Strings and necklaces: on learning and browsing medical image segmentations
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Summary

In today’s medical practice, digital images have evolved to such a degree that they have become a key and pervasive source of anatomical and functional information. Literally, millions of images are generated everyday and the number keeps escalating with advances in imaging technology. It will be impossible to cope with this explosion of image data without the aid of computers. Computers will be indispensable for such tasks as storage, processing, analysis and retrieval of large digital image collections. Thus, it is not surprising to see in contemporary medical imaging science a vivid interest in the development of qualified technology. One of the topics that has received considerable attention is the problem of image segmentation. Numerous methods have been proposed to attack the segmentation problem for a specific task, anatomical structure or imaging sensor. The efforts described in this thesis have concentrated on the development of more generic and robust image segmentation methods. Taking medical imaging problems as example applications, the basic questions we have addressed are a) how to automatically learn what constitutes the boundary of an anatomical structure in an image and b) how its constituents can be exploited for image segmentation and image browsing in large datasets.

Departing from the view that most contemporary segmentation methods still need significant user input to generate acceptable results, in chapter 2 we have focussed on interactive segmentation. We have set our goal to combine computation and interaction in a more structured and integral manner. To this end, we have first characterized human-computer interaction in terms of user input, interpretation of user input and purpose thereof. On the basis of this characterization, we have examined interactive methods in the image segmentation literature. We have found deformable model methods to form a suitable platform for interactive segmentation. For a better understanding of the benefits and drawbacks of deformable models we have characterized, reviewed and examine some well-known deformable model methods in literature. This examination and characterization has allowed us to get more insight in the main components of deformable models and to identify places for interaction within and between these components. We have come to the conclusion that inhomogeneous deformable models and statistical deformable models have many properties required for successful segmentation of complex medical images. This has motivated us to conduct further research on a) the construction of inhomogeneous deformable models by statistical analysis of boundary features derived from a set of annotated example images and b) the application of such deformable models for image segmentation and
image browsing.

Chapter 3 tackles the problem of how boundary features such as edge gradient and contour curvature, are properly captured, summarized and applied for model construction and image segmentation. An important contribution has been the representation of a boundary as a multivariate curve, emanating from recording multiple continuous features along that boundary. This representation permits the combination of techniques from functional data analysis with techniques from chemometrics to arrive at a method which we have called *strings*. In this method two phases are distinguished: learning and segmenting. The problem of learning is transposed into one of statistically analyzing the closed functional curves in feature space that best describe average feature values and the most important variations therein. Segmentation is conceived of as an iterative procedure in which a potential boundary in an unknown image a) is recorded in terms of multiple continuous features b) its feature values are weighted to amplify the statistically most descriptive features and c) its weighted feature values are evaluated with respect to the values seen in the learning set for acceptance or rejection. Strings have been compared with active shape models on 145 digitized X-ray images of cervical vertebrae. The results indicate that strings produce better results when initialized close to the target boundary, especially for visually ill-defined boundaries, and comparable results otherwise.

Chapter 4 focuses on the problem of how to learn the search intention of a user performing content-based image retrieval by example, e.g. for assistance in the diagnosis of the contents of an unknown image. In an attempt to solve this problem, we have developed a method to browse images on the basis of string segmentations of anatomical structures therein. In this method, first feature values of a population of normal anatomical structures in a learning set are captured in a string model. The string model is used to bootstrap retrieval of images that depict abnormal anatomical structures similar to the one contained in, and segmented from, the example image using the string model. In an iterative process, good or specifically bad retrievals are indicated interactively to refine the string model to one that describes the sought anatomical structure more precisely. The features of the structures in the indicated images also form a pilot for a population-based incremental learning technique. This technique explores the feature space using a probabilistic model. The probabilistic model aims at defining relevant parts of the feature space by moving to those area's were the feature values correspond to those seen in the, as positive indicated, retrieved images. At the end of the exploration, the probabilistic model defines a narrow region of the feature space frequently encountered during the browsing process, hence circumscribing the retrieval intention in terms of reoccurring features. Browsing ends with a set of images depicting same abnormalities. The method has been successfully applied for retrieval by example of digitized X-ray images of abnormal cervical vertebrae.

Chapter 5 addresses the question of how to exploit salient boundary features, landmarks, to reduce the complexity of a multi-dimensional image segmentation problem. We have proposed a method in which we conceive of segmentation as a procedure in which a) multiple continuous features are recorded, b) optimal features are selected locally and c) the selected features are step-wise exploited for image segmentation.
As in chapter 3, multiple continuous boundary features in a set of annotated images are extracted and statistically analyzed to obtain a model of the boundary features. The statistical model is used to select optimal features rather than to weight them as done in chapter 3. Feature selection is done for each boundary point on the basis of the curvature properties of the feature values around that point, i.e., landmarks are determined on geometrical grounds. Each boundary point is, in addition, classified as sheet point, curve landmark or point landmark based on the number of dimensions in which the selected feature is well defined. Results of feature selection and classification are input to a priority segmentation scheme which tries to automatically find boundaries in an unknown image, first by point-landmarks, then by curve landmarks and finally by sheet points. To this end a deformable model is used that has been accommodated to identify and exploit boundary landmarks. A user has the liberty to indicate a number of landmark points in the image to guide model deformation. As this deformable model uses different features and different search dimensions at different boundary points, we have called the segmentation method *necklaces*. The application of necklaces for segmentation of three-dimensional CT images of vertebral structures has shown acceptable results when used in an interactive setting.

Unlike the other chapters, chapter 6 takes on a specific segmentation problem, namely that of finding the spinal column in three-dimensional images. The method we have proposed to solve this inherently three-dimensional problem combines strings and necklaces to arrive at a true three-dimensional solution. Necklace models of vertebrae are constructed by statistical analysis of multiple features along boundaries in a given learning set. The necklace models define for each vertebra optimal features and their dimensionality. They are used for deformable model segmentation of single vertebral structures. Necklace models are coupled by string models, which express the spatial relationship between adjacent vertebrae in terms of multiple global spinal features such as curvature and length. The string models define natural variations in spinal curvature values as observed in a learning set. The necklace and string models are coupled to form an integral spine model. The spine model is used as a reference during the segmentation of an unknown image with help of a deformable model. The deformable model fits to the image data by elastic deformation in ways reminiscent to a marionette with interrelated structures moved by strings. The user has the opportunity to guide the deformation process of the entire spine model by pointing and clicking at landmarks in the image. To illustrate, we have segmented a CT image of part of the human lumbar spine. In combination with user interaction the step-by-step segmentation has produced promising results.