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A surface extraction analysis in a multi-material test part for computed tomography in metrology applications

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Abstract

The main advantage of Computed Tomography is the capability of making measurements of non-accessible internal features in a test piece. One of the cases that can usually be found in this sense is the contact zone between two elements that are forming a common surface boundary, where the main complexity is to determine which surface belongs to which piece. Nowadays, this kind of surfaces are measurable only by utilizing Computed Tomography, taking into account that the characteristics of the Tomography can significantly vary depending on the material of the elements that are in contact. In this article a piece that has two different interfaces is analyzed: a Piece in contact with Air, and Material A in contact with Material B. Three different surface extraction algorithms are analyzed for multi-material parts, Threshold, Canny and Deriche, and the results and conclusions obtained are presented.

Keywords: Computed tomography; Multi-material; Surface extraction

1. Introduction

Computed Tomography (CT) for metrology applications is now a reality, since it is more and more applied in the current industry. Its main feature is the possibility of making measurements in non-accessible areas. When these

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measurements are carried out, one of the main difficulties is the access to the transition between two different materials, so that any measurement in this type of areas is only possible by destructive tests unless tomographic techniques are used [1].

The basic function of CT scan is to generate a 3D model of a piece, obtained by means of the interaction of the X ray beam source, the work piece and the X ray detector. It is well known that one of the most critical issues is the surface extraction process, since it has an important influence in the accuracy in measurements. The most common surface extraction method for commercial CT System is based on gray value thresholding. This gray value is highly dependent on the material, the material interface and the radiation. Different to how it is in CT Medical applications, where the grey values are standardized in Hounsfield units, in industrial applications of CT this turns out to be impossible due to the great quantity of existing materials. When working in a mono-material piece, grey value definition is only needed for the piece and the air; however, in a multi-material piece this definition is much more complicated due to the numerous grey values needed, this being one for each material present in the piece.

There are some studies for computer image and vision applications that evaluate this kind of methods but normally they utilized artificial images or images obtained in controlled conditions, which makes it very difficult to replicate with real tomography. In the other hand, there are some real metrological applications where the surface extraction is analyzed on multi-material parts. For instance, in [2-5] measurements between elements in direct contact to each other are made as well as measurements of gaps between different materials; and in [6] the changing material thickness is analyzed in order to know how this influences the remaining intensity after the radiation passes through the workpiece, being made by means of the fusion of multi-energy stacks. All the investigations mentioned before apply a surface extraction method based on grey value thresholding. For that reason, in this article two methods based on discontinuity detection are analyzed for the surface extraction process.

The test part used in this article has three main features: 1) It has a mono-material zone with an interface of Material A in contact with Air, 2) it has a surface forming a common boundary of two elements which made another interfaces when Material A is in contact with Material B and 3) it has measures which are not influenced by the surface extraction algorithm. The specific problem present in the interface between materials is that the tomographic characteristics of this interface changes with respect to that air-piece reference when the air is substituted by different materials, producing an unlimited variety of combinations [7]. This aspect raises the need to analyze the behavior of the different segmentation algorithms in order to obtain metrological capabilities. Therefore, a multi-material workpiece is been designed with interfaces between materials. This piece has characteristics that are useful to analyze the influence of the use of the different algorithms on the surface extraction among other things because the effect of the other influences can be compensated.

For the purposes of this investigation, a General Electric Computed Tomography (CT) system is utilized, and different surface extraction algorithms (Threshold, Canny and Deriche) are analyzed for multi-material parts. The piece of study is composed of two elements: male and female make of different materials. In each one of the sections the equipment utilized is presented, as well as the results and conclusions obtained.

2. Methodology

For the purposes of this research, there are some special considerations that must be taken into account in each of the stages in order to obtain a reliable and accurate measurement (example: Scaling factor correction and surface extraction procedures), explained in detail in [8,9]. Fig. 1 shows a summary of the procedure used.

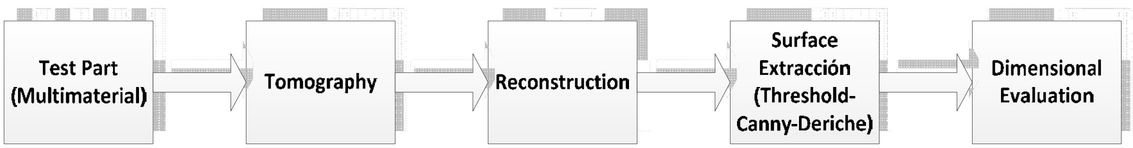

Fig. 1. Methodology.

2.1. Test Parts

For this investigation two work pieces have been utilized. Both of them are composed of two slotted elements (male and female). The first piece is made of Polytetrafluoroethylene (PTFE) and Polyoxymethylene (POM). The Polytetrafluoroethylene or Teflon is considered to be one of the most versatile among plastic materials due to its many applications in what other materials cannot be utilized. It is a high temperature resistant material with a low friction coefficient, high resistance to the action of chemical agents and solvents, among other characteristics. The PTFE is often considered a thermostable polymer and it can be used in a continued process at any temperature between -200 °C and +260 °C [10]. Polyoxymethylene, also known as acetal, polyacetal and polyformaldehyde, is a technical thermoplastic used in precision components that require high rigidity and excellent dimensional stability. POM characterizes for its high resistance, hardness and rigidity up to -40 °C (-40 °F). The most common applications for POM are sectors such as automotive, consumer electronics, heavy loads transport applications and on low temperatures [11]. Both elements have been assembled in a way in which a zone of them is not in direct contact with the other. In addition the contact zone is mounted by an adjustment without interference (see Fig. 2).

Fig. 2. *Part 1 TEFPOM. Male element is fabricated of PTFE and female of POM.*

The second part is made of PTFE and Polyvinyl chloride (PVC). PVC is a thermoplastics very durable and long lasting construction material which can be used in a variety of applications, either rigid or flexible, white or black and a wide range of colors in between. Due to its very nature, PVC is used widely in many industries and provides very many popular and necessary products [12]. Like other thermoplastics materials, the stress /strain response is dependent on both time and temperature. The mechanical properties of PVC are referenced at 20°C. Thermoplastics generally decrease in strength and increase in ductility as the temperature rises and design stresses must be adjusted accordingly [13]. From now on the part 1 will be named TEFPOM and the part 2 TEFPVC (Fig. 3).

Fig. 3. *Part 2 TEFPVC. Male element is fabricated of PTFE and female of PVC.*

The dimensions that have been evaluated are: The width of the groove (R) and the crellenate (A). Each one has a nominal distance of 5 mm (Fig. 4).

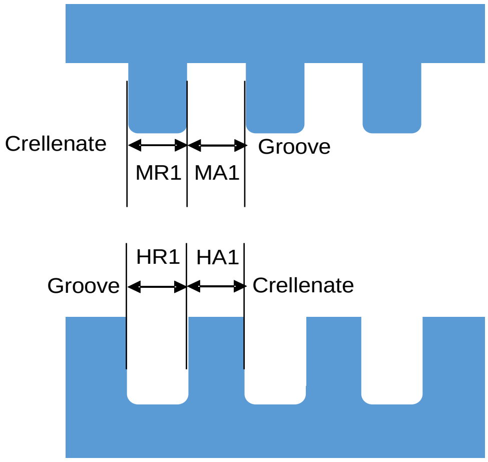

Fig. 4. *Side view of the male element (Top) and the female element (lower).*

In addition to the dimensions presented in Fig. 4, the contact zone between the two pieces was evaluated (Fig. 5), so that 15 dimensions were assessed in total: 5 in the female piece (HR1, HA1, HR2, HA2 and HR3), 5 in the male piece (MA1, MR1, MA2, HR2 and MA3), which makes possible the evaluation of an interface made of material in contact with air; and 5 in the contact zone (C1, C2, C3, C4 and C5), which will permit the analysis of the measurements in an interface between two materials.

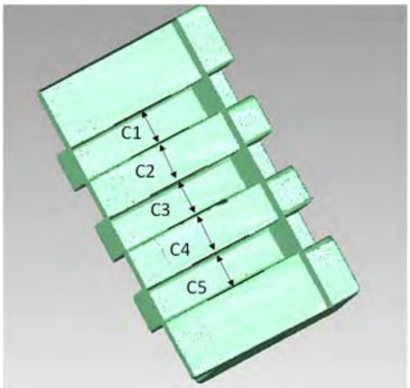

Fig. 5. *Contact zone.*

Both elements were calibrated with a Carl Zeiss coordinate measuring machine with a measurement volume of 850mm x 700mm x 600mm, a resolution of 0.1µm and a longitudinal MEP of 2.0µm + (L / 300) µm (L in mm). It has a central ZEISS VAST-XT with active scanner and allows to work with extensions of up to 500g in weight and 500mm in length.

2.2. Tomography and reconstruction

The machine used for this work is a cone-beam micro-CT General Electric eXplore Locus SP CT-Z machine. It has an X-ray source power from 50 to 80 kV and a minimum resolution of 8µm. (Fig. 6). Although the CT system is not specifically designed for dimensional metrology applications, compensation methods have been used for correcting the measurements [8].

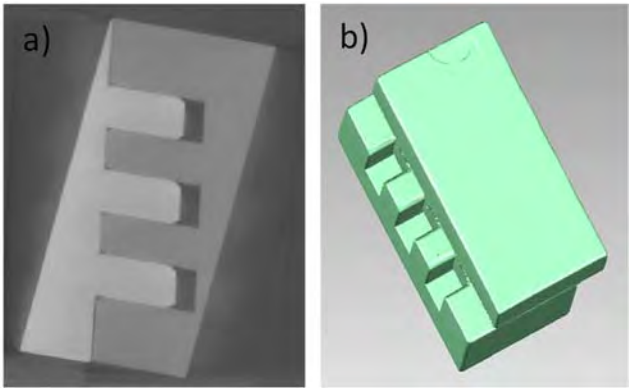

Fig. 6. (*a) 2D image; (b) 3D model-CT Tomography slice*.

Temperature inside the working area of the machine was monitored and a value of 20 ± 2 ◦C during the measurements was recorded. Protocol parameters used for the CT scanning in both parts are shown in Table 1. It can be noticed that the pixel size in the TEFPOM piece is twice the size of the pixel in TEFPVC piece. This is deliberately made with the intention of finding some indication that this difference could have an impact in the measurements.

Table 1. Protocol parameters in CT scanning.

Parameter	TEFPOM	TEFPVC
Voltage (kV)	45	45
Current (µA)	120	120
Angle of increment (˚)	0.3	0.3
Voxel Size (µm)	56	28

2.3. Surface extraction

It is well known that CT has many and complicated influence factors. One of the main ones, due to its major impact on the measurements, is the surface extraction process. In this article a comparative between three algorithms previously utilized with good results in air-material transition pieces is made. These three methods of surface extraction have been selected because the first one is a contrasted and widely used method, while the other two have already been evaluated previously and provided excellent results in mono-material pieces [14]. It is tried to prove their effectiveness in multi-material parts. The compared algorithms are the followings: 1) Local threshold, 2) Canny and 3) Deriche.

1) Local Threshold. The location of the surface for metrological applications is generally based on this technique, where by the definition of a grey value as a characteristic of similitude serves for defining the work piece. This grey level value is call threshold. This algorithm is often applied because of its simplicity of implementation and its low computational cost. This algorithm has been developed for applications in the medical area, where its main purpose is to distinguish elements on an image that do not need high precision, contrary to what happen with Metrology. The most used option in metrological applications is the adaptive threshold, named as such when a different threshold is used in different regions of the image. This is also known as local or dynamic threshold [13].

2) Canny. The followed procedure for applying the surface extraction method firstly applies the Canny gradient operator in the three main directions XYZ of the 3D volume. As a result three different 3D images are obtained, which shows the transition between materials. The maximum intensity gradients correspond to the piece edges. Then, a sub-voxel refinement is made by using a gravity center algorithm, departing from the preliminary detection of the surface

in the maximum gradient position, which improves the spatial resolution of the edges previously detected. As a final result from this refinement, a point cloud is obtained over which the measures are made. Finally, the correction of the measurements is made by calculating and compensating a bias that appears in the measurements. Such a bias is significant but stable, which make its correction easy. The full explained and detailed procedure can be revised in [8].

3) Deriche. Is an edge detection operator developed by Rachid Deriche back in 1987. It is based in the edge detector developed by John F. Canny and the criteria commented before. Despite being initially designed to work on 2D images, the algorithm has been adapted to 3D images by the authors of this article [14]. The algorithm have three successive stages: 1) Preliminary edge detection, 2) Sub-voxel resolution coordinates extraction and 3) Non maximum points suppression.

In the preliminary edge detection an adapted operator is been developed from the gradient Deriche operator. In it, the previous filter has been discarded in order to reduce computational costs and to avoid the loss of information. This lineal operator is applied to the three main directions X, Y and Z, giving as a result a value for each voxel that is equal to the gradient sum up in each one of the three directions.

In summary, the Threshold-based method can be interesting because of its low computational cost, and in this particular piece, due to the fact that it is possible to define separately each of the elements that integrate it, yet this task depends on the skill and experience of the operator. The methodologies of Canny and Deriche are obviously quite similar: the surface extraction is made in one procedure, provides a good surface location capability and reduces in a significant amount the data quantity. However, Deriche may be more attractive because the edge can be determined in a direction close to the perpendicular, so in theory, it can be more accurate, especially with free geometries.

3. Results and discussion

Table 2 shows the deviations between the measurements taken by de UNIZAR CT and the reference of part 1, using the surface extraction methods explained in section 2.3.

Table 2. Part 1 (TEFPOM) deviation from reference value.

Measurement	Threshold		Canny		Deriche	
	Deviation in µm	% of the dimension	Deviation in µm	% of the dimension	Deviation in µm	% of the dimension
HR1	-29.82	0.60	-21.44	0.43	-53.49	1.07
HA1	29.10	0.58	26.90	0.54	27.31	0.55
HR2	22.44	0.45	21.99	0.44	32.83	0.66
HA2	-29.10	0.58	-26.90	0.54	-27.31	0.54
HR3	7.38	0.15	-0.56	0.01	20.66	0.41
MA1	26.07	0.53	1.74	0.04	11.74	0.24
MR1	4.59	0.09	6.92	0.14	-5.62	0.11
MA2	-9.35	0.19	-5.48	0.11	-14.95	0.30
MR2	-4.59	0.09	-6.92	0.14	5.62	0.11
MA3	-16.73	0.34	3.74	0.08	3.20	0.06
C1	13.22	0.27	8.72	0.18	16.40	0.33
C2	12.58	0.25	11.25	0.23	9.70	0.20
C3	-3.17	0.06	-7.81	0.16	-9.63	0.19
C4	-12.58	0.25	-11.25	0.23	-9.70	0.20
C5	-10.05	0.20	-0.91	0.02	-6.77	0.14

In the case of Threshold, it can be observed that the absolute maximum deviation is around 29.82 µm while the absolute average error is 15.38 µm. In the case of Canny, the absolute maximum deviation is 26.90 µm and the absolute average deviation is 10.83 µm. The results for the Deriche algorithm have the highest absolute maximum deviation of them all, this being of 53.49 µm, while its absolute average error is also the highest, this being 17.00 µm. Regarding the deviation rates, it can be observed that in Threshold and Canny all of them are below 1%, while Deriche has the highest percentage of deviation, a 1.07%.

Table 3 shows the measurement deviation of the piece 2. This piece has been calibrated with a CMM Carl Zeiss at the University of Zaragoza.

Table 3. Part 2 (TEFPVC) deviations from reference value.

Measurement	Threshold		Canny		Deriche	
	Deviation in µm	% of the dimension	Deviation in µm	% of the dimension	Deviation in µm	% of the dimension
HR1	-33.28	0.67	15.09	0.30	-8.01	0.16
HA1	-19.28	0.38	-44.33	0.88	-27.26	0.54
HR2	33.21	0.67	-3.39	0.07	35.17	0.71
HA2	19.28	0.39	44.33	0.89	27.26	0.55
HR3	0.00	0.00	-11.70	0.24	-27.15	0.55
MA1	84.18	1.70	44.78	0.90	28.57	0.58
MR1	63.34	1.26	-68.88	1.38	-19.15	0.38
MA2	-1.28	0.03	4.95	0.10	-60.61	1.20
MR2	-63.34	1.27	68.88	1.38	19.15	0.38
MA3	-82.91	1.65	-49.74	0.99	32.04	0.64
C1	30.95	0.62	-8.50	0.17	-23.18	0.46
C2	-126.50	2.53	-12.04	0.24	-18.43	0.37
C3	-2.85	0.06	-11.44	0.23	5.33	0.11
C4	126.50	2.53	12.04	0.24	18.43	0.37
C5	-28.10	0.56	19.94	0.40	17.85	0.36

It can be observed that the absolute maximum deviations are higher than the ones in the previous piece. In the Threshold algorithm results, the highest deviation can be found, this being of 126.50 µm, while Canny holds a maximum deviation of 68.88 µm and Deriche 60.61 µm. Regarding the absolute average deviation, it can be observed that, when using Threshold, this value is of 47.67 µm, while utilizing the Canny algorithm the average deviation is 28.00 µm and when applying Deriche is of 24.50 µm. Besides, six dimensions of Threshold can be observed which are higher that 1%, while in Canny only two dimensions surpass this percentage and in Deriche even just one.

4. Conclusions

In this article it has been presented the utilization of three surface extraction methodologies based on Threshold, Canny and Deriche algorithms, applied on two pieces of two different elements, each one fabricated in a different material allowing the possibility of analyzing the interfaces between materials. According to the results obtained from the dimensional evaluation, it can be concluded that the methods based on Canny and Deriche algorithms produce better results than the Threshold algorithm, due to six of the dimensions surpass the maximum relative of 1% while in Canny and Deriche only two do so. Also, the highest maximum percentage is obtained when utilizing a Threshold method, this being 2.53% (126.50 µm). Regarding the standard deviation, the Threshold based method is the highest of the trio, while the ones obtained for Canny and Deriche are quite similar. It is because of the facts discuss before that it can be concluded that, the surface extraction methods based on discontinuity detection (Deriche y Canny) may offer more exact and precise results, due to Canny has the best results in part 1 and Deriche in part 2. However, about the results of the Canny and Deriche methods, it should be noted that only flat surfaces have been evaluated, which does not bring the main advantage of Deriche on.

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