Conclusion

Summary and contributions

In this manuscript, we focused on curves and shapes extraction in 3D medical imaging.

Path Extraction

We developed a set of original methods, based on the work of *Cohen and Kimmel* [34], in order to extend the minimal path extraction to three dimensional datasets. We worked upon providing several algorithms in order to reduce the computational cost of those methods and to the ease the use of minimal path techniques by any kind of possible users, clinicians among others.

Those results lead to several applications, and among them the implementation of a system of automatic path extraction of trajectories for virtual endoscopy, which has been clinically validated, and is now integrated in a commercial product, *EasyVision*, a software package for image processing sold with acquisition systems, and developed by Philips Medical Systems.

Second application is the construction of a tool for interactive and real-time extraction of objects contours in 2D images, built upon the basis of models such as the *Live-Wire* of *Falcao, Udupa, Mortensen and Barrett* [49, 127]. Our goal was to provide a tool for semi-automatic contour extraction, using the minimal path extraction principles. The resulting method integrated an interesting facility: the user can teach the algorithm which kind of contours he is looking for. This method gives interesting and promising results, and will probably be integrated in a software package for image processing, for delineation of the heart ventricles in ultrasound images.

Surface Extraction

The second part of the thesis focuses on the extraction of surfaces, with the help of minimal path extraction algorithms. We explained the link which exists with similar techniques in mathematical morphology, particularly with the *Watersheds* of *Vincent* [180], and we demonstrated the interest of such a method, which is fast and can produce a valuable initialization for more complex algorithms, with bigger computing times like *Level-Sets*. We presented a collaborative method which combines those different techniques in a single framework.

This framework was applied to several complex segmentation and visualization problems, in the sense that the topology of the object is difficult to recover. We first applied our method to extraction of cerebral aneurysms, which are inflations of the brain vessels that can grow and break, leading to a brain hemorrhage. Those aneurysms have a wide variety of shapes and the suitable model for segmentation should not have any *a priori* on the structure of the final object to be recovered. Second application, using the same principle, is segmentation and visualization of colon polyps. We detailed a method to discriminate areas of the colon to be observed for detecting polyps, based on the curvature of the surface segmented. This last method will be the basis of further developments for automatic detection of polyps at Philips Medical Systems.

Tree Structure Extraction

Finally, in the last part of the thesis we focused on the adaptation of our algorithms to the particular case of tree anatomical structures, where path and shape extraction find an original domain of development. We first develop a technique of fast tree segmentation, with a simple initialization (setting a seed point), adapted to tubular structures, with no constraint on the topology of the final object. We further developed a way to obtain an accurate sub-voxel segmentation method, using the previous algorithm as initialization.

In order to provide a complete analysis of the tree-shaped objects, it is important to use adequate tools to navigate inside the tree hierarchy, and a way to label the different parts of the structure. We first extent the minimal path extraction technique to the automatic detection of a whole set of trajectories, then we found a method to reconstruct the skeleton of our tubular anatomical objects, on the basis of those trajectories, by detecting the branching points and the paths between them.

Those techniques were applied to the segmentation and the reconstruction of vascular and arterial trees, in 3D contrast-enhanced angiographic medical images, and extended to bronchial trees in multislice CT scanners. Comparing our results obtained with a panel of methods already proposed in this domain, we concluded on the interest and validity of our framework, which provides a sub-voxelic accuracy of our tubular objects, in interactive times. Using the information of tree hierarchy, we can localize the branching points and extract the interesting information of the section of our objects in the whole volume. Pathologies like aneurysms, or stenoses can be clearly measured.

Problems encountered and perspectives

Our tree extraction technique has not been clinically validated for the moment. Results are promising, but the initialization technique can be improved: it cannot recover the smaller parts of our structures, even if it is a very fast method. A possible perspective would be to use the perceptual grouping methods of section 9.3 as a second process in order to recover those smaller parts.

The perspectives of this study are essentially to make a clinical validation, as it was

done for the virtual endoscopy tool. However, many of the applications presented in each part of the thesis gives a direction for promising developments, like visualization of the colon polyps and extraction of tree structures.

Moreover, the mathematical methods used for path and surface extraction that we developed all along the thesis can be used in a more general perspective than medical imaging, and can be applied to other industrial applications, such as aerial images.

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Publications

Publications in International Journals:

- T. Deschamps, L. D. Cohen, "Fast extraction of minimal paths in 3D images and applications to virtual endoscopy", *Medical Image Analysis*, Vol. 5, No. 4 , August 2001.

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- R. Truyen, P. Lefere, S. Gryspeerdt and T. Deschamps, "Speed and robustness of (semi-)automatic path tracking", *Virtual Colonoscopy Symposium*, Boston, October 2000.
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- T. Deschamps, J.M. Létang, L. D. Cohen and B. Verdonck, "Automatic construction of minimal paths in 3D images for virtual endoscopy", in *Computer Assisted Radiology and Surgery, CARS'99* (held in Paris, France, June 1999).

Patents:

- T. Deschamps and S. M. Ebeid and L. D. Cohen "Image Processing Method, System and Apparatus for Processing an Image representing a tubular structure and for constructing a path related to said structure", (march 1999).
- M. Greff and O. Gerard and T. Deschamps "Adaptation of potential terms in real-time optimal path extraction", (April 2001).

Curriculum Vitae

The author was born in Paris, France, on January 19, 1974. After having received general secondary education *(Collège Bartholdi, Boulogne)*, he went to an intermediate school *(Lycée Jacques Prévert, Boulogne)* from which he obtained his "baccalauréat" in 1992. During two years, he endured the preparatory classes for French Engineering schools *(Lycée Claude Bernard, Paris)*, and decided, instead of continuing a third year, to enter university.

In June 1997, he received a Bachelor of Science degree in Mathematics and Computer Science from Paris Dauphine University. And in September 1998, he received a Master of Science with honors in Mathematics, Image Processing and Artificial Intelligence, at CMLA laboratory, Ecole Normale Superieure, Cachan. His graduation project concerned the development of a path tracker for virtual endoscopy in 3D medical image data by means of shortest path techniques and was carried out at the Medical Imaging Systems (MediSys) group of Philips Research France(PRF), in cooperation with EasyVision Advanced Development group of Philips Medical Systems (Best, the Netherlands).

In the subsequent month, he started as a Ph.D. student at the CEREMADE Laboratory, University Paris Dauphine, on a research project concerning the extraction of paths and surfaces in medical imaging using level-sets framework. The project was carried out in the MediSYs Department of PRF (Suresnes, France). The results are described in this thesis.

He was awarded a post-doctoral fellowship, for research on electron microscopy and confocal microscope imaging, to be carried out at the Computing Sciences Division in cooperation with the Life Science Division, Lawrence Berkeley National Laboratory (Berkeley, CA, United States). This project will start in January 2002.

Extraction de Courbes et Surfaces par Méthodes de Chemins Minimaux et Ensembles de Niveaux. Applications en Imagerie Medicale 3D.

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Dans cette thèse nous nous interessons à l'utilisation des méthodes de chemins minimaux et des méthodes de contours actifs par Ensembles de Niveaux, pour l'extraction de courbes et de surfaces dans des images médicales 3D.

Dans un premier temps, nous nous sommes attachés à proposer un eventail varié de techniques d'extraction de chemins minimaux dans des images 2D et 3D, basées sur la résolution de l'équation Eikonal par l'algorithme du Fast Marching. Nous avons montré des résultats de ces techniques appliquées à des problèmes d'imagerie médicale concrets, notamment en construction de trajectoires 3D pour l'endoscopie virtuelle, et en segmentation interactive, avec possibilité d'apprentissage.

Dans un deuxième temps, nous nous sommes interessés à l'extraction de surfaces. Nous avons developpé un algorithme rapide de pré-segmentation, sur la base du formalisme des chemins minimaux. Nous avons étudié en détail la mise en place d'une collaboration entre cette méthode et celle des Ensembles de Niveaux, dont un des avantages communs est de ne pas avoir d'à priori sur la topologie de l'objet à segmenter. Cette méthode collaborative a ensuite été testée sur des problèmes de segmentation et de visualisation de pathologies telles que les anévrismes cérébraux et les polypes du colon.

Dans un troisième temps nous avons fusionné les résultats des deux premieres parties pour obtenir l'extraction de surfaces, et des squelettes d'objets anatomiques tubulaires. Les squelettes des surfaces fournissent des trajectoires que nous utilisons pour déplacer des cameras virtuelles, et nous servent à définir les sections des objets lorsque nous voulons mesurer l'étendue d'une pathologie. La dernière partie regroupe des applications de ces méthodes à l'extraction de structures arborescentes. Nous étudions le cas des arbres vasculaires dans des images médicales 3D de produit de contraste, ainsi que le problème plus difficile de l'extraction de l'arbre bronchique sur des images scanners des poumons.

Mots clés : *Chemins minimaux, modèles déformables implicites, segmentation, imagerie médicale 3D, méthodes variationnelles, Level-Sets, Fast-Marching.*

Curve and Shape Extraction with Minimal Path and Level-Sets techniques. Applications to 3D Medical Imaging.

In this thesis, we focus on the use of minimal path techniques and Level-Sets active contours, for curve and shape extraction in 3D medical images.

In the first part of thesis, we worked upon the reduction of the computing cost for path extraction. We proposed several path extraction algorithms for 2D as well as for 3D images. And we applied those techniques to real medical imaging problems, in particular automatic path extraction for virtual endoscopy and interactive and real-time path extraction with on-the-fly training.

In the second part, we focused on surface extraction. We developed a fast algorithm for pre-segmentation, on the basis of the minimal path formalism of the first part. We designed a collaborative method between this algorithm and a Level-Sets formulation of the problem, which advantage is to be able to handle any topological change of the surfaces segmented. This method was tested on different segmentation problems, such as brain aneurysms and colon polyps, where target is accuracy of the segmentation, and enhanced visualization of the pathologies.

In the last part of the thesis, we mixed results from previous part to design a specific method for tubular shape description and segmentation, where description is the extraction of the underlying skeleton of our objects.

The skeletons are trajectories inside our objects, which are used as well for virtual inspection of pathologies, as for accurate definition of cross-sections of our tubular objects. In the last chapter we show applications of our algorithms to the extraction of branching structures. We study the vascular tree extraction in contrast enhanced medical images, and we apply the same principle to the more complex problem of the bronchial tree extraction in multi-slice CT scanners of the lungs.

Keywords: *Minimal Paths, implicit deformable models, segmentation, 3D medical imaging, variational methods, Level-Sets, Fast-Marching.*