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Calibration of X-ray computed tomography for surface topography measurement using metrological characteristics

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Abstract

X-ray computed tomography (XCT) has been shown to be capable of capturing surface topography information comparable to that acquired using established surface measurement systems. However, calibration of XCT for surface measurement has not yet been achieved. The factors that influence XCT measurement are numerous, and the ways in which these factors affect measurements are not always clear. However, the problem of understanding complex, numerous influence factors exists for other measurement technologies as well, with factors being difficult or impossible to quantify in many cases, often because they cannot be measured in isolation from other influence factors. In measurement of areal surface topography, a calibration framework based on understanding the metrological characteristics (MCs) of an instrument has been developed to address the uncertainty problem; recently attaining international acceptance with the publication of ISO 25178-600. This framework was developed to allow calibration without characterising all the influence factors individually. Instead of examining all possible factors within a measurement system, the framework examines a few standardised characteristics of the system (i.e. MCs), as an approximate means to understanding measurement uncertainty. While some individual influence factors are inevitably double-counted (in that some factors contribute to more than one MC), the MC framework can be used to provide calibration for complex systems, with the caveat that double counting leads to slight increases in the determined measurement uncertainties. In this work, we apply the ISO 25178-600 MC framework to an XCT measurement system, demonstrating a method of calibrating such a system for surface measurement. We present a material measure to be used for this purpose. Given the novelty of applying the MC framework to XCT measurement and the associated complexities, we also provide an assessment of the MC framework with respect to its suitability for calibrating XCT systems.

Metrology, surface topography, metrological characteristics, X-ray computed tomography

1. Introduction

X-ray computed tomography (XCT) has become recognised as a viable method of surface topography measurement [1–3]. XCT offers notable advantages over other technologies when measuring internal or hard-to-reach surfaces [3,4]. However, XCT measurements are limited by difficulties relating to uncertainty evaluation, most notably because of a relatively poor understanding of many of XCT's plethora of measurement influence quantities [5].

The metrological characteristics (MCs) framework for surface topography measurements, described in ISO 25178-600 [6], allows for an uncertainty evaluation for a measurement without characterising each influence quantity. Instead, a small number of standardised MCs, related to both the system and the surface being measured, are evaluated. The MCs published in ISO 25178-600 are presented in Table 1.

The MC framework has already been applied to various measurement techniques, such as contact stylus instruments and coherence scanning interferometers (CSI) [7,8]. However, the ISO 25178-600 MC framework has not yet been applied to XCT measurements.

In this work, the ISO 25178-600 MCs approach is applied to XCT surface measurements and an assessment of the MC framework with respect to XCT systems is provided.

Additionally, a measurement artefact to be used for this purpose is presented. The applied methodology is explained in section 2, while some preliminary results can be found in section 3. The conclusions of the progress to date are given in section 4.

Table 1 Metrological charateristics for surface measurements.

Metrological characteristic	Symbol	Error along
Amplification coefficient	$\alpha_x\,\alpha_y\,\alpha_z$	*x,y,z*
Linearity deviation	$l_x\,l_y\,l_z$	*x,y,z*
Flatness deviation	Z_{FLT}	*z*
Measurement noise	N_M	*z*
Topographic spatial resolution	W_R	*z*
x-y mapping deviations	$\Delta_x(x,y)$ $\Delta_x(x,y)$	*x,y*
Topography fidelity	T_{Fi}	*x,y,z*

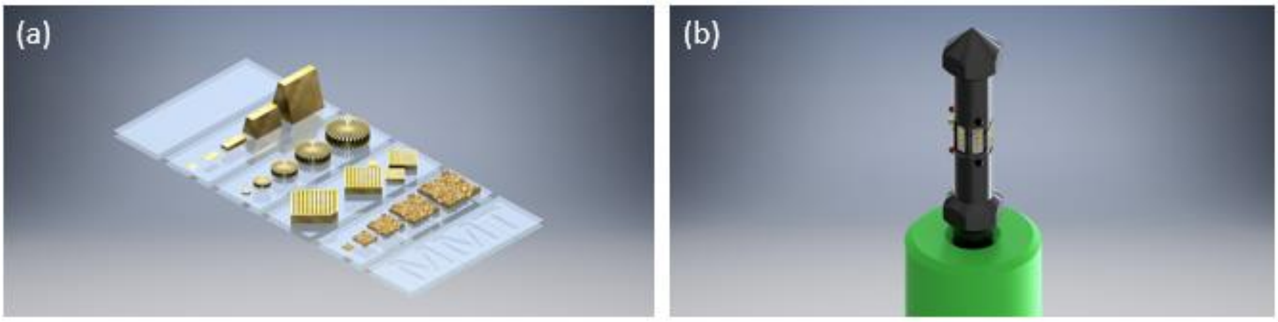

Figure 1 (a) areal material measures adhered to the pillar artefact: flat, steps of different heights, type ASG material measures, type ACG material measures and random surfaces; (b) carbon fibre pillar with the areal material measures and ruby spheres adhered to it.

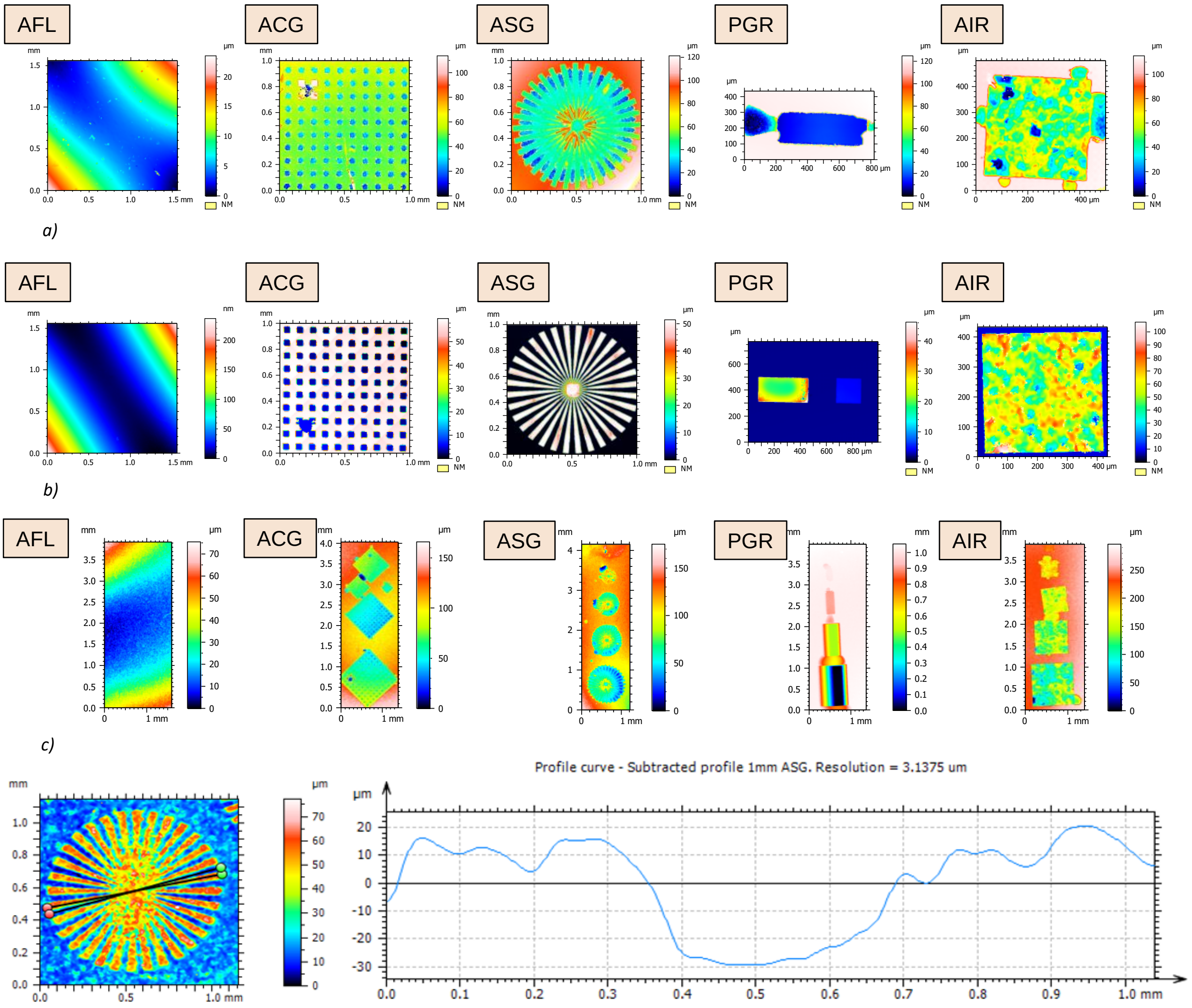

Figure 2 (a) Measurements by Zygo NexView NX2 coherence scanning interferometer (replicated surfaces, levelled only, example measurements); (b) Measurements by Zygo NexView NX2 coherence scanning interferometer (original surfaces, levelled only, example measurements); Preliminary measurements by Nikon MCT225 XCT (replicated surfaces, levelled only, example measurements); and (d) XCT measurement of the 1 mm diameter type ASG replicated material measure; (right) Subtraction of the two profiles marked on image (left), from which the W_R is derived.

2. Methodology

The procedure to be followed for calculating the MCs for other surface topography measuring systems can be found elsewhere [9]. That procedure requires the use of areal material measures, such as cross gratings (type ACG), star shaped groves (type ASG), flats (type AFL) and steps of different depths (PGR type). For optical surface topography measuring instruments, artefacts that can map the metrological characteristics in different scales have been proposed [10,11]. Due to the large size differences between the three dimensions of these material measures (and associated high aspect ratios), they are not well suited to XCT measurement [12]. Thus, a new artefact comprising a hexagonal carbon fibre pillar to which all the required material measures are adhered, has been designed and manufactured to meet the ideal criteria for being measured by an XCT system. The artefact also contains a sphere-to-sphere distance material measure, for in-situ calibration of XCT voxel size (see Figure 1).

The topographic spatial resolution (W_R) and the amplification coefficient and linearity deviation in x and y axes (α_x, α_y, l_x, l_y) were studied using the type ASG and the type ACG material measures.

Both surfaces were measured using a Nikon MCT 225 at a geometric magnification of 30× (voxel size of 6.6 µm), using the following measurement setup: voltage 70 kV, current 96 µA, 3142 projections and exposure 4000 ms. A 0.1 mm copper pre-filter was used; a shading correction was applied and a warmup scan of approximately one hour was performed prior to the scan. Due to delays in instrument maintenance caused by COVID-19, measurements were acquired using the XCT system outside of its measurement specification and, as such, quantities quoted in this paper are preliminary, as calculated voxel sizes are not reliable. In the coming months, we intend to repeat all measurements following a full system adjustment and calibration. Volumetric reconstruction was performed using CT-Pro and surfaces were determined in VGStudioMAX 3.0 using the iterative local maximum gradient algorithm with the ISO-50 isosurface as the start point. Triangulated meshes of each surface were exported as STL files using the same software. The STL files were imported into MountainsMap where they were converted to areal digital elevation models at a lateral resolution of 2.2 µm. The type ACG and type ASG material measures were also measured using a ZYGO NexView NX2 CSI in the following setup: 5.5× objective lens at 1× zoom (numerical aperture 0.15, field of view 1.56 mm × 1.56 mm, optical lateral resolution [Sparrow limit] 1.90 µm).

The W_R MC is calculated from measurements of the type ASG material measure by subtracting two profiles: one extracted through the centre of two diametrically opposed upper petals, and one running through the centre of two diametrically opposed lower petals. The α_x, α_y, l_x and l_y MCs can be derived from measurements of the type ACG material measure by comparison of the measured values of distances between the centre of gravity of the holes in the type ACG material measure and its reference values (derived from the CSI measurements).

3. Preliminary results

The W_R of the XCT system for the specific setup detailed in section 2 was calculated using three type ASG material measures, with diameters 1 mm, 800 µm and 600 µm. The mean of W_R, calculated using the W_R of each type ASG material measure, is 3.3 µm. Figure 2 shows the 1 mm type ASG material measure and the subtracted profile from which the W_R was derived. A low-pass Gaussian convolution filter with a cut-off frequency of 80 µm was applied to the profile to reduce noise (the filter was not used in the calculation of W_R). CSI measurements of the type ASG material measures confirmed that the material measure was capable of assessing the XCT's resolution (i.e. the resolution of the manufacturing process used to create the material measure is significantly better than the resolution of the XCT system).

The reference distances between the centres of gravity of the holes of the type ACG material measures were measured by averaging the distances of five consecutive CSI measurements of the type ACG material measures. A 7 × 7 grid of holes was extracted from a type ACG material measure of 100 µm pitch (distances between 100 µm and 600 µm) from the CSI and the XCT measurements. The comparison of the measured values and the reference values results in the following values of the MCs: $\alpha_x = 0.99$, $\alpha_y = 1.00$, $l_x = 5.6$ µm and $l_y = 3.7$ µm. Here, it should be again noted that these results are made using the XCT system outside of its measurement specification and that, although the methodology of the study will be the same, the final numerical results may differ from those presented in this initial set of results. The results presented in this section are sumarised in Table 2.

Table 2 Results of topographic spatial resolution and amplification coefficient and linearity of x and y axis for the specified settings.

W_R (µm)	α_x	α_y	l_x (µm)	l_y (µm)
3.3	0.99	1	5.6	3.7

4. Conclusions

In this work, we aim to demonstrate the MC approach for calibration of XCT surface measurements. To achieve this goal, each MC of the XCT must be evaluated. Thus far, we have evaluated the topographic spatial resolution and the amplification coefficient and linearity deviation of the x and y axes. Although the measured quantities are preliminary, the methodology presented here represents a framework for making such a calibration and shows that the MC concept can be applied to XCT surface topography measurement. Future work will be focused on calculating the remaining MCs, applying this approach to specific XCT surface measurements and including measurement uncertainty with the MC values.

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