Metrologia
Fortaleza - CE 2017

Manuseio de dados de tomografia computadorizada para a verificação de tolerância geométrica de peças prismáticas

Computed tomography dataset handling for geometrical tolerance analysis of prismatic test pieces

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Resumo: O emprego da tomografia computadorizada como ferramenta da metrologia dimensional tem se evidenciado nos últimos anos. Para tornar a análise de tolerância consistente, programas de avaliação específicos têm sido aplicados. Eles fazem uso de nuvens de pontos geradas pelo processo de segmentação, que é analisado neste artigo sob a perspectiva de verificação de tolerância geométrica. Os resultados indicam ser necessários avanços na filtragem de dados de tomografia utilizados para verificação de tolerância geométrica.

Palavras-chave: tomografia industrial, incerteza de medição, geração de nuvem de pontos, verificação de tolerância geométrica.

Abstract: Computed tomography for dimensional metrology has been introduced in quality control loop for about a decade. To make the tolerance verification consistent, GD&T evaluation programs have been developed, which make use of CT point clouds generated through segmentation. This important step in a CT measurement sequence is explored in this paper under the tolerance verification perspective. The experimental results indicate that there is room for improvements in GD&T-specific dataset filtering.

Keywords: industrial tomography, measurement uncertainty, point cloud generation, geometrical tolerance verification.

1. INTRODUCTION

Computed tomography for coordinate metrology has been integrated into the dimensional quality control loop of industries for more than a decade. Many features can be assessed without damaging the object under investigation or imposing sensor accessibility restrictions for small or even hidden features. Complex-shaped objects with hundreds (or even thousands) of dimensional features can be holistically inspected with relevant operational advantages over some other coordinate metrology technologies, *e.g.* coordinate measuring systems based on tactile and/or optical sensors.

Computed tomography principle relies on the attenuation of X-rays when propagating through the test object, which depends on the test object material and radiographic thickness. For different beam directions, the intensity distribution of the remaining radiation is detected and stored as a grey-value image. The resulting two-dimensional images related to the complete test object rotation are mathematically processed to create the three-dimensional voxel matrix. Posterior segmentation of the voxel data allows distinguish the edges of the test object; finally, dimensional analyses can be performed [1-2].

Many influencing factors affect CT metrology process. They may be related to the X-ray tube (*e.g.* photon energy, focal spot size), detector (*e.g.* sensitivity, pixel size, exposure time), test object (*e.g.* material, geometry), scanner kinematics (*e.g.* magnification axis and turntable accuracy), and image and mathematical processing (*e.g.* artifact reduction, edge detection, measuring strategy) [2]. The complex measurement error behavior makes difficult assessing uncertainties and establishing traceability to the unit of length.

2. SUBJECT MATTER

In 1993, Brown [3] defined *methods divergence* as the realization that dissimilar measurement methods yield different measured results for the same feature. Despite the improvements over the years, practitioners of coordinate technology may still face that measurement performance issue. In fact, some voxel data evaluation software does not include profile tolerances or does not handle correctly some datum reference systems, which may jeopardize the tolerance verification [4].

To make the tolerance verification consistent and nearly independent of metrology personnel decisions, GD&T evaluation programs have been developed and commercialized in recent years. They make use of point clouds from test object measurements performed on any measurement device, merge the points with the corresponding nominal CAD model, and automatically evaluate the tolerance callouts in compliance with GD&T standards such as ASME Y14.5 and ISO 1101.

For CT metrology, the typical input data of standalone GD&T evaluation programs is the CT point cloud, which is obtained from the computed surface through the segmentation process with sub-voxel accuracy. The extracted surface is then represented by a set of points (coordinates) which can be connected to each other to form a triangle mesh (STL format). This important step in a CT measurement procedure is explored in this paper under the tolerance verification perspective.

3. MEASUREMENT DESIGN

In order to analyze the surface extraction effect on the CT-based verification of GD&T tolerances, the exemplary prismatic part illustrated in figure 1 was selected. The figure also shows the datums and tolerances assigned to the part geometries. The part was manufactured in aluminum, having a density of 2 700 kg/m^3 and a thermal expansion coefficient of 23 x 10^{-6} K^{-1}.

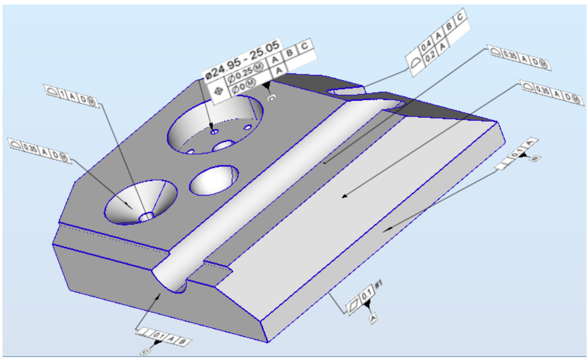

Figure 1. Illustrative image of the exemplary part with the intrinsic characteristics and datums.

The exemplary prismatic part was measured on a Carl Zeiss METROTOM 1500 CT scanner, which is equipped with a 225 kV micro-focus tube and a 2048^2 pixels flat panel detector. The CT scanner is housed in a temperature-controlled room kept at (20 ± 1) °C. To scan the test object, the magnification axis was positioned to project it using the maximum possible area of the detector (thus reducing the voxel size). The source voltage was set high enough to avoid complete beam extinction, and the detector integration time set to a convenient value. The source current was set to enhance image contrast / brightness. The number of angular steps was selected as approximately the number of pixels covered by the resulting shadow of the test object in the projection. Due to part size, detector pixels were merged; otherwise, the focal spot size would be higher than the voxel size, which would result in blurred radiographic images, *i.e.* inappropriate geometric unsharpness. See CT control settings in table 1.

Table 1. Simplified list of the CT settings chosen for scanning the exemplary part.

Parameter	**Unit**	**Value**
Tube voltage	kV	220
Tube current	µA	500
Focal spot size	µm	110
Integration time	ms	3998
Resolution mode	px	1024^2
Voxel size	µm	146
Image magnification	--	2.74
Number of projections	--	1500

Being a mono-material test object, usually the surface definition from the voxel dataset can be specified using the standard 'iso-50%' threshold value applied globally with reasonable accuracy [5-6]. The point cloud could then be created with different default presets, *e.g.* fast, normal, precise and super precise, that differ from each other by sampling distance and point reduction settings (as defined in VGStudio MAX 3.0 software).

In order to assess the efficiency of each point cloud associated with different presets, the point clouds were compared to the nominal model of the exemplary part. In particular, the three datum planes and the datum axis shown in figure 1 were chosen for checking the response of each dataset.

The least squares method was chosen to fit the measured points to the nominal geometries due to better averaging effect and less sensitiveness to outliers. The direction vectors and the form error of each feature were used to assess the efficiency the default presets; data evaluation was executed on KOTEM SmartProfile 4.5 analysis software.

4. EXPERIMENTAL RESULTS

In this section, the most relevant findings for the three datum planes and the cylindrical feature are shown and evaluated using simple statistical tools, *i.e.* average and range control charts, which allow the user checking the consistency of average and range estimates. Two complete measuring cycles of the exemplary part were carried out under repeatability conditions considering the same CT settings listed in table 1.

4.1 Statistical analyses of the datum planes

The control charts of the datum's form errors are exhibited in figure 2. They do not display out-of-control conditions either for average or range.

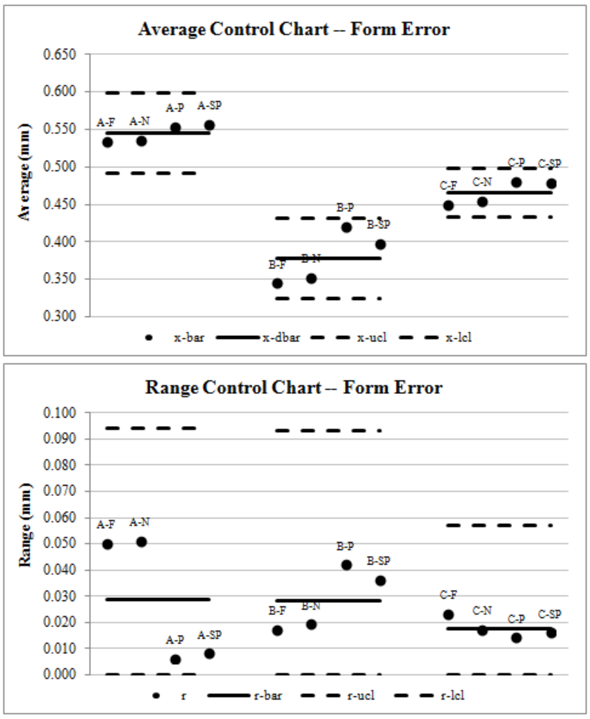

Figure 2. Control charts of the form errors of the datum planes exhibiting no out-of-control points.

Dividing the number of points associated with each plane in the super precise (SP) default preset by the number of points in the fast (F), normal (N) and precise (P) default presets, factors of 8.3, 5.7 and 1.5 respectively could be calculated. Despite that sample size growth, no statistical difference could be evidenced in the form error estimates (*i.e.* uncertainty unaffected). The same inferences could also be drawn to the direction vectors of the datums, which varied by less than 0.025°.

4.2 Statistical analysis of cylindrical features

The control charts of the Ø25 mm hole diameter are exhibited in figure 3. They do not display out-of-control points either for average or range. That means no statistical difference could be observed in the diameter arithmetical average and standard deviation. The reduction of number of points by a factor of nearly ten would not affect the accuracy of the measurement results. In fact, these findings could be extended to the form error (cylindricity) of the hole and to its direction vectors.

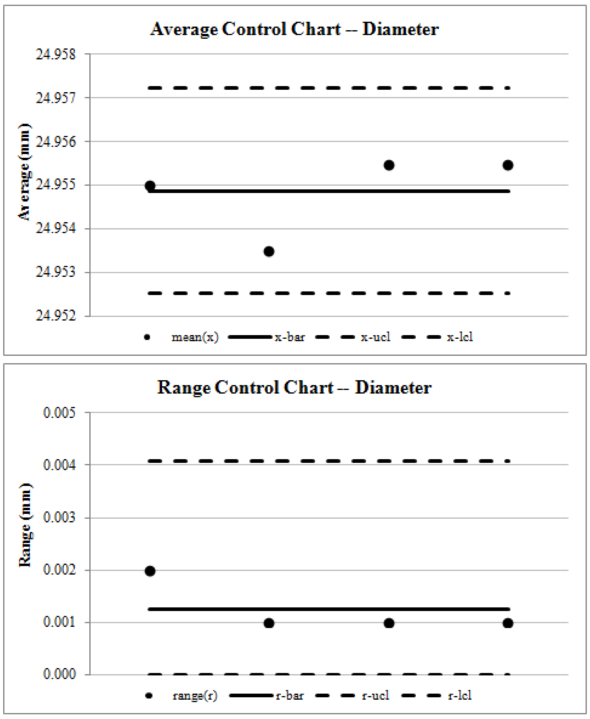

Figure 3. Average and range control chart of the hole diameter estimated with different presets.

5. CONCLUSIONS

From the tolerance verification point of view, the results described in this work indicated that there is room for improvements in CT dataset filtering. The datums of the exemplary part studied did not reveal statistical differences with reduced sample size (*i.e.* no effect on measurement uncertainty). For this reason, to find out an optimal point cloud size for tolerance verification would be of great value for lowering the computer requirements and evaluation time. In fact, that is the main goal of some recent researches of the authors.

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