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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.

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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

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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