A TEST OBJECT FOR CALIBRATION AND ACCURACY ASSESSMENT IN X-RAY CT METROLOGY

Kim KIEKENS[1], Frank WELKENHUYZEN[2], Ye TAN[1], Philip BLEYS[2,3], André VOET[4], Wim DEWULF[1] and Jean-Pierre KRUTH[2]

[1] Group T, International University College Leuven, K.U.Leuven Association, Andreas Vesaliusstraat 13, 3000 Leuven, Belgium, wim.dewulf@group-t.be
[2] K.U.Leuven, Department of Mechanical Engineering, Celestijnenlaan 300B, 3001 Leuven, Belgium, jean-pierre.kruth@mech.kuleuven.be
[3] Sirris, Celestijnenlaan 300C, 3001 Leuven, Belgium, philip.bleys@sirris.be
[4] De Nayer Institute, K.U.Leuven Association, J. De Nayerlaan 5, 2860 Sint-Katelijne Waver, Belgium, andre.voet@denayer.wenk.be

Abstract:
While Computer Tomography (CT) has since long been used for medical applications and material inspection, its application field has recently been broadened to include dimensional metrology in industry. However, the accuracy of CT-based measurements remains yet largely uncertain. Not only are the measurements influenced by a number of factors and parameters like e.g. workpiece orientation, magnification, edge detection… but also the calibration method matters greatly. This paper investigates the influence of these factors and parameters and the calibration method (rescaling and correction) on accuracy and repeatability of the measurements, using a test object with parallel grooves. The test object is also used to illustrate how more accurate CMM measurements can be used to calibrate CT measurements and to compare different calibration and compensation strategies.

Keywords: X-ray Computer Tomography, Measurement accuracy, Calibration.

1. INTRODUCTION

1.1 Computer Tomography for dimensional metrology

Computer Tomography (CT) makes use of the attenuation of X-rays penetrating a material to construct a 3D model of an object. The technology is commonly applied for medical applications and material inspection. Due to its capabilities to provide geometric information of inner and hidden structures of e.g. rapid manufactured or assembled parts, CT has also gained interest recently in the area of dimensional metrology. However, the accuracy of CT-based measurements remains yet largely uncertain. Not only are the measurements influenced by a number of factors and parameters such as workpiece orientation, magnification and edge detection… but also the calibration method matters greatly.

1.2 The basic measurement procedure

Figure 1 depicts the subsequent steps of a CT-based dimensional measurement procedure. The first step comprises the data acquisition (1). 2D X-ray images are taken in typically some hundreds or even thousands of different object orientations.

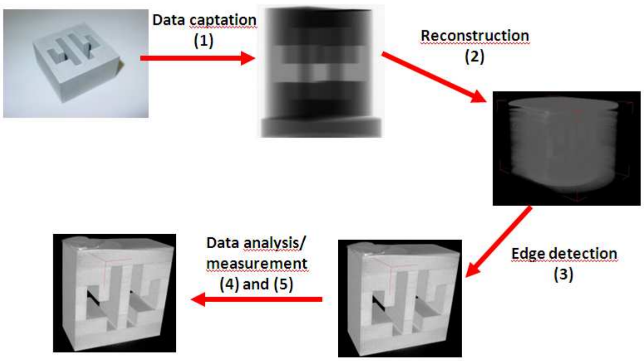

Fig. 1: Overview of the measurement procedure

Subsequently, a filtered back projection algorithm is used to reconstruct the 2D images into a 3D grayscale voxel model (2) [1]. Within this model, an edge detection step needs to be performed (3). It implies a segmentation between background voxels and material voxels in order to define the surface of the workpiece. To this purpose, a threshold grey value is chosen as the edge between background and material. A commonly chosen threshold for mono-material objects is the ISO50% value, representing the average between the peaks for background (light voxels) and material (dark voxels) on the histogram of all voxel model grey values (Fig. 2). Advanced edge detection algorithms are available to vary threshold values locally in order to reduce the influence of noise and CT artefacts such as beam hardening [1]. The edge detection step strongly influences the accuracy of the dimensional measurements.

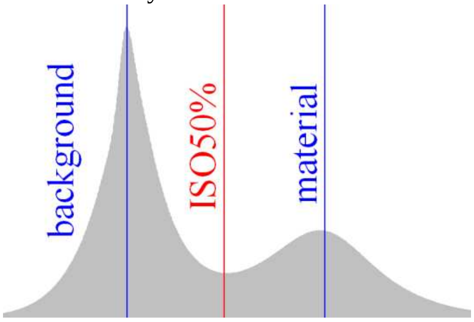

Fig. 2: Histogram of grey values (VGmax)

Dimensional measurements are possible when the resolution of the voxel model is known and traceable. This requires a calibration step (4) [2, 3]. The resolution is primarily influenced by the position of the workpiece between the X-ray source and the detector. The closer the object is to the X-ray source, the larger the magnification of the object on the X-ray images, hence the smaller the voxel size and the better the resolution. The calibration can be performed using the position of the workpiece in the machine to determine the magnification level; this is however little accurate. Another calibration strategy makes use of calibrated reference objects, such as a ball bar, calotte plate, or step cylinder, which is measured together with or just before the actual measurement object [2]. A third option is to perform a number of e.g. tactile CMM measurements on the external surfaces of the measurement object, which are subsequently used as reference measures for the calibration step. The latter calibration strategy is used in this paper. Finally, dimensional measurements can be performed on the calibrated 3D voxel model (5).

2. MATERIALS AND METHODS

2.1 Test object

The geometry of the proposed test object is shown in Fig. 3. It is a prismatic aluminum part (45x45x45mm) with through grooves in the shape of a “cactus”. In zone D the object has ten parallel surfaces (numbered 1 to 8) mutually separated by 5 mm. The features measured on the test object are the horizontal distances between those surfaces, e.g. distance 1-5, measured in zones C or D.

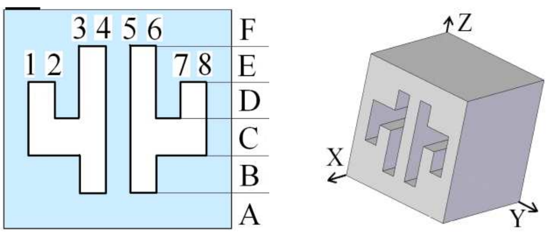

Fig. 3: Front view (a) and 3D model (b) of the test object

2.2 CT-Machine settings

The reconstruction is done with the software CTpro, the data analysis using VG Studio Max. The CT devices specifications and the measurement parameters are summarized in Tables 1 and 2. The repeatability of the distance measurement step on the 3D voxel model (step 5 of Fig. 1) is high, with a sigma of ca. 1µm.

Table 1: Specifications of the measurement equipment

Source	Micro focus source (5µm focal spot size) Max. voltage = 225 kV Max. Current = 2000 µA
Detector	250 x 200 mm 1916 x 1536 pixels Pixel size: 127 x127µm
Scan area	Max. 250 x 330 mm Max. 10 kg

Table 2: Measurement parameters for the test object

Measurement parameter	Value
Acceleration voltage	180 kV
Tube current	35 µA
Number of projections	3010
Magnification	Ca. 3.4x
Integration time (exposure)	1000 ms

3. PROPOSED CALIBRATION AND EDGE CORRECTION METHODOLOGY

3.1 Influence of edge detection on calibration accuracy

The issues of calibration and edge detection have been introduced in Section 1.2 as two distinct steps in the dimensional CT measurement procedure. However, Figure 4 indicates that both steps are interdependent. When an edge is incorrectly defined (wrong grey value), the distance in Fig. 4a will be either too large or too small, whereas the distance shown in Fig. 4b will be much less or even not influenced by the threshold grey value. Consequently, the voxel calibration should be based preferentially on the latter type of distance (i.e. left-left or right-right distances), to avoid over or under scaling the voxel model.

The categorization of *good* and *bad* distances can be made by classifying the surfaces as transitions between air and material (AM-type) or vice versa between material and air (MA-type). The test part is designed to have different such transitions. Starting from the left hand side of Fig. 4a, we measure the distance between an MA-type and an AM-type transition, e.g. the width of a groove (concave distance). Similarly, a distance between a AM-type and an MA-type transition could represent a wall thickness (convex distance). The desirable situation for voxel calibration occurs between two transitions of the same type, e.g. between the left hand sides of two subsequent walls (fig 4a).

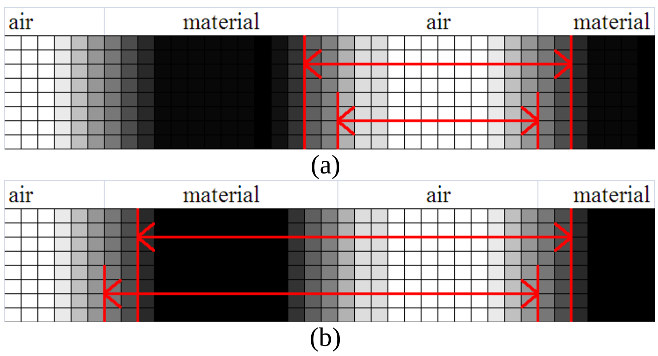

Fig. 4: Distances can be classified as either heavily (a) or minimally (b) dependent on the edge detection

3.2 Calibration

In view of the potential interdependency of edge detection and voxel calibration described above, the magnification factor has been determined as follows:

$$CT^{RS}_{i,j} = CT_{i,j} \cdot \frac{CMM_{a,b}}{CT_{a,b}} \quad (1)$$

where $CT_{i,j}$ represents the distance between plane *i* and plane *j* on the original voxel model after edge detection using the ISO50% value, $CMM_{i,j}$ represents the tactilely measured distance, and $CT_{i,j}^{RS}$ the distance on the CT model after rescaling. The planes *a* and *b* represent transitions of the same type (AM/AM or MA/MA), and are mutually as remote as possible in order to reduce the influence of residual systematic errors on the magnification factor. Both distances (1,7) and (2,8) are appropriate for the test case. In this paper, the average of both is used, hence:

$$CT_{i,j}^{RS} = CT_{i,j} \cdot \text{average}\left(\frac{CMM_{1,7}}{CT_{1,7}}, \frac{CMM_{2,8}}{CT_{2,8}}\right) \quad (2)$$

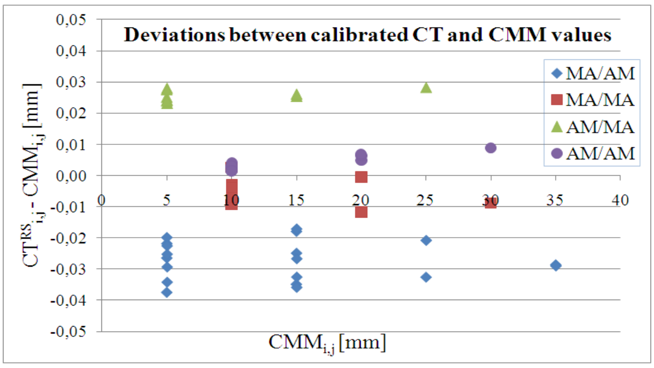

Fig. 5: Deviation between calibrated CT and CMM values

The deviations between the calibrated CT values and the CMM reference values, depicted in Fig. 5, clearly visualize that the 50% isosurface does not result in a correct edge. Whereas all distances between transitions of the same type (AM/AM or MA/MA) are measured relatively correctly, the distances AM/MA are all too large while the distances MA/AM are too small. A correction term for this edge offset can be determined based on the measured deviations. Hence,

$$CT_{i,j}^{Corr} = CT_{i,j}^{RS} \pm (CMM_{x,y} - CT_{x,y}^{RS}) \quad (3)$$

Where $CT_{i,j}^{Corr}$ represents the distance between plane *i* and plane *j* after edge correction. The planes *x* and *y* represent transitions of different type (AM/MA or MA/AM), and are mutually as close as possible in order to reduce the influence of residual scaling errors on the edge correction term. The sign is positive if both distances *(i,j)* and *(x,y)* are AM/MA or MA/AM and negative otherwise.

In order to reduce the effect of random errors, more than one distance (*x,y*) can be used dependent on the availability of reference data. Considering the appropriate signs, the general formula for using *n* distances is:

$$CT_{i,j}^{Corr} = CT_{i,j}^{RS} \pm \frac{\sum_{k=1}^{n} \text{abs}\left(CMM_{x_k,y_k} - CT_{x_k,y_k}^{RS}\right)}{n} \quad (4)$$

Figure 6 provides an overview of the range of correction terms obtained when varying *n* from 1 to 7 of the smallest distances of the test part. For the remainder of this paper, *n*=7 has been used. This implies a maximum repeatability and independence of the random selection of reference planes. However, it also represents a best-case scenario. Figure 6 hence allows assessing the maximum systematic error that could be introduced when lowering *n*. For example, *n*=2 would entail a maximum additional systematic error of ±7µm, see marks right of Fig. 6. Errors after correction (n=7) are given in Fig. 7.

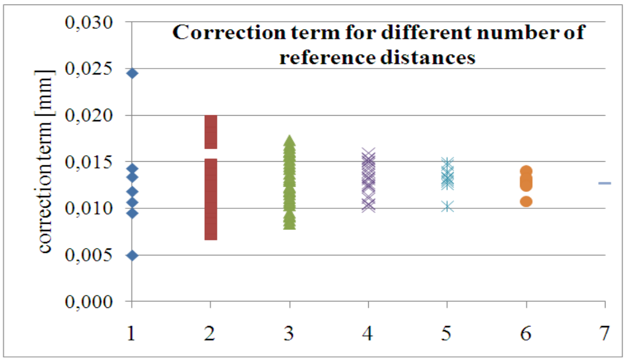

Fig. 6: Influence of the number of reference distances on the correction term

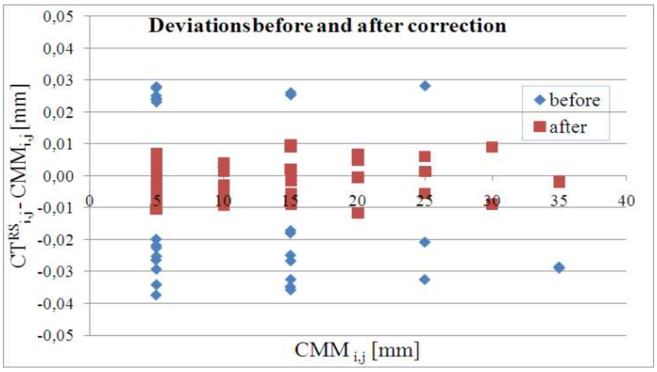

Fig. 7: Comparison of calibrated CT and CMM values before (same as Fig. 5) and after correction (n=7)

4. INFLUENCE OF MEASUREMENT PARAMETERS

4.1 Previous research

The accuracy of CT measurements is influenced by various factors, such as power, magnification, object orientation, detector parameters, focal spot size, etc. [4]. Some influences have been investigated in literature based on simulations (effect of source pre-filtration, alignment accuracy and detector exposure time [5], magnification, instabilities of voltage and position of workpiece [6]), while others have been investigated experimentally (orientation of the workpiece, magnification and number of projections [7], alignment of the scanner geometry and the edge detection method [8]). In this section, the proposed test object is used to quantify experimentally the influence of object orientation, the magnification and the X-ray source settings current and voltage.

4.2 Object orientation

The orientation of the workpiece in the machine is important. For the data acquisition, objects with high aspect ratios (width/thickness) are difficult or even impossible to measure in certain orientations. Moreover, Figure 8 shows that the accuracy of the distance measurements is more accurate for those orientations in which the distances to be measured are perpendicular to the rotational axis of the CT device [2, 7]. Orientation 1 is, compared to the represen-tation in Figure 3 turned 90° clockwise around the Y-axis, orientation 2, 90° clockwise around the X-axis and orientation 3, 180° around the X-axis. Due to scattering, planes perpendicular to the rotational axis are more subject to noise, impeding accurate measurement of their mutual distance.

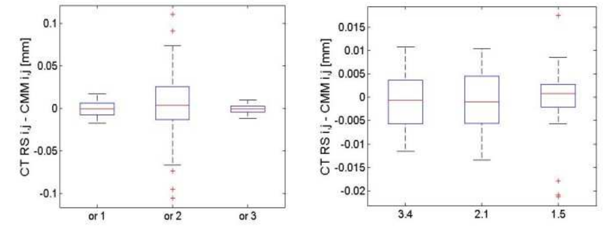

Fig. 8: Deviations of (corrected) CT values from the CMM reference measurements for different orientations (left) and magnifications (right)

4.3 Magnification

The magnification is given by the ratio of the distance between source and detector and the distance between source and object. Moving the workpiece closer to the source, improves the resolution, but increases blurness of images. A higher magnification results in smaller voxel sizes. Computer simulations indicate that increased magnification increases the accuracy [6]. However, these improvements could not be validated in our experiments; the influence of the magnification is not significant in our results. The outliers for magnification 1,5 are measurements in zone E, probably due to scatter.

4.3 X-ray source settings

The settings (voltage and current) to measure a workpiece are user-defined. The voltage needs to be sufficient to penetrate the workpiece, whereas the current determines the contrast of the image. Meanwhile, saturation needs to be avoided. Between these limits, different combinations of voltage and current have been used (Figure 10). Once more, the anticipated improvements could not be validated.

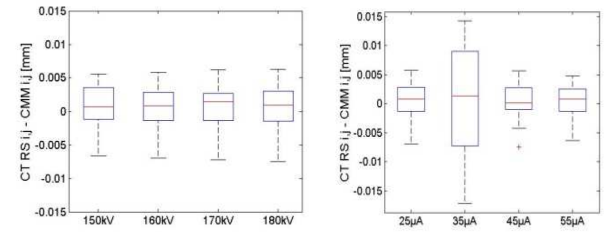

Fig. 10: Deviations of (corrected) CT values from the CMM reference measurements for different voltage (left, 25µA) and current (right, 160kV) settings (in zone D).

5. CONCLUSIONS

The test part proposed in this paper allows to correct for scale errors (pixel calibration) as well as for offset errors (edge detection threshold). Unlike other proposed calibration methods that use different reference objects made from different materials (e.g. ceramic ball bar for scaling and aluminium bush for thresholding) [9], a single reference part was proposed here for both, allowing scaling and thresholding calibration to be performed with a single material object with the same properties as real workpieces. Furthermore, the workpiece allows internal as well as external reference measurements. It was shown that the proposed calibration and edge correction method significantly improves the accuracy of the measurements. Investigating the influence of various measurement parameters did not allow validating previously reported influences. New measurements are currently ongoing with step gages in order to confirm the presented results; the measurements will investigate whether the accuracy limits reported in this paper are due to accuracy limitations of the currently used testpart, or are the limits of the used method and equipment.

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