Three-Dimensional Reconstruction of Coronary Tree using Intravascular Ultrasound Images

O Pujol, C Cañero, P Radeva, R Toledo, J Saludes, D Gil, JJ Villanueva, J Mauri*, B Garcia*, J Gomez*, A Cequier*, E Esplugas*

Centre de Visió per Computador/Departament d' Informàtica, UAB Bellaterra, Barcelona, Spain
*Departament d' Hemodinàmica, Hospital de Bellvitge, Barcelona, Spain

Abstract

In this paper we propose a new Computer Vision technique to reconstruct the vascular wall in space using a deformable model-based technique and compounding methods, based in biplane angiography and intravascular ultrasound data fusion. It is also proposed a general-purpose three-dimensional guided interpolation method. The three dimensional centerline of the vessel is reconstructed from geometrically corrected biplane angiographies using automatic segmentation methods and snakes. The IVUS image planes are located in the three-dimensional space and correctly oriented. A led interpolation method based in B-Surfaces and snakes is used to fill the gaps among image planes

1. Introduction

IntraVascular UltraSound (IVUS) images present a unique tool to visualize the lumen and vessel wall that makes possible to study and diagnose the arterosclerotic plaque in the vessel. Nevertheless, the longitudinal measurements of the plaque and its morphology along the vessel need an analysis of the 3D frame that contains important details about the position and orientation of different structures of the vessel and plaque. Therefore, the precise 3D reconstruction of the vessel form multiple IVUS image frames is of great clinic interest.

Deformable models represent a very useful technique to reconstruct the lumen and vascular wall and allow to model the vessel as an elastic and dynamic structure that adjust to the image features from different IVUS planes in order to reconstruct the vessel in space. Once the vessel contours are determined, compounding methods are applied to interpolate the data from the IVUS images. To determine the exact position and orientation of the IVUS planes in space and to complete the 3D reconstruction of the vascular structures, a 3D reconstruction of the vessel centerline is obtained from biplane angiography.

Previous works has been done to improve the IVUS imaging features, von Birgelen et al.[1] or Prause and Dejong et al.[7]. The first one dealt with the IVUS images as a stack with all its limitations of lack of 3D information. The second one try to reconstruct the 3D vessel and propose a method to attain it, but is based on Frenet frame approaches. Taking into account all those works and projects, we propose another reconstruction methodology.

2. 3D reconstruction methods

In this section, we discuss how to solve some of the problems of IVUS images that arise in the reconstruction process. Let us take some of the previous works results. First of all, in von Birgelen et al.[1] some problems intrinsic to IVUS images are shown such as changing size when a speed-constant pull-back is performed. They introduce the concept of an ECG-gated pullback in order to achieve nearly unaffected images, this first correction can be taken for a better performance of the three dimensional reconstruction system. The main problem with this system is that for a reliable reconstruction the same phase images must be used, causing a loss of information (the rest of images are not reliable in the sense that the sizing can not be trusted).

2.1. Three-dimensional reconstruction of the vessel trajectory

The first problem that arises with angiographies is the vessel detection. Angiographies are not particularly well suited for segmentation due to their inherent noise. The second, but not less important one, is the point matching along the trajectory of the desired vessels projections. In order to be able to reconstruct the three-dimensional skeleton of the vessel, a correspondence between pairs of points in each of the angiographies from the biplane images must be solved.

To solve the segmentation problem a valley-ridge method is used [5]. Once the segmentation has been done a B-Snake performs the semi-automatic detection and the point matching of the desired vessel centerline.

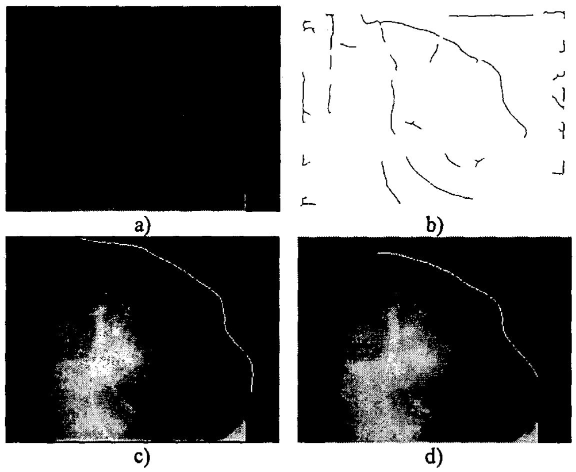

Figure 1. a) Original angiography image. b) Vessel detection using valley-ridges methods. Fig. 1.c,d illustrates the adaptation of a snake to the vessel centerline detected in figure b).

Once those two problems have been solved, the method for the exact reconstruction [4] of the vessel is as follows. First of all, and the most important step is to find the image acquisition system parameters, the *rotation* and *angulation* angles, the reference system location, the focus distances to each of the acquisition planes and magnification. This step is critical for an exact reconstruction. Once all the parameters have been retrieved, the exact position of the point in the space can be calculated. It is supposed to be in the intersection of the lines between the focal point and the point to be reconstructed in each of the angiographies, but as often, this would be the ideal case. What happens is that in real reconstruction those lines do not intersect each other, so the point of minimum distance to the crossing will be chosen as the candidate point in the 3D space.[3]

2.2. Solving the location problems

Our major concern in this section is to propose a method to find the 3D placement of the image planes. Some works has been made considering just geometrical constrains for the IVUS location. In those works Frenet frame based methods are used. However, when dealing with the Frenet frame approximation, some problems arise: [6]

1) the normal vector is not defined for linear segments or at inflection points.

2) the normal vector flips abruptly to the opposite direction around an inflection point.

3) for three-dimensional trajectories, the normal vectors can rotate excessively around the tangent vectors, causing unwanted twists.

4) the geometric approximation does not model the physical phenomena caused by the movement of the probe.

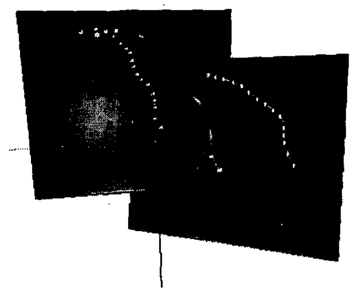

Figure 2. Three-dimensional reconstruction of the vessel trajectory.

To solve all these problems and those concerned with physical laws ruling the movement of the catheter, we propose a dual method based on geometrical and computer vision techniques.

The two main problems we address are the right position of the image planes in three-dimensional space and their accurate orientation. To solve the first problem a sweeping based method is proposed based solely in geometrical constraints. This method allows to cope with the 3 first problems due to the conventional approaches based on the Frenet frame. The result is a set of image planes with the right position but with wrong orientation. To solve this later problem an angular cross-correlation is used.

$$rotation = \max_{\theta:0\to 2\pi} \sum_{\varpi=0}^{2\pi} I_j(\varpi+\theta) I_{j+1}(\varpi)$$

where I represents the image plane j. If the rotation of a frame j respect to the frame $j+1$ is r, then r is such that the cross correlation rotation transformation

2.3. Splines and snakes

Sometimes it can be useful the representation of curves in a parametric form. Although low degree polynomials are computationally efficient and easy to work with, it is not usually possible to define a satisfactory curve using single polynomials. Instead it is customary to break the curve into some number of pieces called *segments*, so the whole curve is a piecewise polynomial curve. It is also desirable require to satisfy some continuity constraints at the joints, as derivability.

One of these representations is the B-Spline curves and surfaces. A particular property of this kind of curves is the *local control*, by which, we mean that altering the position of a single data point causes only a part of the curve around this point to change. These points are called *control points*. This property is particularly useful when recomputing the curve after a control vertex has been moved since only a small part of the curve has changed. This property has been proven very interesting when using snakes.

A snake is defined as a continuous curve that given an initial location begins to deform in order to get adjusted to certain features in the image [2][9]. The snake moves guided by *external forces* that push it towards the image features. These forces are derived from a potential field that is designed to propagate information about the available image features. Thanks to the external forces, the snake is attracted by image features to different extent depending on their strength and distance to the snake. On the other hand, the snake is not deformed in an arbitrary way. It moves under certain constraints on continuity and smoothness that do not allow the snake an unconstrained shape. These opposing constrains are called *internal forces* and are proportional to the elastic energy of the curve. The final goal of the snake is to minimize the accumulation of forces.

3. Guided interpolation

The new challenge to overcome is the fact that in the 3D space the vessel is like a continuous limb and images shows just a sampled section from it. Following these lines a new 3D interpolation method is developed which will aid in our reconstruction method. This interpolation method will be called *guided interpolation*, because it uses a priori 3D knowledge of the shape to interpolate. In our case we want to interpolate 3D data along a trajectory inside a shape of our choice. This shape is a three dimensional volumetric cylinder, but the method can be generalized easily to other shapes.

In order to create the volume or the surface, B-Splines will be used. *B-surfaces* are a good way for representing a surface. However, there must be a way to place that surface in the location we want in order to interpolate the data in a proper way. In this point snakes "come into play". The B-surfaces will be placed in an initial location and then they will be deformed to adapt to the desired features.

To exemplify this point, let us take the intravascular ultrasound images. In this case, we want to interpolate the vessel, plaque and lumen, so a cylinder shape must be chosen for the interpolation. Besides, the vessel is not a cylinder but close to it, that means that with our B-cylinder and the snakes mechanism, the cylinder will deform in a semiautomatic way in order to adapt to the features of the vessel. Once this has been accomplished, we will have a vessel-shape surface, which will be used for the interpolation.

As it has been shown in [9], B-surface is controlled by a serie of control points. In order to interpolate the data inside the B-surface a volume must be built. The solid can be thought as a set of surfaces sharing a common axe. This is easily done by calculating the gravity center point of the control points in each of the slices that controls the outer surface and create a new set of control points for the inner layers.[8]

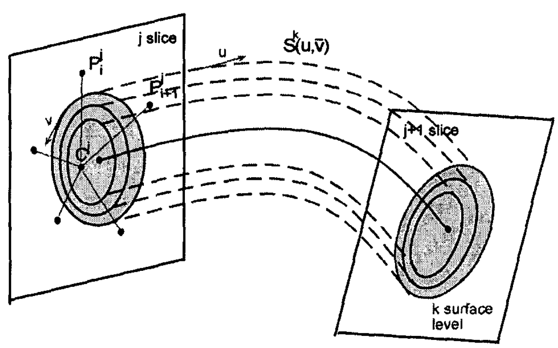

Figure 3. Parameters of the multi-surface spline interpolation method.

At this point we have a set of inner surfaces characterized by the fact that all of them follows the deformation of the outer one, but with the advantage of having to apply snakes to one surface instead of a volume. Now we have a solid cylinder parameterized by three variables, *{u,v,k}*, where, *u* is the parameter which let us move along the vessel, *v* is the parameter which let us move in cross-sectional cut of the vessel, and *k* allows us to change the surface.

Once the surfaces have been found, the next step is to interpolate along the isoparametric curves of each of the surfaces, this is done by maintaining *{v,k}* parameters constant and applying an interpolation function along the trajectory of the delimited curve. This step is repeated for all v and k in the set of meaningful parameters. In each isoparametric curve, the interpolation is made among the pixels to fill the gaps without grey value.

For each level in the multi-surface, let $S^k(u,v)$ be the cylindrical surface in level k. The isoparametric curves characterized by $v=const$ and let $\Pi^j(x,y,z)$ be the image plane j.

$$t_j^k(v) = \Pi^j(x,y,z) \cap S^k(u,v), \forall v = 1 \ldots CtrlPts$$

Then for all u, so that $t_j^k(v) < S^k(u,v) < t_j^{k+1}(v)$

$$S^k(u,v) = f(value(t_j^k), value(t_j^{k+1}), u), \forall v = const.$$

with f(.) a interpolation function. We chose a linear interpolation for sake of simplicity. The whole method is fully described in [8].

4. Results

Three kind of views are presented here to show the results of the interpolating method. The first view is a render of the real data cube once the image planes have been properly allocated and the reconstruction and interpolation has been done (fig. 4). The second one is an ordinary cross sectional view of the data interpolated in the same sense as IVUS are (fig. 5 a,b). And the third view is a longitudinal section along the trajectory of the curve (fig. 5 c,d).

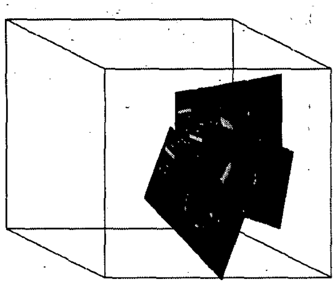

Figure 4. Three dimensional reconstruction of the vessel.

5. Conclusions

A new general method of three dimensional data interpolation is proposed and applied to the reconstruction of the coronary tree using Intravascular Ultrasound and Angiographies data fusion. The resulting quality of the interpolation and reconstruction is well suited for automatic segmentation, volume measurements, information extraction and data compression and storage.

Acknowledgements

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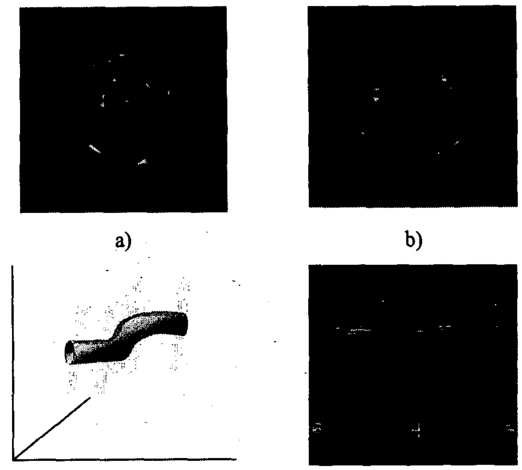

Figure 5. a) Original image. b) Cross sectional cut of the interpolation data. c) Image illustrating how the transversal cut is done. d) Longitudinal section following the trajectory of the vessel. Note the three vertical planes displayed and the interpolated data.

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Address for correspondence.

Oriol Pujol Vila
Centre de Visió per Computador, Edifici O, Campus UAB,
08193 Bellaterra (Cerdanyola), Barcelona, Spain
e-mail: oriol@cvc.uab.es