Segmentation of Coronary Arteries of the Human Heart from 3D Medical Images

Ren Hui Gong, Stefan Wörz and Karl Rohr

School of Information Technology, Computer Vision & Graphics Group
International University in Germany, 76646 Bruchsal
Email: renhui.gong@i-u.de

Abstract. We introduce two new approaches for 3D segmentation of coronary arteries. The first approach is based on local intensity maxima and is computationally very efficient as well as yields superior results than standard thresholding. The second approach is based on semi-global intensity models, which are directly fit to the image intensities through an incremental process based on a Kalman filter. The approaches have been successfully applied to segment both large-size and small-size coronary arteries from 3D MR image data.

1 Introduction

Coronary heart disease is caused by narrowing of the coronary arteries that feed the heart. In clinical practice, images of the human heart are acquired using different imaging modalities, e.g., ultrasound, MRA, X-ray angiography, or ultra-fast CT. Segmentation and analysis of the coronary arteries (e.g., estimation of the diameter) from these images is crucial for diagnosis, treatment, and surgical planning. However, given 3D medical image data, segmentation is difficult and challenging. Main reasons are that 1) the thickness (diameter) of coronary arteries is relatively small and the thickness also varies along an artery, 2) the images are often noisy and the boundaries between the coronary arteries and surrounding tissues are generally difficult to recognize, and 3) 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 approaches based on differential measures (e.g., [1,2]) and those based on (semi-)global models (e.g., [3,4,5]). The main 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 (semi-)global models typically 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 addition, it is often the case that approaches are only applicable for special applications.

We have developed two new approaches for 3D segmentation of coronary arteries. The first approach is based on local intensity maxima and is computationally very efficient as well as yields superior results than standard thresholding. The second approach is based on semi-global intensity models which are directly fit to the image intensities (see [6] where such an approach has been proposed for segmenting 2D corner and edge features). In comparison to previous contour-based models more image information is taken into account, which improves the robustness and accuracy of the segmentation result. In comparison to [7] we use a sound and robust tracking scheme based on a Kalman filter and also introduce a calibration procedure to cope with systematic estimation errors. The approaches have been successfully applied to segment both large-size and small-size coronary arteries from 3D MR image data.

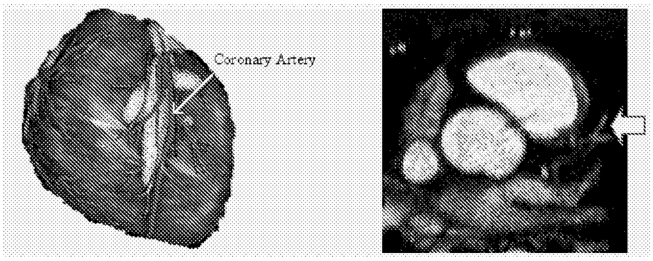


Fig. 1. A 3D view of the human heart (left, source: Coronary Artery Surgery Forum) and one slice of the MR image (right, source: FIT).

2 Approaches

2.1 Local Intensity Maxima (LIM)

This approach first calculates the image gradient and then determines local maxima of the intensity in particular directions (gradient and inverse gradient directions). A threshold is used to sort out weak local maxima due to image noise. The segmentation result consists of detected centerline points of coronary arteries. Since this approach determines local intensity maxima, it is a generic technique that is suitable for segmentation of general tubular structures.

2.2 Incremental 3D Gaussian Line Fitting (I3GLF)

This approach uses a parametric model of the intensities, called 3D Gaussian Line (3GL), to represent segments of coronary arteries. The complete coronary artery is represented by a sequence of concatenated 3GLs. The 3GL model has 10 parameters:

$$g_M\left(\mathcal{R}\left(x, y, z, \alpha, \beta, \gamma, x_0, y_0, z_0\right), a_0, a_1, \sigma_x, \sigma_y\right) = a_0 + (a_1 - a_0)\, e^{-\frac{X^2}{2\sigma_x^2}} e^{-\frac{Y^2}{2\sigma_y^2}} \quad (1)$$

where a_0, a_1 are the intensities of the peripheral and central part of the segment, and σ_x, σ_y determine the diameters of the segment along X- and Y- directions.

$\mathcal{R}$ denotes a 3D rigid transformation including rotation parameters α, β, γ and translation parameters x_0, y_0, z_0 of the segment. The length of the segment is determined by the size of the region-of-interest (ROI) used for fitting (e.g., in our case we used 7-15 voxels). Arteries are segmented by incrementally fitting the 3GL model to the image intensities on the basis of a discrete linear Kalman filter. The tracking process starts from a given point of the artery and proceeds along a given direction of the artery until the end of the artery or the image border is reached. In each increment, segments of an artery are found as follows:

1. Fitting the model in an ROI using Levenberg-Marquardt optimization;
2. Computation of Kalman filter estimates for the position x_0, y_0, z_0;
3. Predicting the starting position for the next increment using the Kalman filter.

To cope with deviations of our 3GL model from a correct Gaussian smoothed cylinder we also apply a calibration procedure, where the estimation of the artery thickness (radius) is adjusted based on a quadratic function of σ_x and σ_y, respectively. Once the sequence of 3GL segments is found, a VTK model is generated for 3D visualization using 3D Slicer (SPL, Boston).

3 Results

The two approaches have been applied to 3D synthetic as well as 3D MR data. A number of synthetic images of straight and curved tubular structures have been generated by using different diameters, curvatures, and noise levels. The MR image has a size of 512×512×20 voxels and a resolution of $0.7\times0.7\times3\text{mm}^3$ (cf. Fig. 1). Fig. 2 shows an example of the result of the LIM approach for two synthetic images - rotated cylinder and torus. The images were generated with noise level (standard deviation) of 3 grey levels, and an object radius of 2 voxels. Fig. 3 shows the result of the I3GLF approach applied to the same synthetic images. The estimation result of the radius for the I3GLF approach along the whole torus is presented in Fig. 4. It can be seen that the estimation result is around 2 voxels and fairly good in comparison to using no calibration (ca. 1.5 voxels). Fig. 5 shows the results of the I3GLF approach for the 3D MR data.

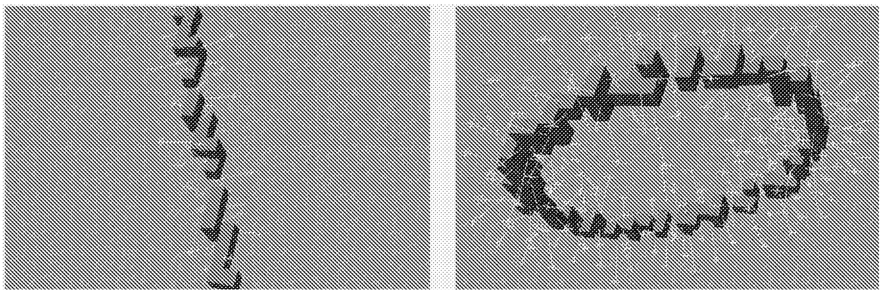


Fig. 2. Segmentation results of the LIM approach for synthetic images: Cylinder (left) and torus (right). The arrows indicate gradient directions.

Fig. 3. Segmentation results of the I3GLF approach for synthetic images: Cylinder (left) and torus (right).

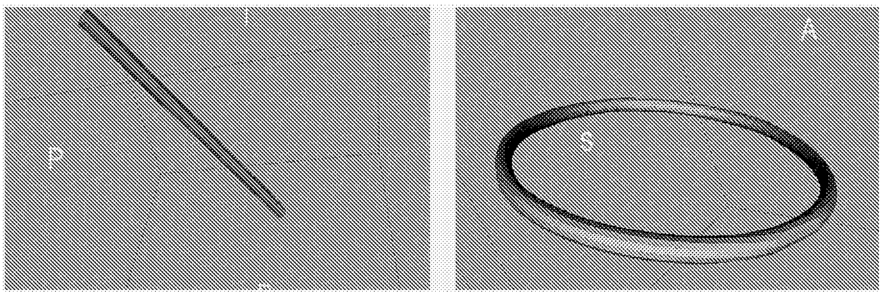
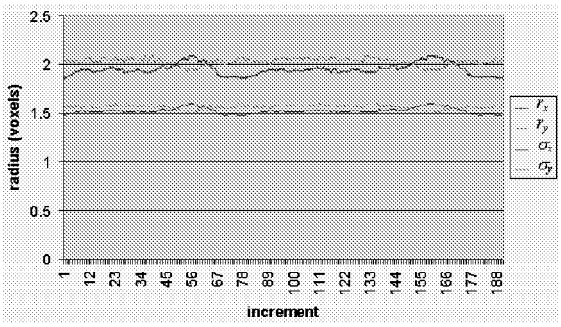


Fig. 4. Measurement results of the radius using the I3GLF approach along the whole torus for all increments of the Kalman filter.



4 Discussion

From our experiments it turns out that the LIM approach has very good execution performance and produces better results than simple standard thresholding, because fewer points are detected. The problems of this approach are that 1) it is relatively sensitive w.r.t. noise, 2) unwanted points are detected and also gaps sometimes exist in the segmentation result, which make the 3D interpretation more difficult, and 3) the thickness information of the coronary arteries is missing because only centerline points are detected. However, the approach is useful when execution performance is superior to segmentation results. Also, it is a generic approach for determining the centerlines of tubular structures and could be used to initialize the I3GLF approach.

The I3GLF approach is found to be a suitable method for segmentation of coronary arteries. The approach is quite robust against noise and produces better results in comparison to the LIM approach. In particular, both position and shape information is estimated from the 3D image data and this information can nicely be visualized. Note, that we estimate two parameters for the thickness (diameter) along an artery, thus we can cope with elliptical cross-sections. Although we only tested the approach using 3D synthetic and 3D MR image data, we assume that it is also suitable for other imaging modalities because of the generic nature of the scheme. Problems exist at artery junctions and this issue requires further attention in future work.

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References

1. Th.M. Koller, G. Gerig, G. Székely, and D. Dettwiler, "Multiscale Detection of Curvilinear Structures in 2-D and 3-D Image Data", *Proc. Int. Conf. on Computer Vision (ICCV'95), IEEE Computer Society Press*, Washington, 1995, 864–869
2. K. Krissian, G. Malandain, N. Ayache, R. Vaillant, and Y. Trousset, "Model Based Multiscale Detection of 3D Vessels", *Proc. IEEE Workshop on Biomedical Image Analysis, IEEE Computer Society Press Washington*, 1998, 202–210
3. T. Behrens, K. Rohr, and H.S. Stiehl, "Using an Extended Hough Transform Combined with a Kalman Filter to Segment Tubular Structures in 3D Medical Images.", *Proc. Workshop Vision, Modeling, and Visualization (VMV'01)*, IOS Press/infix, 2001, 491–498
4. A.F. Frangi, W.J. Niessen, R.M. Hoogeveen, T. van Walsum, M.A. Viergever, "Model-Based Quantitation of 3D Magnetic Resonance Angiographic Images", *IEEE Trans. on Medical Imaging*, 18:10, 1999, 946–956
5. M. Hernández-Hoyos, A. Anwander, M. Orkisz, J.P. Roux, P.C. Douek, I.E. Magnin, "A deformable vessel model with single point initialization for segmentation, quantification and visualization of blood vessels in 3D MRA", *Proc. MICCAI'00*, Springer, 2000, 735–745
6. K. Rohr, "Recognizing Corners by Fitting Parametric Models", *International J. of Computer Vision*, 9:3, 1992, 213–230
7. H.J. Noordmans, A.W.M. Smeulders, "High accuracy tracking of 2D/3D curved line structures by consecutive cross-section matching", *Pattern Recogn. Letters*, 19:1, 1998, 97–111

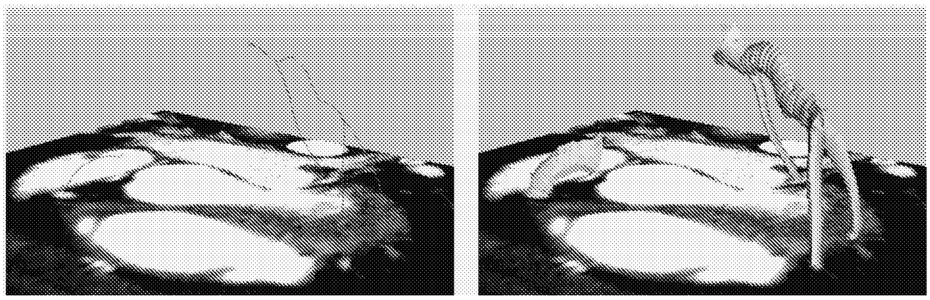

Fig. 5. Segmentation results of the I3GLF approach for a 3D MR image: Centerlines of the arteries (left) and tubular shapes (right).