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Automatic image segmentation and analysis with applications to diatom identification

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Chapter 6

Concluding Remarks

6.1 Summary and Contributions

In this thesis we have discussed automating the procedures for segmentation and identification of diatoms by digital image analysis. The main development in the first part of the thesis has been a framework for automatic segmentation of high-magnification, grey-scale diatom images, which improved initial segmentation results obtained within the ADIAC project (Fischer et al. 2002, du Buf and Bayer 2002). The ultimate goal of the methods described in the second part is to perform automatic identification of diatoms, for which two multi-scale methods with roots in mathematical morphology were developed and employed for feature extraction and analysis of the segmented diatom images.

It is one of the merits of this thesis that the methods described are not tailored only to cope with diatom images (e.g. they do not explicitly use any knowledge about the fact that most diatoms are oriented parallel to the horizontal axis and that the images contain only one central diatom), but instead, they are quite general and can be adapted and used with other inputs as well (as we show in Chapters 3 and 5). A more detailed description of the material of the thesis, emphasizing its contributions, follows.

Chapter 1 provides some background on diatoms, from diatom organism and morphology, to microscopy and image acquisition. Emphasis is put on the inherent obstacles to be overcome by all segmentation and identification methods described later in the thesis. Also, the methodology employed by diatomists for the tedious task of diatom identification is described. Sources of characteristics useful for computerized identification are evidenced, and specific issues due to the impact of the diatom life cycle on these are stated.

A framework for automatic segmentation of diatom images is presented in Chapter 2. We adapted popular segmentation methods to this difficult problem, and finally developed a method which substantially improved existing results. This method is based on the watershed segmentation from mathematical morphology, and belongs to the class of hybrid segmentation techniques. The novelty of the method is in the use of connected operators for the computation and selection of markers, a critical ingredient in the watershed method to avoid over-segmentation. As the number of markers does not change during the watershed evolution, a marker region lost during marker selection cannot be recovered later.

All considered methods were used to extract binary contours from the large database of diatom images and the quality of the contours was evaluated both visually and based on identification performances. In the visual inspection, all techniques yielded more than 75% correctly extracted contours, while the best result was that of the proposed hybrid technique, 98%.

A novel, physically-motivated deformable model for shape recovery and segmentation is introduced in Chapter 3. The model, referred to as the charged-particle model (CPM), is inspired by classical electrodynamics and is based on a simulation of charged particles moving in an electric field. The charges are attracted towards the contours of the objects of interest by an electric field, whose sources are computed based on the gradient-magnitude image. The electric field plays the same role as the potential forces in the snake model, while internal interactions are modeled by repulsive Coulomb forces.

After a critical review of the active contour model and a discussion of its variations, we demonstrate that specific problems of snakes are surmounted by our model. More specifically, we have shown that the CPM exhibits some important characteristics: (i) much less sensitivity to initialization than snakes (e.g. the particles can be initialized completely inside, outside, or in one part of the object, or may cross over object boundaries); (ii) increased capture range, granted by both Coulomb and Lorentz forces; (iii) good convergence into boundary concavities; (iv) possibility to handle topological changes; and (v) good behaviour on noisy images. We showed the flexibility and potential of the model in a wide variety of settings: shape recovery using manual initialization, automatic segmentation and skeleton computation. In our opinion, the most important advantage of the CPM over active contours is that the method can be used for automatic segmentation, even with very simple initialization procedures. Experimental results performed on the database of diatom images, with the same experimental setup as in Chapter 2, confirmed that the model is indeed reliable, and may outperform even hybrid segmentation methods.

The hat-transform scale spaces (introduced in Chapter 4) constitute novel multiscale constructions for the representation of n-dimensional signals. We proved causality of the extrema in the scale spaces, an essential characteristic to any scale-space formulation, and showed that these representations can be successfully used for image filtering. The advantages of using the proposed representations are: (i) a small number of scale space entries, compared with the number of peak components; (ii) all the extracted scales are important because major changes in the topology of the signal occur at these scales; (iii) once some entries in the scale space are obtained, they can be characterized by computing not only shape and size features, but also features related to the 'height' of each peak component.

Applications of the morphological hat-transform scale spaces to various pattern recognition tasks are described in Chapter 5. Two types of feature-extraction methods are presented, a contour-based method which analyzes shape features, and another which computes image-based (texture) features. The first method uses morphological curvature scale spaces, a construction based on 1-D hat-transform scale spaces applied on the curvature function, as the underlying 1-D signal. The second method extracts features from (textured) images and is based on 2-D hat scale spaces, in combination with unsupervised cluster analysis, in order to select representative features. We demonstrate object recognition based on curvature scale spaces for three large data sets, the set of diatom contours, the set of silhouettes from the MPEG-7 database and the set of 2-D views of 3-D objects from the COIL-20 database. Our approach outperforms other methods for which comparative results exist. The method based on 2-D hat scale spaces has been tested on two large sets, the database of diatom images and a set of images from the Brodatz texture database. The identification performance for the diatom data set was almost 98 %, and 93.5 % for the Brodatz data set.

For the sake of reproducibility we provided (or indicated) pseudo-code of efficient algorithms which can be used to implement any of the methods enclosed in this thesis.

Last, but not least, we included brief overviews on image segmentation, deformable models and multi-scale methods for signal representation and description.

Back to diatom identification, it is unrealistic to expect that the material presented here would resolve every single issue related to this subject, and that the software developed can readily be used in real-world applications. However, with respect to automatic identification, the performances reported in this thesis are among the best results obtained during the ADIAC project. Moreover, they even exceeded those achieved by most human experts (du Buf and Bayer 2002), and from this point of view one can conclude that automatic identification of diatoms by computerized means is indeed possible, and can be achieved with very good results.

6.2 Further Research Directions

The hybrid method may be extended to segmentation of phase-contrast images of cells such as leukocytes. In phase-contrast imagery, well defined information about the cell morphology is available, and can be extracted and used to monitor molecular reorganization during early immune response.

Of high interest is the applicability of the CPM (Chapter 3) for segmentation of medical data sets. Another direction to be explored consists in supplementing the skeleton with some information useful in the reconstruction phase. A shortcoming of the current method is that it cannot guarantee that the recovered contours (surfaces) are without gaps. Further investigations might focus on including more constraints in the model. For example, some region information can be included, which means that shape reconstruction should be done at each time step (which is feasible since the reconstruction algorithms are fast) in order to identify regions.

A possible extension in the formulation of the hat-transform scale spaces (Chapter 4) would be to make the size of the geodesic dilation (i.e. n in Definition 4.3.3) adjustable in Eq. 4.3. The benefit is that the robustness of the operator θ in Eq. 4.2 would be increased (one can imagine cases in which, because of one pixel which does not conform to others, a larger feature can be split in more), at the expense of setting one extra parameter.