Proceedings of the International MultiConference of Engineers and Computer Scientists 2008 Vol I
IMECS 2008, 19-21 March, 2008, Hong Kong

Fuzzy Rule-based Boundary Extraction of Plaque in Intravascular Ultrasound Image

Ryosuke Kubota, Shohei Ichiyama, Noriaki Suetake, Eiji Uchino, Genta Hashimoto, Takafumi Hiro, and Masunori Matsuzaki *

Abstract—**In this paper, we propose a fuzzy rule-based boundary extraction method for a plaque in an intravascular ultrasound (IVUS) image. In the present method, a plaque boundary to be extracted is piecewise approximated by the polynomials inferred by fuzzy rules. The coefficients of the polynomials are determined by the weighted least square method using the separability measure obtained from the IVUS image. The proposed method achieves a precise and noise-robust extraction of the plaque with use of a small number of seed points and without any time-consuming iterative processes. The validity and the effectiveness of the proposed method have been confirmed by applying it to the boundary extraction problem of the plaque in the IVUS image.**

Keywords: ***boundary extraction, fuzzy inference, intravascular ultrasound (IVUS), polynomial-interpolation, separability***

1 Introduction

A backscattered intravascular ultrasound (IVUS) method is one of the tomographic imaging techniques. The IVUS method provides a real-time cross sectional image of a coronary artery in vivo, and is effective for a diagnosis of the acute coronary syndromes (ACS) [1]. In the diagnosis of ACS, a precise boundary extraction of a plaque is required.

In the conventional boundary extraction methods, medical doctors are asked to put the several seed points on the IVUS image. Those points are then interpolated smoothly by a spline function [2],[3]. However, its precision is considerably affected by a number of the seed points and/or a distance between those points.

On the other hand, the conventional methods which are based on optimum search algorithms have been proposed so far [4]. However, those methods need some iterative processes and take big computing time. For the practical plaque boundary extraction in clinic, it is preferable to extract quickly its boundary by a small number of seed points in a short time.

In this paper, to cope with those problems, we propose a new fuzzy rule-based boundary extraction method, which achieves a precise and robust extraction of a plaque in the IVUS image. In the proposed method, a boundary to be extracted is piecewise approximated by polynomials inferred by fuzzy rules [5]. The coefficients of the polynomials are determined by the weighted least square method using the separability of image, which is a kind of statistical measure for the edge detection of the image [6].

The proposed method employs not only the information of the seed points but also the separability information obtained from the IVUS image. It performs a fine extraction of a plaque boundary without any time-consuming iterative processes.

The validity and the effectiveness of the proposed method have been verified by applying it to the practical boundary extraction problem of a plaque in the IVUS image.

2 IVUS Image and Conventional Boundary Extraction Method

2.1 Intravascular ultrasound (IVUS) image

The radiofrequency (RF) signal is emitted from an ultrasound probe mounted in a catheter. The transmitting frequency is 40 MHz. Fig.1 shows an example of the IVUS image. The IVUS image is constructed by the RF signal.

The probe rotates at the tip of the catheter inserted in the arterial lumen. The probe also receives an IVUS RF signal reflected from the plaque and the vascular wall. The RF signal is sampled at 400 MHz.

The sampled RF signal is transformed into intensity. The intensity signals in all radial directions are formed as a tomographic cross-sectional image of a coronary artery as shown in Fig.1. This image is called "B-mode image."

*Manuscript received December 25, 2007. This work was supported in part by "Knowledge Cluster Initiative" funded by Japan Ministry of Education, Culture, Sports, Science and Technology for 2004-2009.

R. Kubota, N. Suetake, and E. Uchino are with the Graduate School of Science and Engineering, Mathematics and Complex Systems Science, Yamaguchi University, 1677-1 Yoshida, Yamaguchi 753-8512, Japan (phone: +81-83-933-5699; fax: +81-83-933-5699; e-mail: uchino@yamaguchi-u.ac.jp).

S. Ichiyama is with the Faculty of Science, Yamaguchi University, 1677-1 Yoshida, Yamaguchi 753-8512, Japan.

G. Hashimoto, T. Hiro, and M. Matsuzaki are with the Graduate School of Medicine, Yamaguchi University, 1-1-1 Minamikogushi, Ube 755-8505, Japan.

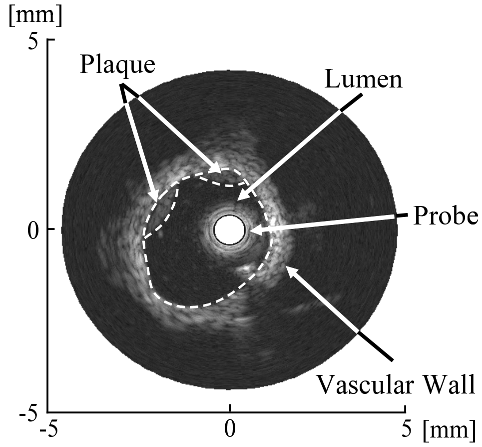


Figure 1: An example of IVUS B-mode image. The dotted lines show the boundaries of plaque, arterial lumen and vascular wall.

2.2 Conventional boundary extraction method by using spline function

Here we consider two boundaries to be extracted. One is an inner boundary between the lumen and the plaque, and the other is an outer boundary between the plaque and the vascular wall as shown in Fig.1.

The conventional method using spline function needs several seed points. The seed points are to be marked directly on the IVUS image by a medical doctor. Those points are then interpolated smoothly by a parametric spline function [3]. In this interpolation, not only the marked seed points but also the marking order of the seed points are taken into account. However, its precision is considerably affected by a number of the seed points and/or a distance between those points. Moreover it is difficult to mark precisely the seed points on the true boundary in the noisy IVUS image.

3 Proposed boundary extraction method based on fuzzy rules

In this paper, we propose a novel fuzzy rule-based boundary extraction method using the separability of image.

3.1 Data structure

In the proposed method, the IVUS image shown in Fig. 1 is transformed into the image in the Cartesian system as shown in Fig.2. The vertical axis corresponds to the distance from the probe located at the center of the IVUS image. The horizontal one corresponds to the angle in clockwise radial direction. The angle in Fig.2 starts from the 3-o'clock direction of the IVUS image of Fig.1.

Fig.2 consists of 256 lines in radial direction, and one line consists of 2,048 pixels. The resolution of distance and angle are $1.95\mu m$/pixel and $1.41°$/line, respectively.

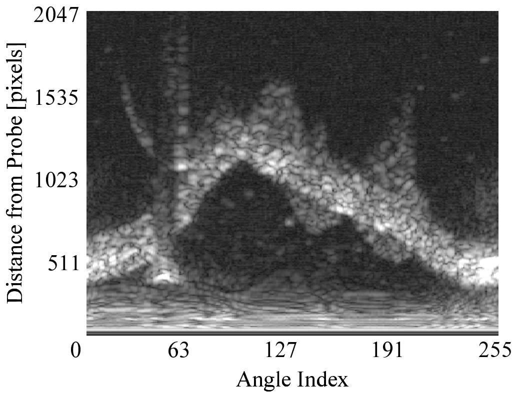


Figure 2: IVUS image of Fig.1 transformed into the Cartesian system.

3.2 Separability for boundary detection

The proposed method employs a statistical discriminant measure of separability of image [6] for the precise detection of the boundary of a plaque. The separability η_{ij} for the pixel (i, j) shown in Fig.3(a) is defined by:

$$\eta_{ij} = \frac{n_A(\bar{I}_A - \bar{I}_m)^2 + n_B(\bar{I}_B - \bar{I}_m)^2}{\sum_{k=1}^{S}(I_k - \bar{I}_m)^2}, \tag{1}$$

where n_A and n_B represent a number of the pixels in regions A and B, respectively. $\bar{I}_A$ and $\bar{I}_B$ represent averages of the intensities in regions A and B. $\bar{I}_m$ stands for the average of the intensities in the combined regions A and B. S and I_k are a number of the pixels and a intensity of the k-th pixel in the combined regions A and B. η_{ij} satisfies $0 \leq \eta_{ij} \leq 1$, and takes a large value when two regions are separated with each other.

Fig.3(b) shows the separability η_{ij} calculated for each pixel of Fig.2. When η_{ij} is large, the brightness assigned to the corresponding pixel becomes high. A line of white pixels with high brightness can then be a candidate of a boundary.

3.3 Proposed boundary extraction by use of fuzzy inference

We propose here a boundary extraction method which is based on the approximation of boundary by piecewise polynomials inferred by fuzzy rules.

In the first step, the seed points given in advance by a medical doctor are linearly interpolated in the Cartesian system as shown in Fig.4(a) by the thick dotted line. This interpolated curve is a primitive boundary. The search area for the extraction of the target boundary is specified in Fig.4(a) by the thin dotted lines.

In the proposed method, the boundary to be extracted is piecewise approximated by the polynomials in the Cartesian system according to a series of the following fuzzy if-then rules:

Rule 1: if x_i is A_1 then $u = f_1(x_i)$,

ISBN: 978-988-98671-8-8

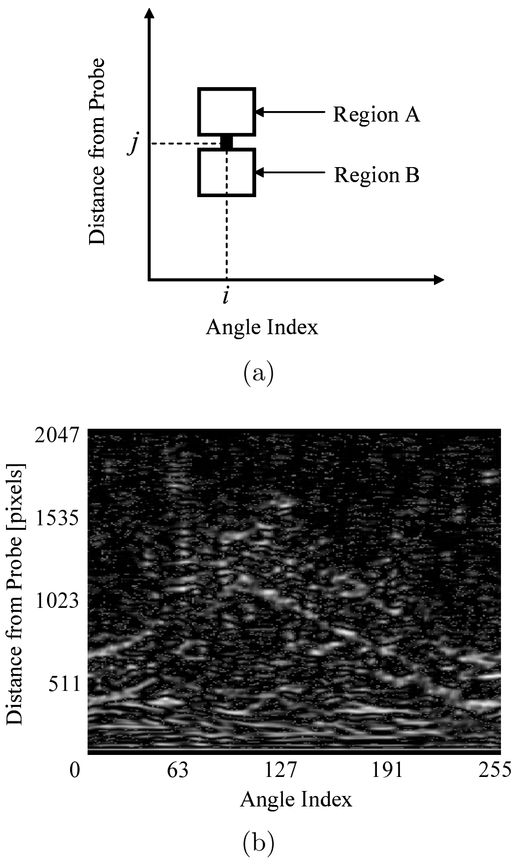


Figure 3: Calculation of the separability. (a) Regions to be used for the calculation of separability. (b)Separability of the IVUS image of Fig.2.

$$\vdots$$

Rule ℓ: if x_i is A_ℓ then $u = f_\ell(x_i)$,

$$\vdots$$

Rule L: if x_i is A_L then $u = f_L(x_i)$,

where A_ℓ is a fuzzy set whose membership function is μ_ℓ as shown in Fig.4(b). x_i corresponds to the angle index, and u corresponds to the location of the boundary from the probe in the Cartesian system. $f_\ell(x_i)$ is a polynomial defined by:

$$f_\ell(x_i) = \sum_{m=0}^{p} a_{(\ell,m)} x_i^m. \tag{2}$$

The ℓ-th rule thus stands for the piecewise approximation of boundary by polynomial in the interval $[t_{\ell-1}, t_{\ell+1}]$. The inferred value $\hat{y}(x_i)$ is given by [5]:

$$\hat{y}(x_i) = \frac{\sum_{\ell=1}^{L} \mu_\ell(x_i) f_\ell(x_i)}{\sum_{\ell=1}^{L} \mu_\ell(x_i)}. \tag{3}$$

When the complementary triangular functions are employed for the membership functions as shown in Fig.4(b), (3) is simplified as:

$$\hat{y}(x_i) = \mu_\ell(x_i) f_\ell(x_i) + \mu_{\ell+1}(x_i) f_{\ell+1}(x_i), \tag{4}$$

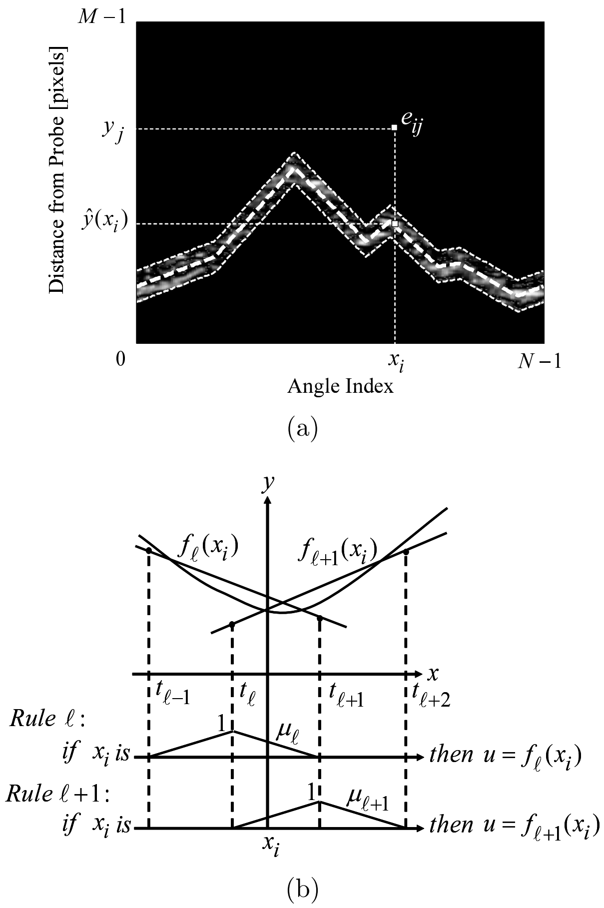


Figure 4: Polynomial assignments by fuzzy rules. (a) Boundary search area and a primitive boundary. (b) Membership functions assigned to each $f_\ell(x_i)$, and the fuzzy rules for the interval of x_i.

when x_i is in the interval $[t_\ell, t_{\ell+1}]$.

The optimum coefficients $a^*_{(\ell,m)}$ of (2) are determined with use of the weighted least square method by minimizing the following weighted error function:

$$E = \sum_{j=0}^{M-1} \sum_{i=0}^{N-1} \eta_{ij}^2 e_{ij}^2, \tag{5}$$

where e_{ij} is an error defined by:

$$e_{ij} = \{y_j - \hat{y}(x_i)\}. \tag{6}$$

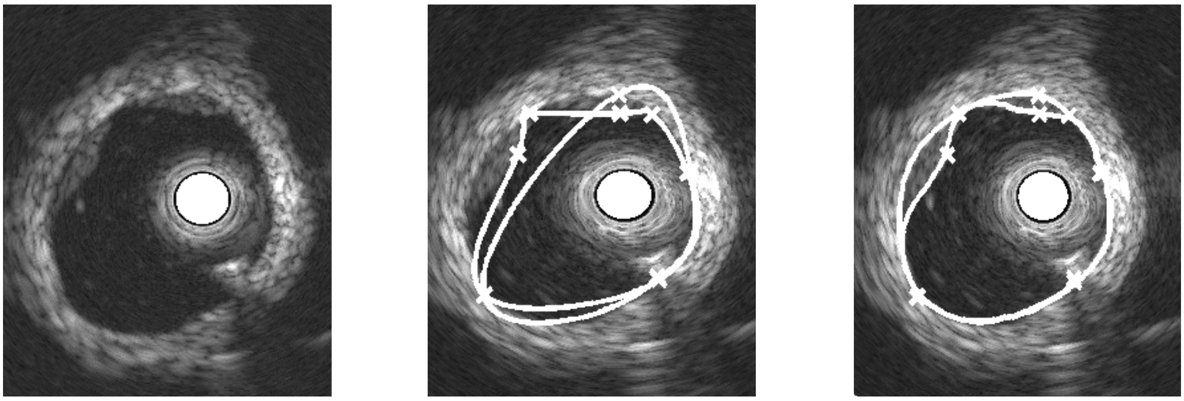
In this method, η_{ij} only inside the boundary search area shown in Fig.4(a) are taken into account as the weights of (5).

The proposed method performs a boundary extraction quickly without any time-consuming iterative processes.

4 Experimental Results

In order to verify the validity and the effectiveness of the proposed method, it is applied to the practical boundary extraction problem of the IVUS data shown in

ISBN: 978-988-98671-8-8



(a) (b) (c)

Figure 5: Boundary extraction results. × marks represent the seed points given by a medical doctor. (a) Enlarged IVUS image of Fig.1. (b) Extraction results by the conventional method using parametric spline-interpolation. (c) Extraction results by the proposed method.

Table 1: RMSE for boundary extraction results. One pixel corresponds to 1.95μm in the actual size.

	Inner Boundary	Outer Boundary
Conventional Method	60.4 (pixels)	187.4 (pixels)
Proposed Method	26.5 (pixels)	23.6 (pixels)

Fig.5(a) (enlarged image of Fig.1). The extraction results by the proposed method are compared with that of the conventional method using the parametric spline-interpolation.

In the proposed method, the membership functions of the fuzzy rules are assigned at even interval. The number of the fuzzy rules is L=11, and the order of the polynomial is p=1. The horizontal and vertical sizes of the region of Fig.3(a) for calculating η_{ij} are 7 and 30, respectively. The inner and the outer boundaries shown by the dotted lines in Fig.1 are independently extracted by the proposed method. The numbers of the seed points for the extraction of the inner and the outer boundaries are 7 and 4.

Figs.5(b) and (c) show the extraction results by the conventional and the proposed methods. These results show that the proposed boundary extraction method works very well compared with the conventional method. Moreover, the proposed method, by employing the separability of image, is robust for the extraction in the real IVUS image corrupted by the speckle noise.

Table 1 shows the root mean square error (RMSE) between the desirable boundary and the extracted one. It can be said that the proposed method gives a fine extraction of boundary better than the conventional method.

With these results, we conclude that the proposed method is effective for the plaque boundary extraction in the IVUS image.

5 Conclusion

We have proposed a new fuzzy rule-based boundary extraction method of a plaque which employs the separability information obtained from the IVUS image. In the proposed method, the boundary to be extracted is piecewise approximated by the polynomials inferred by fuzzy rules. The present method performs a precise and robust extraction of the boundary of a plaque in the IVUS image corrupted by the speckle noise.

Future work is the applications of the proposed method to the boundary extraction problems of various types of plaques and to other object extraction problems.

References

[1] Potkin, B.N., *et al.*, "Coronary artery imaging with intravascular high-frequency ultrasound," *Circulation*, 81, pp. 1575-1585, 1990.

[2] Ahlberg, J.H., *The theory of splines and their applications*, Academic Press, 1967.

[3] Ferguson, J., "Multivariable curve interpolation," *Journal of the Association for Computing Machinery*, 11, pp. 221-228, 1967.

[4] Sonka, M., *et al.*, "Segmentation of intravascular ultrasound images: A knowledge-based approach," *IEEE Trans. on Medical Imaging*, 14, pp. 719-732, 2006.

[5] Sugeno, M., *Fuzzy Control*, Nikkan Kogyo, Tokyo, 1988 (in Japanese).

[6] Fukui K., "Edge extraction method based on separability of image features," *IEICE Trans. on Inf. Syst.*, E78-D, pp. 1533-1538, 1995.