USING GENETIC ALGORITHMS TO SUPPORT THE PROSTHESIS DESIGN IN THE CAD SYSTEM

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Abstract. *This research deals about the use of three-dimensional images reconstructed from computed tomography in order to provide support for prosthesis modeling in CAD (Computer-Aided Design) system. The work proposes a method that uses an automatic and intelligent aid based on genetic algorithm (GA) to improve the virtual modeling applied to prosthesis conception. GAs are probabilistic search algorithms of evolutionary computation field combining the mechanics of natural selection and survival of the fittest. These algorithms are capable of efficiently finding an optimal solution for complex problems without necessitating reformulation for the evaluation of individual solution candidates. Unlike calculus-based methods, genetic algorithms are robust, global, and do not require the existence of derivatives for search. In the context of this paper, a GA was used to fit an ellipse in order to complete a defect in a skull. The bone piece that was missed in skull could be virtually created using the arcs extracted from the adjusted ellipses for each tomographic slice. And then we can generate profiles with the cloud of points to build a 3D model using a CAD system. A synthetic image of the missing bone piece was built to fill a hole at defect position in the skull. A case study shows the use of the method and discusses the obtained results.*

Keywords*: CAD, Prosthesis Modeling, Genetic Algorithm, 3D image, Image Processing*

1. INTRODUCTION

The actual level of scientific knowledge and the development of new technologies permits that several engineering areas make contribution with solutions to improvement of quality of people's lives. Some of them, as computing, mechanics, mechatronics, production and biomedical engineering can act together in order to creation of complex products and systems. In a transversal form among them, the technologies that deal about digital images are present in the context of process automation. Prototyping processes that involve image data of tomography can be seen in several applications levels, as in 3D virtual modeling of bone structure to prosthesis production. The prosthesis conception based on 3D reconstructed images is an important research area. In this case, a CAD (Computer-Aided Design) system can be used to modeling of bone shape and to generate the profiles used in machining preparing.

Basically, all the modeling process works from 3D reconstructed images from tomography scans. These images can be rotated and viewed in any plane, allowing acquiring of the morphologic features of the bone structures as in Rudek (2011). Three-dimensional figure generated from computed tomographic (CT) images can aid in understanding the region of complex anatomy, because the evaluation of this region is difficult (Fatterpekar *et al.*, 2006). An accurate precision of 3D modeling is needed to perform anatomic adjustment between prosthesis and bone defect area. Then the 3D surface representation must bring guaranties of real bone's measures. Some solutions to representation of skull curvature have been developed in the last years. Some of them are proposed based on the symmetry, as the bilaterally symmetric closed Fourier curves developed by Sengupta *et al.* (2005). In this case, we have some guaranties of the shape is very similar in the left or right side of human body as described by Li *et al.* (2009).

This idea can be applied in the skull problems, because the existing good bone area of one side can be mirrored to repair a missing area in opposite side. However it's true only when the local of defect is symmetric from the both sides how shows (Greboge *et al*., 2010). In several cases, the skull defect is not ever symmetric. In this case, a missing bone piece must be created from a criterion that guarantees their curvature. For this problem (You *et al.*, 2009) proposes a method based on sub-cube pixel technique to obtain a surface model of a loss part of a defective skull. His work operates the 3D modeling by triangulations techniques.

In a different way in this research, we are proposing a manner to adjust an ellipse with parameters based on the skull border curvature to fill a missing area. The problem is that several ellipses can be created with similar shape of the bone border, differing themselves only by small angles. Then, another problem is also to decide what the best solution is. In this context, optimization approaches can be useful. However, conventional optimization methods generally are associated with the following types of disadvantages: (i) exhibiting convergence dependency on the initial solution, (ii) getting stuck in suboptimal solutions, (iii) requiring a separate algorithm for each problem, (iv) being inefficient for problems with discrete search spaces, (v) being inefficient for simultaneous use on parallel machines, (vi) taking point-by-point approaches, and (vii) requiring unimodel or multimodel assumption. Alternatives to the traditional mathematical approaches, evolutionary algorithms, such as genetic algorithms (GAs), evolution strategies, evolutionary programming, differential evolution, among other, overcome these disadvantages.

In this paper, we adopt a GA with binary representation as defined in Goldberg (1989) in order to find the best ellipse for each tomography slice. Once defined all of them for each slice, the missing bone area (hole) in a skull can be created by a logic subtraction from existing border in original image. The volume can be reconstructed in 3D together with the rest of existing border. The process results in a new image, that is the anatomic prosthesis adjusted in the hole. The slices of this new 3D image are the profiles exported to a CAD system to create the virtual bone piece that was missing. The work covers the main steps of the proposed methodology and presents the progress of research in prosthesis modeling through a case study of a skull problem. A computational implementation was developed in MatLab software (MathWorks) to generate the virtual prosthesis and to build a 3D visualization.

The remainder of this paper is organized as follows. In section 2, the proposed method is detailed. In section 3, the description of the case study and results are presented and discussed. Finally, section 4 outlines the conclusion and future research.

2. PROPOSED METHOD

The method proposed here is an extension of traditional method described in Canciglieri Jr. *et al.* (2009) that presents a conceptual model to prosthesis design. The figure shows the entire process, where before 3D surface reconstruction, it's necessary to detect a part of skull that has a defect.

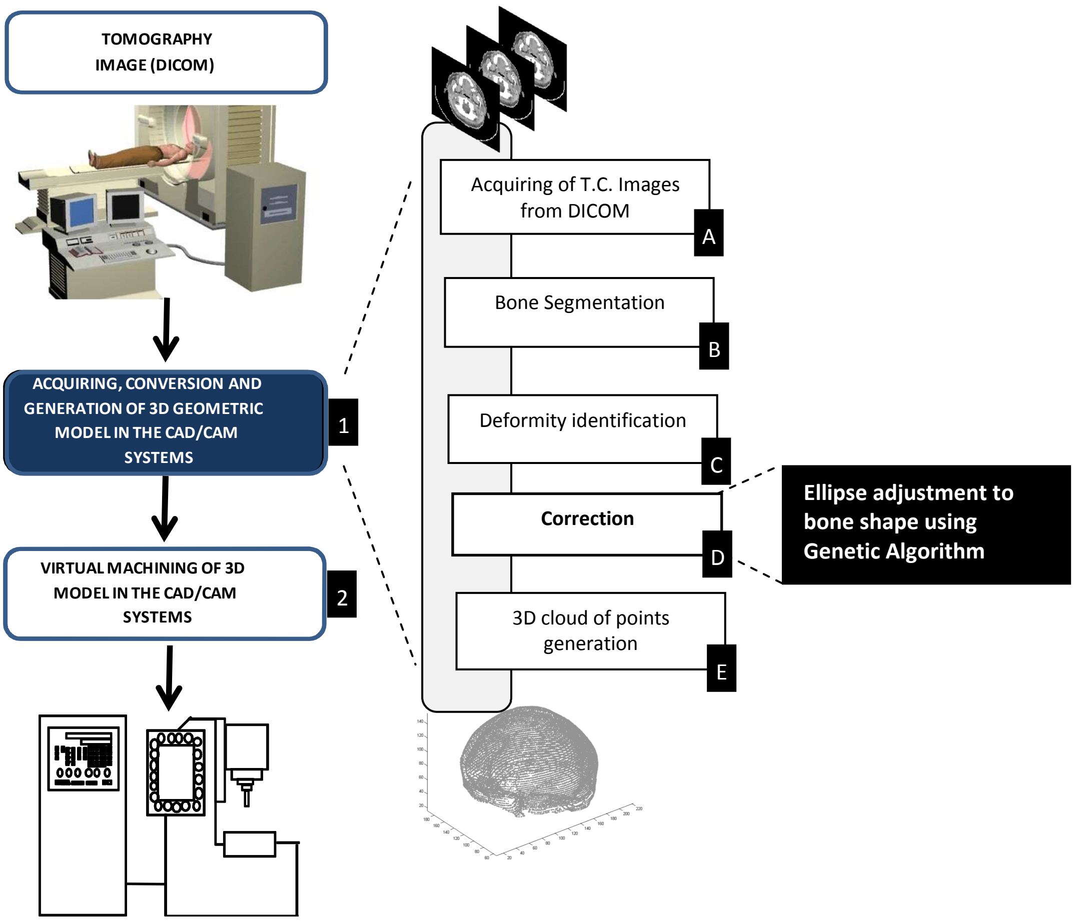


Figure 1. Proposed method adapted from Canciglieri Jr. *et al.* (2009).

Figure 1 shows the context of process. There is a part, numbered as '1', concerned with image processing and there is a second one, numbered with '2' concerned with software requirements to virtual modeling in CAD/CAM (Computer-Aided Design/Computer-Aided Manufacturing). The interest here is to work with part '1' because there are some important questions to be answered before the virtual machining. In the part '1', the two initial steps, called in figure as (A) *Acquiring* and (B) *Bone Segmentation*, are the problems well known. They deal each one about how to read an image of DICOM file, and how to extract the bone edge from each slice of tomography respectively. But, some problems can occur in this stage when the bone has a defect. Then the step (C) *Deformity Identification* must be executed. The main problem in this case is if the edge of bone have a missing part (a hole in a skull can do this in the tomography slice).

In Greboge (2009), it is explained a method using a FIFO (*First-in-First-out*) queue to identify bone fragments in the slice and how to extract the skull bone edge for that slice. After the edge is identified, it is necessary to fill the area where there is not bone in the image. The step (D) *Correction* deals about a GA technique to create a virtual bone piece that had not existed yet. This is the key point in this research and it will presented following. Once it's solved, the last stage (E) called *3D cloud of points generation* is to permit the 3D reconstruction process, also well documented in the literature and recently used in Lodygowsky *et al.* (2009).

All stages of the presented method depends that we have a corrected representation of bone virtually processed. Then, the part of method of interesting here is focused in step 'D', that it is how to build a piece of bone missing in the image. The Genetic Algorithm can be used together to image processing in many ways, as presented in Hashemi *et al.* (2009) and Jennane *et al*. (2010). In this research the GA deals about of the creation of an ellipse fitted into existing bone area in the image. The next topic will explain how to do it.

2.1. Ellipse Adjustment

This part of the text will explain how to make the correction process. If a bone border at an image slice has not a closed contour, it is needed close it. A piece of correcting border must be virtually built. The figure 2 shows the main idea of the process. This is must be doing at each slice that contains a problem.

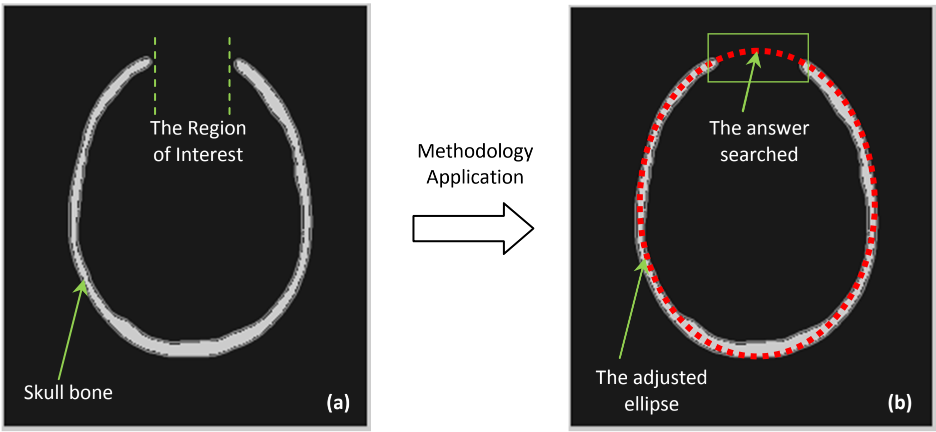


Figure 2. The expected result: (a) An example of a CT image slice with not closed border. (b) The virtual ellipse circled.

In the Figure 2(a) we can see an example of a CT image with no closed skull bone. The region of interest (ROI) can be seed in a frontal position of skull slice. There is a gap with no pixels information. Then, the problem is to create a bone piece adjusted. The proposed method is to create an ellipse with the size adjusted around the skull bone for each slice. It can be seed in Figure 2(b). The answer searched is an arc formed by a piece of the adjusted ellipse.

The main problem is to know the best solution, because a lot of ellipses can be created with different adjustments. In a genetic algorithm, values of fitness are the basis of the selection process. The selection mechanism searches the improvement of the next population quality. During selection, statistically only the most fitted individuals are chosen in order to allow them to take part in creation of the next population (Renner and Ekárt, 2003; Lodygowsky *et al.*, 2009).

Then it is used a fitness function that will find the best set of ellipse parameters among a population of ellipses. The fitness function is given by the equation 1.

$$f(x) = \frac{\sum_{i=1}^{l}\sum_{j=1}^{c} x(i,j) * E(i,j)}{\sum_{i=1}^{l}\sum_{j=1}^{c} x(i,j)} \quad (1)$$

where, the *l* and *c* are respectively the total of lines and columns in the image *x*. The *x*(*i*,*j*) is the position of one pixel in the slice image. And, the *E(i,j)* is the position of a pixel in the generated ellipse. The ellipse point (*x*(*t*),*y*(*t*)) can be obtained by,

$$x(t) = x_0 + a * \cos(t)$$
$$y(t) = y_0 + \mathrm{b} * \sin(t) \quad (2)$$

The equation 2 is the parametric form of ellipse equation. The *t* is a variable with values from 0 to 2π, x_0 and y_0 are the centers, and '*a*' and '*b*' are the axis. Here it is considerate the center is not in the origin of system. The parameters of center and axes can be evaluated by the GA that generates the best solution. After these values were obtained, the thickness must be still calculated. Then the process has two stages:

i. In the first stage it is executed the GA to obtain the best values of *a*, *b*, x_0 and y_0 using equations 1 and 2.

ii. In the second one, using the set values gotten from stage one, the value of 'e' is adjusted between a minimum and maximum value, until it achieve the best thickness.

2.2. The main algorithm

Figure 3 presents the components of an individual (chromossome), and the respective size of bits and possible values.

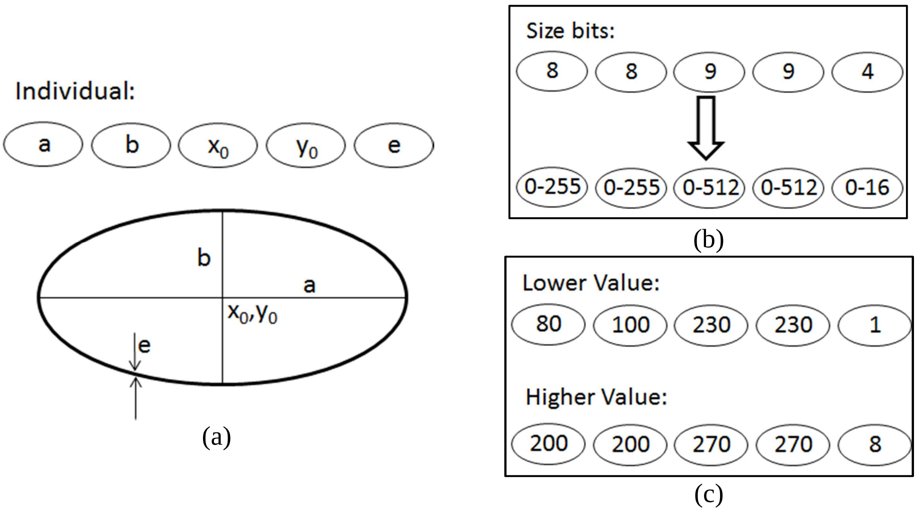


Figure 3. The GA parameters. (a) individual (chromossome); (b) size of bits; (c) range of values.

It can be seen in Figure 3(a) the parameters of each individual ellipse. The necessary parameters are the cartesian coordinates (x_0,y_0) of center, the major and minor axes '*a*' and '*b*' and also, the thickness '*e*' of the adjusted ellipse. In figure 3(b) it is shown the size in bits of entire chromosome and the range of values that can be assumed for each one. The limited range restricts the points in the initial population by specifying the lower and upper bounds. By the analysis of the image in tomography, a lower and a higher value can be defined. The conditions are that the '*a*' value is ever between 80 and 200, and '*b*' value is ever between 100 and 200. The coordinates of the center of image will be between 230 and 270, and the border size '*e*' (thickness) can be for 1 until 8. The unit of measurement is in pixels.

GAs operate on a coding of the parameter set rather than the parameters themselves. The locus of search is over a population rather than a single point. The GA only requires information from the objective function, not derivatives of the objective or other collateral information. Transition rules in genetic algorithms are probabilistic, not deterministic (Goldberg, 1989).

Implementation of a problem in GA always starts from the parameter encoding. In this study, the binary representation is adopted. In this context, the GA starts with a set of solution formed by binary-encoded individuals (chromosomes) with the form described in Figure 3. Then, a lot of ellipses can be drawn due to given range of possible parameters. We are looking for one solution in the search space which will be the best among all others. A possible basic form of a Genetic Algorithm was presented by Renner and Ekárt (2003), Kanungo *et al.* (2004), and Joshi (2007) and it was adapted as follows:

Step 1. Create an initial population filled with individuals generated randomly using a uniform distribution that are obtained from initial image within the minimum and maximum limits of the control variables and it is chosen as a parent population. The range of values for the initial population was defined as shown in Figure 3.

Step 2. Each individual in the current population is evaluated using the fitness measure according to the equation 1.

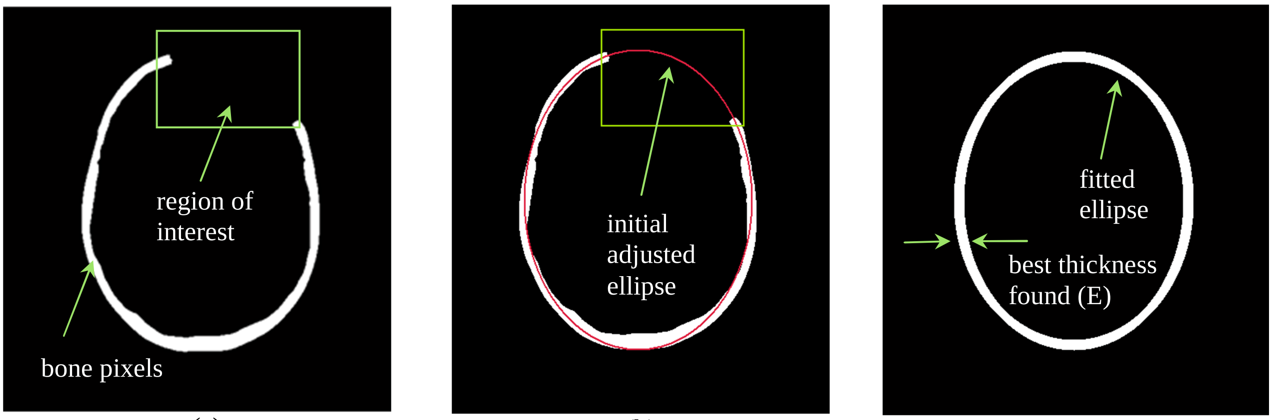
Step 3. Create a new population formed by applying the genetic operators (selection-reproduction, crossover, mutation) to these chromosomes. The main idea of selection is that the better individuals get higher chance in the next generation depending upon their fitness values. These selected individuals are called parents and the individuals resulting are offspring of them. On other hand, the purpose of crossover operator is to produce new chromosomes that are distinctly different from their parents, yet remain some of their parents characteristics. Mutation is performed by randomly selecting a string as well as a bit position within that string and changing it.

Step 4. Return until *Step 2* to next generation. The loop starts from *Step 2* and it is repeated while the stopping criterion is not satisfied. The criterion is the maximum percentage of correspondence between bone pixels image and pixels of the evaluated ellipse.

The adjusted ellipse has the values of '*a*' and '*b*' known, but it has a unitary thickness yet. It is useful to eliminate the main border of image, and it can be used to define an arc only along the gap. Then, this first ellipse marks the position of curvature. Once it defined, the GA must to operate with the thickness ('*e*' parameter). A case study in the next section will show an example of this process.

3. DESCRIPTION OF THE CASE STUDY AND ANALYSES OF THE RESULTS

It is proposed here a case study based on a hollow human skull. Here, it is simulated a hypothetic case when a piece of bone are missing. The hole in the bone was open of synthetic form. The analysis was made using some TC slices. The GA script was programed in MATLAB. Figure 4(a) shows the bone's pixels for a sampled slice where there is a defect. This is one that contains the initial set of values (pixels positions).



(a) (b) (c)

Figure 4. This is a sample of a slice with a defect. (a) The original pixels in TC image.
(b) The initial adjusted ellipse. (c) The final ellipse with adjusted thickness.

In the Figure 4(b) it is presented an initial ellipse adjusted after the genetic algorithm run. In this step, the center and axes of ellipse were obtained. The found partial solution has a unitary thickness yet. It is useful to eliminate the main border of image, and it can be used to define an arc only along the gap. Then, this first ellipse marks the position of curvature. Once it defined, the process must to operate with the thickness improvement. Despite these two phases apparently have existed, the all parameters values of ellipse were obtained together for the same fitness function in the same time. Figure 4(c) shows an example for the best fitness in the search space. Thus it is possible to known the best ellipse that can be used to form a curvature of bone shape.

After the process finished, it is obtained the final solution highlighted in Figure 5. This is the best solution found by the GA. The crossover probability used was 0.8 and mutation probability was used as 0.05. The maxim number of interactions was 1000.

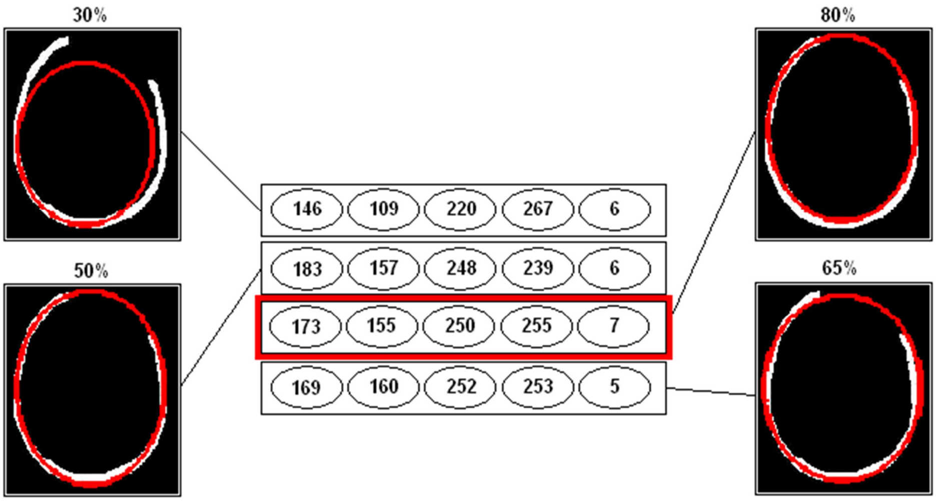


Figure 5. Some ellipse generated and the possible solution.

The fitness function gives the best parameters combination as seed in Figure 5. In this case, the percentage value of 80% permits to select the ellipse that is the solution. This solution contains: (a = 173; b=155; x_0=250; y_0=255; e=7).

Then it is still necessary to evaluate this result. Figure 6 presents a grafted piece forming the missing bone region.

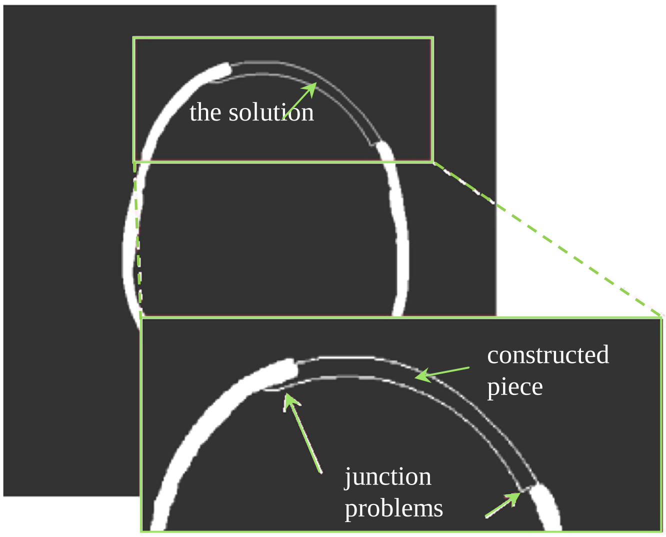


Figure 6. The best piece constructed for a sampled CT slice.

The important question is how much the solution is even the best. The found best ellipse is based in the result of the optimization, but for our case study is not the best solution. Some junction problem can be seen in the region marked by a zoomed rectangle in Figure 6. In this presented case, the both inner and outer borders are not completely aligned with the bone circumference. Then, by human viewpoint the solution is not good enough. For all simulations the result was very similar, and a few cases the adjusted ellipse was better. The good or weak result depends of the slice which was processed.

Despite the problem exists, it is not focused in this research at the moment. This involves others procedures by medical viewpoint that are directly related with the project of fixation's elements and surgery planning. It is an interesting question and will be studied later in a future work.

According the proposal, here we are concerned with the process to generate a CAD model. For the all computed slices, this process generates various arcs that can be superposed to make a 3D shape. Figure 7 shows the results in 3D reconstructed surface performed in SolidWorks system.

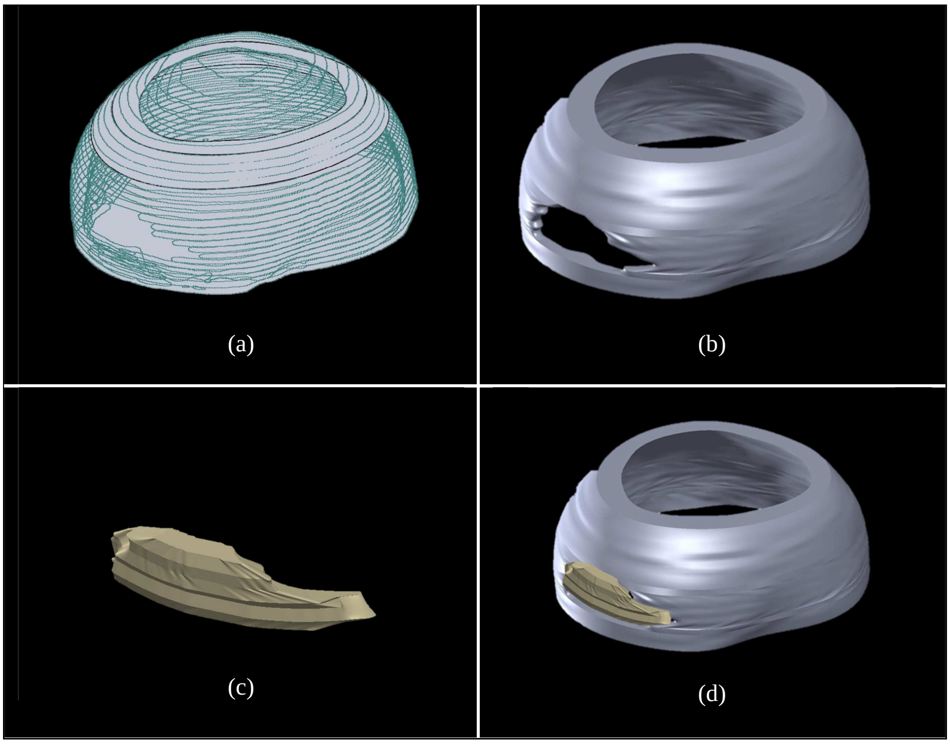


Figure 7. The skull surface and 3D piece modeling in CAD system.

The figure 7(a) show the profiles generated in a CAD system that was obtained from the CT original slices. The 3D surface was constructed as sampled in figure 7(b) where the hole is evident. The missing part was created and the volume of virtual piece can be visualized as presented in figure 7(c). As shown in figure 7(d), the final solution gotten is the complete surface model. This solution represents the position of hole filled with the previously obtained piece. The result is still not conclusive, but it was possible to do an initial validation of the proposed method. By the geometric viewpoint, it is possible to represent the missing area of skull shape. Some other points about prosthesis adjustment will be addressed in future researches.

4. CONCLUSION AND FUTURE RESEARCH

In this paper was presented the progress of studies in order to build a virtual bone piece to be used as prosthesis model. The problem of a hole in a skull was presented as study case. The suggested method was based in the creation of ellipses that were capable to perform a self-adjustment at bone curvature through a GA. GAs have been used as optimization techniques and they are become very useful as can see in many recent researches in engineering problems.

The obtained results show that still there is some problems to be solved. The union problems between bone segment and reconstructed piece are an open question. The reason is not only because some weak adjustment can occur, but it involves other medical questions. These questions were not discussed here. The main importance of this work is to know, how it is possible to modeling a piece of inexistent information. This information (part of bone missing) can be obtained for other ways, as numerical methods or user interaction. But the question was to verify a manner to make prosthesis modeling automatically.

Other key points are been analyzed to complete this research, and new steps of study are necessary to answer the open problems. These points are:

- To do analysis about the quality of results based on a set of true images of skull with problem (for example, real case of fractures);
- Overview by a medical analysis of functionality aspects of method and the evaluation of the measurement accuracy;

- To make a machined piece from CNC and comparing with real skull shape;
- To generate a software tool to support the modeling the prosthesis.

We can to consider that the proposed method is a promising technique to geometric prosthesis modeling of this kind of problem. This consideration is about the aspect of the capability to use some intelligent computational resource to aid the human decisions. This study is in progress, and the new results are near to be obtained.

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