Custom-made software tool for the automatic implementation of surface extraction methods based on gradient operators

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Abstract
The computed tomography (CT) process for metrology applications is affected by many factors that influence its measurement uncertainty. One of the most critical ones is the edge detection algorithm used, also called surface extraction or image segmentation. The authors of this paper have developed several segmentation algorithms based on gradient methods for metrological applications. These algorithms focus on improving the accuracy and reducing the influence of the user decisions during the segmentation process. In order to reach these goals, it is not only necessary to develop the segmentation algorithm but to implement it in a complete tool that guides the user from the tomography file to the Point Cloud. This paper presents the custom-made software developed by the authors for the surface extraction with gradient techniques and the results achieved when used in the dimensional verification of two calibrated parts.

Keywords: Edge detection; metrology; computed tomography; software

1 Introduction
One of the most critical factors during the CT measuring procedure is the surface extraction. This is the process of surface formation from the CT’s volume data, which represents the mass attenuation coefficient of the object material of each voxel using a grey value as described in VDI/VDE 2630-1.2 (2010) [1]. Surface extraction methodologies for metrology applications are usually based on the definition of a grey level value as a similarity reference called threshold value. However, the authors of this work have published some alternative techniques based on gradient operators: Canny [2] and Deriche [3,4]. Since the aim of the surface extraction in CT is the geometrical definition of the part boundaries, it is necessary to implement these gradient operators in a software tool able to carry out the complete process: from the reconstructed volume to the defined surface information. There is a number of file formats that are able to store the surface information, such as Standard Triangle Language (STL), widely used in 3D printing, or Point Cloud. For metrological purposes, Point Clouds can simulate the contact point of CMMs probes, so this format is usually accepted by most of the metrological software. In addition, STL format can be easily converted into Point Cloud and vice versa using the appropriate tool.

This article presents the software tool developed to carry out the segmentation process using gradient based algorithms. It allows reading the tomography file, configuring some user settings, carrying out the gradient operators and creating and saving the Point Cloud.

With the aim of testing the reliability of the software tool and show its capabilities, two calibrated artifacts have been evaluated. These artifacts have been evaluated using the developed software tool with both, Canny and Deriche algorithms, and also with a third technique based on the local threshold adjustment, presented and applied in previous works [5].

2 Developed software
In order to carry out the surface extraction, a custom-made software tool has been developed. This tool has been programed using Matlab. In order to help and guide the user during the process, a graphical interface has been developed taking advantage of the features of Matlab programming environment.

The developed software is based on a similar process flow to applicable to both algorithms. This is as follows:

1. Selection and loading of the DICOM files.
2. Algorithm configuration.
3. Preliminary edge detection using the gradient operator.
4. Sub-voxel refinement.

2.1 Selection and loading of the DICOM files
At this stage, the operator selects the directory where the files of the tomography to be processed are. The software automatically detects the names of the compatible files, performs the ordering of the files and extracts the basic parameters of them as the voxel size. The voxel size can be modified by the user in case of perform scale corrections.
2.2 Algorithm configuration
In this step, the desired gradient operator is selected and some general settings are established. These settings allow the selection of a Region Of Interest (ROI) to reduce the computational cost and the selection of the minimum distance between points. This last parameter is used in the last step in order to avoid the generation of very close points, which probably represent the same transition between materials. This parameter must be chosen taking into account the voxel size and the minimum thicknesses of the part. A too high value would not allow the detection of certain surfaces of the part, but a too small value would cause the surfaces to appear duplicated with a small gap. This is because it would consider two consecutive voxels with a strong gradient as two different surfaces, when those gradients actually belong to a single transition between materials.

2.3 Preliminary edge detection using the gradient operator
In this step the selected operator gradient is used in order to determine the rough surface points. Due to the differences in computational cost and other characteristics, this step has slight differences depending on the chosen gradient operator.

2.3.1 Preliminary edge detection using the Canny operator
Firstly, a Gaussian filter attenuates the image noise. Secondly, the maximum gradient is computed along the three main directions X, Y, Z of the 3D volume. Gradients of high intensity determine the part edges and the 3D volume is obtained from the changes of intensity detected. In order to apply the Canny filter to the images along each of the three Cartesian directions, an $1 \times 10$ convolution mask, oriented along the direction, has been applied. With this, only the information surrounding the voxel along the studied direction is taken into account. This is applied for all the three Cartesian directions, so that all the 3D information is taken into account and no information is lost. After this phase, three different 3D images (X–Y, Y–Z and Z–X in Figure 1: Module to help in the determination of the gradient threshold) are obtained, each showing the transition between materials along the corresponding direction.

2.3.2 Preliminary edge detection using the Deriche operator
A gradient operator adapted from the Deriche operator is applied in each of the three orthogonal XYZ directions of the 3D volume. The modules of the three obtained values are added to obtain a single representative value of the gradient for each voxel of the volume. Therefore, this step’s result is only a 3D image representing the variation level with respect its adjacent voxels.

Figure 1: Module to help in the determination of the gradient threshold
2.4 Sub-voxel refinement

Based on the information obtained in the previous phase it is necessary to determine which voxels are true surface points of the parts. This is performed by setting gradient thresholds in order to determine the voxels on which an accurate local determination is carried out. The user could have an important influence on this step, since choosing too wide thresholds can lead to excessive noise in the surfaces, or even the generation of false surfaces. On the other hand, selecting too narrow thresholds may result in missing surfaces part.

In order to help the user in this step, the developed software tool includes a module that offers information about the different gradient levels the tomography and allows the visualization of the results of the different gradient threshold configurations. Although results are not calculated with the highest accuracy, this module allows testing if the surfaces are being generated correctly (See Figure 2).

Once the gradient threshold is determined correctly, the criterion of minimum distance between points configured in the second step is applied. In this way, the voxels on which an accurate determination will be carried out, using the selected gradient operator are selected.

At this point, the user can choose the file where the surface points will be stored and can start the process of the accurate determination of the surface points. Again, in this step, the process is different depending on the selected gradient operator.

2.4.1 Sub-voxel refinement for the Canny operator

From the preliminary surface detected in the previous step, obtained from the calculated local maximum positions, a gravity center algorithm is applied to a neighborhood around each of those local maximum positions. This refinement is carried out separately and independently along all the three directions XYZ obtaining the three different coordinates of each surface point.

In order to obtain each of the coordinates, only the 3D image along that direction, obtained from the Canny filter application, is used, i.e. X–Y for the X coordinate, Y–Z for the Y coordinate and Z–X for the Z coordinate (See Figure 2).

![Figure 2: Sub-Voxel resolution refinement. Source [2]](image)

2.4.2 Sub-voxel refinement for the Deriche operator

When the Deriche operator is selected, it is applied along the normal (perpendicular) surface. In order to calculate the gradient through the normal surface or close to it, the Deriche operator is applied along 13 directions: The three main directions (+X, +Y, +Z) and the ten diagonals between them (shown in Figure 3b). The value of the gradient in each of those directions will be calculated within a search window of a fixed size. The direction with the largest gradient value is considered approximately equal to the surface normal (see Figure 3c). Once the surface normal is estimated, gradient values are obtained for each voxel in the search window. The center of gravity of the search area gradients is calculated and used to define the XYZ surface position.
3 Materials
The developed software tool has been validated by measuring two calibrated artifacts made of dimensionally stable materials (ruby and glass) and constituted by features with very low form errors and roughness. Both parts have been scanned using a non-measuring oriented CT machine.

3.1 Calibrated reference standards
The first reference standard is called “CT tetrahedron”; it was developed by the University of Padova [6] and consists of four calibrated spheres made of synthetic ruby mono-crystal supported by a carbon fiber frame. The centers of the four spheres are ideally positioned on the vertexes of a tetrahedron. The frame is made with carbon fiber bars with diameter of 2 mm (Figure 4a). For this item the diameters of all the four spheres (D) were verified, being the nominal dimensions: D1 = 5.0 mm, D2 = 4.0 mm, D3 = 4.0 mm and D4 = 3.0 mm.

The second calibrated part is called “Pan Flute Gauge”; it was also developed by the University of Padova [6] and consists of five calibrated tubes made of borosilicate glass supported by a carbon fiber frame (Figure 4b). For this item three dimensions were verified in the five tubes: outer diameter (OD), inner diameter (ID) and length (L). The five tubes have the same nominal dimension for the OD = 1.9 mm and ID = 1.5 mm, but different lengths: L1 = 12.5 mm, L2 = 10.0 mm, L3 = 7.5 mm, L4 = 5.0 mm and L5 = 2.5 mm.

3.2 Computed Tomography System
The workpieces were measured on a cone-beam micro-CT eXplore Locus SP machine by General Electric (Boston, MA, USA). The CT machine has an X-ray source that has a power range from 50 to 90 kV, a resolution (minimum voxel size) of 8 µm, and a cylindrical work volume of 44 mm in diameter by 56 mm in height. During the scanning of the workpiece, the temperature was continuously recorded inside the machine, obtaining a temperature range of 20 ± 2 °C for all pieces. In Table 1 the measurement parameters used to measure the different pieces are shown.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CT tetrahedron</th>
<th>Pan Flute Gauge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage (kV)</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Current (µA)</td>
<td>80</td>
<td>80</td>
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<tr>
<td>No. of projections</td>
<td>1800</td>
<td>1000</td>
</tr>
<tr>
<td>Voxel size (µm)</td>
<td>45.5</td>
<td>16.5</td>
</tr>
</tbody>
</table>
4 Results

The software tool has been applied to the parts described in section 3.1 in order to validate and evaluate the results it is able to offer. These parts have also been measured with a technique based on threshold adjustment which was presented in previous works [5]. In this work the threshold-based technique is applied as well as some corrections of the measurements. In order compare the results, these corrections have also been applied to the measurements obtained with the software tool developed. In Figure 5, the results of the dimensional evaluation, using both gradient operators, for both calibrated artifacts are shown. The results of the third technique based on the local threshold are also displayed. These results are shown as a percentage of the difference between calibrated and measured values with respect to their nominal values. For the CT Tetrahedron, the deviation of the four diameters (D) is shown. For the Pan Flute Gauge, the average deviation of the five Inner Diameters (ID), the five Outer Diameters (OD) and the five Lengths (L) are presented.

![Figure 5: Measurement deviations showed as ratio with respect to the nominal value.](image)

As shown in Figure 5, the measurements results of the CT Tetrahedron present better accuracy than those of Pan Flute Gauge. In the first calibrated referend standard, the Deriche operator implementation clearly gets the best results in all the dimensions. However, it is not clear which algorithm gets better results when comparing the one based on Canny or the one based on Threshold.

In the second calibrated referend standard results for both Canny-based and Deriche-based algorithms present similar results. Threshold-based algorithm presents the worst accuracy for the three kind of dimension.

5 Conclusions

The developed software tool allows a complete and easy application of gradient operators to the reconstructed CT volumes. The use of gradient operators and this tool for the surface extraction in metrological applications could potentially reduce both the measurement uncertainty and the user induced error. Although the user may select a gradient threshold value, this parameter only affects the generation of a surface point but not its precision. Other decisions that should be made, such as the minimum distance between points, are easy to make with a minimum knowledge of the part geometry.

Accuracy archived with gradient based algorithms are also acceptable for both parts, especially for the Deriche-based algorithm. The excellent accuracy achieved by the Deriche-based algorithm may be due to the improvement implemented in the sub-voxel refinement step. However, the results of all the tested algorithms are very good in this part.

The developed software tool presents a good general performance. The computational cost is slightly higher than necessary in the algorithms based on threshold, but this is compensated by the user’s lower influence on the accuracy. This computational cost can be reduced by implementing the detection step based on grey value threshold algorithms since this step has very low influence in the final accuracy. In addition, the selection of a gradient threshold would be unnecessary.

In future works the analysis of a third workpiece – a multi-material standard part – will be also carried out. This third standard will be also measured using the commercial software VGStudioMAX. The results obtained with the software and the algorithms presented in this article will be compared with the ones obtained by that commercial software for this workpiece.

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References


