ACCURACY EVALUATION OF 3D RECONSTRUCTION FROM CT-SCAN IMAGES FOR INSPECTION OF INDUSTRIAL PARTS

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Abstract : In this paper, we study the accuracy of reconstruction of industrial parts from a medical CT-scanner. The reconstruction is performed using a modified Marching Cubes algorithm. We study the influence of several acquisition, image processing and reconstruction parameters on the overall reconstructed model. We compare the reconstructed model with its CAD model after estimating the best rigid transformation that minimizes the distance between the two models.

1 Introduction

1.1 Problem Statement

The inspection of industrial parts implies three different tasks : the digitalization, the reconstruction and the evaluation of the discrepancy between a part and its CAD model. In the case of complex industrial parts, such as engine cylinder head for example, the geometry combines smoothly curved areas with sharp edges as well as internal structures. The existence of internal structures, invisible from outside, makes impossible the digitalization with classical triangulation-based range techniques. The use of CT scanner is then the only way of acquiring the whole part geometry.

In this paper, we evaluate the reconstruction accuracy of industrial test parts digitalized with a medical CT scanner. The acquisition with a CT-scanner, provides a set of serial slices that are combined into a single volumetric image. From that image, we first apply some image processing algorithms, then perform a tridimensional reconstruction of the part and subsequently compare it with its CAD model. The total measured distance error E_{T} is actually the result of the cumulative effect of four errors : the error of acquisition E_{A}, the error of image processing E_{I}, the error of reconstruction E_{R} and the true shape difference between the industrial part and its original CAD model E_{S} :

$$E_{\mathrm{T}} = E_{\mathrm{A}} + E_{\mathrm{I}} + E_{\mathrm{R}} + E_{\mathrm{S}}$$

In order to provide an upper bound for $E_{\mathrm{A}} + E_{\mathrm{I}} + E_{\mathrm{R}}$, we evaluate in this work the accuracy of the tridimensional acquisition, image processing and reconstruction stage. This bound will then give us maximum accuracy at which we can measure the shape defect E_{S}.

1.2 Previous work

There exist several reconstruction methods of tridimensional models from volumetric images. A first class of methods consists in creating a set of contours on each slice and then applies a meshing algorithm that links contours on neighboring slices. For instance the NUAGES[1] software of Geiger and Boissonnat [BG93] uses planar Delaunay triangulation to link two sets of contours. Those algorithms require that contours have been previously extracted on each slice and have the advantage of producing a controlled number of vertices, simply related with the number of vertices on each slice contour. However, they are fundamentally anisotropic and cannot provide subvoxel accuracy. Finally, they are subject to topological problems when reconstructing complex shapes.

We have chosen a reconstruction method based on the Marching Cubes algorithm [LC87] that provides subvoxel accuracy through a trilinear interpolation within each voxel. The reconstruction is fully automatic and only requires a single value corresponding

[1] http://www.inria.fr/prisme/personnel/geiger/nuages.html

to the isovalue of the isosurface. To solve the topological ambiguities, we have modified the original algorithm by adding the mean face voxel value similarly to [WG90].

1.3 *Originality of this work*

This work aims at providing a quantitative study of 3D reconstruction from CT scanners. Even if the accuracy of acquisition from CT scanners has been extensively studied especially in the field of medical imaging, to our knowledge, no comprehensive study has been done on accuracy evaluation of tridimensional reconstruction. The difficulty of that study is twofold.

First, a reliable tool for the registration of tridimensional models is required. In order to compare the geometry of two models, it is important to find the best rigid transformation between those shapes.

Second, there is a high number of parameters that have an influence on the reconstructed models. Those parameters are linked with the acquisition, image processing or reconstruction stage. The high number of parameters implies that all algorithms must be automatic and computer efficient.

Finally, our study has been achieved with industrial parts having sharp edges. This is in contrast anatomical models reconstructed in medical imaging that can be considered as smooth surfaces.

2 Presentation of the 3D reconstruction process

Our procedure of 3D reconstruction has four main stages: the digitalization stage, the image filtering stage, the thresholding stage, and the 3D reconstruction stage.

2.1 *CT-scan acquisition parameters*

For the digitalization process, we use Computed Tomography (X-Ray CT) scan digitization, a non-invasive technique for digitalizing internal and external structures of tridimensional objects.

The CT-scanner focuses several X-Ray beams around the object at regular angular positions and therefore produces several X-Ray projections. Each of those projections yields a one dimensional absorption profile. These profiles are then used to reconstruct serial slices of the object. Those reconstructed slices are acquired sequentially along the third axis (Z), and then stacked into a volumetric image of the object.

We use a General Electric CE1200 CT-scanner with the following characteristics:

- the size of the acquisition field (105mm), and the slice resolution (512x512), which gives the pixel size: 0.205mm.

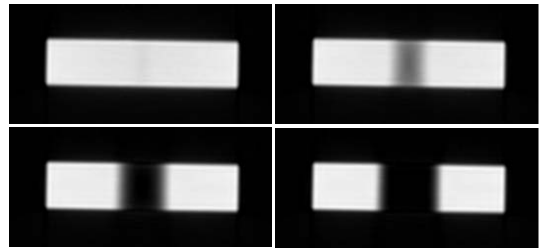

Figure 1: CT-scan images of the first test part

- the slice thickness (1.5mm or 3mm).
- the inter-slice distance (1mm at best).

However, since the image formation is intrinsically anisotropic (influence of the scanning), the orientation of the part inside the CT scanner has an influence on the reconstruction process. Therefore, we consider the orientation as a parameter influencing the image acquisition.

2.2 *The volumetric image processing parameters*

The computed tomography process that produces the CT scan slices is based on various image processing algorithms. However, in this section, we will consider several post-processing algorithms that may influence the reconstruction process.

On those images, we have tested two kinds of filter:

1. under-sampling filters: on image size (512x512 to 256x256), and on image intensity (12 bits/pixel to 8 bits/pixel).
2. noise reduction filters: with 2D Median filter, and with 3D Anisotropic filter.

2.3 *Thresholding method*

There exist many algorithms for computing a threshold given a grey-level distribution (see [PSC88] for a survey of 2D thresholding techniques). However, CT-scan images have specific grey-level histograms : it has a very unbalanced distribution since the number of background pixels is much greater than the number of foreground pixels.

Among thresholding methods, three global and point-dependent techniques (therefore easy to extend in 3D) seem to be adapted for our application. They lead to good results with respect to the shape and uniformity criteria [PSC88]) for 2D images, and have good results in the case of an unbalanced histogram. More precisely :

- **Otsu Method** [Ots79]: the threshold operation is regarded as the partitioning of the pixels of an image into two classes (objects and background) at a certain grey-level. An optimal threshold can be determined by minimizing a criterion like the within-class variance or the between-class variance.

- **Moment Preserving Method (MPM)** [Tsa85]: the threshold values are computed deterministically in such a way that the moments of an image are preserved in the output (binary) image.

- **Volume Preserving Method (VPM)**: the threshold is computed such that the volume of the reconstructed model is the same as the original CAD model.

2.4 The Marching Cubes

The 3D reconstruction stage is based on a modified version of the Marching Cubes algorithm (MC) [LC87] that guarantees the topological closure of all surface patches [WG90]. As pointed out in section 1.2, the main advantage of the MC algorithm over the contour-based reconstruction of Boissonnat et al. [BG93] is that it achieves an automatic extraction of isosurfaces with subvoxel accuracy, independently of the complexity of the object topology.

The MC algorithm generates an isosurface from a discrete data set (3D image in our case), using a predefined threshold. The surface is then approximated by triangular patches.

3 Evaluation of 3D Reconstruction

3.1 3D Registration of two meshes

The registration of two meshes consists in finding the best rigid transformation (rotation and translation) that minimizes a distance criterion between the two meshes. Our registration technique is based on an *Iterative Closest Point* approach [BM92] that iteratively estimates the best transformation until a displacement threshold is reached. To take into account the presence of outliers, a robust algorithm has been implemented that removes vertices that are located too far, similarly to the *Least Median Square* method[MY95]. The most computationally expensive task consists in finding the closest point on a mesh from a given vertex. The complexity of this computation is $O(nm)$ where n and m are the number of vertices in the two meshes. Specific speed-ups have been implemented to keep the computational time within few minutes.

3.2 Definition of the distance criteria between two models

Once the two meshes have been registered, we compute several criteria that evaluate the shape similarity between the two meshes. Since the CAD model is the reference model, we always compute the distance between a vertex of the CAD model and its closest point on the reconstructed model.

The different distance criteria used for the accuracy evaluation are :

- **Median distance** corresponding to 50% and 80% of the distance distribution.

- **Maximum signed distance**. The distance between a vertex of the CAD model and its closest point is signed by considering the normal at the vertex. Positive distance corresponds to point located outside the CAD model. We compute the maximum positive and negative distance.

- **Maximum and median distance at edge and corner vertices**. We compute the maximum and median (50%) distance at vertices lying on sharp edges of the CAD model. We isolate those vertices by computing a curvature information at each vertex and then keeping the vertices whose curvature is over a given threshold. The curvature is computed as the sum of the absolute value of the dihedral angles adjacent to a given vertex.

4 Results

4.1 The three test parts

The methodology previously described is now applied to three test parts (see figure 2). Those parts are composed of planar, curved surfaces and sharp edges. Despite their simplicity, they are quite representative of industrial parts.

We generate from the CAD model of each part, a uniform triangulation. Those triangulations are used as reference shape for evaluating the accuracy of reconstruction. Furthermore, at each vertex of the triangulation, we compute the dihedral angle between adjacent triangles. This curvature information characterizes the flatness of the part and is used to discriminate between flat areas and sharp edges. The table below gives the main dimension of the first part and its percentage of curved vertices :

Material (density)	Aluminum (2.7)
Bounding Box	1cmx4cmx9cm
Planar vertices	81.1 %
Cylindrical vertices	5.4 %
Circular edge vertices	3.6 %
90° edge vertices	9.5 %
Corner vertices	0.4 %

We present in table below the complete results related to the first part. Similar information have been obtained with the other two parts. The analysis of the results are presented in the next sections.

		Whole geometry				planar surfaces		Edges		Corners	
		Median		Maximum		Med 50	Max	Med 50	Max	Med 50	Max
		50	80	-	+						
	NUAGE	0.043	0.139	-1.07	0.47	0.043	1.07	0.29	0.91	0.817	0.97
	Reference	**0.034**	**0.1**	**-0.86**	**0.22**	**0.03**	**0.33**	**0.34**	**0.6**	**0.74**	**0.86**
Acquisition	45 Orient.	0.027	0.1	-0.9	0.18	0.027	0.18	0.38	0.6	0.53	0.9
Acquisition	Thickness 3 I.S.Distance 3	0.017	0.094	-0.85	0.62	0.012	0.62	0.36	0.63	0.79	0.85
Processing	8 bits	0.034	0.102	-0.85	0.218	0.03	0.33	0.338	0.59	0.74	0.85
Processing	256x256	0.035	0.106	-0.88	0.212	0.035	0.35	0.366	0.62	0.79	0.88
Threshold	MPM	0.018	0.097	-0.88	0.2	0.018	0.36	0.35	0.62	0.76	0.88
Threshold	Otsu	0.047	0.105	-0.95	0.145	0.045	0.45	0.403	0.695	0.84	0.95
Threshold	Best	0.018	0.080	-0.89	0.20	0.018	0.37	0.36	0.62	0.77	0.89

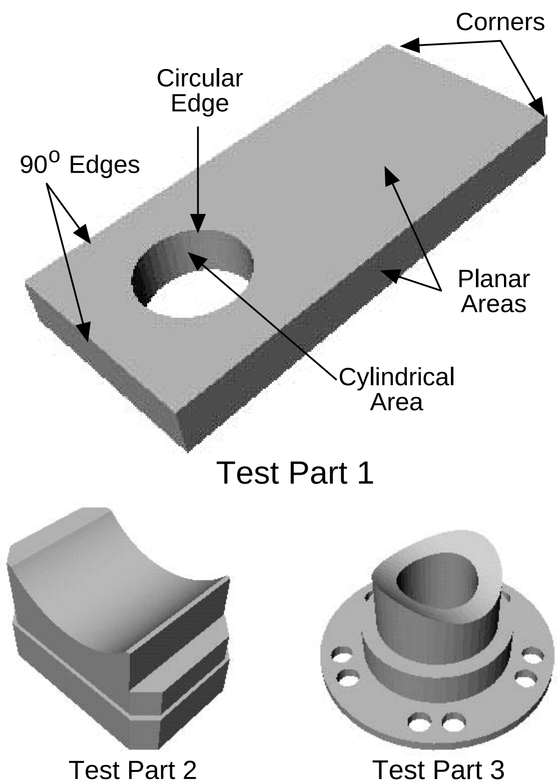

Figure 2: The different test parts

4.2 Reference set of parameters

We choose a set of acquisition, image processing and threshold parameters corresponding to a standard procedure. We then evaluate the impact of a given parameter on the reconstruction accuracy by modifying that parameter from the standard set. Since we only change one parameter at a time, we will always refer to the standard set of parameters to see if the reconstruction accuracy has evolved positively or negatively. The reference parameters are presented in the table below :

Image size	512×512
Slice thickness	1.5 mm
Inter-slice distance	1 mm
Pixel size	0.205mm
Pixel resolution	12 bits
Thresholding method	VPM
Reconstruction method	MC
Orientation	Axial

The results obtained with this set of parameters are good from a general point of view. The 50% median distance between the CAD model and the reconstructed model is 0.034mm. There is a very small distance at the flat areas of the model (0.03mm). However, due to the acquisition technology, the median distance increases on sharp edges (0.34mm) to become maximal at corners points (0.74mm). Figure 3 that shows the error distribution on test part 1 confirms this analysis.

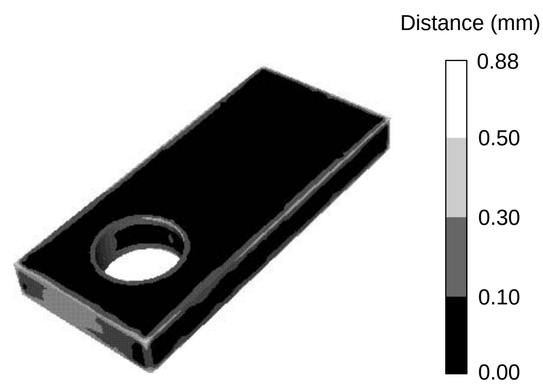

Figure 3: Visualization of the distance on the CAD model of test part 1

4.3 Influence of the Acquisition Parameters

Three acquisition parameters are examined here: the orientation of the part with respect to the scanning direction, the inter-slice distance and the slice thickness. The last two parameters are directly related to the anisotropic sampling problem.

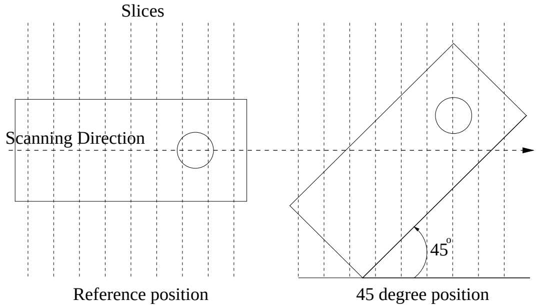

Figure 4: Top view of the part orientation

If the part is rotated by 45 degrees from the reference position (see figure 4) the results are slightly better in comparison with the reference case. We actually observe a decrease of the median distance of 20% and an increase of the maximum distance of 5%. This phenomenon can be explained by observing that the distance is greater at vertices whose normals are oriented along the scanning direction. The table below shows the distance at flat and curved areas as a function of the angle α between the vertex normal and the scanning direction.

α	Median distance at flat areas	Median distance at sharp edges
$90°$	0.028mm	0,34mm
$45°$	0.048mm	0,4mm
$0°$	0,24mm	none

We observe that the accuracy at vertices where $\alpha = 0°$ is much worse than vertices where α is equal to $45°$ or $90°$. This is why we get better results when the part is rotated at $45°$, since we no longer have vertices with $\alpha = 0°$.

The increase of inter-slice distance and thickness from 1 to 3 mm multiplies by 3 the anisotropic effect but divides by the same factor the number of slices (which can be of interest in the case of computer hardware limitation). This anisotropic effect has not the same impact on all parts. For the first part, the results appears surprisingly better than for the reference case. For the other two parts, on the other hand, the increase of inter-slice distance and thickness significantly increases the median distance by 50%. We explain this discrepancy by noting that the first part has a parallelepipedic shape that does not suffer from under-sampling. The other two parts have more complex geometries that are largely affected by under-sampling.

4.4 Influence of the Image Sampling Parameters

No significant influence of the pixel resolution and the image size have been demonstrated with our experiments (less than 2%). As with the inter-slice distance and thickness increase, this can be of great interest in the case of hardware limitation since using 8 bits/pixel reduces the memory requirement by 2 and using an 256x256 image size reduces it by 4.

4.5 Influence of the Image Filtering Parameters

Using additional filters such as 3D Anisotropic Diffusion, or Median 2D has no significant effect on the accuracy of the reconstructed model (less than 2%).

4.6 Influence of the Thresholding Algorithm

As mentioned previously, we use as a reference thresholding method the *volume-preserving method* (VPM) algorithm. If we now examine the influence of the choice of the threshold on the accuracy of the reconstruction, we can see that the median distance is largely influenced by the threshold values. In average, the median distance can vary from 20% to 60% with the choice of the threshold. The threshold obtained with the Moment preserving method MPM seems to be consistently better than the Otsu and VPM threshold. This is an important result because the MPM (as well as the Otsu) threshold can be computed directly from the image whereas the VPM threshold requires the knowledge of the theoretical volume of the CAD model.

4.7 Influence of the Reconstruction method

The influence of the reconstruction method is examined here through the comparison between the NUAGES software [BG93] and Marching Cubes algorithm. The best reconstruction generated with NUAGES has a median distance from 30% to 100% greater than the reconstruction generated with the MC algorithm depending on the geometry complexity. This confirms the superiority of tridimensional methods in terms of accuracy.

5 Conclusion and perspectives

From our experiments, we draw the following conclusions :

1. We have observed a good approximation of the geometry in the areas of low curvature (Median distance close to 0.05 mm).

2. An erosion phenomenon have been measured on sharp edges (median distance close to 0.35mm and maximum distance to 0.75 mm) and corners (median distance close to 0.5mm and maximum distance to 0.9 mm).

3. The increase of the slice thickness and inter-slice distance to 3mm results in worse reconstruction that largely depends on the shape complexity.

4. The orientation of part with respect to the scanning direction has a significant influence of the accuracy of reconstruction. The best orientation is obtained when the number of vertices having their normal vector along the scanning direction is minimized.

5. No real influence of image processing algorithms (8 bits, 256x256, filtering,...) have been noticed.

6. Better results have been obtained with the MC algorithm in comparison with contour-based method (such as NUAGES).

7. The MPM threshold seems to be the best-suited for the extraction of isosurfaces when compared with the Otsu and the VPM threshold.

As a conclusion, this methodology based on medical CT-scan images proves to be particularly well-suited for the inspection of smoothly curved mechanical parts such as engine intake pipes or combustion chambers geometry.

However due to the resolution of the CT-scanner, the erosion of edges could be limitative in some cases. The use of more accurate scanning devices like industrial CT-scanner may significantly reduce this problem.

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