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**MATHÉMATIQUES APPLIQUÉES ET TRAITEMENT
D'IMAGES**

par

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**EXTRACTION DE COURBES ET SURFACES
PAR MÉTHODES DE CHEMINS MINIMAUX ET
ENSEMBLES DE NIVEAUX. APPLICATIONS
EN IMAGERIE MEDICALE 3D.**

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A toi

(*J. Dassin, 1938-1980*)

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Abbreviations

1D	one-dimensional
2D	two-dimensional
3D	three-dimensional
3DRA	3D rotational angiography
AAA	abdominal aortic aneurysm
CAF	cost assignment function
CNR	contrast-to-noise ratio
CT	computed tomography
CTA	computed tomography angiography
CRC	colorectal cancer
DSA	digital subtraction angiography
DSR	digital subtraction radiography
fMRI	functional magnetic resonance imaging
Gd-DTPA	gadopentetate dimeglumine
GWDT	gray-weighted distance transform
MDL	minimum description length
MIP	maximum intensity projection
MPR	multi planar reformatting
MRA	magnetic resonance angiography
MRI	magnetic resonance imaging
pixel	picture element
SNR	signal-to-noise ratio
TTP	Tissue Transition Projection
US	Ultrasound (Imaging)
VOI	Volume of Interest
voxel	volume element
XRA	X-ray angiography

Introduction

Context

Since several decades, the number of medical images produced in the world is constantly increasing. Three-dimensional medical images are becoming more and more used by the clinicians and the volume of datasets produced by the hospitals has created the need for an efficient structure for managing and processing those datasets. If 2D images are still useful and have numerous applications, since their acquisition cost is limited, cost for 3D images tend to reduce, and the frequency of their use is increasing.

3D images are produced as succession of slices that the clinician must mentally stack, in order to reconstruct and understand the 3D information they provide. This fact leads to misunderstanding of the 3D anatomical objects, and most of the manual processing tools lead to loss of information, since one dimension is not taken into account.

Automatic understanding of medical images is the underlying framework of this PhD study. We worked upon segmentation of anatomical structures, in other words extraction from the image of an anatomical object of interest, in order to visually inspect it and to quantify the extent of its possible pathologies. This segmentation process consist in isolating visible structures by recognizing their contours. The number of available methods to achieve this task in medical imaging is constantly growing. We can roughly classify those segmentation tools in two categories: a direct approach which consists in applying operators directly working on the image information; a modeling approach which uses an *a priori* information, trying to match a pre-defined modelization to the image in order to extract the targeted objects.

More specifically, tubular objects can be extracted and visualized, by discriminating them in the image, on the basis of their particular shape. The best way to study this kind of objects is to extract both their shapes and underlying structures, namely their skeletons, in order to guide a virtual inspection inside them, or to measure their diameters for example.

Using geometrical optic techniques, and the theory of wave light propagation in continuous medium, we are going to study more precisely fast and efficient algorithms for tubular shape extraction, and their geometric primitives, the curves that define their skeletons. Our methods are specifically dedicated to the particular shape of those objects.

And we will build tools in order to fly through the objects, and to numerically

characterize the extent of possible pathologies. Those tools will help clinicians in taking decisions concerning surgical issues and treatments.

Contents

In the first part of the thesis, we propose a study of different problems related to path extraction in 2D and 3D medical images. The first chapter is a review of different techniques already used in the domain of the minimal paths, in particular techniques related to the active contours model. We focus on the formulation derived from the geodesic active contours and on a fast scheme for minimal path extraction, based on the formalism of the Level-Sets. The second chapter contains most of the work that has been done in the minimal paths domain, in particular it concerns the reduction of the user interaction and of the computing cost needed, in order to ease the use of the methods. The third chapter introduces two applications of the techniques developed in the previous one. The first application concerns virtual endoscopy, where the path to be extracted is a trajectory for a virtual camera which moves within the 3D datasets, and the second application is the development of an interactive segmentation tool, for real-time path extraction in 2D images, using the same minimal path principles.

Similarly, the second part of the thesis focus on surface extraction, using the same paradigm of the Level-Sets, as done in the first part. Chapter 4 reviews applications of the Level-Sets formalism in 3D medical imaging. Chapter 5 contains several algorithms which aim are to improve several drawbacks of the Level-Sets, including: introduction of interactivity in the segmentation process in order to make it robust, and several ways to decrease the huge computing cost generated by those methods. Chapter 6 is dedicated to applications of those improvements to two medical imaging problems: first one is visualization of cerebral aneurysms, in order to derive the optimal surgical treatment to avoid disorders, like cerebral hemorrhages that can occur; second application is visualization of the colon polyps. The more accurate the early detection of those tumors, the more efficient the treatment.

Third part of the manuscript focuses on the study of more specific anatomical structures: tree structures, like vascular or bronchial trees. Our goal is to optimize visualization and quantification of the pathologies of those objects. In chapter 7, we detail tools which enable to see and measure pathologies on the basis of surfaces and curves extracted in the images. Chapter 8 links all the previous algorithms, to extract, in a single process, the surface and the skeleton of the object considered, using our curve and shape extraction tools elaborated in the two preceding parts of the thesis. In this chapter, tools are specifically adapted to the particular topology of the category of object studied. This surface information and the tree centered structures inside our tubular objects finds a natural justification in chapter 9, where its applied to vascular tree extraction in contrast-enhanced medical images. Those techniques are also applied to a more complex problem: bronchial tree extraction in multislice CT scanner datasets. Another application presented concerns reconstruction of vascular tree in 2D and 3D angiographic medical images, with methods based on perceptual grouping techniques.

Contributions

In the first part of the thesis, we have enhanced significantly path extraction through the following major contributions:

- extension to 3D of the method proposed by *Cohen and Kimmel* [34];
- reduction of the computing cost of this method;
- reduction of the user interaction for initialization;
- design of a new method to extract centered paths;
- creation of a 3D trajectory extraction for virtual endoscopy, currently integrated in a commercial product, after succeeding clinical validation;
- development of a training tool for interactive and real-time path extraction on basis of the *Live-Wire*.

In the second part of the thesis, major contributions are

- development of a fast algorithm for pre-segmentation, on the basis of the minimal path techniques, and in particular the *Fast-Marching* algorithm;
- developments of techniques to improve interactivity of the *Level-Sets* which are able to handle topology changes but so include any interactivity property;
- design of a collaborative approach, based on the *Fast-Marching* and the *Level-Sets*.

Moreover, these contributions find their justification in the last chapter of this part: fast segmentation and accurate visualization of the pathologies are needed for segmentation of the cerebral aneurysms, and the characterization of the colon polyps.

In the last part, we present contributions specifically dedicated to the extraction and the quantification of tubular and tree structures:

- we adapt the minimal path formalism in order to provide a fast pre-segmentation of the tube-shaped objects;
- we find how to obtain from a segmentation the set of useful trajectories for inspection of those tubular objects;
- we explain how to derive the tree structure from the trajectories previously extracted;

And finally, we detail applications of those methods to three different problems in medical imaging:

- segmentation of vascular trees with pathologies like aneurysms and stenoses;
- creation of new segmentation methods for the complicated problem of bronchial tree extraction;
- reconstruction of vascular trees in 3D contrast-enhanced angiographic images, using perceptual grouping techniques derived from the minimal path formulation.