# Deformable Templates for Plaque Thickness Estimation of Intravascular Ultrasound Sequences*

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**Abstract**

Deformable Template models are first applied to estimate the wall of coronary arteries in intravascular ultrasound sequences. Two circular templates (inner and outer) are used to localise and track an image zone that contains the atheroma plaque. Moreover robust wall thickness estimations are derived from this analysis.

*Key Words* : Intravascular ultrasound, deformable templates, tracking.

# 1 Introduction

## 1.1 Intravascular Ultrasound Sequences

Intravascular Ultrasound is a recent technique that provides a source of high quality medical imaginery for precisely quantifying arterial obstruction and in consequence for the assessment of coronary interventions (bypass, balloon angioplasty, stent deployment or atherectomy) [7]. A catheter with a transducer mounted on its tip is placed inside the artery and rotated to generate, by emitting pulses of ultrasound and receiving echoes, planar cross-sections corresponding to the traversed arterial structure. In the output obtained (see Fig. 1) the center of the catheter is taken as origin of the new reference system and the image typically reveals three types of echo: *vessel lumen* (dark echoes), *plaque* (soft grey echoes) and *vessel wall* (white echoes). The analysis of the type of plaque helps specialists to choose the best interventional modality.

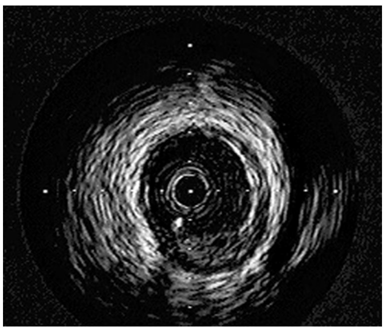

Figure 1: Slice obtained by intravascular ultrasound

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## 1.2 Previous Approaches for Representation and Analysis

The problem of automatically obtaining suitable representations of the intravascular structure from two dimensional slices has been addressed in the past. These models must be suitable for extracting and analysing quantitative features, in order to help both in diagnosis and intervention control. The most significant approaches developed to date are the following:

1. *Rendering Stacked Slices* [6], [2], [5].
   (a) Static geometry and non-curved vascular structure are assumed. Visualisations are based on slice stacking. The problem of this approach is that the obtained geometry is usually unrealistic and distorted.
   (b) Extended approaches [4] introduce curved, but still static, structure.
2. *Introducing Snakes:* [1]
   (a) Spatio-temporal structure extraction by application of deformable models is addressed in the context of angiography (tracking of the 2D projections of the lumen).
   (b) Deformable models allow to obtain the actual dynamic geometry.
3. *Integration with Angiography:* [3]
   (a) First step consists of obtaining, by variational stereo-matching based on snakes, the three-dimensional angiographic structure.
   (b) This information is integrated, using the spatio-temporal synchronisation of the transducer and the angiography, with the transversal slices for generating the visualisation by volume rendering based on interpolation.
   (c) In this sense slice positioning is guided by *landmarks* corresponding to branching points located at the arterial tree.

In our opinion future approaches must address the problem of analyse the internal structure of the slices in order to detect plaque (or to bound the zone where the plaque could be) or to improve clinical procedures (i.e. angioplasty).

## 1.3 The Proposed Approach: Outline of the Paper

The approach presented in this paper is based on *Deformable Templates*, [8], [9]. We introduce improvements in *Wall Tracking:* given the morphology of the vessel walls (typically circular or elliptical), the problem of wall tracking can be addressed by using deformable templates. Wall tracking is interesting in, at least, two cases:

1. *Locating plaque:* once the wall is identified the zone where the plaque can be located is bounded . In consequence a texture driven local search, from the wall to the center of the vessel, can extract the actual boundary of the plaque in order to obtain the thickness of the lesion. Tracking experiments with circular templates are presented in Section 2.2.

2. *Control of medical procedures:* In the context of intravascular ultrasound images, one of the medical procedures in which the use of non-rigid tracking can introduce some level of automation is the *Coronary Angioplasty*. Such procedure consists of placing a small balloon at the catheter end in order to dilate the plaque that obstructs the artery

(see Figs. 2, 3 and 4). Balloon inflating induces a pressure that compresses and slashes the plaque and reduces or eliminates the arterial stenosis. Then wall shape can become elliptical in these conditions.

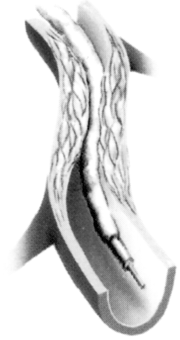

Figure 2: Introduction of the catheter with a balloon.

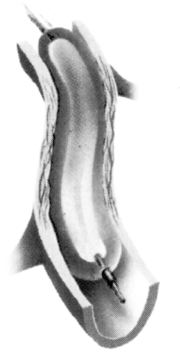

Figure 3: Balloon deployment to compress and fracture the plaque.

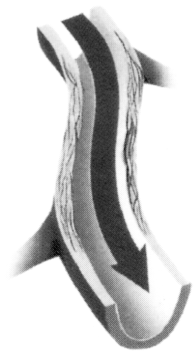

Figure 4: Plaque extinction, stenosis clearing and flow normalization.

## 2 Tracking based on Deformable Templates

A *single deformable template model* is defined by a *geometrical structure* $g_{\mathcal{D}}(\Theta)$ (circle, parabola, ellipse, segment, etc.), where $\Theta$ is a vector of relevant parameters and $\mathcal{D}$ is the spatial domain. This structure reacts to a specific *image model* or *potential field* $\Psi(u, v)$. Reaction behavior (dynamics) is established by an *energy function* $\mathcal{E}(\Theta)$. In this way optimal positioning of the structure over the potential is characterized by a minimum of $\mathcal{E}(\Theta)$ that is usually found by gradient descent. In this section we present the application of a circular template to track the inner wall of the artery.

### 2.1 Image Model: Potential Fields

Given the high rate of non-correlated noise generated by ultrasounds it is necessary to apply a strong filter in order to obtain a compact potential. As we need to bound the zone where the plaque can be first we apply grey thresholding. This is followed by a morphological closing that clears local structures that can introduce distortions, and, finally, we apply a Gaussian filter to smooth the geometry of the gradient. The result is shown in Fig. 5 whereas Fig. 6 contains the filtered gradient. Both images will be used as potential fields in our experiments.

### 2.2 Circular Templates: Wall Tracking and Initialisation

Circular Templates (CT) were first proposed in [10] as a part of a method to find the skeleton of a binary shape[1] with certain levels of noise tolerance. Let be $(x, y)$ the center position, $r$ the radius and $\mathcal{D}$ the circular domain bounded by the CT. We consider a binary image as potential: the function $I(x, y)$ returns 1 if the pixel is inside the template domain, and

[1]This model was originally named The Free-Travelling Circle.

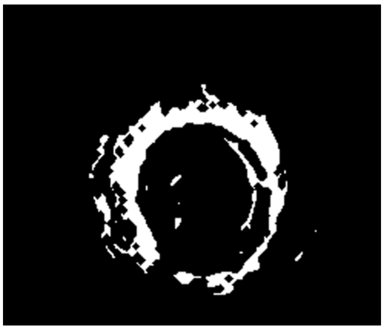

Figure 5: Binary potential fields after filtering.

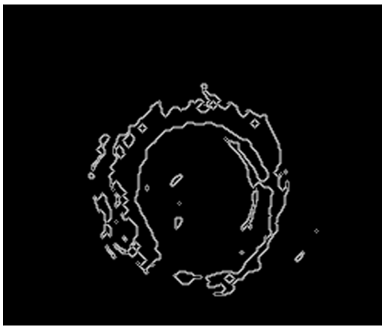

Figure 6: Gradient potential after Gaussian filtering.

otherwise returns 0. The dynamic of the CT is defined by the function:

$$\mathcal{E}(x,y,r) = \iint_{\mathcal{D}} \mathcal{E}_{shape}(u,v,r) * \mathcal{E}_{image}(x+u,y+v)\,du\,dv + \mathcal{E}_{noise}(r) \tag{1}$$

where:

$$\mathcal{E}_{shape}(x,y,r) = (r - \sqrt{x^2+y^2}) \qquad \mathcal{E}_{image}(x,y) = \mathcal{I}(x,y) \qquad \mathcal{E}_{noise}(r) = -\frac{\alpha}{a} r^a \tag{2}$$

and its optimum is obtained by gradient descent.

**Dynamics of the center**

$$\begin{pmatrix} \frac{dx}{dt} \\ \frac{dy}{dt} \end{pmatrix} = -\begin{pmatrix} \frac{\partial \mathcal{E}}{\partial x} \\ \frac{\partial \mathcal{E}}{\partial y} \end{pmatrix} = \int_{\Gamma \cap \mathcal{D}} (r - \sqrt{u^2+v^2})(-\nabla \mathcal{I})\,ds \tag{3}$$

Let be $\Gamma$ the shape contour and $\nabla \mathcal{I}$ the gradient. Then $-\nabla \mathcal{I}$ can be considered as a force of opposite direction that is weighted by $r - \sqrt{u^2+v^2}$. The CT motion will converge when all the forces inside the CT are balanced (See Fig. 7).

**Dynamics of the radius**

$$\frac{dr}{dt} = -\frac{\partial \mathcal{E}}{\partial r} = -\iint_{\mathcal{D}} \mathcal{I}(x+u,y+v)\,du\,dv + \alpha r^{a-1} \tag{4}$$

The first term is the white pixels area inside the CT domain (See area $A$ in Fig. 7) and represents a force that makes the radius decrease. The second term is the expansion force of the CT. The CT will converge when the area $A$ will be equal to $\alpha r^{a-1}$. The $\alpha$ and $a$ parameters determine the tolerated noise level. Typical values used are: $1 < a < 3$ and $0 < \alpha < 20$.

We have applied this basic model to locate an estimate of the inner and outer walls. Results are show in Fig. 9. The spatio-temporal structure obtained is shown, by rendering and interpolation, in Fig. 8. Arterial tightness can be observed at the bottom example. This approach is also useful for robust initialisations of other templates (i.e. elliptical). This will simplify tracking of angioplasty procedures.

## 3 Conclusions and Future Developments

This paper first introduces the use of deformable templates for estimating wall thickness, by tracking the inner and outer walls, of vessels in intravascular ultrasound sequences.

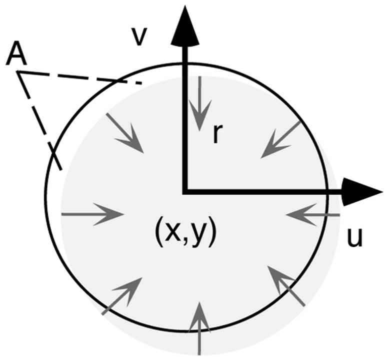


Figure 7: CT: Noise ($A$) and gradient forces

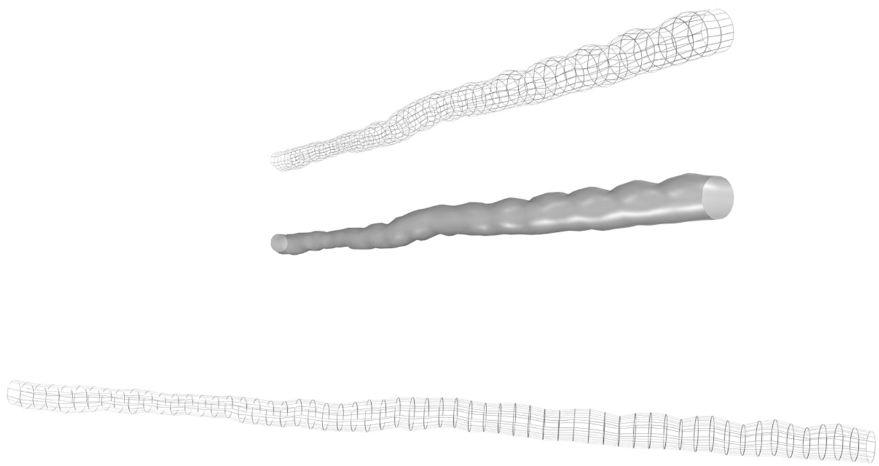

Figure 8: Rendered sequences of inner radius.

Tracking is applied by using a simple circular template along the transducer path. Noise parameters are previously tuned. This framework is useful as a basis of geometric analysis of the sequence. Future work includes: automatic learning of noise parameters, the improvement of the quality of the fields (i.e. solving boundary discontinuities) and, finally, extensive application of Principal Component Analysis to extract constraints that accurately define clinical quality criteria of the angioplasty process.

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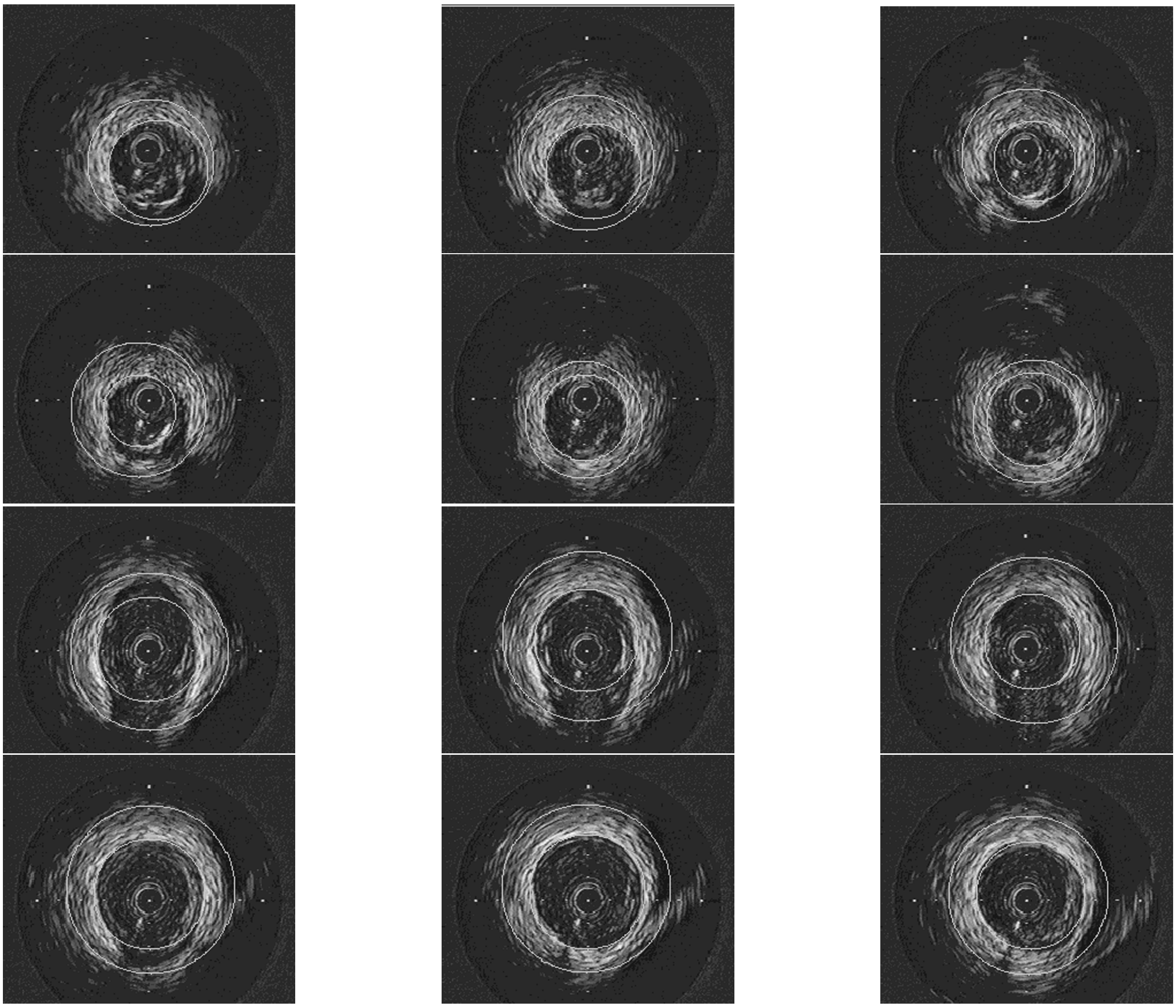

Figure 9: Tracking results in angioplasty.


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