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Reference standard for the uncertainty estimation of X–ray Computed Tomography measurements of complex macro- and micro-geometries

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Abstract: Traditionally, measuring both macro and micro geometries with a single device has been challenging in metrology. Coordinate Measuring Machines (CMM) are common devices for the inspection of large features, while optical microscopes can achieve resolutions in the order of micrometers in small areas. X-Ray Computed Tomography (XCT) has become a solution not only to characterize both micro and macro geometries, but also to inspect internal features without destroying the sample. In this field, various reference standards have been developed in order to verify the capabilities of XCT systems, these artefacts include geometrical features or profiles for roughness inspection. This paper shows the design and develompent of a reference standard for XCT test which includes internal and external geometrical features and profiles for macro and micro geometrical inspection. The model is manufactured by additive manufacturing (AM), easing the process of fabrication of the artefact and allowing to test the capabilities of this technology to produce reference standards.

Keywords: Computed tomography, Reference standard, Uncertainty, Additive manufacturing.

1. Introduction

Currently there is a wide range of equipment and systems focused on metrological applications for both macro-geometric and micro-geometric dimensional characterization. For measuring macro geometries, metrological equipment such as Coordinate Measuring Machines (CMM) can be used, moreover, they can assure traceability. However, these instruments have limitations when the pieces to be measured are micro geometries with dimensions below 1 mm. For the measurement of micro geometries, the use of instruments such as optical microscopes is widespread. However, despite of the high precision of CMMs and optical microscopes, one of their limitations is that the measuring features must be accessible. Even for contactless microscopes, the measuring feature must be visible, so that it can be captured by the lens. Thus, they cannot measure inner or hidden geometries. Another limitation is presented when measuring complex and non-standard geometries, or parts with micro and macro geometries.

As a solution, in recent years, X-ray Computed Tomography (XCT) has emerged as the only non-contact and non-destructive imaging technique that allows to inspect the geometrical dimensions of mechanical parts without any accessibility issue, including micro and macro-geometries, and both internal and external features [1]. In traditional uses of XCT, such as medical diagnoses or detection of flaws in industrial parts, a qualitative analysis is enough and dimensional accuracy is not required.

Nevertheless, in dimensional-metrology applications, the measurements need to achieve a certain degree of accuracy. An XCT measurement consists in the emission of X-rays through the sample to be measured. The rays are emitted from different angles in order to obtain different sections of the sample which will digitally rebuild its volume. Thus, the geometries of the part, its manufacturing process, as well as its materials play an important role in the final accuracy of the measurements. The main disadvantage of XCT is that it has many uncertainty sources which appear not only during the measuring process but also when post-processing the measured data. There is a high interest in investigating the accuracy of XCT in metrology applications [2-7]. Due to the fact that the use of XCT in metrology applications is relatively new, specific norms about systems verification and their standard estimation are still being developed. Reference standards are commonly used to overcome the difficulty of the measuring errors identification due to the complexity of the XCT measuring process.

One of the main beneficiaries of the development of XCT in metrology applications is additive manufacturing (AM). AM technologies have rapidly evolved during the past decades, they allow to build the part directly from the CAD model by adding layers of material. They are capable of manufacturing complex designs with free form surfaces and inner geometries. Sectioning the AM produced part to verify internal dimensions or features is impractical and time consuming. Thus, these technologies require new measuring techniques, such as XCT, which allow measuring complex and inner features without having to section the sample. Thus, one of XCT main applications is to analyse components produced by AM processes which have inner cavities that are not accessible and may be multi-material or have internal properties such as porosity, that need to be controlled [8].

This work proposes a novel design of a reference standard which will allow to perform the uncertainty quantification of the XCT system by the substitution method. That is, the reference standard will be calibrated by other traceable instruments and the results will be used to extract the errors of the XCT machine measurements. Therefore, its design must be compatible with other metrological instruments. In addition, the design of the reference standard must include features which shape the dimensions to be calibrated. AM has been selected as the manufacturing technology for building the reference standard due to the fact that the metrological capabilities of XCT are directly related to the advances in AM.

This paper, first, reviews and studies the state-of-the-art in reference standards that are used for the calibration of XCT systems. Then, a novel design is proposed and its first prototype is calibrated. Lastly, the conclusions extracted from the study are explained.

2. State of the art in reference standards used in tomography

This section presents a study of the state-of-the-art reference standards which can be used for the calibration of XCT machines. A brief summary of some of them is shown in table 1. The most relevant aspects that are taken into account in this study are the type of measurable geometries, their dimensions and the reference standard manufacturing process and material.

Although some of these artefacts, such as the CT tetrahedron [9] or the silicone sheets cube [10], have been specifically designed to be used as reference standards for XCT, others were made for different applications. This is the case of the Toggle [11], which was made for a hearing aid application, or the Dog bone [11], which was used for micro-mechanical testing. However, these precisely manufactured components have been used as calibration artefacts in some studies due to their characteristics. Artefacts such as the Cubic standard [12] or the NIST standard [13], which have been used for the study of AM machines capabilities, have also been included.

Most of the reference standards that have been studied include simple geometries, such as spheres or cylinders [9,11,14]. In some of the reference standards linear dimensions are represented as the distance between spheres [9,12], or as the distance between planes in stepped stairs [15] or by means of a cuboidal shape [11,14]. An exception is the NIST standard which includes multiple geometries such as staircases, ramps, cylinders and holes on a squared base. Regarding the size of the features, most of them have sizes larger than 1 mm. However, there are some reference standards with micro geometries, such as the Silicon sheets cube [10] which has micro geometries engraved in the silicon sheets, and the NIST standard which also includes some fine features.

Table 1. Summary of some state-of-the-art reference standards applied for XCT.

Reference Standard	Geometries	Size	Material	Research group
CT Tetrahedron	Spheres	Ø = 3; 4; 5 mm	Ruby	University of Padua, Italy [9]
	Cylindrical bars	Ø = 2 mm L = 25 mm	Carbon fibre	
	Framework	Not specified	Carbon fibre	
Dog bone	Bone shape	L = 11,8 mm W = 1,5; 3 mm T = 1 mm	POM	Denmark Technical University (DTU) [11]
Steps	Cylinders	$Ø_\mathrm{e}$ = 40; 60; 80; 120; 160; 200; 220 mm $Ø_\mathrm{i}$ = 20 mm	Aluminium	Swiss Federal Laboratories for Materials Science and Technology (EMPA) [15]
Silicon sheets cube	Sheets	4 × 4 × 1 mm^3	Silicon	University of North Carolina at Charlotte (UNCC) [10]
	Block	6 × 6 × 4 mm^3	Glass	
NIST Standard	Various geometries on a squared base of 40 × 40 mm^2		ABS	National Institute of Standards and Technology (NIST) [13]

Ø = Diameter; $Ø_\mathrm{e}$ = External diameter Ø; $Ø_\mathrm{i}$ = Internal diameter Ø; L = Length; W = Width; T = Thickness; H = Height

As mentioned, XCT is capable of measuring inner cavities, thus, some of the reviewed reference standards include hidden geometries. For instance, in [10] the engraved sheets are introduced in epoxy and then, embedded in glass. Before this process, the engraved features are external and can be measured using conventional metrology instruments such as optical microscopes. In [12], the artefact has cylindrical inserts with artificial porosities in the base, which remain hidden. These inserts are removable, so that the porosities can be measured by other means.

The reviewed reference standards are built using different materials. In the CT tetrahedron [9], the spheres are made of synthetic ruby and the structure is made of carbon fibre. The Pan flute gauge [9] structure is also made of carbon fibre, while the tubes are made of glass [9]. Another common material is the aluminium [15, 16]. Plastics such as ABS and POM are also used, although they are more unstable through time than the previous. The manufacturing processes are also varied, injection moulding is used to manufacture the Dog bone [11], the Lego block [14] and the Toggle [11]. The Silicon sheets cube micro geometries have been engraved in the silicon wafers by lithographic processes, known by their precision [10]. The Cubic standard has been manufactured by a powder bed fusion process, an AM technology [12].

Another line of research in XCT is its capability to extract areal surface texture data. This is especially relevant when the surface topography of interest is internal or not accessible. The roughness profiles developed by the University of Huddersfield [17] have been included in this state-of-the-art study. The AM technology of powder bed fusion has been used to manufacture the roughness profiles and their micrometric features.

3. Design of the novel reference standard

The target of the project is to design an AM produced artefact which can be used as reference standard for the calibration of XCT systems. In this section, the initial design constrains are expounded and then, the design of the novel reference standard is explained and described.

3.1. Initial constrains of the design

The manufacturing technology that has been selected to build the reference standard is AM. The direct relation between AM and XCT as a metrology instrument was mentioned in the introduction: AM enables the production of complex hidden geometries and internal structures such as scaffolds, whereas the ability of XCT to measure internal and hidden surfaces makes it the only suitable instrument when sectioning the part is not desired.

Although in the last years, many artefacts for testing AM process have been designed, they lack the design optimization for the use in XCT [18]. The reference standard design must not only comply with AM design rules, but also it must minimize aspects which negatively affect the XCT measurements [19]. For this reason, it has been decided that the reference standard will be manufactured in plastic, even though AM is able to work with different types of materials, from ceramic to metals. In this first phase of the project, the choice of plastic is justified by the fact that X-rays weaken when they penetrate dense materials. In future works, the effect of measuring the same reference object manufactured in thicker materials could be studied. In addition, since the calibration is going to be performed by the substitution method, its features must also be measurable by other metrology instruments such as a CMM and a Focus Variation Microscope (FVM). The initial constraints that the design must fulfil are summarized below:

- Limited thickness of the walls: The maximum wall thickness depends on the XCT system voltage and the scanned material. For polymers, it should be under 90 mm for a low voltage (130 kV) [19].
- Avoid thin layers and sharp edges: When the X-rays are perpendicular to the thin wall, just a small portion of them will pierce the material. Similarly, sharp edges should also be avoided because they cause scatter of the X-rays, causing a lack of definition of the edge [19].
- Measurable by other existing techniques: The measuring features must be physically accessible; dimensions larger than 2 mm will be measured by a CMM while dimensions smaller than 4 mm will be measured by a FVM. The main issue are the hidden geometries, which need to be made accessible.
- Features and geometries must be compliable with applicable norms for the expression and estimation of uncertainty with calibrated workpieces [20,21] and [22].
- Avoid cantilever features in order not to need support structures which would affect the surface finish of the part.

It is worth mentioning that the characteristics and settings of the XCT system are not considered in this paper because the target is to obtain a reference standard which can be used to calibrate most XCT systems used for metrology applications.

3.2. Design of the reference standard

The reference standard has been designed considering the above mentioned constrains and the state-of-the-art previously studied. Most of the reviewed reference standards consist of simple geometries with limited types of dimensions [9,11,14,15] that often serve for calibration [9,12]. The novel design proposed in this article aims to allow the characterization of XCT systems when measuring micro and macro geometries, dimensions and roughness profiles, in visible and hidden parts.

The final design is shown in figure 1. The hidden parts are made accessible to the measuring instruments by removable parts. The assembly with the covers attached is shown in figure 1(a), the main body is shown in figure 1(b) and the covers are shown in figures 1(c) and 1(d).

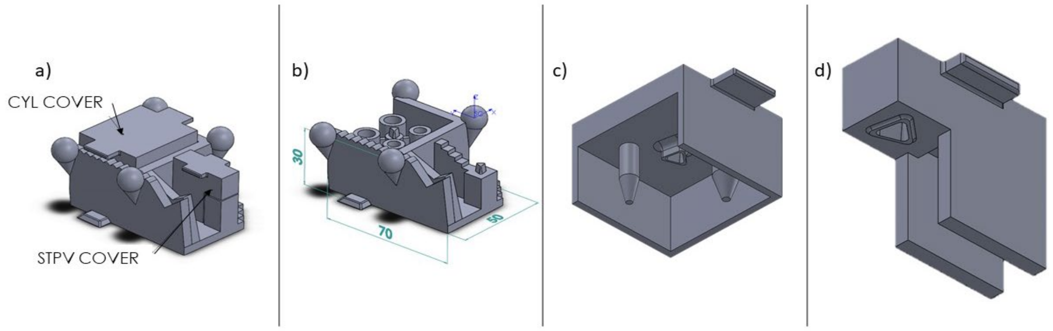

Figure 1. (a) Reference standard assembly with the covers attached. **(b)** Main body of the reference standard. **(c)** Cover for the cylinders. **(d)** Cover for the stepped stairs.

The geometrical features that have been included in the model are based on the reference standards previously reviewed, namely: reference spheres [9,12], cylinders and stepped stairs [13-15], distances [9,12], different profiles for roughness measurement [17] and internal cavities [10]. Having these geometrical features in one artefact leverages the XCT systems capability of characterizing all of them in just one measurement without sectioning or dismounting the artefact.

As shown in the figure 1(b), the dimensions of the artefact are approximately 70 mm × 50 mm × 30 mm, which is within the range of the state-of-the-art reference standards. It has a cubic body with four spheres at the top corners which serve as reference datum for performance evaluation. The artefact has stepped stairs and leaning walls attached perpendicularly to one side of the cubic body, resulting in a prism shape with a rectangular base. The leaning walls are designed to leverage the layered structured of the AM produced artefact to generate different roughness profiles depending on the angles, which go from 7.5º to 45º. Whereas, the stepped stairs have been designed in two different planes to evaluate the effect of the printing direction. A sinusoidal profile has also been included to observe the printing effect. Inside the cubic body there are two pairs of hollow cylinders. In the centre there is a solid cylinder with a fiducial for the cover. The cover (figure 1(c)) includes two pins which are inserted in one hollow cylinder of each pair. In this manner, it is possible to analyse the effect produced by the inserts in the XCT measurements. The cubic body is open in two of its sides, which are closed when the cover is assembled. Similarly, the stepped stairs have another cover (figure 1(d)) which is mounted in another fiducial. The removable covers allow to create hidden geometries which can be measured by XCT. These geometries are accessible to the CMM and the focus variation microscope by removing the covers. Fiducials are designed to keep the repeatability of the assembly when mounting/dismounting the covers.

4. Experimental measurements

This section presents the results of the inspection of the first prototype. Measurements have been performed with a CMM ZEISS PMC-876 CNC and a FVM InfiniteFocusSL of Alicona.

4.1. Measuring features

First, a reference system is created with three of the reference spheres (S1, S2 and S3). A XY plane is built by the centres of the reference spheres, setting the origin in S1 as shown in figure 2.

The geometries that have been evaluated with the CMM are the diameters of the reference features and the distances between these elements, while the FVM has been used to characterize the horizontal dimensions due to the limitations of the instrument. A total of three measurements of each geometry have been taken, considering the average as the reference result. The measured features are shown in figure 2(a) and 2(b) and summarized in table 2.

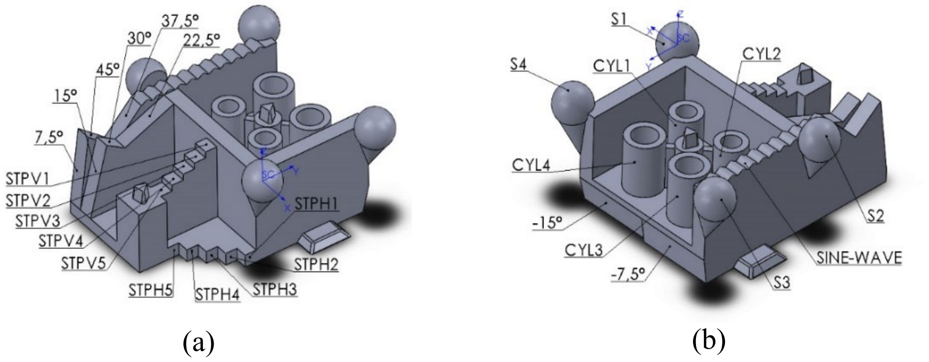

Figure 2. (a) Ramps and stepped stairs. **(b)** Spheres, cylinders and sinusoidal profile.

Table 2. Measurable geometries in the designed reference standard.

Geometries	Nominal dimension	Reference instrument	Hidden by the covers	Deviations from nominal (µm)
4 x Spheres (S1, S2, S3, S4)	Ø = 12 mm	CMM	No	101.5
Distance between spheres (S1-S2, S3-S4)	L= 57 mm	CMM	No	55
Distance between spheres (S1-S4, S2-S3)	L= 40 mm	CMM	No	95
2 x Hollow cylinders/circles (CYL1, CYL2)	Øi = 6 mm Øe = 10 mm	CMM and FVM	Yes	204
2 x Hollow cylinders/circles (CYL3, CYL4)	Øi = 8 mm Øe = 12 mm	CMM and FVM	Yes	252.75
5 x Vertical stepped stairs (STPV1 to STPV5)	H = 2 mm	CMM and FVM	Yes	82
5 x Horizontal stepped stairs (STPH1 to STPH5)	H = 4 mm	CMM and FVM	No	28.33
Leaning walls	Roughness	FVM	No	10-30
Sinusoidal profile	Roughness	CMM and FVM	No	

Ø = Diameter; Ø$_e$ = External diameter Ø; Ø$_i$ = Internal diameter Ø; L = Length; H = Height

The leaning walls (ramps from -15° to 45°) and the sinusoidal profile of the artefact have been used to generate roughness profiles. The instrument used to measure these profiles is the FVM InfiniteFocusSL of Alicona. The roughness has been evaluated according to the norm ISO 4288:1996, the average roughness parameter (Ra) has been measured for each surface. Results show that for the profiles, with an evaluation length of 4 mm and a sampling length of 0,8 mm, the range of the average roughness parameter (Ra) oscillates from 10 to 30 µm. An example of the data extracted from the FVM of Alicona is shown in figure 3.

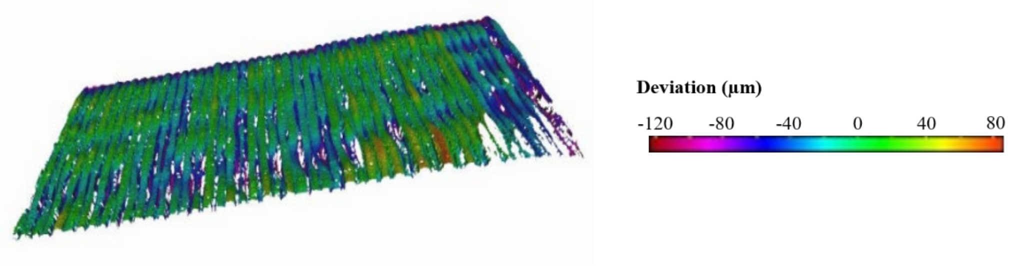

Figure 3. 15° ramp roughness color map.

4.2. Uncertainties

The evaluation of the expanded measuring uncertainty of the measurements obtained by the reference instruments (CMM and FVM) has been done according to the norm ISO 15530-3:2011 [21]. Equation 1 shows the calculation of the expanded measuring uncertainty.

$$U = k\sqrt{U_{cal}^2 + U_p^2 + U_b^2 + U_r^2 + U_{res}^2} \tag{1}$$

Where k is the coverage factor, U_{cal} is the calibration uncertainty, U_p is the process uncertainty, U_b is the temperature effect uncertainty, U_r is the noise standard uncertainty, and U_{res} is the resolution uncertainty. A coverage factor of k = 2 for a 95% of confidence is considered.

The dimension selected as a reference is the distance between the vertical steps 1 and 2 (STPV1 and STPV2 in figure 2(a) because it is the most accessible feature for both instruments. The results of the uncertainty sources and the experimental measurements are shown in table 3.

Table 3. Uncertainty calculations for CMM and FVM.

Description	CMM	FVM
Nominal value [mm]	2.00	2.00
Average measurement [mm]	1.915	1.897
u_{cal} [µm]	1.15	1.00
u_p [µm]	24.87	4.85
u_b [µm]	0.001	0.001
u_r [µm]	0.00	0.04
u_{res} [µm]	0.29	0.03
U (k=2) [µm]	49.81	9.91

To verify the results, the parameter E_N is calculated. This value relates the deviations measured by different instruments in the same dimension. A value of $E_N < 1$ indicates that results can be comparable. Calculations are summarized in Eq. 2.

$$En = \frac{|Measurement\ 1 - Measurement\ 2|}{\sqrt{{U_1}^2 + {U_2}^2}} = \frac{|1915-1897|}{\sqrt{49.81^2+9.91^2}} = 0.354 < 1 \tag{2}$$

5. Conclusions and further work

A state-of-art review of the reference standards used for the calibration of XCT has been done, and a novel reference standard for XCT uncertainty quantification has been designed accordingly. The model includes macro and micro geometrical features; also, both hidden and shown elements. The design has been verified by a contact CMM and a FVM, with an uncertainty study following the normative to validate the results. These measurements will be considered as a reference to compare with further XCT results.

An integrated methodology for the macro- and micro-geometric characterization of parts with critical geometries (due to their size or shape) would make it possible to take advantage of the results of the different macro and micro techniques and thus carry out an accurate complete dimensional measurement.

As the research continues, the next step will be the measurement of the artefact with different XCT devices, to test the accuracy of the instruments and to compare them. As a result, a study of the capability of a XCT system when characterizing various geometries will be extracted from the experimental measurements. Furthermore, additional tests could be performed in order to study the behaviour of the devices with different polymer materials or a combination of materials.

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