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# A Discussion on Performance Verification of 3D X-Ray Computed Tomography Systems

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**Abstract**

Computed tomography capability of scanning internal and external surfaces makes it a valuable emerging technology to inspect geometrically complex products, e.g. those manufactured by additive technologies. However, traceability is still an issue due to the lack of well-established methodologies. In this work, we will discuss the problems encountered defining the procedures to test two 3D X-Ray CT systems. The required artifacts comply with the VDI/VDE 2617 part 13 standard but are as simple as possible to ease manufacturing and calibration. The artifacts and procedures may be useful for both measuring system manufacturers and users to ensure measurement traceability.

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*Keywords:* Measuring instrument; 3D X-Ray Computed Tomography; Performance Verification.

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## 1. Traceability of Computed Tomography for Geometric Measurement

Computed Tomography is a much-diffused diagnostic technique in medicine. Starting from a series of X-ray projections of an object taken from different directions, and applying a back projection algorithm [1] to these projections, it can reconstruct a voxel representation of the measuring volume in terms of local X-ray absorption (approximately proportional to the local density). In the ’80s, the technique has been applied for non destructive testing in industry [2]. In recent years, this same technique has begun to spread in industry also for the metrological inspection of components [3,4]. There are several reasons for this success. With the use of CT, metrologists are finally allowed to inspect the inner surfaces of components. In fact, there are many mechanical components whose functionality is guaranteed by inner cavities. Traditional coordinate measuring systems rely on either contact probes, imaging probing systems, or optical distance sensors: with this kind of sensor the only way to access these cavities is to physically cut the component, which usually turns into a destructive test of the part. The use of CT solves this problem: if it is possible to segment the measuring volume in the portions constituting the scanned object and the surrounding medium, and then to identify the boundary between the component and the medium filling the cavities (usually air), it is possible to measure geometric characteristics on this boundary. CT can solve also other issues in metrology: for example, it is not affected by the presence of undercut surfaces, which can be difficult to reach even if external. Finally, with the introduction of micro- and nano-focus X-ray sources, CT has become suitable even for the measurement of micro-mechanical components [5].

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 [3] gave a good review of these approaches. Here we will try to update this review; for additional details on the subject, the reader is addressed to the cited paper.

Two main streams of research deal with traceability of CT scanners: research on CT measurement uncertainty [6–14], and research on CT scanners performance verification and calibration. Only the second is discussed here, as it is the sole related to the subject of the paper.

Testing the performance of CT scanners and calibrating them tries instead to solve in part the traceability problem a priori by demonstrating the degree of traceability of the measurements at least on one or more reference artifacts. In practice, procedures are developed to set the geometric parameters of the CT scanner, and to verify 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.* [15,16] 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.* [17] and Fujimoto *et al.* [18] also proposed artifacts and calibration methods. Müller *et al.* [19] proposed three dif-

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ferent 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.* [20] began to study the geometric error compensation of CT scanners. This approach in principle should both improve measurement accuracy and ease performing CT scans, thus 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.* [21] propose the measurement of a simple ruby ball plate, which can be calibrated by means of a coordinate measuring machine;
- Welkenhuyzen *et al.* [22] studied in particular the problem of the verification of an high voltage CT scanner by means of a "forest of styli" reference artifact;
- a simple artifact constituted by four alumina balls shaped as a tetrahedron is proposed by Léonard *et al.* [23] 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 [23], but these standards have not been published yet, and the discussion on them is still ongoing [24]. In perspective, the publication of the ISO 10360-11 standard, which will be part of the ISO 10360 series of standards [25] devoted to the performance verification of coordinate measuring systems (CMS), will solve this situation. However, at preset there is no recognized international standard. The most considered standard for the verification of the performance of CT scanners is the VDI/VDE 2617 part 13 [26]. This standard includes probing error, length measurement error, structural resolution tests, and influence of the material (which will not be addressed in this paper).

### *1.1. Tests in the VDI/VDE 2617 part 13*

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 predefined pattern of 25 points is extracted from the segmentation. A gaussian sphere fits this cloud of points. The test result includes $P_F$ and $P_S$, which are respectively the range of the distances between any of 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. To state that the machine conforms to the specifications these two parameters must be smaller than the corresponding "maximum permissible errors" $P_{F,MPE}$ and $P_{S,MPE}$ (considering the test uncertainty). There are two reason for which only 25 points are considered in the estimation of the gaussian sphere. In fact usually from a single CT scan several thousands of points could be extracted. First, the test must be coherent with the test for single-stylus probing coordinate measuring machines defined in the ISO 10360-5 standard [27], which considers the same pattern of 25 points, and was the first probing error test to be defined. Second, if a large cloud of points is taken, the chance an outlying point is found increases dramatically, leading to the risk of an overestimation of $P_F$.

The test for the length measurement error instead involves the measurement of five calibrated material standards of size spanning seven positions within the measuring volume of the scanner, and each standard at each position must be measured three times. In the past many authors proposed different solution for the artifact representing the calibrated material standard [3,21,22]; most solutions are constituted by arrays of calibrated spheres. The measured size is then compared to the calibrated size of the artifact. When the length measurement error is verified for contact coordinate measuring systems, only a couple of points shall be probed, and their reciprocal distance measured [28]. This way, the length measurement error includes the probing error. When spheres are measured by means of a CT scanner, usually the distance between the centers of a couple of spheres is considered instead. The averaging effect of the fitting of the spheres eliminates, or at least mitigates, the impact of the probing error on the length error, making the test result not comparable to the same test result for the reference case of contact measurement. Furthermore, if the center of the spheres is considered, the impact of the segmentation of the CT scan on the length measurement error is mitigated, due to the symmetrical geometry of the spheres. As such, the VDI/VDE 2617 part 13 suggests that 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 the results of the respective test are kept independent. Again, these errors must be compared with the maximum permissible error $E_{MPE}$ (considering the uncertainty).

The structural resolution test involves the use of calibrated spheres: the structural resolution equals the diameter of the smallest sphere that can be measured. However, tiny spheres are difficult to source and use when high resolution scanners are considered. A procedure proposed by Carmignato et al. [29] is considered in this paper instead. This test is based on the measurement of two contacting spheres ("hourglass artifact", Figure 1). Due to the non-infinite resolution of the scanner, the contact area cannot be completely resolved. The value of $h$, the minimum separation that can be resolved, is an estimate of the resolution. As a direct measurement of $h$ would be difficult, a better way of evaluating it would be by calculating $h = D - \sqrt{D^2 - d^2}$, where $D$ is the distance between the centers of the spheres, and $d$ is the diameter of the area in which the two spheres are not completely resolved.

In this paper, extending the discussion started in a previous work [30], we will describe our experience in the application of the VDI/VDE 2617 part 13 standard to two CT scanners. Even if this standard seems unambiguous, actually its application still largely relies on the user's experience. In fact, despite the support from expert operators of the CT scanner manufacturers, the results were not as expected, but quite poor. We will try then to explain why this difference was present and what solutions can be considered.

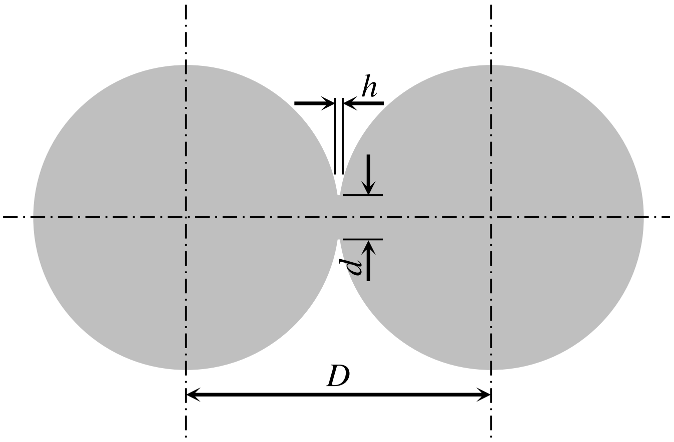

Fig. 1. Two-sphere artifact scheme for the evaluation of the structural resolution.

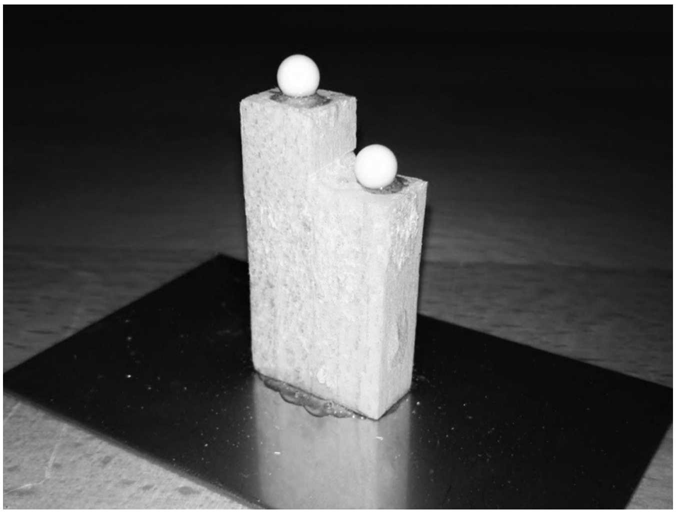

Fig. 2. Two-sphere artifact for the probing error test.

## 2. Performance testing of CT scanners

Our experience includes the testing for two CT scanners: an EidoSolutions ME 225 CNC (a large volume scanner, originally developed for non-destructive testing) and an NSI X25 (a microfocus CT scanner). As the ME 225 CNC was not originally developed metrology, the manufacturer did not state any performance indication for it; however, he was interested in understanding the actual performance of its system. The manufacturer of the NSI X25 did not state any maximum permissible error for these parameters, in a discussion he suggested the values $P_{F,MPE} = 6$ μm and $P_{S,MPE} = 2$ μm were reasonable for an NSI X25 scanner.

The next few paragraphs describe our results and considerations.

### 2.1. Probing error test

The probing error test of the ME 225 CNC was originally conducted on a calibrated Ø25 mm ceramic sphere. The parameters for the probing error were estimated equal to:

- $P_F = 68.1$ μm
- $P_S = -104.9$ μm

The uncertainty of the test was estimated equal to 0.2 μm according to the ISO/TS 23165 standard [31].

The test on the NSI X25 instead was conducted adopting a 5 mm ceramic sphere, as the measuring volume of this system was significantly smaller than the measuring volume of the ME 225 CNC, and we were interested in the micro CT performance. The results were:

- $P_F = 2.2$ μm
- $P_S = 9.0$ μm

The uncertainty of the test was estimated equal to 0.8 μm. It is worth noting that, in this case, the test was not passed, due to the high value of $P_S$.

In both cases the measurement procedures and results analysis were agreed with expert operators of the systems who were also personnel of the manufacturers of the scanners. What emerges from the results presented so far is that the $P_S$ parameter seems more critical than the $P_F$ parameter. This is counterintuitive: in fact, the former comes from the diameter of the sphere estimated on 25 measuring points. As such, an averaging effect of measurement errors is expected, and the evaluation of the diameter should be accurate. The same averaging effect is not present in $P_F$, which is a peak-to-valley value. This is coherent with the statement of NSI, according to which $P_{F,MPE} > P_{S,MPE}$. The reason for this result should be looked for elsewhere.

To understand better the reason of this result, the test was conducted again but this time on a new artifact constituted by a couple of Ø5 mm ceramic spheres (Figure 2). The two spheres were located at different height in order to avoid reciprocal influence during the scan.

After the measurement, an intermediate step was added to the measurement procedure: the iso value for the segmentation of the voxel volume has been chosen so that the fitted diameter of one of the two spheres (actually the top one) was as close as possible to the calibrated diameter of the sphere itself. Then, the $P_F$ and $P_S$ parameters were evaluated on the other sphere. With this procedure, the results for the ME 225 CNC were:

- $P_F = 29.4$ μm
- $P_S = -30.5$ μm

In addition, for the NSI X25 the results were:

- $P_F = 3.0$ μm
- $P_S = 2.2$ μm

These values show that, with a correct choice of the threshold for the extraction of the iso surface, a better performance of the machines can be estimated.

### 2.2. Length measurement error test

The results obtained for the probing error test also reflects on the results of the length measurement error test. In fact, the length measurement error can be evaluated, in absolute value, as $|E| = |L_{ka} - L_{kr} + P_S| + P_F$. It is apparent that an incorrect evaluation of $P_S$ can lead to an overestimation of this error.

To test the length measurement error, two artifacts were de-

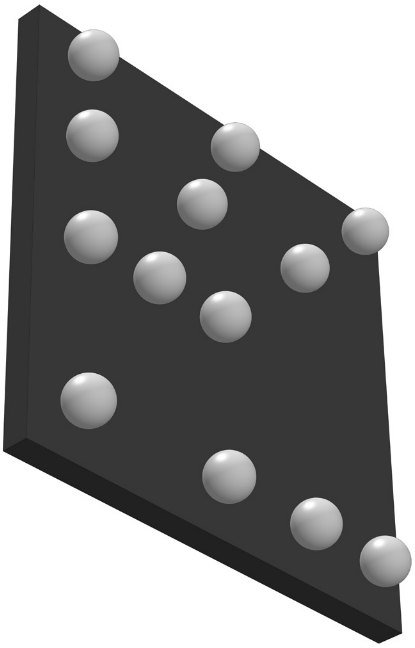

Fig. 3. Concept of the developed artifact.

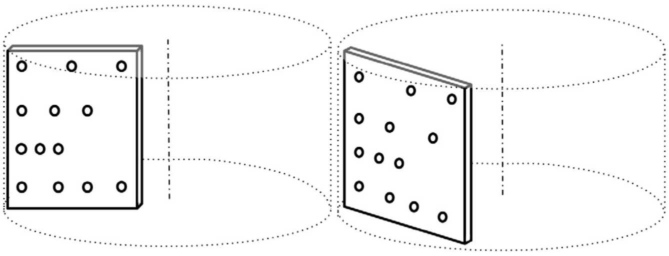

Fig. 4. Two positions for the length measurement error artifact.

Fig. 5. Artifact for the length measurement error test of the NSI X25 scanner.

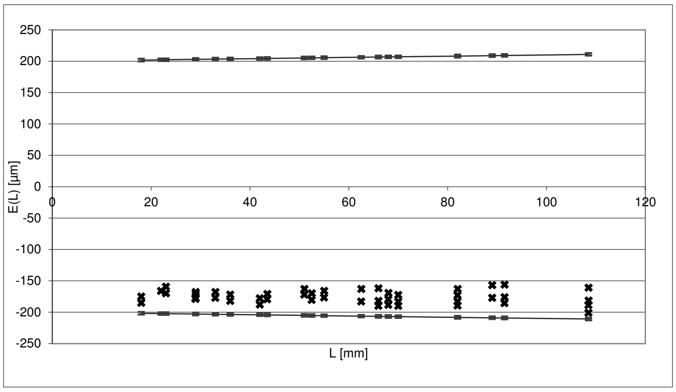

Fig. 6. Length measurement error test results for the ME 225 CNC scanner.

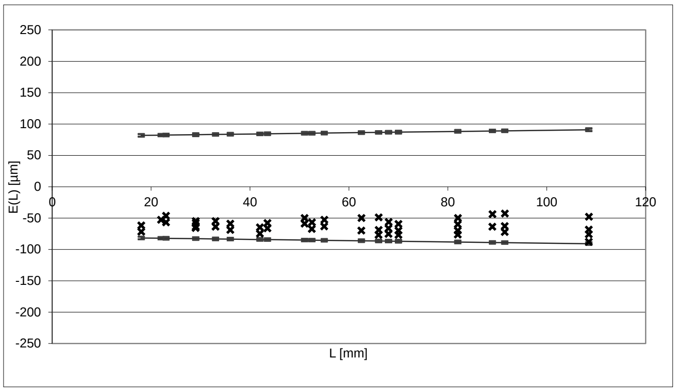

Fig. 7. Length measurement error test results for the NSI X25 scanner.

veloped, manufactured, and calibrated, constituted each one by 13 calibrated spheres (Figure 3). The need for two artifacts is to look for in the different measuring volume of the two CT scanners. As shown in Figure 3 this artifact carries four series of four aligned spheres (sharing a single “origin” sphere). By taking different couples of spheres, each series of spheres in this design provides the five calibrated material standard of length required by VDI/VDE 2617 part 13 standard. Furthermore, the artifact allows to carry out the three measurement repetitions with just six CT scans in total. One needs to move the artifact only once within the measuring volume, in order to have a position in which the artifact lies on a diameter, and the other one on a chord of the measuring volume (Figure 4). Finally, this artifact is easy to calibrate by means of a coordinate measuring machine with a adequately low uncertainty. Figure 5 shows the artifact manufactured for the test of the NSI X25 scanner.

Considering the estimates of $P_\mathrm{F}$ and $P_\mathrm{S}$ obtained with a single sphere artifact, the results of the length measurement error tests can be summarized in Figure 6 and Figure 7.

In particular, in the case of the ME 225 CNC scanner, the test was run to estimate the performance of the machine, which resulted compatible with $E_\mathrm{MPE} = \left(\frac{L}{10} + 200\right)$ µm and the test uncertainty is, for all lengths, less than 2 µm according to the ISO/TS 23165 standard. But one can point out that all the length measurement errors are lower than zero and far from the zero line. This indicates that probably the value of $P_\mathrm{S}$ is not correctly estimated. In fact, if one considers the values of $P_\mathrm{F}$ and $P_\mathrm{S}$ estimates on the two-sphere artifact the results are compatible with a statement $E_\mathrm{MPE} = \left(\frac{L}{10} + 80\right)$ µm (figure 8).

Similar considerations can be drawn for the NSI X25 scanner. In this case, the uncertainty of the test was less than 1 µm. In this case, the customer required a $E_\mathrm{MPE} = \left(\frac{L}{50} + 20\right)$ for the machine. Figure 7 demonstrates that if $P_\mathrm{F}$ and $P_\mathrm{S}$ are estimated on a single sphere the error in the evaluation of $P_\mathrm{S}$ leads to a non-conformance statement. If the estimate obtained from the two-sphere artifact is considered instead, then the machine can be declared conforming to the performance statement (Figure 9).

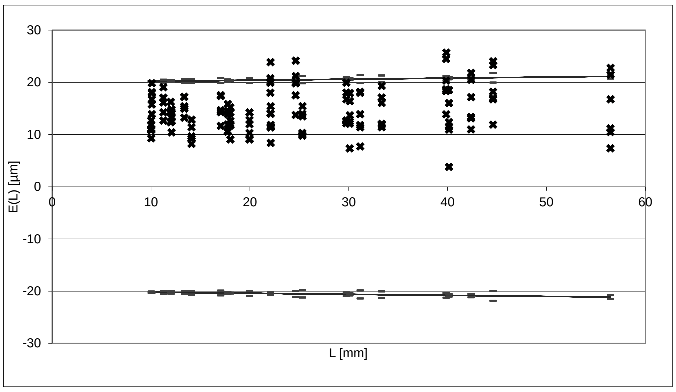

Fig. 8. Length measurement error test results for the ME 225 CNC scanner after the $P_S$ correction.

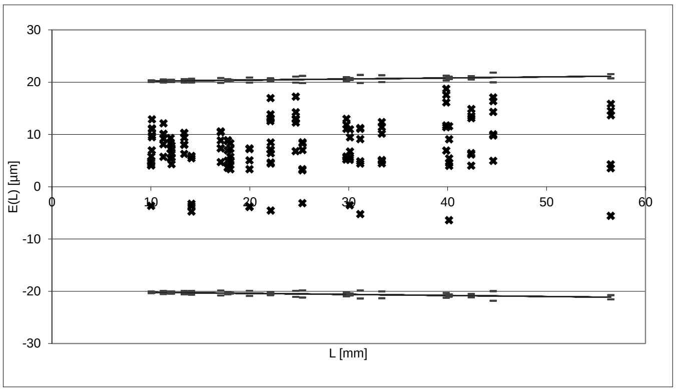

Fig. 9. Length measurement error test results for the NSI X25 scanner after the $P_S$ correction.

### 2.3. *Resolution test*

Finally, let us consider the 3D resolution of a CT scanner. The measurement of this parameter is more complicate than the others and requires some study. The autors of this paper developed then an unambiguous procedure for the estimation of the resolution. This procedure is an original contribution by the authors of the present paper. In fact, a typical approach would simply consider a manual measurement of some section of the CT scan. With this approach, any problem of misalignment of the scan or ambiguity in the manual measurement is avoided.

The steps to estimate the resolution are as follows:

1. scan the hourglass artifact;
2. extract an iso surface;
3. identify the points belonging to the two spheres;
4. fit the spheres and identify their centers;
5. calculate $D$ as distance between the centers;
6. identify a plane perpendicular to the segment connecting the centers and passing through its middle point;
7. intersect the plane and the iso surface;
8. fit the intersection with a circle, whose diameter is $d$;
9. calculate the resolution as $h = D - \sqrt{D^2 - d^2}$.

In the case of the ME 225 CNC scanner a Ø5 mm hourglass artifact was used, while for the NSI X25 scanner, whose resolution should be better, Ø1 mm spheres were adopted.

By applying the proposed procedure to the two scanners the resolution was initially estimated equal to 31 µm for the ME 225 CNC and 21 µm for the NSI X25 (the uncertainty being equal to 0.8 µm). If the first manufacturer considered its scanner result reasonable, the second one was deemed not coherent with the second manufacturer's experience, since he supposed the resolution was about one order of magnitude lower.

To solve this inconsistency, again the iso value adopted for the extraction of the iso surface was found to be the main issue. By selecting this value so that the diameter of one of the two fitted spheres is as close as possible to the calibrated diameter of the sphere, two new evaluations of the resolution were obtained, 43 µm for the ME 225 CNC and 2 µm for the NSI X25. Please note this did not require any additional scan of the samples. The latter is coherent with the manufacturer statement about the NSI X25 performance. It is worth noting also that originally the ME 225 CNC resolution seemed better: actually, an incorrect choice of the iso value can lead to a very thin non-resolved area, thus obtaining a lower value for the resolution, or even generate two separated spheres in the scan.

Finally, it is worth noting that the voxel size was equal to 37 µm and 2.1 µm for the ME 225 CNC and NSI X25 respectively. It is apparent that the resolution value estimated by this procedure is compatible with the voxel size.

## 3. Conclusions

Computed tomography is a very promising technology for the geometric inspection of mechanical components. Its unpaired ability of scanning the internal part of objects allows measurements impossible for any other technique (maybe with the exception of scanning ultrasound microscopy, which anyway at present is far from being mature). The possibility of scanning all the measuring volume simultaneously can significantly reduce measurement time for complex components and even assemblies. The lack of any contact allows the measurement of tiny geometric features and flexible parts.

However, today traceability of CT scans is hard to guarantee, and even just testing a CT scanner performance is not straightforward at all. In this paper we have shown that, even if the scans are performed correctly, like in the case of resolution evaluation, analyzing correctly the available data is not easy. Even expert operators have shown not to be able to choose the correct parameters to obtain the estimates of the performance parameters. This has lead in some cases to an underestimation and in some cases to an overestimation of the performance parameters, which can lead to state non-conforming a good CT scanner or vice versa. We have also proposed some workarounds for the problems encountered that can help reaching a better evaluation of the performance parameters. However, these solutions are very far from the typical working conditions of CT scanners and can be applied only to the specific case of performance verification. For CT to have a real success in geometric verification of mechanical components, new procedures need to be developed, and some "computer aided CT inspection" is probably necessary. Continuing this research, the authors intend to focus on the problem of choosing the optimal threshold for the segmentation of the measurement volume. We think this is a really important issue to solve if you aim at reaching micrometric accuracy in the evaluation of dimensional characteristics.

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