Image Analysis, Geometrical Modelling and Image Synthesis for 3D Medical Imaging

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I. INTRODUCTION

Up to the end of the 70’s, Medical Imaging was mainly related to the study of planar data sets resulting from direct physical acquisitions (e.g. X-Ray radiographs). Then, the development of inverse methods associated with the increasing power of computers enabled the visualization and the analysis of human being cross-section images (e.g. CT scans, MRI): these images are the result of mathematical processes and do not present direct physical acquisitions. The visualization of these data in three-dimensional space was made possible by the use of a set of parallel cross-sections: the result was spectacular but not sufficient for further development, especially in the case of clinical applications. Such applications need the characterization of a geometrical model, e.g. for the capture of sophisticated geometrical parameters or to provide a mathematical support to mechanical simulations.

Recent advances in Computer Science, especially in Computer Graphics and Image Analysis, enabled the development of such new applications of Medical Imaging, in particular in the field of diagnosis and surgical planning. In this paper, we illustrate the role of a geometrical model and the need of cooperation between the different processes (image analysis, geometrical modelling and image synthesis) to achieve the goals of this new vision of 3D Medical Imaging.

First, we give general considerations on the scientific and medical aspects of medical imaging. Then, we illustrate the developed ideas with two examples of clinical applications:

- the representation of abdominal aortic aneurysms – for the evaluation of the disease severity and the design of adapted endoprostheses ;
- the geometrical modelling of the corneal surface using videokeratography – for the preparation of eye surgery.

In these two cases, the cooperation between the different processes (analysis, modelling and synthesis), as well as the role of the expert in this system, will be pointed out and the need of a geometrical model will be discussed.

II IMAGE ANALYSIS AND IMAGE SYNTHESIS

For a long time, Computer Graphics and Image Processing have been considered as completely different fields of Computer Science: on the one hand, Computer Graphics deals with the generation of nice pictures, and also with geometrical modelling; on the other hand, Image Processing deals with Discrete Signal Processing and Pattern Recognition. Most problems with the first one are related to complexity of algorithms and data representation: most problems with the second one are related to data interpretation and Artificial Intelligence.

Then, besides Image Synthesis and Image Analysis, a third scientific field emerged: Geometrical Modelling. This field deals with the characterization of geometrical models (e.g. free form surfaces) for Image Synthesis but also with Computational Geometry and Reconstruction problems [1].

In fact, strong relations exist between Image Analysis, Geometrical Modelling and Image Synthesis, for theoretical considerations (i.e. we try to understand and to structure the underlying information) and in the frame of applications: Image Analysis provides a set of relevant data that are structured through a Geometrical Modelling process and showed to the expert using and Image Synthesis one.

III 3D MEDICAL IMAGING

The acquisition of serial cross-section images using a non invasive device is quite usual nowadays (e.g. X-Ray scanner, MRI). But we do not forget that these images have not been directly acquired but computed (as a solution of an inverse problem) and this has been possible mainly thanks to the incredible development of computer performances and also to scientific work in Mathematics, Physics and Computer Science to solve these problems.

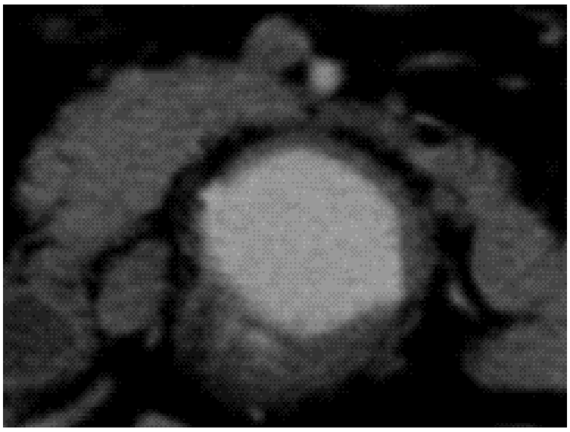

Fig.1 Cross section of the abdominal aorta
(computed on a X-Ray scanner)

Then, Image Analysis provides a segmentation of such images as illustrated below.

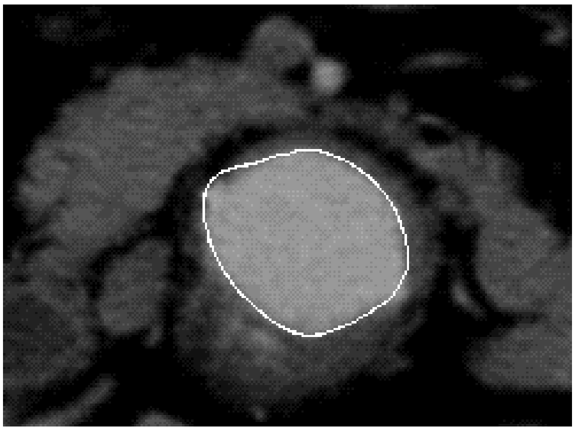

Fig. 2 Image Analysis :
Detection of the aorta using an active contour

We guess that from a set of such planar contours registered in three dimensional space we could obtain a visualization of the anatomical structure, as showed below.

Fig.3 3D Medical Imaging :
Abdominal aorta with iliac and renal arteries

Many approaches have been proposed for producing such views of the anatomical structures from serial cross sections. Some of them compute a set of contours and then characterize a surface that approximates these contours (it can be a triangulated surface joining these contours). Other approaches consider the whole data set as a digital volume and perform either a direct visualization combined with a local analysis (e.g. Active Ray Tracing), either a volume segmentation followed by a geometrical modelling (e.g. Marching Cubes to obtain the triangulated envelope of the segmented data).

Such approaches enable the visualization of 3D structures but are not sufficient for most of the clinical applications. In order to provide an efficient support for such applications, we have to design a « true geometrical model » that can permit a morphological analysis, a local geometrical analysis (e.g. differential properties) and simulation processes.

IV. ABDOMINAL AORTIC ANEURYSMS ANALYSIS AND THE DESIGN OF SPECIFIC ENDOPROSTHESES

Endovascular treatment is an interesting alternative to classical abdominal aneurysms surgery, but it requires accurate knowledge of the shape and size of the aneurysm (the major risk using this new technique with standard devices is the perigraft leak). Visualizations of aneurysm lumen provide an efficient support for qualitative decisions, but the extraction of quantitative parameters for the design and the positioning of a specific endoprostheses needs the characterization of a geometrical model of this cavity.

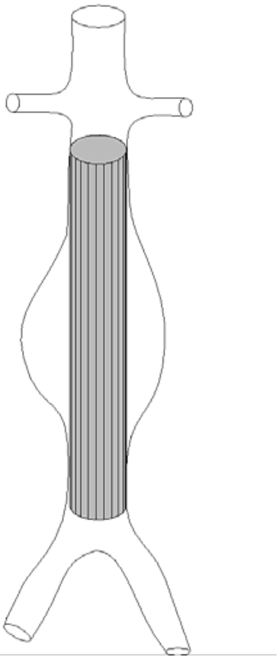

Fig. 4 Positionning an aortic endoprosthesis

Anatomical parameters required for this process are lengths and diameters of the different parts of this cavity (aneurysm, proximal neck, distal neck) and they cannot be obtained directly from images (e.g. because of the cavity orientation).

In order to provide such a 3D model, we use two primitives [2]: one is the « generalized cylinder » and the other one is the « junction ».

The geometrical model is a set of such primitives that are assembled to fit the data (e.g. contours) extracted from images, with respect of given regularity constraints (e.g. G^1-continuity). The figure below illustrates such a geometrical characterization of the cavity using the given primitives.

A « generalized cylinder » can be understood as an extension of the concept of « cylinder ». It is defined as the surface generated by a variable plane closed curve moving along an open curve (called its « central axis ») in 3D space (this surface is not supposed to intersect itself).

This primitive can be implemented very easily as a single patch of free form surface (e.g. a B-Spline patch) on which we impose conditions (e.g. in the case of an uniform cubic B-Spline, the condition is that the first three columns of control points are identical to the last three ones.

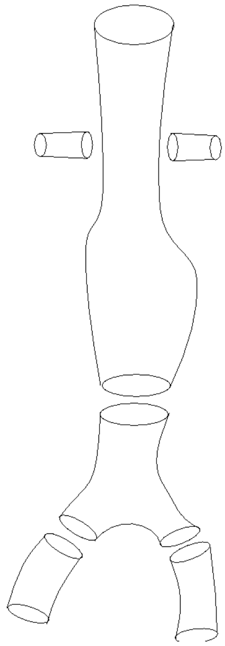

Fig. 5 The geometrical model

A « junction » has to satisfy differential conditions on its boundary to continuously set the geometrical relation with three « generalized cylinders » : the three closed curves bounding it have to be identical to given curves (the extremities of the « generalized cylinders ») and the tangent plane to the « junction » along these curves has to be identical to the corresponding one on the « generalized cylinder ».

This primitive can be implemented as a set of five basic patches, (Fig 7) three of them rectangular and two of them triangular, on which we have defined regularity constraints (triangular patches are Bézier-Gregory ones, and rectangular patches are uniform cubic B-Splines ones).

Images are computed on a helical scanner and are encoded in the DICOM format (Digital Imaging and Communication in Medicine). Then, they are transferred to a graphics workstation and are presented to the physician as a set of small images. The physician can then select the relevant ones (for its clinical application) and a global « Image

Analysis » is performed on this set of images: this process is based on the use of « snakes » (active contours) and is supervised by the physician who can interrupt the process and give an information to « help » it.

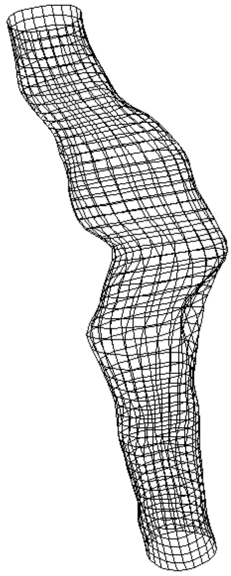

Fig. 6 A « generalized cylinder » representing the aortic lumen

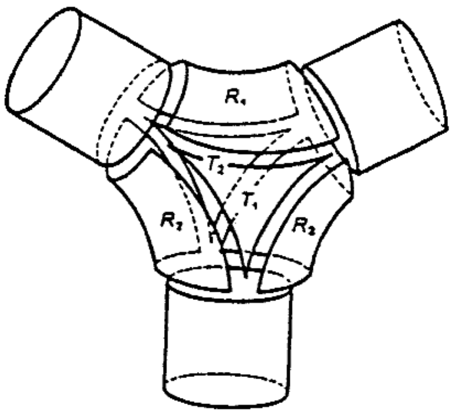

Fig. 7 Patches making of the « jonction »

Fig. 8 Detection of the aortic lumen using a « snake »

The geometrical model is then characterized (i.e. its components and its approximate position are computed from the information of the Image Analysis step). Finally, it is automatically and continuously deformed (it is possible because it is made of free-form surfaces) until it fits the extracted contours (and maintaining different stiffness along and across its sections).

The next two figures illustrate the interest of having such a geometrical model.

On the first one, we interactively « open » the model of the cavity using its central axis and the Frenet referential to provide an ergonomic simulation tool.

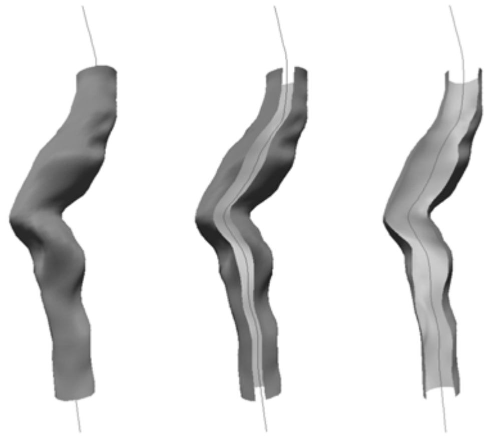

Fig. 9 Opening the aortic cavity along its axis

On the second one, we have simulated the positioning of the endoprosthesis in the aneurysm (and we have also represented the iliac arteries).

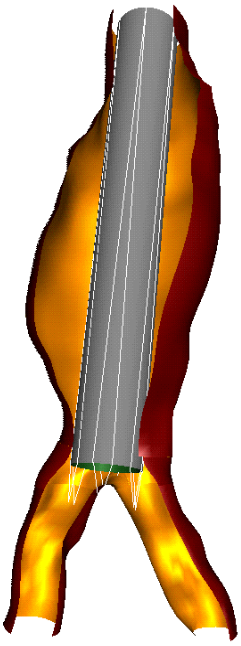

Fig 10 Positioning of the endoprosthesis in the aortic cavity

The next figure shows an integration of the model in selected data (a given cross section).

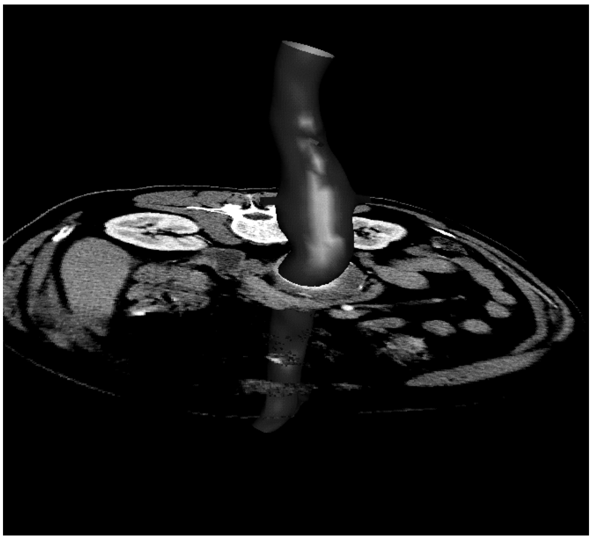

Fig. 11 Intgeration of model and data

V STUDYING THE SHAPE OF THE CORNEA USING VIDEOKERATOGRAPHY

The cornea is the main optical element involved in the geometrical part of the human vision process. Thus, modifying its shape is usually sufficient for correcting the vision defaults induced by corneal shape ones. The picture below gives us an example of such a default (a keratocone).

Fig 12 A kératocone (the eye drops)

A videokeratograph is a device that gives an image of such defaults: it projects a given pattern (usually a set of black and white concentric rings) on the cornea and captures the reflected image.

In order to estimate the cornea deformation, we first have to analyse the corresponding image. But many artefacts induce a wrong edge detection. The next figure shows us some of these artefacts: shadows of the eyelashes (1), of the eyelid (4) and of the nose (5), projection of a card for telemetry (2), vanishing contours (3).

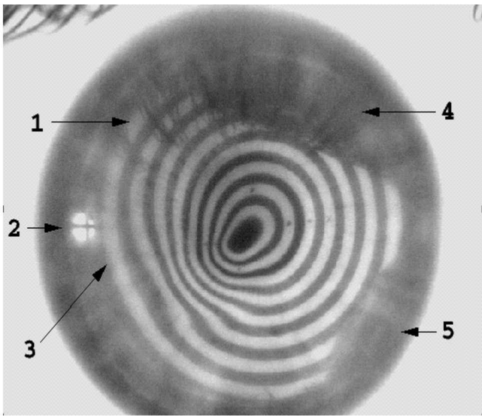

Fig 13 Types of artefacts in a videokeartographic image

A new approach [3] has been designed to take into account these artifacts in the edge detection process : first, we analyze the global structure of the image, i.e. we look for the approximate location of the contours (or parts of contours), then we refine the definitive contour detection with the help of the structural information extracted at the first step : using this structure, we can efficiently initialize and control an elastic matching process for producing the right contours.

The image structure is obtained as follows: we first detect points that could belong to contours (e.g. with an important gradient value) ; then, for each of these points, we estimate the local parameters (orientation and curvature radius) of a curve that could go through this point and its neighbours (the estimation of the local geometrical parameters uses a Hough Transform on circle arcs) ; and last, we solve a set of constraints to join these points, such constraints depending on geometrical and contextual rules.

The next image shows the detection of a contour.

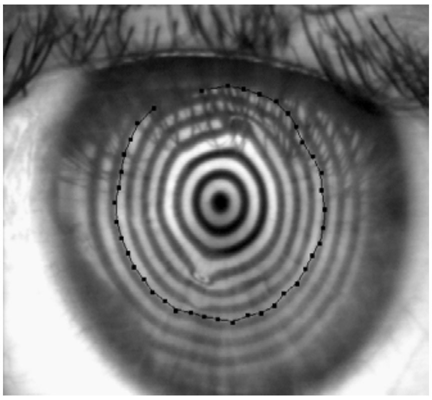

Fig. 14 Structural detection of a contour

The set of deformed contours implicitely gives us the cornea shape. We use a deformable surface to provide the geometrical model that could produce such a set of deformed contours : a Backward Ray Tracing process is used to deform the surface model until Rays associate the corresponding points (after a reflection on the surface model).

The 3D geometrical model of the cornea will be included in a model of the eye and will then be used for mechanical simulations (e.g. to precisely evaluate the action of the internal pressure on the cornea shape when operating on it). Such a model can also be useful in the frame of a « Scientific Visualization » process (e.g. displaying the path of rays in the eye).

VI CONCLUSION

Through these two clinical applications, we tried to emphasize the need of interactions between Image Analysis, Geometrical Modelling and Image Synthesis. And we especially point out the role of the geometrical model in the global process of 3D Medical Imaging.

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Works on cornea have been developed in collaboration with the Monticelli Ophtalmology Clinic in Marseilles.

REFERENCES

References below only concern the works of the "Imagerie Numérique" group of the LIM. A very large set of refernces are given in the paper [1] of this list (Sequeira and Barsky).

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