Effect of surface roughness on uncertainty of X-ray CT dimensional measurements of additive manufactured parts

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1. Introduction

Over the last years, X-ray CT field of application has evolved towards dimensional and geometrical measurements of industrial products [1]. However, lack of standardisation, and difficulties in quantification of measurement uncertainty are limiting its application in industry. CT process chain indeed is affected by numerous influence quantities which interact among themselves in a non-linear and complex way. One of the critical aspects to deal with in CT measurements is the high influence of surface roughness. Up to now, in literature, there are few studies concerning the influence of surface roughness. In [2] uncertainty is assessed for a workpiece with roughness value \( R_z \) in the order of 6 \( \mu \)m. Surface roughness effects are there quantified on the basis of averaged \( R_z \) measurements and assuming that the surface lies half within the part material. In [3] the authors estimate effects of less than a quarter of the maximum pick to valley height of the profile in the sampling length \( (R_z) \) for a workpiece with \( R_z \) up to 134 \( \mu \)m, however they state that this assumption needs to be further verified.

When scanning parts affected by higher surface roughness, the problem of how to treat roughness uncertainty contribution becomes more relevant, since assumptions made to quantify the effect of surface roughness may produce uncertainty statements that are not appropriate. In the present paper an experimental study based on repeated CMM and CT measurements on an industrial workpiece produced by Additive Manufacturing (AM) and characterized by \( R_z \) up to 125 \( \mu \)m is reported. The influence of surface roughness as a systematic component has been investigated. The results enable the correction of this effect and a significant decrease in the CT measurement uncertainty.

2. Determination of CT measurement uncertainty

At the state of the art, there are no internationally accepted standards for determination of measurement uncertainty for CT measurements. The set-up of a model equation, as outlined in the GUM [4], is not practically possible for CT systems due to the amount of complex error sources influencing the entire process chain. The experimental approach, outlined in ISO 15530-3:2011 [5] makes use of calibrated workpieces respecting similarity conditions with those for which measurement uncertainty must be evaluated. Expanded measurement uncertainty \( U \) is then determined through a series of repeated measurements, by equation (2.1):

\[
U = 2 \cdot \sqrt{u_{cal}^2 + u_p^2 + u_w^2 + u_b^2}
\]

where \( u_{cal} \) is the calibration uncertainty of the calibrated workpiece, \( u_p \) the uncertainty of measurement procedure, \( u_w \) the uncertainty resulting from material and manufacturing variations (form errors, surface roughness etc.), and \( u_b \) the uncertainty of the systematic error.

For CT measurements, however, due to the multitude of error sources, in many cases it is extremely difficult to determine the single components of the systematic error \( b \), and hence the associated uncertainty component \( u_b \). Therefore, it is sometimes preferred to use uncorrected results and compute the uncertainty adding the bias contribution \( b \) directly to the uncertainty value, e.g. as it was suggested in ISO/TS 15530-3:2008 [6].

In [2] roughness uncertainty component is calculated for a workpiece with an average \( R_z \) of 6.82 \( \mu \)m, scanned with a voxel size of 145 \( \mu \)m. A rectangular distribution with limits \( \pm R_z/2 \) is there assumed. This component is added to \( u_w \) which then contributes to \( U \). If this assumption is applied also to measurement of parts characterized by high surface roughness, \( u_w \) can reach several tens of microns, giving a considerable overestimation of measurement uncertainty.

Moreover, if the bias \( b \) is added to the uncertainty budget, in case of relevant systematic errors, it could be the predominant component in the uncertainty budget. This is the case for parts characterized by high surface roughness. The different principle
on which tactile measuring instruments and non-contact techniques rely cannot be neglected indeed. Tactile CMMs, for example, acquire points by means of the mechanical contact between the probe stylus tip and the surface of the workpiece. The finite dimensions of the tip cause a mechanical filtering which increases with the dimensions. The profile acquired by means of tactile measurements, therefore, is shifted toward roughness peaks. On the other hand, CT measuring principle relies on the attribution of a medium grey level, according to the material attenuation and the path followed by the X-rays, to each voxel composing the 3-D model.

While measuring parts characterized by a relevant surface roughness, therefore, systematic effects between tactile CMM measurements and CT measurements are expected. In this case, adding the $u_w$ contribution coming from roughness as reported in [2] and the bias $b$ to the uncertainty budget as well would produce a high overestimation of the measurement uncertainty.

3. Experimental investigation and results

To investigate the influence of surface roughness on CT dimensional measurements, a set of repeated measurements has been carried out on a steel part produced by Selective Laser Sintering (SLS), featuring internal and external cylinders with diameters from 40 mm to 90 mm. The workpiece was previously calibrated using a tactile CMM (MPE of length measurement: $2.7 + L$(mm)/300 µm). Calibrated values of internal and external diameters of different dimensions where obtained through 10 repeated CMM measurements in scanning mode with approximately 1500 points, using a ruby sphere probe with a diameter of 3 mm.

Then 7 repeated CT scans of the part were performed with a voxel size of 120 µm. CT data were then analysed by means of VGStudio MAX 2.2, using advanced local threshold determination method. The same alignment conditions used for CMM measurements were replicated on the CT model. Each diameter was then measured by fitting a least square cylinder for CMM measurements and CT measurements were expected. To consider the zone in which the CMM probe, of finite dimensions, has acquired points.

Surface roughness was measured with a stylus measuring instrument using a 5 µm stylus tip. Values of $R_z$ up to 125 µm were obtained. In this work, CMM measurements were considered as reference results; therefore, it was decided to attribute all the uncertainty due to roughness to CT measurements, to upper-bound CT uncertainty.

Experimental results are shown in Figure 1. CT measurements of external diameters are always smaller than CMM measurements, with a difference of approximately $R_z/2$. Symmetrically, CT measurements of internal diameters are larger than CMM calibrated values, with a difference of nearly $R_z/2$. After correcting the $R_z/2$ systematic error, a residual roughness uncertainty component $u_R = R_z/8$ can be estimated. This component is completely attributed to CT, to upper-bound CT uncertainty. An average reduction of more than 59 % of CT measurement uncertainty is obtained for internal diameters, reductions up to 85 % are obtained for external diameters.

4. Conclusions

The influence of surface roughness in CT measurement has been evaluated through repeated CT scans on an industrial part produced by SLS characterized by $R_z$ up to 125 µm. Experimental results based on 49 CT measurements on diameters of different dimensions have shown that surface roughness causes a systematic shift between CT and CMM measurements. CT measurements on internal diameters are always larger than calibrated values whereas CT measurements on external diameters are always smaller than calibrated values, with a difference of about $R_z/2$. This difference can then be treated as a systematic component. A residual uncertainty coming from surface roughness $u_w = R_z/8$ can be estimated. This leads to a reduction ranging from 59 % to 85 % of CT measurement uncertainty.

Further studies will be conducted to investigate the relation between surface roughness and the dimensions of the voxel.

References