reduces the dimensional measurement error. However, the authors claim that some random error is anyway present, and that the improvement of accuracy is guaranteed only when dimensions are threshold independent. Shi *et al.*[16] and Fujimoto *et al.*[17] also proposed artifacts and calibration methods. Müller *et al.*[18] proposed three different methods, based respectively on a reference artifact (ball plate), on the measurement of some part of the workpiece with a conventional measuring system (e.g. a coordinate measuring machine), and on a correction database. The work is completed by the evaluation of the measurement uncertainty of the three approaches, which are found to be similar. Recently Ferrucci *et al.*[19] began to study the geometric error compensation of CT scanners. This approach in principle should both improve measurement accuracy and ease performing CT scans, this making CT measurement easier to apply in an industrial environment.

Performance verification consists instead in the definition of some test that, if passed, certifies a machine can guarantee some metrological performance. Several tests procedure have been proposed in past years:

- Müller *et al.*[20] propose the measurement of a simple ruby ball plate, which can be calibrated by means of a coordinate measuring machine;
- Welkenhuyzen *et al.*[21] studied in particular the problem of the verification of an high voltage CT scanner by means of a “forest of styli” as reference artifact;
- a simple artifact constituted by four alumina balls shaped as a tetrahedron is proposed by Léonard *et al.*[22] as reference artifact. The authors claim that “a sub-voxel accuracy was achieved with errors as small as $1/10$ of a voxel obtained for the size error”.

However, performance verification should be always performed according to some procedure recognized in international standards [22], but these standards have not been published yet, and the discussion on them is still ongoing [23].

2.1. Performance verification of CT scanners in the VDI/VDE 2617 part 13 standard

At present the most considered standard for the verification of the performance of CT scanners is the VDI/VDE 2617 part 13 [4]. This German standard is an extension of the well known ISO 10360 performance verification tests for coordinate measuring machines to CT scanners adopted for dimensional and geometric metrology. Two acceptance tests are included: probing error test (corresponding to the ISO 10360-5 test [24]), and

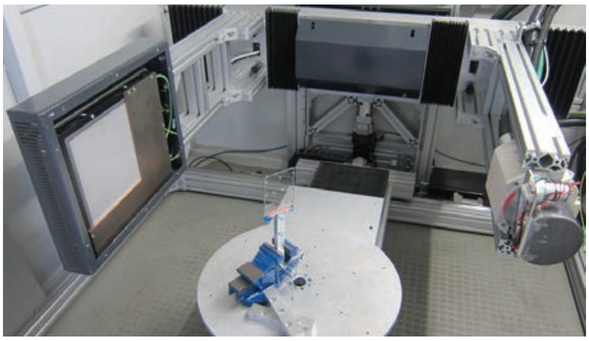

Fig. 1. Large CT scanner with the reference artifact for the length measurement error test.

length measurement error test (corresponding to the ISO 10360-2 test [25]). Tests for the evaluation of the influence of the material and geometry of the sample, and for the evaluation of the structural resolution are proposed as well, but will not be considered in this work.

The test for the probing error is based on the measurement of a calibrated reference sphere. The sphere is scanned, the scan is segmented, and a set of 25 points is extracted from the segmentation. This cloud of points is fitted by a gaussian sphere. The test result includes P_F and P_S, which are respectively the range of the distances between the 25 points and the center of the gaussian sphere, and the difference between the diameter of the gaussian sphere and the calibrated diameter of the reference sphere. These two parameters must be smaller than the corresponding "maximum permissible errors" $P_{F,MPE}$ and $P_{S,MPE}$ to state that the machine conforms to the specifications.

The test for the length measurement error instead involves the measurement of five calibrated material standard of size (in most cases ball plates or ball bars), spanning seven positions within the measuring volume of the scanner, and each standard at each position must be measured three times. For each measurement result, in the case in which the material standard of size is a ball plate or rod, the length measurement error is calculated as $|E| = |L_{ka} - L_{kr} + P_S| + P_F$, where L_{ka} and L_{kr} are respectively the measured and calibrated length of the material standard. It is worth noting that this definition of E makes it dependent on P_F and P_S, while in the typical tests defined in the ISO 10360 for coordinate measuring machines these parameters are independent.

3. Application of the VDI/VDE 2617 performance verification to a large CT scanner

A large CT scanner (Fig. 1) has been tested according the VDI/VDE 2617. The characteristics of the scanner are summarized in Tab. 1.

The artifacts adopted for the test were a calibrated ceramic ø25 mm sphere, and a specifically designed ball plate, which allowed performing all seven positions by moving the plate only once, for a total of six CT scans. The test were conducted as described in §2.1. From the measurement of the sphere, the following parameters were obtained:

- $P_F = 0,0681$ mm
- $P_S = -0,1049$ mm

In both cases, the uncertainty of the test was estimated equal to 0,17 μm . These results can seem poor, but are considered adequate for the large CT scanner, as this system is not designed for metrological applications, but mainly for non-destructive testing.

Now, let's consider the length measurement error test. Its results are summarized in Fig. 3. This plot is coherent with a maximum permissible error $E_{MPE}(L) = \left(\frac{L}{10} + 200\right)$ μm , where L is the measured length in [mm]. This seems a very poor performance. However, having a look at Fig. 3, the reader can note that all the length measurement errors are concentrated in the lower part of the graph. One could think this is due to an incorrect definition of the scale of the scan. However this can be

Table 1. Characteristics of the large CT scanner.

Maximum Voltage	225 kV
Focal Spot	0,4 mm
Digital Detector	8' Flat Panel Detector with pixel size 0,4 mm
Number of axes	5
Maximum diameter of the sample	400 mm

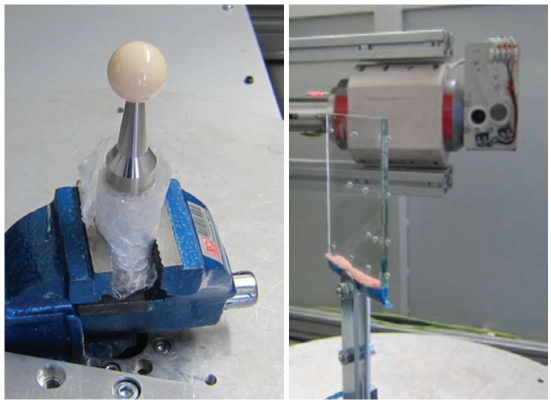

Fig. 2. Artifacts used for the verification of the large CT scanner: on left, ceramic sphere; on the right, ball plate.

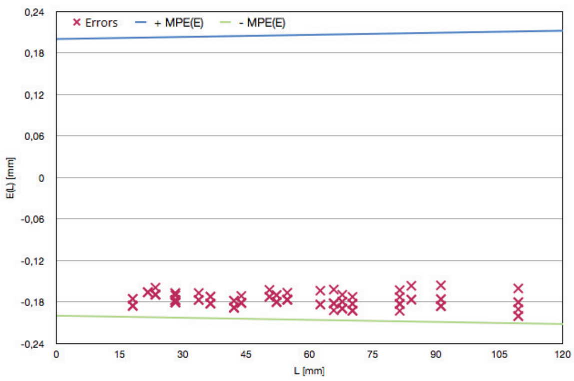

Fig. 3. Results of the length measurement error test for the large CT scanner.

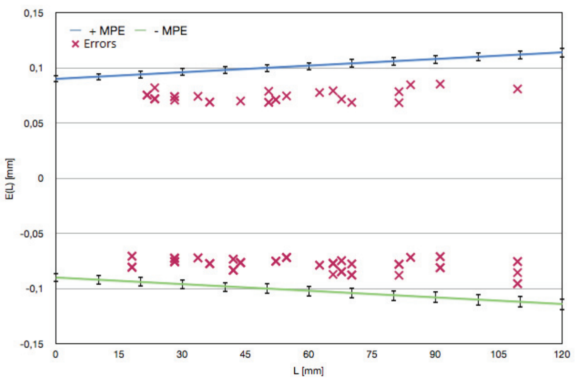

Fig. 4. Results of the length measurement error test for the large CT scanner when P_S is neglected. The small black interval around the E_{MPE} indicates the uncertainty range ($U = 2$ µm).

Table 2. Characteristics of the µCT scanner.

Maximum Voltage	160 kV
Focal Spot	< 2 µm
Digital Detector	119 x 149 mm Flat Panel Detector with pixel size 75 µm
Number of axes	5
Maximum diameter of the sample	120 mm
E_{MPE}	$(0,02L + 20)$ µm

due also to the very high value of $P_S = -0,1049$ mm. Actually, if P_S is set equal to zero, the results of the length measurement error changes as shown in Fig. 4, and are coherent with a maximum permissible error $E_{MPE}(L) = \left(\frac{L}{5} + 90\right)$ µm . Moreover, these new results are not concentrated in either the upper or the lower part of the plot, so this result is not coherent with a scale error.

We concluded that the reason for the high value of P_S was to look for in an incorrect choice of the threshold [26]. Even if the classical indication about the choice of this value has been followed (choosing the threshold in the middle of the histogram peaks representing the air and the material, usually referred as “the 50% method”), the result was not reliable. Unfortunately, at the time these results were obtained, we had not the chance to deepen this problem, e.g. by conducting additional tests.

4. Application of the VDI/VDE 2617 performance verification to a µCT scanner

A new series of test was conducted on a NSI X-View X25 µCT scanner. The characteristics of the scanner are summarized in Tab. 2. Please note the performance statement according to the VDI/VDE 2617 part 13 standard was defined by the customer (Politecnico di Milano) during a competitive bid.

Again two artifacts were needed to test the performance of the µCT scanner (Fig. 5). For the length measurement error test, a ball plate similar the one proposed for the large CT scanner was designed and manufactured. However, considering our experience, a couple of calibrated ceramic ø5 mm spheres constituted the artifact for the test of the probing error. The idea is

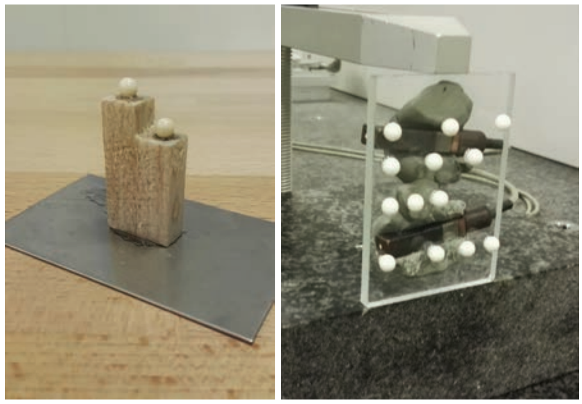

Fig. 5. Artifacts used for the verification of the µCT scanner: on left, couple ceramic spheres; on the right, ball plate.

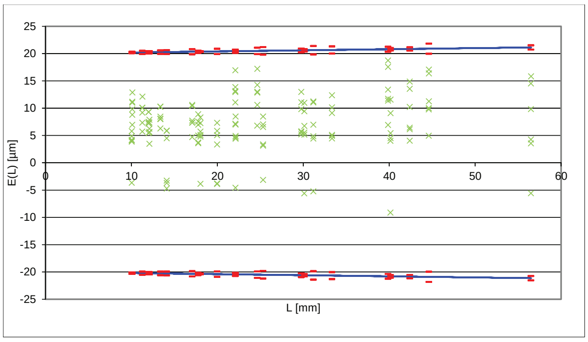

Fig. 6. Results of the length measurement error test of the µCT scanner. The short red lines denote the uncertainty range of the test ($U \leq 1$ µm).

that the threshold is set so that the diameter of one of the two spheres is measured, and the measurement result is as close as possible to the calibrated diameter; then the P_S and P_F parameters are estimated on the other sphere using the chosen threshold.

This approach leads to the choice of a counterintuitive threshold, as it is far from the center of the two peaks of the scan histogram. Anyway, by following the proposed approach, it was possible to obtain the following results:

- $P_F = 3,0$ µm
- $P_S = 2,2$ µm

For both tests, the uncertainty was estimated equal to $U = 0,8$ µm . It is worth noting that, from a customer point of view, and considering the uncertainty, these results do not allow to state the specifications stated by the manufacturer and reported in Tab. 2 are not satisfied. Now let’s consider the length measurement error test: the results are summarized in Fig. 6. The test suggest the µCT scanners performs according to the manufacturer statements.

By choosing the threshold using the 50% method, it follows::

- $P_F = 2,2$ µm
- $P_S = 9,9$ µm

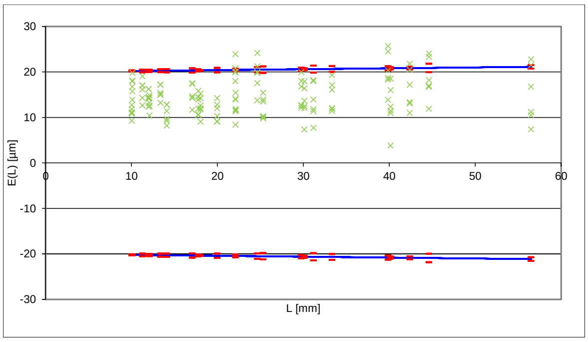

Fig. 7. Results of the length measurement error test for the µCT scanner when the wrong threshold is chosen. The short red lines denote the uncertainty range of the test ($U \leq 1$ µm).

The related result for the length measurement error test is shown in Fig. 7. The performance test is no more passed.

5. Conclusions

With the spread of the use of computerized tomography in industry, and in particular for dimensional and geometric conformance assessment, the need for a real traceability of the measurements arises. While the diagnostic use of CT in medicine or the non-destructive test of mechanical components does not propose really relevant issues of traceability, as one just looks for any sort of illness or the presence of manufacturing defect, but do not aim at stating the size of these features accurately. When dealing with few µm tolerances, very small errors in the definition of the scale of the scan or the threshold for the identification of a surface of a component may become very critical. This can significantly affect the traceability of CT scanners, which today cannot be guaranteed, unless the CT scanners are adopted only for low resolution measurements, affected by a high degree of uncertainty. To obtain reliable measurements, suitable to verify the accuracy of mechanical components, new procedures need to be developed.

The choice of the threshold also affects the performance verification of CT scanners, as we demonstrated in this paper. The wrong choice of the threshold, for instance, can lead to state non conforming a machine which actually behaves according the manufacturer statements. We also proposed a workaround for this problem, by scanning two calibrated spheres in the probing error test rather than just a single one, and then using the scan of one of the two spheres as guide for the choice of the correct threshold.

However, this approach is not sufficient in most situations. For CT scans to be used in industry one needs the threshold not to be chosen so "freely" by the operator: specific guidelines need to be developed, and in perspective the choice of the threshold should be completely automatic, without the need of any human intervention, in order to guarantee the objectivity and repeatability of the measurements. Solving this problem is not easy at all. In general, the correct statement of the threshold requires a deep knowledge of the X-rays absorption properties of the material(s) scanned. In most situation this knowledge is not available, and as such again operator's experience is considered. One possible solution could be the use of multisensor systems and datafusion, so that reliable sensor measurement result is used as guide for the choice of the threshold, at least supposing that the scan is good (i.e. not excessively affected by artifacts).

Acknowledgments

Financial support to this work has been provided as part of the project AMALA Advanced Manufacturing Laboratory, funded by Politecnico di Milano (Italy), CUP: D46D13000540005, and the project "HAF - Hybrid Allumininum Forging" (Ref. N. 42660345) funded by Regione Lombardia and Cariplo.

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