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Design of a reference standard for X–ray CT and other contact and non-contact metrological instruments

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Abstract

This work proposes a novel design of a reference standard for X-ray Computer Tomography (XCT) for the macro- and micro-geometric characterization of parts with critical geometries (due to their size or shape), which will allow to carry out an accurate complete dimensional measurement. Firstly, a brief study of the state-of-the-art of reference standards used for the characterization of XCT systems is presented in order to analyse their limitations. Then, we propose a novel reference standard consisting in detachable parts with different types of measurable features with several types of accessible external and internal macro and micro-geometries that make it suitable for both different macro and micro measuring technologies. Its use will allow to determine the XCT surface extraction and measurement procedure that optimizes the precision and resolution of the measurement, as well as to develop an integrated and synergistic methodology for macro and micro-geometric characterization through different metrological techniques.

Keywords: X-ray computed tomography, reference standard, focus-variation microscope.

1. Introduction

The development of additive manufacturing (AM) has allowed to create complex designs with freeform surfaces, hidden geometries and also porous internal structures for scaffolds. In addition, the precision of these technologies has evolved to the point that they are capable of building macro and micro geometries in one print.

This has derived in the need of new measuring technologies, such as X-ray Computed Tomography (XCT) which allows the inspection of geometrical dimensions of mechanical parts, including both internal and external features without contact nor any accessibility issue. It also has the potential for measuring submillimetre and macro features in just one measurement [1].

In traditional uses of XCT, such as medical diagnoses or detection of flaws in industrial parts, a qualitative analysis was enough, and dimensional accuracy was not required. However, in dimensional-metrology applications, the measurements need to achieve a certain degree of accuracy, which requires the measuring uncertainty of the XCT system to be known. The use of XCT in these applications is relatively new; thus, there is a great effort in the development of specific norms about systems verification and their uncertainty estimation. However, the consensus has been the use of reference standards for the measuring errors identification due to the complexity of the XCT measuring process.

This work, firstly, presents a study of the state-of-the-art in reference standards that are used for the characterization of XCT systems and, then, proposes a novel design. The target is to obtain a test artefact that will be used as reference standard to estimate the measuring uncertainty of XCT systems. This will be done by the substitution method, meaning that the reference standard must be first calibrated by other traceable measuring instruments. Therefore, its design must be compatible with other metrological instruments. In addition, due to the fact that the metrological capabilities of XCT are directly related to the advances in AM, AM has been selected as the technology to manufacture the reference standard.

2. State of the art in reference standards

In the last years, several reference standards for XCT have been proposed by different research groups [2]. These reference standards have been studied and a summary of some of them and their measurable geometries are shown in Table 1.

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

Research Group	Geometry	Dimension	Material
University of Padua [3]	Spheres	Ø = 3; 4; 5 mm	Ruby
	Cylinders	Ø = 2 mm	Carbon fibre
University of Padua [4]	Central cylinder	H = 15 mm Ø = 5 mm	Aluminium
	Removable cylinders	Ø = 15 mm H = 7.5; 8.5 mm	
University of Nottingham [5]	Cube sides	L = 40 mm	Polymer
	Spheres	Ø = 5 mm	
University of Huddersfield [6]	Roughness profiles		Titanium alloy Ti_6Al_4V

*H = Height; Ø = Diameter; $Ø_e$ = External diameter Ø; $Ø_i$ = Internal diameter Ø; L = Length

Although there are artefacts with multiple geometries and roughness profiles, the most common geometries are spheres and cylinders: virtually representing a point and a line, respectively. Some of them have hidden geometries that can be accessible using removable parts, as in [4]. The materials of these standards vary from metals to plastics. The manufacturing processes are also varied, form injection moulding to AM technologies.

3. Design of the novel reference standard

The study of the state-of-the-art shows that the design of the reference standards can be very different depending on their purpose. However, most of them consist of simple geometries that are used to characterize exclusively one or two types of dimensions. In contrast, in this work, the target is to obtain a reference standard whose design is optimized for the use in XCT and that allows the estimation of the uncertainty of XCT when measuring several distances, micro and macro geometrical features, and roughness profiles, in visible and hidden parts.

As mentioned, one of the prominent use of XCT is directly related to the development of AM technologies, which allow manufacturing complex geometries and hidden cavities. Thus, a desirable requirement is that the reference standard can be manufactured using these technologies. For this reason, the standard is designed, in a more general way, without overhanging features in order not to require support structures which would affect the surface quality of the part. Although the surface and geometrical quality of AM parts may be deficient in comparison to other technologies, it is not crucial because the artefact used as reference standard will be calibrated by reference instruments. Moreover, in order to assure the stability of the dimensions over time, the calibration will be performed before and after the XCT measurements.

Thus, the geometries need to be measurable not only by XCT but also by other calibrated instruments. In this case, the focus-variation microscope (FVM) InfiniteFocus of Alicona will be used to measure roughness and small and micro features (< 4 mm), while a coordinate measuring machine (CMM) will be used to measure small and larger features (> 2 mm). The design must take into account the measuring restrictions that these two instruments impose. Thus, the geometries have been made accessible for a CMM 1-mm-radius stylus sphere. The microscope working distance of 17.5 mm with a x10 magnification lens has also been taken into account.

The reference standard has been designed considering the restrictions mentioned above; the final model is shown in Figure 1. Its external dimensions are approximately 70 mm × 50 mm × 30 mm. As can be seen, the main body of the model has a cubic shape with four spheres in the corners, which can be used as reference datum when measuring the absolute position of other features. The model also has stepped stairs and leaning walls built in different directions in order to observe the printing effects of the AM technology. The layered structure has also been leveraged to generate different roughness profiles in the leaning walls with angles from 7.5º to 45º. A sinusoidal profile has also been included. Two pairs of hollow cylinders of two sizes have been printed inside the cube. In Table 2, the main geometries of the model and their respective dimensions have been summarized. The table also indicates which reference instrument is going to be used to characterize the dimension.

As can be seen, two of the six walls of the cube are open in order to make the features accessible for the CMM and the FVM. Nevertheless, the model includes a removable cover which closes the cube and hides the cylinders. Moreover, the cover includes two pins that are inserted in the cavities of two hollow cylinders, one from each size. There is a second cover for one of the stepped stairs. In this manner, the measurement of hidden geometries can be performed in XCT and compared with the measurements without covers performed by the calibrated instruments. The use of dismountable covers allows assessing the uncertainty for XCT measurements of internal geometries. The assembly with the two covers is shown in Figure 1b.

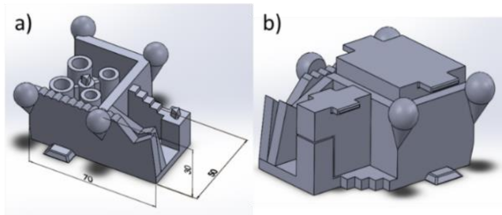

Figure 1. a) Main body of the reference standard. b) Reference standard assembly with the covers attached.

Table 2. Measurable geometries in the designed reference standard

Geometries	Dimension	Reference instrument
4 × Spheres	Ø = 12 mm	CMM
Distance between spheres	L= 57 mm; L= 40 mm	CMM
2 × Hollow cylinders/circles	$Ø_i$ = 6 mm $Ø_e$ = 10 mm	CMM and FVM
2 × Hollow cylinders/circles	$Ø_i$ = 8 mm; $Ø_e$ = 12 mm	CMM and FVM
Stepped stairs	2 mm	CMM and FVM
Stepped stairs	4 mm	CMM and FVM
Leaning walls	Roughness	FVM
Sinousoidal profile	Roughness	CMM and FVM

4. Manufacture and measurement of the reference standard

The first prototype has been manufactured by a Polyjet printer, which is able to achieve better accuracy. The geometries of this final model have been measured with the CMM and the FVM according to Table 2 and the expanded uncertainties of the measurements have been calculated. In the dimensions that can be measured by both instruments, it has been verified that the measurements and uncertainties of both instruments show a satisfactory agreement.

5. Conclusions

This work presents a novel reference standard for XCT systems. The model allows estimating the uncertainty of measurements of micro and macro geometries, in visible and hidden cavities. The uncertainty estimation is performed by the substitution method, thus, the model has detachable parts, so that the inner cavities can also be measured by CMM and FVM.

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