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# Higher-order regularization and morphological techniques for image segmentation

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## 1 Introduction

Image segmentation is an important field in computer vision and one of its most active research areas, with applications in image understanding, object detection, face recognition, video surveillance or medical image processing. Image segmentation is a challenging problem in general, but especially in the biological and medical image fields, where the imaging techniques usually produce cluttered and noisy images and near-perfect accuracy is required in many cases.

In this thesis we first review and compare some standard techniques widely used for medical image segmentation. These techniques use pixel-wise classifiers and introduce weak pair-wise regularization which is insufficient in many cases. We study their difficulties to capture higher-level structural information about the objects to segment. This deficiency leads to many erroneous detections, ragged boundaries, incorrect topological configurations and wrong shapes. To deal with these problems, we propose a new regularization method that learns shape and topological information from training data in a non-parametric way using higher-order potentials.

## 2 Non-parametric higher-order random fields

The last few years have seen the successful application of higher-order CRFs and MRFs to some low-level vision problems such as image restoration, disparity estimation and object segmentation. These models are composed of higher-order potentials, *i.e.*, potentials defined over multiple variables, that have higher modeling power than standard pair-wise potentials. However, the exact representation of a general higher-order potential defined over many variables is computationally infeasible. This has led researchers to propose a number of parametric families of higher-order potentials that can be compactly represented.

In this thesis we use a compact non-parametric representation of the potentials based on a finite set of patterns learned from training data that, in turn, depends on the observations. Thanks to this representation, higher-order potentials can be converted into pairwise potentials with some added auxiliary variables and minimized with tree-reweighted message passing (TRW) and belief propagation (BP) techniques.

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Using a combination of many higher-order potentials, we also introduce the *Non-parametric Higher-order Random Field*, a new method that is able to capture structural, geometric and topological information in a non-parametric manner. We carry out both synthetic and real experiments to confirm that our model fixes the errors of other weaker approaches that are unable to exploit this kind of higher level information.

## 3 Morphological evolution of curves and surfaces

Even with these advanced models, perfect accuracy is still unattainable and human editing of the segmentation results is necessary. The manual edition is tedious and cumbersome, and tools that assist the user are greatly appreciated. These tools need to be precise, but also fast enough to be used in real-time. Active contours are a good solution: they are good for precise boundary detection and, instead of finding a global solution, they provide a fine tuning to previously existing results by minimizing an energy functional in a steepest descent manner. However, they require an implicit representation to deal with topological changes of the contour, and this leads to PDEs that are computationally costly to solve and may present numerical stability issues.

In the last part of this thesis, we provide a formal, theoretically grounded, approach for stable and fast local contour evolution. We base our framework in the mathematical morphology. We substitute the terms that appear in the PDEs of contour evolution algorithms for morphological operators that have equivalent infinitesimal behavior. Then, the numerical solution of the PDE is approximated by the successive application of morphological operators over a binary level-set. These operators are very fast, do not suffer numerical stability issues, and do not degrade the level set function, so there is no need to reinitialize it. Moreover, their implementation is much easier than their PDE counterpart, since they do not require the use of sophisticated numerical algorithms. To formally support our solution we present new theoretical results that relate differential and morphological operators. We introduce the *curvature morphological operator* for curves and formally prove that can be generalized to an arbitrary number of dimensions. Hence, it can be used for the evolution of curves, surfaces and hyper-surfaces of any dimension. Using this set of new mathematical tools, we describe three new morphological algorithms: the *Morphological Geodesic Active Contours*, the *Morphological Active Contours Without Edges* and the *Morphological Turbopixels*. In the experiments conducted, the morphological implementations converge to solutions comparable to those achieved by traditional numerical solutions, but with significant gains in simplicity, speed, and stability. In general, morphological algorithms are about one order of magnitude faster, which makes them suitable for real-time applications in resource-limited hardware such as tracking in mobile devices, or for processing large images such as those from EM imaging in neuroscience applications.

## Selected publications resulting from the thesis

[1] P. Márquez-Neila, P. Kohli, C. Rother, L. Baumela, "Non-parametric Higher-Order Random Fields for Image Segmentation", *European Conference on Computer Vision (ECCV)*, 269–284, 2014.

[2] P. Márquez-Neila, L. Baumela, L. Álvarez, "A Morphological Approach to Curvature-Based Evolution of Curves and Surfaces", *IEEE Transactions on Pattern Analysis and Machine Intelligence (TPAMI)*, 36(1):2–17, January 2014.

[3] L. Álvarez, L. Baumela, P. Henríquez, P. Márquez-Neila, "Morphological Snakes", *IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, 2197–2202, 2010.