Optimized CT Skull Slices Retrieval based on Cubic Bezier Curves Descriptors

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***Abstract*— The paper presents a method applied to the geometric modelling of skull prosthesis. The proposal deals over definition of the representative descriptors of skull bone curvature based on Cubic Bezier Curves. A sectioning of the bone edge in CT image is performed to create small sections in order to optimize the accuracy of fitness of the Bezier curve. We show that is possible to reduce around 15 times the amount of points from original edge to an equivalent Bezier curve defined by a minimum set of descriptors. The final objective is to apply the descriptors to find similar images from CT databases in order to modelling customized skull prosthesis. A study case shows the feasibility of method.**

I. Introduction

Among several applications involving image processing and automated manufacture, the medical context represents new challenges in engineering area. In the context of machining process, the 3D printers are capable to build complex structures in different materials geometrically compatible with tissues of human body.

The congenital failure or trauma in skull bone require surgical procedures to prosthesis implant as functional or esthetical repairing. In this process, a customized piece built according individual morphology is an essential requirement. Normally in bone repairing, the geometric structure is unrepeatable due its “free form” [1]. Due the complexity in geometry, the free form objects does not have a mathematical expression in a close form to define its structure. However, numerical approximations are feasible way to the geometric representation. The link between the medical problem and the respective manufactured product (i.e. prosthesis) is the geometric modelling and the different approaches in bone modelling have opened new researches interest as in [2],[3] and [8].

In prosthesis modelling, we face different levels of information handling, from the low level of pixel analysis in image to the automated production procedure. In general, there are the following levels: a “preparation level” (containing CT scanning, segmentation, feature extraction, i.e. entire image processing) and a “geometric modelling level” (containing the polygonal model, curve model, extraction of anatomic features, i.e. entire CAD based operations) [2].

In our strategy, we need to generate the geometric representation of bone without enough information (e.g. no mirroring or symmetry applicable). A common image segmentation procedure is executed as pre-processing in the preparation level. Moreover, from segmented images we defined a set of descriptors based on Bezier Curves [7] in order to describe the geometry of skull edge on a CT image. This approach is applied with objective to reduce the amount of points capable to represent de skull bone curvature. It was adapted from method of [8] now using the *de Casteljau* algorithm to define the Bezier parameters. The paper explores the accuracy of prosthesis modelled through the balanced relationship between curve fitness versus number of descriptors.

II. Proposed Method

A. The conceptual proposal

In our study, the main question is related to the information recovering for automation of the prosthesis modelling process. Sometimes it is possible to reconstruct a fragmented image by using information of same bone structure, e. g. by mirroring using body symmetry from same individual. However, in many cases, there are not enough information to be mirrored. A handmade procedure can be performed by a specialized doctor by using a CAD system [4], [5].

In order to circumvent mirroring limitations and user intervention, we are looking for by an autonomous process to geometric modelling of skull prosthesis. Thus, the basis of our hypothesis is to find compatible information from different healthy individuals from image database. The problem addressed here is the method to find a compatible intact CT slice to replace the respective defective CT slice.

When working with medical images, it exists a lot of information to processing [6]. After image segmentation and edge detection, the total of pixels in edge are still to much information for processing. Our approach is a content-based retrieval procedure and a pixel-by-pixel comparing it is a hard processing task we need avoid.

In order to optimize the search by similarity, we propose to define shape descriptors by Cubic Bezier Curves. In this way it is possible to reduce the amount of data to processing to a few parameters. Then, the important question is to find these descriptors capable to describe the edge shape as better as possible. Thus, we also look for by a balance between accuracy and the minimum quantity of information. The next section will explain about our approach in curve modelling.

B. The Curve Modelling

The curve modelling adopted in this research is based on *de Casteljau* algorithm applied in calculation of the points of a *Bézier Curve* [7], [8]. The *de Casteljou* method [9],[10] operates by the definition of a “control polygon” whose vertices are the respective “control points” (or “anchor points”) used to define the shape of the Bezier Curve. A Bezier curve of degree n is built by $n+1$ control points. The Cubic Bezier Curve have two endpoints (fixed points) and two variable points. They define the shape (flatness) of curve. The Figure 1 show an example of a *Cubic Bezier*

Curve where P_0, P_1, P_2, P_3 are the vertices of the control polygon. The points P_0, P_3 are the fixed points and they are respectively the begin and end of the curve; - these points belong to the curve. The P_1, P_2 are the variable points and they occupied any random position in $\mathbb{R}^2$.

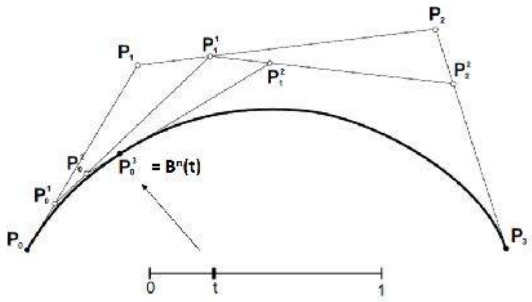


Figure 1. Graphical Representation of *de Casteljau* method. Adapted from [10].

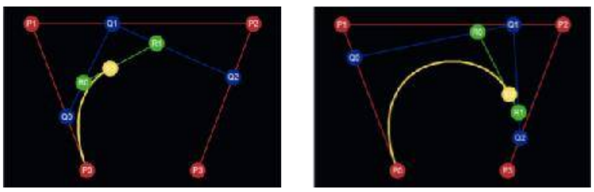
According (1), for all points $P_i^r(t) = P_i$, we have a $P_0^n(t)$ as a point on the Bezier curve. The Bezier curve $B^n(t)$ with degree 'n' is a set of points $P_0^n(t)$, $t \in [0,1]$, i.e. $B^n(t) = \{P_0^n(t); t \in [0,1]\}$. Then the polygon formed by the *n* vertices $P_o, P_1, \dots, P_n$ is so called "control polygon" (or Bezier polygon) [10].

Through the *de Casteljau* algorithm each line's segment results in $(n-1)$ baselines as $\overline{P_0P_1}$, $\overline{P_1P_2}$, $\overline{P_2P_3}$ which are recursively divided to define a new set of control points. By changing the 't' value as defined in (2) we obtain the position of the point in the curve.

$$P_i^r(t) = (1-t)P_i^{r-1}(t) + tP_{i+1}^{r-1}(t), \quad \begin{cases} r = 1,2,\dots,n \\ i = 0,1,\dots,n-r \end{cases} \tag{1}$$

$$t = \frac{t_1 - t_0}{t_2 - t_0} \tag{2}$$

The control points for $P[t0\ t1]\ (t)$, are $P_0^0, P_0^1, P_0^2, \dots, P_0^n$, and the control points for $P[t1\ t2]\ (t)$ are $P_0^n, P_1^{n-1}, P_2^{n-2}, \dots, P_n^0$. In order to avoid misunderstanding in representation, the figure 2 shows the control points, and recursive subdivision of *de Casteljau* algorithm labelled as P, Q, R and S, where S is the final position of a point in the curve for different values of *t*. In figure 2.a the t = 0.360 and in figure 2.b the value of t = 0.770.



(a) (b)

Figure 2. Position of the control points and its respective Bezier Curve adapted from [9][1].

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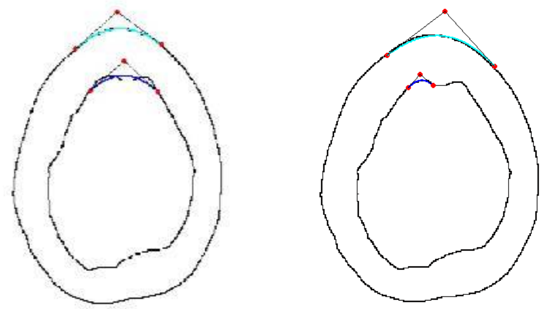
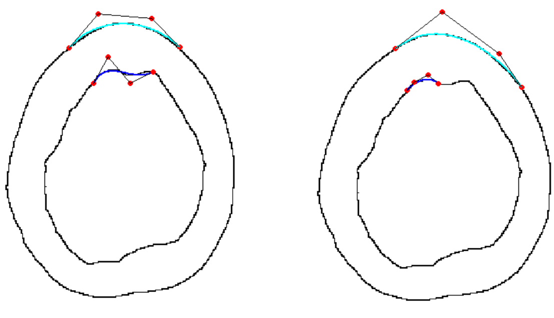
As presented in literature, for practical applications, the most common is to apply the Cubic Bezier Curves (*n*=3) due large possibilities in adapting shape (flatness) according our necessities. Also in our proposal, the Bezier with *n*=3 is more suitable to fit the skull contour in tomographic cuts. A graphical example of a segmented CT slice is shown in figure 3. In figure 3.a is presented a Quadratic Bezier Curve ($B^n(t)$ with n = 2) adjusted on skull edge. In this case we have three control points and only two baselines. Note that the adjustment in outer edge seems satisfactory, but in inner edge, the result is weak. By the same way, in figure 3.b was applied the *de Casteljau* algorithm to a smallest segment of inner edge; then in this case the curve representation was improved. In figure 3.c is presented a *Cubic Bezier Curve*. Now it exists more control points and as result the adjust looks like very good for the both outer and inner edge. Also, in figure 3.d the method applied in a small section (the inner edge) is more accurate.

The question that we intend to discuss in next section is about the similarity measurement. In other words, how good is the quality of a Bezier curve that represents a CT skull edge? This is essential in our approach, because we need to define the best curve based descriptor. The good descriptors will permit us to retrieve compatible CT images to produce the skull prosthesis.



(a) (b)



(c) (d)

Figure 3. A CT slice sample and respective Bezier representation. (a) The Quadratic Bezier Curve (n=2). (b) The Quadratic Bezier Curve on small region. (c) The Cubic Bezier Curve (n=3). (d) The Cubic Bezier Curve on small region.

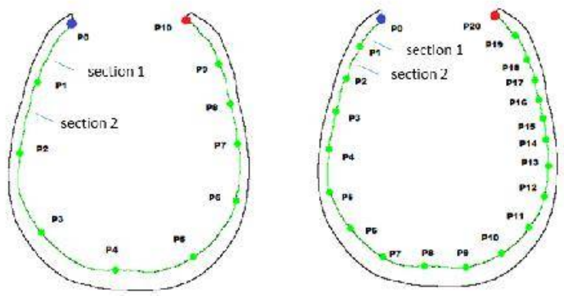
III. Application of the Method

The aim of this research is to define a small set of descriptors to represent the bone curvature. The strategy is to use the Cubic Bezier Curve method calculated through *de Casteljou* algorithm.

In our previous section we presented that the accuracy of curve fitting in our approach by Bézier depends of its degree *n* and the length of edge section to be reproduced.

A. The Secctioning of Edge

As before presented in figure 3, the curve generated on the edge seems to fit better to smallest length region (i.e., the shape of curve looks like similar with original edge shape). The first question is about the best number of sections to produce the best-fitted curve. As an example, the edges of a CT image can be sectioned as figure 4.



(a) (b)

Figure 4. A CT slice sample with (a) k=10 sections; (b) k=20 sections.

Figure 4.a show the total of *k*=10 cuts (with P_0 to P_{10} fixed points) whose section edges lengths are bigger than sections of figure 4.b with *k*=20 cuts (with P_0 to P_{20} fixed points). For each section a fitness value *F* is calculated trough (3), defined in [8] as:

$$F(k) = \sum_{i=1}^{n} \sqrt{\left(x_B(i) - x_O(i)\right) + \left(y_B(i) - y_O(i)\right)} \qquad (3)$$

Where *F*(*k*) is the fitness value to each section *k*. The fitness *F* calculates the error between Bezier coordinates (x_B, y_B) and original edge coordinates (x_O, y_O) for each pixel '*i*' in the edge. The sectioning procedure and control points calculation are fully covered in [8]. The table 1 shows the average of fitness (error) to the respective 5, 10, 15 and 20 sections cuts.

Table 1 shows the cumulative error evaluated by (3) and the average of fitness for different values of sectioning. As expected, the error is minimized with larger values of *k*. The graph in figure 5 presents the relationship between number of sections and calculated error (difference between original edge and calculated Bézier).

As presented in figure 5, the average of error calculated from fitness equation goes down according the number of sections are increased. Then, in this condition, maybe we could define the *k* value as the maximum possible, i.e. the length of total of pixels of edge. However, the computational cost to Cubic Bézier Curve calculation for hundreds of sections is also increased. The same proportion of error occurs for all CT slices from different images. From the graph, selecting the value of *k*=20 is enough to match a relative good fitness with small error and give us an adequate balance between precision and computational cost. Thus, for *k*=20 we have in *de Casteljau* algorithm, 20 "fixed points" and another 20 "variable points", (i.e. 4 points per section) calculated as in [8]. Now, it is possible represent the total length of each edge (inner and outer) in a CT slice with 80 points descriptors each instead ≈ 1250 in original edge (around 15 times information reduced).

Table 1. Relationship between number of cuts and respective fitness (error).

# of Section	*F*(5)	*F*(10)	*F*(15)	*F*(20)
1	61.81640	26.03820	8.96430	6.22810
2	87.16330	22.63830	17.94760	9.27160
3	99.14170	21.17040	20.07230	9.34800
4	78.18280	25.94340	16.91680	10.25800
5	68.10270	26.46990	18.00790	10.09840
6	-	30.86040	17.19840	9.31330
7	-	28.55470	19.37670	14.06260
8	-	24.36930	22.17160	9.27060
9	-	36.52540	17.10820	9.50420
10	-	48.82190	19.46810	11.26640
11	-	-	19.99220	12.80600
12	-	-	21.37690	7.48890
13	-	-	18.15550	10.65490
14	-	-	27.96400	12.36890
15	-	-	40.85040	8.37890
16		-	-	9.40440
17	-	-	-	9.74180
18	-	-	-	17.47880
19	-	-	-	15.90830
20	-	-	-	25.4706
Σ (error)	394.40690	291.39190	305.57090	228.32270
Fitness (avg.)	78.88138	29.13919	20.37139333	11.416135

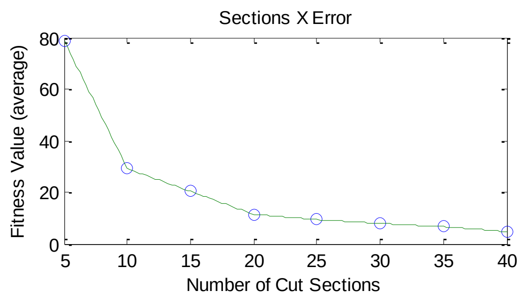


Figure 5. The relationship between the number of cuts in the edge and respective error from fitted Bézier curve in each section.

B. Compatible CT slice Recovering

The curve fitting procedure is applied on each CT slice of defective skull. The same procedure is also applied on each searching image on database. The compatible answer image is retrieval as example presented in figure 6.

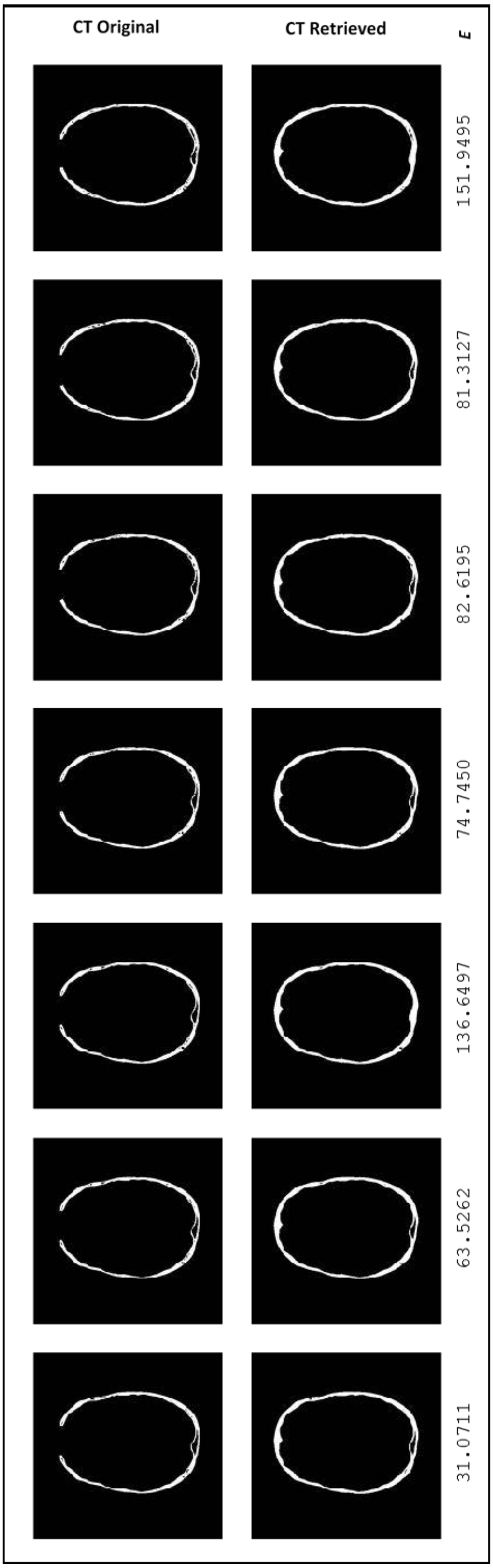
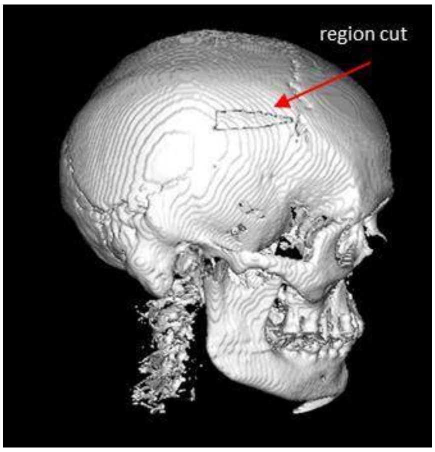


Figure 6. The defective set of slices and respective compatible CT recovered from medical image database.

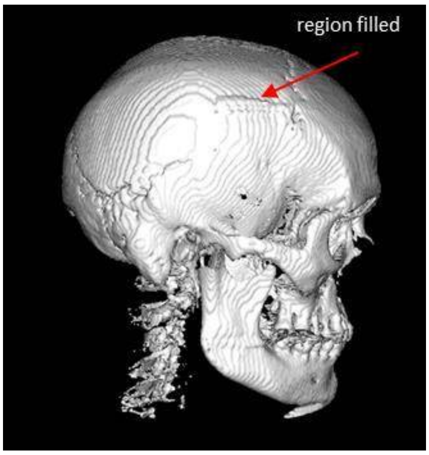
In figure 6 it is shown some samples of defective CT from the original dataset and respective retrieved CT with compatible descriptors (*i. e.*, minimum error in descriptors). The figure 6 also shows the error value (E) for each images pairs. The error is the cumulative difference between original bone and calculated Bezier curve by applying (3).

IV. 3D Example from Recovered Data

A handmade testing failure was built in a skull trough the FIJI software [11]. It is an open source Java suite to medical image analysis. A set of toolboxes permits to handle the CT slices from DICOM file [6]. The edge from individual slices can be cut in sequence to build a failure on a region. Thus, after 3D reconstruction it is obtained a synthetically built failure in skull as the example in figure 7. a.



(a)



(b)

Figure 7. Testing image. (a) A handmade testing failure built on original image. (b) Region filled with prosthesis modeled.

In figure 7.b is presented the failure region filled with compatible CT slice from medical database. The piece was cut from different slices where Bezier descriptors were compatible, i.e. those all CT retrieved with minimum error. The retrieved slices numbers and respective patient are shown in table 2. Note that the slices retrieved is not ever from same patient. The set of retrieved slices (good slices) were recovered from healthy individuals (intact skull) whose descriptors matches with original image in each CT slice (defective slice). From table 2 it is possible to see that many CTs are coming from individual #6.

In fact, the individual #6 have similar morphological characteristic with testing patient, as similar age and gender.

Table 2. Retrieved set of CT slices.

Original Slice #	Compatible individual #	Compatible CT image #	Fitness
279	6	280	128.0724
280	7	278	130.2566
281	5	279	118.3946
282	6	285	143.4175
283	5	287	176.9402
284	6	282	128.9885
285	7	281	179.4653
286	6	285	139.1415
287	6	288	127.1768
288	5	284	189.7201
289	6	287	132.4534
290	7	286	226.1416
291	6	289	137.2678
292	6	290	140.9704
293	5	290	113.8132

The filled region was evaluated through Geomagic® software [12]. The differences between original bone and prosthesis piece are presented in figure 8. The software permits to overlap 3D structures and provide a colored scale to show spatial the difference, whose the lower error values are represented in green and the higher error tends to red. As shown in figure 8 the region A008 has error closest to zero because is the original skull (skull of patient). The other colored identifications are into prosthesis area like A001, A003, A005 and A006; they are below of 1mm difference and the maximum error is in region A004 with value about 1.7087 mm.

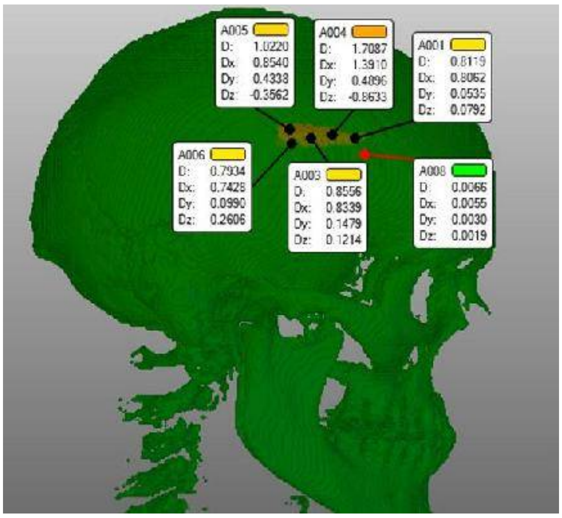


Figure 8. 3D evaluation of filled region.

V. CONCLUSIONS

The paper presented a method to generate skull shape descriptors based on Bezier Curves whose parameters were generated by *de Casteljou* algorithm. A sectioning of edge in k=20 sections with same length permits define two markers as the respective "fixed points" in Bezier curve generator. More two "variable points" calculated by *de Casteljau* defines the total of 4 descriptors for each section. Thus, it is possible to reduce all edge size in CT to be represented by a set of 80 descriptors. The descriptors are used to look for compatible CT images whose bone edge shape versus Bezier curve calculated by their descriptors have a minimum error. The example shows the result with maximum error in image around 1.7mm. We show it is possible represent a missing region of a patient's skull by a set of similar CT from healthy individuals selected by a reduced descriptors group.

In addition, the example shows that retrieved slices are from individuals with similar characteristic as age and gender. In a future work, the database searching engine can group individuals with these characteristics before proceed with descriptors calculation.

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