3D Parametric Intensity Models for Accurate Segmentation and Quantification of Human Arteries

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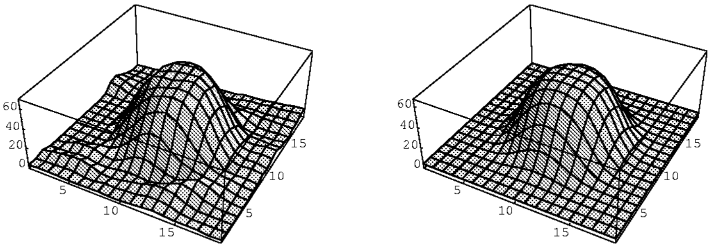
Abstract. We introduce a new approach for 3D segmentation of arteries. The approach is based on a cylindrical parametric intensity model, which is directly fit to the image intensities through an incremental process based on a Kalman filter. The new model has been successfully applied to segment arteries from 3D MRA image data. In addition, we developed a model which describes a stenosis in an artery. The applicability has been demonstrated using images of a human leg.

1 Introduction

Heart and vascular diseases are one of the main causes for the death of women and men in modern society. In Germany, for example, about 45% of all cases of death in 2001 were related to these diseases. An abnormal narrowing of arteries (stenosis) caused by atherosclerosis is one of the main reasons for these diseases as the essential blood flow is hindered. Especially, the blocking of a coronary artery can lead to a heart attack. Moreover, a stenosis in arteries of other organs or limbs can also have severe consequences. In clinical practice, images of the human vascular system are acquired using different imaging modalities, for example, ultrasound, magnetic resonance angiography (MRA), X-ray angiography, or ultra-fast CT. Segmentation and quantification of arteries (e.g., estimation of the diameter) from these images is crucial for diagnosis, treatment, and surgical planning.

The segmentation of arteries from 3D medical images, however, is difficult and challenging. The main reasons are: 1) the thickness (diameter) of arteries depends on the type of artery (e.g., relatively small for coronary arteries and large for the aorta), 2) the thickness typically varies along the artery, 3) the images are noisy and partially the boundaries between the arteries and surrounding tissues are difficult to recognize, and 4) in comparison to planar structures depicted in 2D images, the segmentation of curved 3D structures from 3D images is much more difficult. Previous work on the segmentation of vessels from 3D image data can be divided into two main approaches, one based on differential measures (e.g., [1,2]) and the other based on deformable models (e.g., [3,4,5]). The main

Fig. 1. Intensity plot of a 2D slice (19 × 19 pixels) of the artery iliaca communis in a 3D MRA image (left) and fitting result of the cylindrical model (right).



disadvantage of differential measures is that only local image information is taken into account, and therefore these approaches are relatively sensitive to noise. On the other hand, approaches based on deformable models generally exploit contour information of the anatomical structures, often sections through vessel structures, i.e. circles or ellipses. While these approaches include more global information in comparison to differential approaches, only 2D or 3D contours are taken into account. In [6] we described an approach for the segmentation of coronary arteries based on a parametric model (Gaussian line model). The model assumes a Gaussian shaped intensity function along the cross-section of an artery. For thin arteries (diameter below ca. 4 voxels) this model works very well. However, for arteries of medium size (diameter of ca. 4 to 8 voxels) this model needs a calibration in order to estimate the diameter of the vessel. For larger arteries (diameter above ca. 8 voxels) this model is not suitable.

We have developed a new 3D parametric intensity model for the segmentation of arteries from 3D image data. This analytic model is based on a cylindrical structure of variable diameter and directly describes the image intensities of arteries and the surrounding tissue. In comparison to previous contour-based deformable models much more image information is taken into account which improves the robustness and accuracy of the segmentation result. In comparison to our previously proposed Gaussian shaped model, the new model represents a Gaussian smoothed cylinder and yields superior results for arteries of medium and large size. In addition, a calibration of the model is not necessary. The new model has been successfully applied to segment arteries from 3D MRA image data. Moreover, as an extension we developed a model which describes a stenosis where the artery is blocked for a variable length. The applicability of this model has been demonstrated using images of a human leg.

2 Parametric Intensity Models for Tubular Structures

The intensities of an artery segment and its neighborhood can be well modeled by a Gaussian smoothed 3D cylinder, specified by the radius R (thickness) of the artery segment, the intensity levels a_0 (surrounding tissue) and a_1 (artery), and Gaussian smoothing σ. Unfortunately, the exact solution of a Gaussian smoothed cylinder cannot be expressed analytically and thus is computationally expensive.

Based on [7], we have developed an accurate approximation which involves the Gaussian error function $\Phi\left(x\right)=\int_{-\infty}^{x}\left(2\pi\right)^{-1/2}e^{-\xi^2/2}\,d\xi$ and can be written as

$$g_{Cylinder}\left(\mathbf{x},R,a_0,a_1,\sigma\right)=a_0+\left(a_1-a_0\right)\,\Phi\left(\frac{c_2-1}{c_1}+c_1\right) \tag{1}$$

where

$$c_1=\frac{2}{3}\sigma\frac{\sqrt{\sigma^2+x^2+y^2}}{2\sigma^2+x^2+y^2}\ ,\ c_2=\left(\frac{R^2}{2\sigma^2+x^2+y^2}\right)^{1/3}, \tag{2}$$

and $\mathbf{x}=\left(x,y,z\right)^T$. This approximation models the plateau-like intensity profile of medium and large arteries very well (see Fig. 1), which is not possible with a Gaussian function. In addition, we include a 3D rigid transform $\mathcal{R}$ with rotation parameters $\boldsymbol{\alpha}=\left(\alpha,\beta,\gamma\right)^T$ and translation parameters $\mathbf{t}=\left(x_0,y_0,z_0\right)^T$. This results in the parametric intensity model with a total of 10 parameters $\mathbf{p}$:

$$g_{M,Cylinder}\left(\mathbf{x},\mathbf{p}\right)=g_{Cylinder}\left(\mathcal{R}\left(\mathbf{x},\boldsymbol{\alpha},\mathbf{t}\right),R,a_0,a_1,\sigma\right) \tag{3}$$

Our new intensity model for a stenosis is an approximation of a Gaussian smoothed cylinder which is interrupted for a certain length d, where the slope of the transition is controlled by σ_z. The sizes of the semi-axes of the elliptical cross-section are specified by the parameters σ_x and σ_y. The model is based on the Gaussian function and the Gaussian error function and can be written as

$$g_{Stenosis}\left(\mathbf{x}\right)=a_0+\left(a_1-a_0\right)e^{-\frac{x^2}{2\sigma_x^2}-\frac{y^2}{2\sigma_y^2}}\left(\Phi\left(\frac{z-\frac{d}{2}}{\sigma_z}\right)+\Phi\left(\frac{-z-\frac{d}{2}}{\sigma_z}\right)\right) \tag{4}$$

In addition, we include a 3D rigid transform. The translation parameters define the position of the center of a stenosis in the 3D image.

3 Incremental Artery Segmentation

To segment an artery we utilize an incremental process which starts from a given point of the artery and proceeds along the artery. In each increment, the parameters of the cylinder segment are determined by fitting the cylindrical model to the image intensities $g(\mathbf{x})$ within a region-of-interest (ROI), thus minimizing

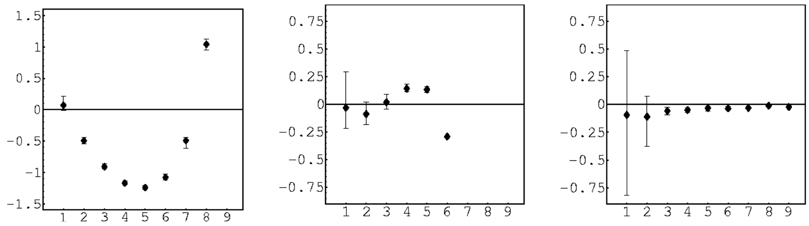
$$\sum\nolimits_{\mathbf{x}\in\mathrm{ROI}}\left(g_M\left(\mathbf{x},\mathbf{p}\right)-g\left(\mathbf{x}\right)\right)^2 \tag{5}$$

by applying the Levenberg-Marquardt optimization method. The length of the segment is defined by the ROI size which typically is 9-19 voxels. Initial parameters for the fitting process are determined from the estimated parameters of the previous segment using a linear Kalman filter, thus the incremental scheme continuously adjusts for varying thickness and changing direction. Since we use a Kalman filter, the incremental scheme is highly robust.

4 Experimental Results

We have applied our new cylindrical model using 3D synthetic as well as 3D MRA image data.

Fig. 2. The differences of the estimated radius (mean, minimum, and maximum for ca. 55 segments) and the true radius of a synthetic cylinder are shown for different radii for the uncalibrated (left) and calibrated Gaussian line model (center), and for the new cylindrical model (right). Note, the missing values in the left and center diagram are far outside of the shown range.



3D Synthetic Data In total 432 synthetic 3D images of straight and curved tubular structures have been generated by using the cylindrical model itself as well as Gaussian smoothed discrete cylinders and tori (with different parameter settings, i.e. radii of $R = 1, \ldots, 9$ voxels, smoothing values of $\sigma = 0.5; 1; 1.5; 2$ voxels, and a contrast of 100 grey levels) with added Gaussian noise ($\sigma_n = 1; 3; 5; 10$ grey levels). From the experiments we found that the approach is quite robust against noise and produces significantly more accurate results in comparison to the previous Gaussian line model for all experiments except for relatively thin radii of less than 3 voxels. For example, the maximal error of the estimated radius of a straight tubular structure (smoothed discrete cylinder) for a radius of 3 voxels turned out to be 0.30 voxels and for a radius of 9 voxels only 0.09 voxels. In contrast, the previous Gaussian line model yields for a radius of 3 voxels a maximal error of ca. 1.5 voxels (0.80 voxels calibrated) and for a radius of 9 voxels more than 6 voxels (with and without calibration). Fig. 2 shows the result for the estimated radius of the smoothed discrete cylinder for a noise level of $\sigma_n = 10$ and a smoothing value of $\sigma = 1$. It can be seen that the cylindrical model is superior for all radii larger or equal than 3 voxels.

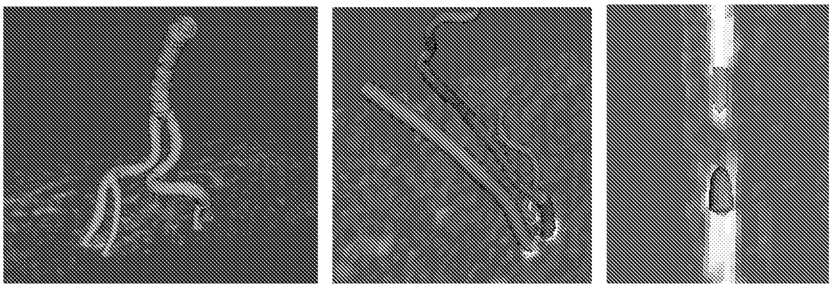
The new stenosis model has been applied to about 500 3D images generated by the model itself with added Gaussian noise. The experiments verify that the model is robust against noise and the choice of initial parameters.

3D Medical Images With our approach both position and shape information (diameter) are estimated from the 3D image data. Fig. 3 shows segmentation results of applying the new cylindrical model and the stenosis model to 3D MRA images of the human pelvis and leg. It can be seen that the cylindrical model successfully segments arteries of different sizes and high curvatures. The successful application of the stenosis model to a real stenosis demonstrates the applicability of this new model.

5 Discussion

The new 3D cylindrical intensity model yields robust and accurate segmentation results comprising both position and thickness information. In combination with

Fig. 3. Segmentation results of applying the cylindrical model (left image and left artery in center image) and the Gaussian line model (smaller arteries in center image) to arteries of the pelvis. In addition, the fitting result of the stenosis model for a stenosis in an artery of a leg is shown (note, only a part of the artery close to the stenosis is segmented). For visualization we used 3D Slicer [8].



the previously proposed Gaussian line model, we are now able to accurately segment 3D arteries of a large spectrum of sizes, i.e. from very thin coronary arteries (e.g., a diameter of only 2 voxels [6]) up to very large arteries (e.g., a diameter of 26 voxels). The new stenosis model is a first step to provide additional information about abnormalities to the physician.

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