Conclusion

Résumé et contributions

Dans ce manuscrit, nous nous sommes intéressés à l'étude des courbes et surfaces en imagerie médicale tridimensionnelle.

Extraction de chemins

Nous avons développé un ensemble de techniques originales, basées sur les travaux préliminaires de *Cohen et Kimmel* [34], pour étendre l'extraction de chemins aux images tridimensionnelles. Nous nous sommes aussi attachés à fournir un éventail d'implémentations différentes afin de réduire les temps de calculs nécessaires, et de réduire l'intéraction d'un éventuel utilisateur.

Ces résultats ont mené à diverses applications, dont les plus avancées concernent en premier lieu l'implémentation d'un système de tracé automatique de chemins pour l'endoscopie virtuelle, qui a fait par la suite l'objet d'une validation clinique et d'une application industrielle, puisque ce système est dorénavant intégré dans un produit commecial, une console de traitement d'images médicales, *EasyVision*, développée par Philips Medical Systems. La seconde application est la construction d'un outil de délinéation intéractive des contours d'un objet dans des images bidimensionnelles, sur la base du modèle du *Live-Wire* [49, 127]. L'objéctif était de fournir un outil de tracé de contours semi-automatique, à l'aide des méthodes de chemins minimaux. Le résultat intègre une fonctionnalité intéressante au sens que l'utilisateur peut "apprendre" au programme quels sont les contours de l'image qu'il recherche. Cette méthode a fourni des résultats prometteurs, est fera sans doute l'objet d'une intégration à un environnement de traitement d'image, pour les contours des ventricules du coeur en ultrasons.

Extraction de surfaces

Dans un deuxième temps nous nous sommes intéressés à l'extraction de surfaces à l'aide des algorithmes de calcul de chemins minimaux. Nous avons montré le lien avec des techniques similaires en morphologie mathématique, notamment la *Ligne de partage des eaux* [180], et nous avons montré l'intéret d'une telle méthode, qui est rapide mais approximative, pour initialiser des algorithmes plus complexes, plus "savants", mais qui ont des temps de calculs beaucoup trop longs, comme les *Ensembles*

de Niveaux. Nous avons présenté une méthode regrouppant ces diverses techniques en un seul et même algorithme.

Cet algorithme a ensuite été appliqué à des problèmes de segmentation et de visualisation difficiles, au sens de la topologie des objets à récupérer. En premier lieu, nous avons extrait des anévrismes cérébraux, qui sont des gonflements sur des veines du cerveau dont la rupture peut entrainer une hemorragie cérébrale fatale. Ces anévrismes ont une grande variété de formes et le modèle adéquat de segmentation ne doit pas présenter d'à priori sur la structure de l'objet à segmenter. Nous avons ensuite le même principe à la segmentation et la visualisation de polypes du colon, où nous avons présenté une méthode originale de discrimination des zones à observer, en utilisant les propriétés de la surface obtenue (principalement sa courbure). Cette dernière méthode est à l'origine de développements plus poussés pour la détection automatique des polypes du colon, qui vient de commencer à Philips Medical Systems.

Extraction de structures arborescentes

Finalement dans la dernière partie de la thèse nous nous sommes attachés à adapter nos algorithmes au cas particulier des structures arborescentes, où l'extraction de chemins et de surfaces trouve une utilisation originale. Nous avons commencé par développer une technique de segmentation rapide, avec une initialisation très limitée (à un point), adaptée aux structures tubulaires, sans aucune contrainte sur la topologie de l'objet final. Nous avons ensuite fourni un moyen d'obtenir une segmentation de précision sous-voxélique utilisant le premier algorithme comme initialisation.

De plus, pour offrir la possibilité d'une analyse complète d'un réseau arborescent, il faut pouvoir fournir les outils pour d'une part une navigation intelligente dans des données 3D, et d'autre part un moyen d'indexation pour le repérage au sein de cette structure. Nous avons tout d'abord élargi les capacités de notre système d'extraction de trajectoires à l'extraction d'un ensemble de trajectoires, puis au cas de l'extraction d'arborescences.

Ces techniques ont ensuite été appliquées à la segmentation et la reconstruction de réseaux vasculaires et artériels, dans des images de produit de contraste tridimensionnelles. Comparant les résultats obtenus à l'état de l'art dans ce domaine, nous concluons de la validité de notre méthode qui donne avantageusement une précision sous-voxélique des surfaces de nos objets tubulaires, en des temps intéractifs. L'utilisation de l'information de structure arborescente nous permet de localiser l'information de section des objets qui nous permet clairement de distinguer les pathologies dont ils font l'objet, comme les sténoses et les anévrismes.

Problèmes rencontrés et Perspectives

Il reste malgré tout que les techniques d'extraction d'arborescences n'ont pas fait l'objet à l'heure actuelle de validation clinique. L'exploitation des résultats montrent que la méthode d'initialisation, si elle est très rapide, ne donne pas totalement satisfaction au sens qu'elle peut ne pas récupérer des branches de nos structures qui sont très fines, auquel cas, la méthode de reconstruction de la section 9.3 peut s'avérer

intéressante. Mais ce développement n'a pas été fait à l'heure actuelle.

Donc les perspectives de ce travail portent essentiellement sur une étape de validation clinique, comme cela a pu être fait dans le cas de l'endoscopie virtuelle. Quoi qu'il en soit chacune des applications présentées à chaque partie donne la direction pour de possibles développements, comme la visualisation de polypes, et l'extraction de structures arborescentes.

Mais les méthodes mathématiques mises en oeuvre pour l'extraction de chemins, et l'extraction de surfaces que nous avons développées dans ce manuscrit peuvent être utilisées dans un cadre beaucoup plus général que l'imagerie médicale et donner lieu à des applications dans d'autres cadres industriels.

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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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- T. Deschamps and L. D. Cohen, "Grouping connected components using minimal path techniques", *Computer Vision and Pattern Recognition (CVPR'01)*, Kauai, Hawai, December 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.*