

## MIT Open Access Articles

*Fully automated lumen segmentation of intracoronary optical coherence tomography images*

The MIT Faculty has made this article openly available. **Please share** how this access benefits you. Your story matters.

**Citation:** L. S. Athanasiou et al. "Fully automated lumen segmentation of intracoronary optical coherence tomography images," Proceedings of SPIE 10133, Medical Imaging 2017: Image Processing, Orlando, Florida, United States, 24 February 2017, SPIE. © 2017 SPIE

**As Published:** <http://dx.doi.org/10.1117/12.2254570>

**Publisher:** SPIE

**Persistent URL:** <http://hdl.handle.net/1721.1/112763>

**Version:** Final published version: final published article, as it appeared in a journal, conference proceedings, or other formally published context

**Terms of Use:** Article is made available in accordance with the publisher's policy and may be subject to US copyright law. Please refer to the publisher's site for terms of use.



# PROCEEDINGS OF SPIE

[SPIEDigitalLibrary.org/conference-proceedings-of-spie](https://SPIEDigitalLibrary.org/conference-proceedings-of-spie)

## Fully automated lumen segmentation of intracoronary optical coherence tomography images

L. S. Athanasiou, Farhad Rikhtegar, Micheli Zanotti Galon, Augusto Celso Lopes, Pedro Alves Lemos, et al.

L. S. Athanasiou, Farhad Rikhtegar, Micheli Zanotti Galon, Augusto Celso Lopes, Pedro Alves Lemos, Elazer R. Edelman, "Fully automated lumen segmentation of intracoronary optical coherence tomography images," Proc. SPIE 10133, Medical Imaging 2017: Image Processing, 101332I (24 February 2017); doi: 10.1117/12.2254570

**SPIE.**

Event: SPIE Medical Imaging, 2017, Orlando, Florida, United States

# Fully automated lumen segmentation of intracoronary optical coherence tomography images

L. S. Athanasiou<sup>\*a,b</sup>, Farhad Rikhtegar<sup>a</sup>, Micheli Zanotti Galon<sup>c</sup>, Augusto Celso Lopes<sup>d</sup>, Pedro Alves Lemos<sup>c</sup>, Elazer R. Edelman<sup>a,b</sup>

<sup>a</sup>Institute for Medical Engineering and Science, Massachusetts Institute of Technology, Cambridge, MA, United States; <sup>b</sup>Cardiovascular Division, Brigham and Women's Hospital, Harvard Medical School, Boston, MA, United States; <sup>c</sup>Heart Institute (Incor), University of Sao Paulo, Sao Paulo, Brazil, <sup>d</sup>Monte Klinikum Hospital - Fortaleza, Fortaleza, Brazil.

## ABSTRACT

Optical coherence tomography (OCT) provides high-resolution cross-sectional images of arterial luminal morphology. Traditionally lumen segmentation of OCT images is performed manually by expert observers; a laborious, time consuming effort, sensitive to inter-observer variability process. Although several automated methods have been developed, the majority cannot be applied in real time because of processing demands.

To address these limitations we propose a new method for rapid image segmentation of arterial lumen borders using OCT images that involves the following steps: 1) OCT image acquisition using the raw OCT data, 2) reconstruction of longitudinal cross-section (LOCS) images from four different acquisition angles, 3) segmentation of the LOCS images and 4) lumen contour construction in each 2D cross-sectional image.

The efficiency of the developed method was evaluated using 613 annotated images from 10 OCT pullbacks acquired from 10 patients at the time of coronary arterial interventions. High Pearson's correlation coefficient was obtained when lumen areas detected by the method were compared to areas annotated by experts ( $r=0.98$ ,  $R^2=0.96$ ); Bland-Altman analysis showed no significant bias with good limits of agreement.

The proposed methodology permits reliable border detection especially in lumen areas having artifacts and is faster than traditional techniques making it capable of being used in real time applications. The method is likely to assist in a number of research and clinical applications - further testing in an expanded clinical arena will more fully define the limits and potential of this approach.

**Keywords:** Lumen detection, Optical Coherence Tomography, Image filtering.

## 1. INTRODUCTION

Optical coherence tomography [1, 2] is an invasive imaging modality, which provides high resolution cross sectional images of the coronary arteries. OCT uses light to capture micrometer-resolution allowing visualization of the vessel in high analysis: lateral and axial resolution is 20-90  $\mu\text{m}$  and 12-18  $\mu\text{m}$ , respectively [3]. Due to its unique imaging resolution, OCT is the method of choice in assessing high risk plaques, i.e. fibrous cap thickness [4] and in performing accurate lumen measurements [5]. Initially, OCT lumen detection [6] was performed manually; a time consuming process sensitive to intra and inter observer variability. These drawbacks led to implementation of automated and semi-automated methodologies detecting only vascular lumen borders [7-11] or detecting lumen border and estimating vessel plaque area [12].

Existing processing methodologies can detect lumen borders from 2D OCT images but over the pullback length used is power and time consuming, requiring simplifying assumptions challenged by many clinical scenarios and almost never performed in real time. Moreover, because of the 2D nature of the images none of these methods can accurately detect lumen contours in segments with complex geometries and noisy signals [13]. Existing methodologies can only roughly

---

\*[lambros@mit.edu](mailto:lambros@mit.edu); phone +1 617 715 4569.

estimate the lumen border in segments with side branches, and fail to segment the lumen when applied to images with artifacts such as multiple reflections, saturation and motion [13].

We overcome these drawbacks by imposing *spatial continuity* between adjacent frames and focusing on interframe point-point connectivity. By *spatial continuity* we refer to the imposition of a spatial continuum of sequential 2D OCT images which form longitudinal cross sectional OCT frames (LOCS): i.e. the lumen contours in any given frame fall within the contour continuum envelope imposed by adjacent frames. Leveraging *spatial continuity* restricts the segmentation process to physically realistic and anatomically relevant detection space and avoids time consuming fits that are prone to noise artifact and cannot deal with discontinuities. In brief (Fig. 1) we:

1. acquire sequential raw OCT data from the OCT pullback,
2. create four LOCS images of the full image where each LOCS is the image representation along a single projection spaced 45° apart,
3. detect the longitudinal contour of each LOCS and
4. place (translate) contour detection back onto each 2D OCT pullback frame image.

The innovative aspects of proposed lumen detection method are:

- entire detection of lumen borders throughout the OCT pullback in a fully automated manner requiring no user interaction,
- more accurate definition of lumen areas with potential disruptive artifacts as the spatial continuity of the vessel is involved in the segmentation procedure, and
- production of accurate, reliable and fast lumen detection which can be applied during real time OCT acquisition.

## 2. METHODS

The methodology uses as input raw OCT data to reconstruct LOCS images of the artery at four different angles and detects the lumen using LOCS (Fig. 1).

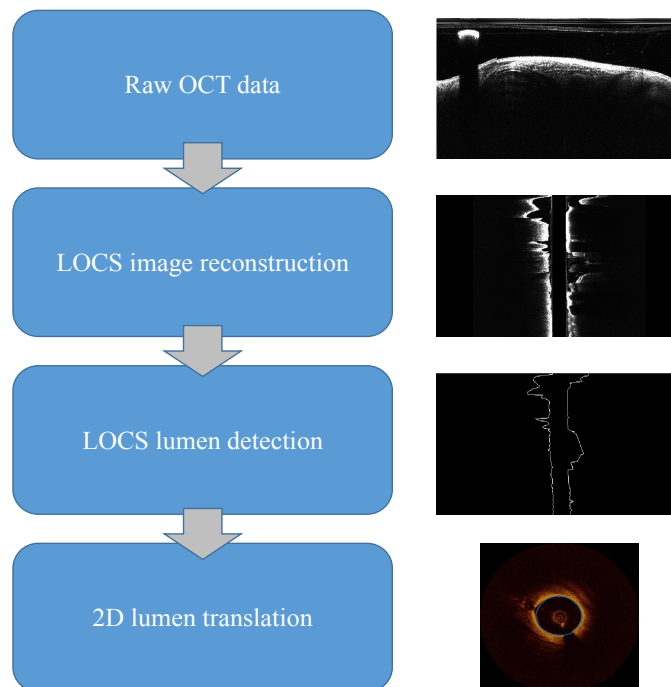


Figure 1: Flow chart of the proposed lumen detection method.

## 2.1 Image acquisition

The OCT equipment, for each cross section of the vessel acquires individual A-lines representing the image in polar intensity data  $I(r, \theta)$ , where  $r$  is the range dimension and  $\theta$  the acquisition angle. Each set of A-lines represent a single artery cross section in polar 2D space ( $I(r, \theta)$  grayscale image). The polar data are converted to Cartesian coordinates ( $I(i, j)$ ) with  $i = r \cos \theta$  and  $j = r \sin \theta$  and the true morphology of each OCT cross section is revealed.

## 2.2 LOCS reconstruction

The LOCS images represent sagittal cuts of the vessel. In order to reconstruct the LOCS images the 2D OCT cross sectional images (Cartesian) are used. Pixels that correspond to cross section lines of four different angles (0, 45, 90 and 135) for each 2D image, are sequentially stored and construct four different images, one for each angle. For the  $N$  2D images of the OCT pullback, with each image having dimensions  $L \times L$ , four different LOCS images are constructed having dimensions  $N \times L$ . Where Figure 2-a shows the cross section lines of the four different angles (0, 45, 90 and 135) and Figure 2-b shows the four constructed LOCS images.

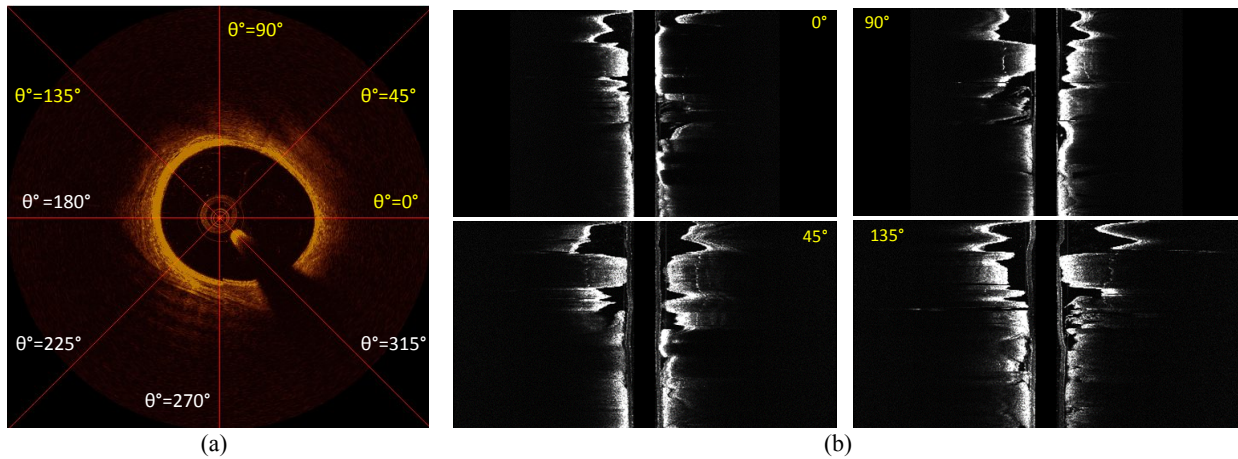


Figure 2: (a) The cross section lines at the four different angles (0, 45, 90 and 135) imposed over a 2D OCT image for a single pullback frame and (b) the 2D cross sectional LOCS at each of the four angular projections along the full pullback length.

## 2.3 Lumen detection

To detect the lumen border of each of LOCS image a smoothing filter [14] is applied to the LOCS images and then by using K-means algorithm [15] the borders are detected.

### 2.3.1 Bilateral filtering

A bilateral filter [14] is a non-linear smoothing filter used to preserve image edges and reduce noise. The intensity value of each pixel in the image is replaced by a weighted average of the intensity values from neighboring pixels, in a manner similar to Gaussian convolution. In contrast to Gaussian filters, the bilateral filter takes into account the difference in intensity values in the neighborhood and assigns relative weights based on intensity differences relative to each specific neighboring pixel. The consideration of multiple adjacent pixel achieves smoothing and weighting based on differences in intensity enhances edge detection.

A bilateral filter is defined as:

$$I'(x) = \frac{1}{W_p} \sum_{x_i \in W} I(x_i) f_r(\|I(x_i) - I(x)\|) g_s(\|x_i - x\|), \quad (1)$$

where  $W_p$  is the normalization factor:

$$W_p = \sum_{x_i \in W} f_r(\|I(x_i) - I(x)\|) g_s(\|x_i - x\|), \quad (2)$$

where  $I'$  is the filtered image,  $I$  is the initial image,  $x$  are the coordinates of the central pixel whose value is to be calculated and  $W$  is the window mask (neighborhood of the central pixel). Parameters  $f_r$  and  $g_s$  are the range of the Gaussian kernel for smoothing differences in intensities and the the spatial Gaussian kernel for smoothing differences in coordinates.

### 2.3.2 K-means algorithm

K-means [15] is an unsupervised learning algorithm able to solve a clustering problem [16]. The algorithm follows a simple procedure to classify the given data to a fixed a priori clusters  $k$ . K-means aims to partition a given a set of  $M$  observations  $\{x_1, x_2, \dots, x_M\}$ , into a fixed number of  $k$  clusters  $S = (S_1, S_2, \dots, S_k)$  in order to minimize the within-cluster sum of squares:

$$\arg \min_S \sum_{h=1}^k \sum_{x_h \in S_k} \|x_h - \mu_k\|^2, \quad (3)$$

where  $\mu_k$  is the mean of points in  $S_k$ .

By applying K-means algorithm to the LOCS images using  $k = 2$  clusters, the pixels are segregated into two different classes: vessel pixels and lumen/background pixels, establishing the segmented image  $I_{LOCS}^\theta$ . The first pixels to the left and right of the middle row of the  $I_{LOCS}^\theta$  image are lumen borders of the LOCS image.

### 2.4 Contour translation

The detected lumen borders in the four LOCS images are translated to their corresponding points in the 2D cross sectional images using the following algorithm:

1. set  $n = 1$ ,
2. while  $n \leq N$ :
3. for each of the four LOCS images having dimensions  $N \times L$ , find the two border points of the  $n$  row,
4. place the two points of the detected borders onto the 2D OCT image having dimensions  $L \times L$ ,
5. increase  $n$  to  $n + 1$  and go to step 2 to process the next pullback image.

The above described algorithm is shown schematically in Figure 3. In order to detect all the point of the lumen border a cubic spline function [17] is applied to these points (Figure 3-d).

## 3. DATASET

The population of this study consists of 12 elective patients who underwent a scheduled optical coherence tomography (OCT) restudy 18 to 24 months after percutaneous coronary stent implantation for the treatment of coronary artery disease. All OCT images were acquired by a commercial Fourier Domain OCT system (C7-XRTM OCT Intravascular Imaging System, St. Jude Medical, St. Paul, Minnesota) at Heart Institute of University of São Paulo (São Paulo, Brazil). Intracoronary nitroglycerine was initially administrated and the OCT catheter (C7 Dragonfly, St. Jude Medical, St. Paul, Minnesota) was advanced through a “0.014” guidewire to the distal target vessel. Images were acquired using a pullback speed of 20 mm/s during intra-coronary blood displacement by a contrast media injection (Iodixanol 320, Visipaque™, GE Health Care, Ireland) through the guiding catheter. All images were digitally stored for offline evaluation and subsequent stent and vessel analysis.

613 images were extracted randomly from OCT pullbacks acquired from ten patients undergoing coronary arterial intervention and contours delineated manually by expert clinicians blinded to patient information. Algorithm performance was determined using the expert detection as gold standard: Pearson’s correlation coefficients between the two determinations was computed and Bland-Altman analysis was conducted (Figure 4).

## 4. RESULTS AND DISCUSSION

High Pearson’s correlation coefficient was obtained when lumen areas detected by the proposed methodology were compared to areas annotated by experts ( $r=0.98$ ,  $R^2=0.96$ ); Bland-Altman analysis showed no significant bias with good limits of agreement.

The proposed methodology permits reliable border detection especially in lumen areas having artifacts, and is faster than traditional techniques making it capable of being used in real time applications. The methodology is based on the analysis of the OCT images from actual patients undergoing arterial intervention, representing real-world clinical applications, and was validated using the estimations of an expert observer as gold standard. The method is likely to

assist in a number of research and clinical applications. However further validation and testing in an expanded clinical arena will more fully define the limits and potential of this approach.

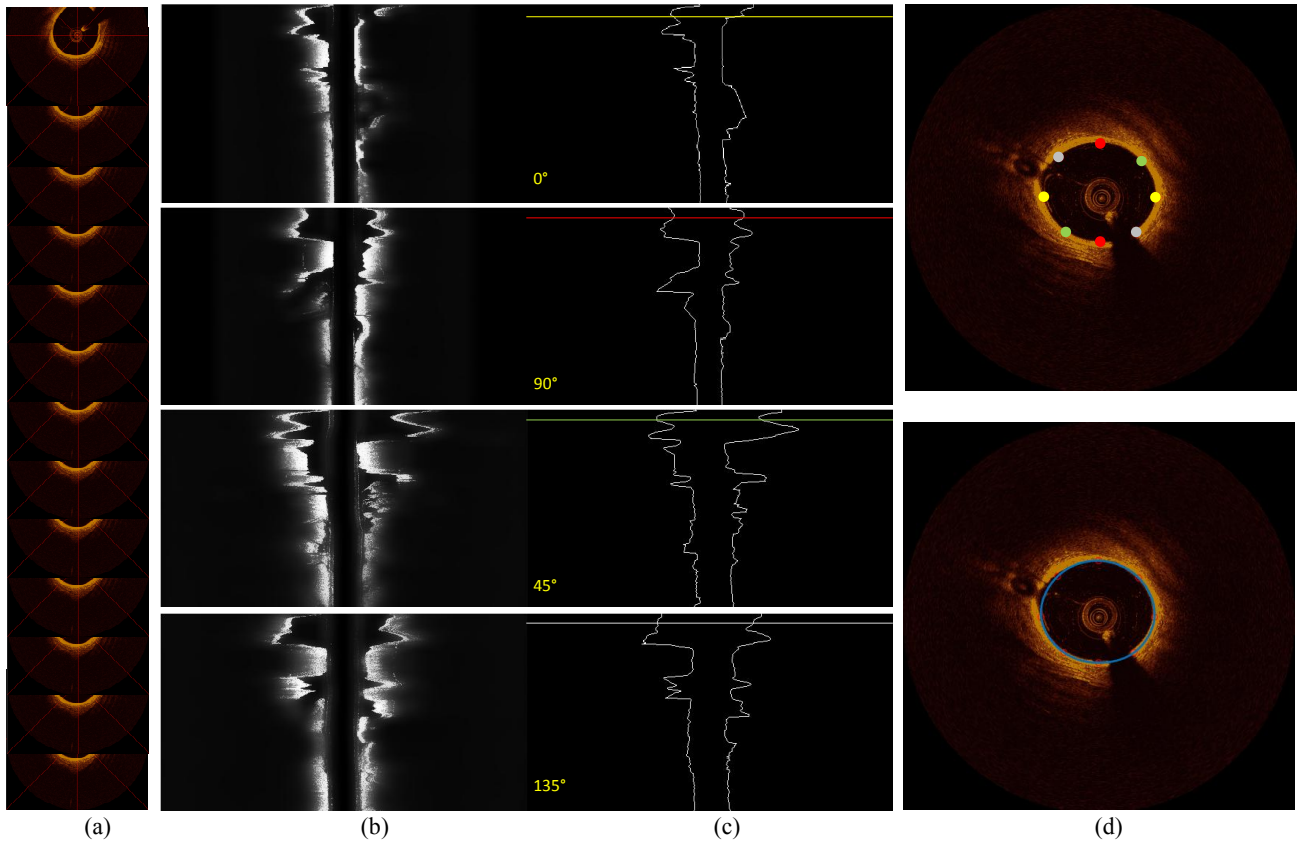


Figure 3: The proposed lumen detection methodology: (a) initial OCT images, (b) four constructed LOCS images one for each angle: 0, 45, 90 and 135, (c) segmented LOCS images and (d) lumen detected in the 2D OCT images based on the LOCS segmentation.

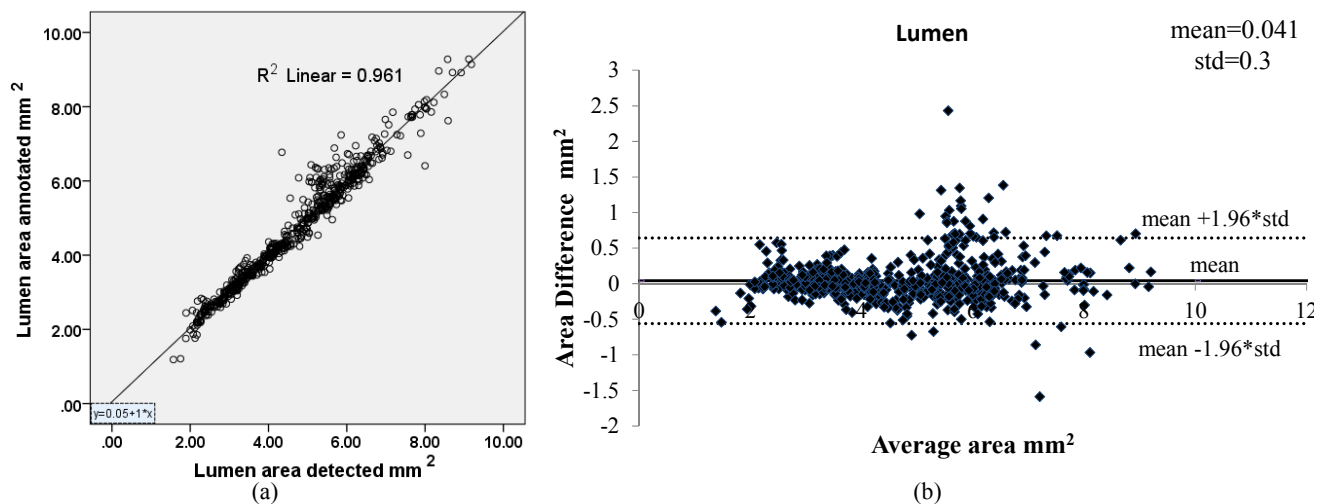


Figure 4: (a) Regression analysis plot between the lumen areas detected by our methodology and annotated by the experts and, (b) Bland and Altman analysis plot for the lumen areas detected by our methodology and annotated by the experts.

## 5. CONCLUSIONS

We present a fully automated segmentation of lumen borders using intracoronary OCT images. The method is based on reconstructing and processing LOCS images which represent the sagittal projections of a coronary vessel at a specific angle. This method advances the state-of-the-art and can detect the lumen borders of all the images in an OCT including segments at bifurcations and with imaging artifacts. The efficiency of the developed method was evaluated using 613 annotated images from OCT pullbacks acquired from ten patients at the time of coronary arterial interventions. Such a real time, high fidelity processor can readily be implemented into clinical practice and imaging instrumentation.

## ACKNOWLEDGMENTS

This work was part funded by a Postdoctoral Fellowship at Harvard Medical School awarded to LA from the George & Marie Vergottis Foundation and R01 GM 49039 from the US National Institutes of Health to ERE.

## REFERENCES

- [1] E. Regar, A. M. G. van Leeuwen, and P. Serruys, [Optical Coherence Tomography in Cardiovascular Research] Informa Healthcare, United Kingdom(2007).
- [2] F. Prati, E. Regar, G. S. Mintz *et al.*, "Expert review document on methodology, terminology, and clinical applications of optical coherence tomography: physical principles, methodology of image acquisition, and clinical application for assessment of coronary arteries and atherosclerosis," *European Heart Journal*, 31(4), 401-415 (2010).
- [3] H. G. Bezerra, M. A. Costa, G. Guagliumi *et al.*, "Intracoronary Optical Coherence Tomography: A Comprehensive Review Clinical and Research Applications," *Jacc-Cardiovascular Interventions*, 2(11), 1035-1046 (2009).
- [4] J. Hou, L. Xing, H. Jia *et al.*, "Comparison of Intensive Versus Moderate Lipid-Lowering Therapy on Fibrous Cap and Atheroma Volume of Coronary Lipid-Rich Plaque Using Serial Optical Coherence Tomography and Intravascular Ultrasound Imaging," *American Journal of Cardiology*, 117(5), 800-6 (2016).
- [5] N. Gonzalo, P. W. Serruys, H. M. Garcia-Garcia *et al.*, "Quantitative ex vivo and in vivo comparison of lumen dimensions measured by optical coherence tomography and intravascular ultrasound in human coronary arteries," *Rev Esp Cardiol*, 62(6), 615-24 (2009).
- [6] H. Yabushita, B. E. Bouma, S. L. Houser *et al.*, "Characterization of human atherosclerosis by optical coherence tomography," *Circulation*, 106(13), 1640-5 (2002).
- [7] K. Sihan, C. Botha, F. Post *et al.*, "Fully automatic three-dimensional quantitative analysis of intracoronary optical coherence tomography: method and Validation," *Catheter Cardiovasc Interv*, 74(7), 1058-65 (2009).
- [8] S. Tanimoto, G. Rodriguez-Granillo, P. Barlis *et al.*, "A novel approach for quantitative analysis of intracoronary optical coherence tomography: high inter-observer agreement with computer-assisted contour detection," *Catheter Cardiovasc Interv*, 72(2), 228-35 (2008).
- [9] S. Tsantis, G. C. Kagadis, K. Katsanos *et al.*, "Automatic vessel lumen segmentation and stent strut detection in intravascular optical coherence tomography," *Med Phys*, 39(1), 503-13 (2012).
- [10] G. J. Ughi, T. Adriaenssens, K. Onsea *et al.*, "Automatic segmentation of in-vivo intra-coronary optical coherence tomography images to assess stent strut apposition and coverage," *Int J Cardiovasc Imaging*, 28(2), 229-41 (2012).
- [11] C. Y. Ahn, B. K. Kim, M. K. Hong *et al.*, "Automated Measurement of Stent Strut Coverage in Intravascular Optical Coherence Tomography," *Journal of the Korean Physical Society*, 66(4), 558-570 (2015).
- [12] L. S. Athanasiou, C. V. Bourantas, G. Rigas *et al.*, "Methodology for fully automated segmentation and plaque characterization in intracoronary optical coherence tomography images," *Journal of Biomedical Optics*, 19(2), 026009-026009 (2014).
- [13] G. J. Tearney, E. Regar, T. Akasaka *et al.*, "Consensus standards for acquisition, measurement, and reporting of intravascular optical coherence tomography studies: a report from the International Working Group for Intravascular Optical Coherence Tomography Standardization and Validation," *Journal of the American College of Cardiology*, 59(12), 1058-72 (2012).

- [14] C. Tomasi, and R. Manduchi, "Bilateral filtering for gray and color images," Sixth International Conference on Computer Vision, 839-846 (1998).
- [15] T. Kanungo, D. M. Mount, N. S. Netanyahu *et al.*, "An efficient k-means clustering algorithm: Analysis and implementation," Ieee Transactions on Pattern Analysis and Machine Intelligence, 24(7), 881-892 (2002).
- [16] C. M. Bishop, [Pattern recognition and machine learning] Springer, New York(2006).
- [17] R. H. Bartels, J. C. Beatty, and B. A. Barsky, [An introduction to splines for use in computer graphics and geometric modeling] M. Kaufmann Publishers, Los Altos, Calif.(1987).