Real-Time Gating of IVUS Sequences Based on Motion Blur Analysis: Method and Quantitative Validation

Carlo Gatta^{1,2}, Simone Balocco², Francesco Ciompi², Rayyan Hemetsberger³,
Oriol Rodriguez Leor³, and Petia Radeva²

¹ Dept. Matemtica Aplicada i Anlisi, Universitat de Barcelona,
Gran Via 585, 08007 Barcelona, Spain

² Centre de Visió per Computador, Bellaterra, Spain

³ Unitat d'hemodinàmica cardíaca hospital universitari Germans Trias i Pujol
Badalona, Spain

Abstract. Intravascular Ultrasound (IVUS) is an image-guiding technique for cardiovascular diagnostic, providing cross-sectional images of vessels. During the acquisition, the catheter is pulled back (pullback) at a constant speed in order to acquire spatially subsequent images of the artery. However, during this procedure, the heart twist produces a swinging fluctuation of the probe position along the vessel axis. In this paper we propose a real-time gating algorithm based on the analysis of *motion blur* variations during the IVUS sequence. Quantitative tests performed on an in-vitro ground truth data base shown that our method is superior to state of the art algorithms both in computational speed and accuracy.

1 Introduction

Intravascular Ultrasound is a catheter-based invasive diagnostic procedure used intraoperatively to assess cardiovascular diseases. The ultrasound probe is placed at the tip of the catheter and, while rotating on its axis, it emits and receives ultrasound pulses, successively reconstructed in radially distributed A-lines. The envelope detection of acquired radio frequency signals allows the reconstruction of cross-sectional images of the artery. During the acquisition, the catheter is pulled back at a constant speed in order to acquire spatially subsequent images of the artery. However, during this procedure, the heart twisting produces artificial fluctuations of the probe position along the vessel axis (swinging effect). Moreover, due to the heart cyclic contraction/expansion, an apparent rotation with respect to the catheter axis and in-plane translation can be observed.

The image visualization and automatic analysis, e.g. volumetric lumen segmentation and/or volumetric plaque characterization of IVUS pullbacks require a pre-processing motion compensation [1,2]. Given the intraoperative nature of IVUS imaging and the need of instantaneous diagnosis of the patient conditions, the motion compensation cannot be computed off-line and the computational cost of the gating algorithm must be very low. The combined effect of the three

movements can be reduced by image-based gating algorithms [3,4,5] i.e. by extracting the most stable frames from the pullback sequence. Such techniques are composed by two parts: 1 - the extraction of a signal (1D or 2D) correlated with the cardiac phase; 2 - the selection of stable frames based on the previously extracted signal. The method in [3] extracts two signals based on two different principles; they conclude that the more reliable is based on the computation of the Absolute Intensity Difference (AID) applied to subsequent frames of a circular ROI centered in the middle of the short-axis image. The method in [4] computes a Dissimilarity Matrix based on the Normalized Cross Correlation (NCC) between couples of frames; subsequently a dynamic programming algorithm finds optimal gating frames. In [5], the method by O'Malley et. al. [4] is modified using a textural descriptor for each frames and computes the dissimilarity matrix in a faster and robust way; moreover, the dynamic programming algorithm has been substituted by a local minima search in a 1D signal obtained from the dissimilarity matrix. It is important to stress that the quality of an image-based gating algorithm strongly depends on the ability of the method to extract a signal (1D or 2D) correlated with the actual vessel oscillation. In this paper, we present a novel and real-time image-based gating method that exploits *motion blur* variations during the cardiac cycle in coronary artery pullbacks.

Up to now, the experiments to validate image-gating techniques are questionable. The ECG signal used in the validation of [4] has been demonstrated to be a suboptimal descriptor of the relative oscillations between the catheter tip and the coronary artery [6]. In [5] the authors propose an indirect methodology to assess the smoothness of the reconstructed sequence.

In this paper a reliable validation of the technique is obtained by designing a novel ad-hoc in-vitro experiment in which ground-truth data was generated using an oscillating mechanical device. The performance of our algorithm is compared against the other state-of-the-art methods using such reference data.

2 Method

Image gating algorithms consist of two stages: the extraction of a 1D or 2D signal correlating with the cardiac cycle and the identification of the signal's instants corresponding to the most stable cardiac frames.

2.1 Cardiac Signal Extraction

The proposed cardiac signal extraction is based on the idea that, provided a high frame rate acquisition equipment, every tissue displacement causes, in the image being captured, a *motion blur* proportional to the speed of the tissue movement. We propose a *motion blur* intensity estimator $B(I)$ computed as minus the average of the absolute value of vertical derivative over the polar IVUS image:

$$B(I) = -E \left(\left| \frac{\delta I(r, \theta)}{\delta r} \right| \right) \quad (1)$$

Fig. 1. Trend of the *motion blur* estimation on the simulated blurred IVUS images

where r is the radial position and θ is the angle of the probe during the image scan. The estimation is averaged (expected value E) over all the image A-lines in order to reduce outliers effect. In order to illustrate the suitability of the proposed estimator, we simulate increasing *motion blur* effect in a set of in-vivo IVUS image. Such phenomenon can be modeled by a convolution between the non-degraded image with a set of linear point spread functions (PSFs) with increasing length. This causes a blurring of the image, and thus the reduction of edge sharpness [7] [8]. Figure 1 shows the plot of the estimator B over the length of the simulated *motion blur* PSF. Since the actual PSF in clinical images is unknown, each PSF has been rotated in steps of 10° . This resulted in a set of curves exhibiting similar trends. The relationship between B and the PSF length is monotonically non decreasing and thus suitable to compute comparison between different frames. In order to obtain the variation of the *motion blur* during the sequence, we apply equation (1) to all the images in the sequence obtaining a signal $B(I_t)$, where t is the temporal variable, as depicted in Figure 2 (a). It is important to highlight that changes in the vessel structures, e.g. plaques, bifurcations, etc., modify the image texture thus influencing the signal $B(I_t)$, as it can be seen in Figure 2 (a). Since the pullback speed is significantly lower than the speed of the oscillation [4], we can separate the oscillatory part of the signal $B(I_t)$ from the changes in the vessel structure. This has been done by applying a Butterworth high-pass filter (order = 10) with cut-off at 0.5Hz , obtaining the signal $B_{HP}(I_t)$. An oscillation below 0.5Hz is below 30 beat per minute (BPM) and thus it cannot be related to phenomena induced by heart beating. Figure 2 (b) shows the high-pass filtered version of the signal $B(I_t)$; periodic local minima, spaced about 1 second to the other, can be easily identified (see Figure 2 (c)). This repeating pattern has a frequency of $1.02 \pm 0.06\text{Hz}$ which is in agreement with the ECG captured during the pullback (1.13Hz). The peak at about 1 Hz and the harmonics at multiple frequencies in Figure 2 (d) confirm the periodic nature of the signal. A possible explanation of the sharp periodical variations (from local minima to local maxima) in the $B_{HP}(I_t)$ signal can be drawn from the physiology of the cardiac cycle. The systolic phase is composed by the iso-volumetric contraction followed by the blood ejection from the left chamber. During the iso-volumetric contraction the pressure increases until the

Fig. 2. Motion blur signal $B(I_t)$ obtained from a patient sequence (a); its respective high-pass filtered version $B_{HF}(I_t)$ (b); first 10 seconds of the signal $B_{HF}(I_t)$ (c); amplitude of the Fourier transform of $B_{HF}(I_t)$ (d)

ventricle pressure exceeds the aortic pressure, causing the abrupt opening of the aortic valve. This causes the sudden heart motion due to the rapid ejection of the blood, reflecting to a motion that can be captured by the proposed *motion blur* estimator.

2.2 Gating

Once the *motion blur* signal $B_{HF}(I_t)$ is computed, the stable frames in an arterial IVUS sequence must be reliably identified. Unfortunately not all the local minima corresponds to stable frames, so noise artifacts must be discarded. As it can be noticed in Figure 2 (c), the local minima corresponding to a stable frame are immediately followed by a local maximum. Exploiting this fact, we propose a method that selects a set of stable frame candidates among the local minima of $B_{HF}(I_t)$. A local minimum is retained as candidate if it is immediately followed by a local maximum which satisfy a zero-crossing criteria. The list of candidates is further refined by removing cases in which the gradient between the couple of minimum-maximum is lower than a certain threshold T . T is computed such that it separates the gradient distribution in two distinct modes.

3 Results

In this section, the proposed image-gating algorithm is quantitatively validated, and its performance are compared against the state-of-the-art methods. Reliable ground-truth data was obtained by designing a novel ad-hoc experiment.

3.1 *In vitro* Experiment

A mechanical device simulating the periodical heart movements has been designed in order to generate reliable ground-truth data. Figure 3 shows the mechanical device and its power supply. The apparatus is composed by a rotating eccentric wheel connected to a transversal arm generating horizontal swinging oscillations. The amplitude of the oscillation ΔL can be tuned using a regulating knob from 1 to 5 mm, in steps of 1 mm. The oscillation speed can be controlled setting the power supply voltage V , following the equation $F[BPM] = 4.1912 [BPM/Volts] V [Volts]$. The catheter guide is connected to the oscillating arm. A total of 21 pullbacks from three *post-mortem* arteries have been acquired at 30 *frame/s* using a Galaxy II IVUS Imaging System (Boston Scientific) and a catheter Atlantis SR Pro 40 MHz (Boston Scientific). For each artery 7 pullbacks have been recorded varying the mechanical device parameters ($\Delta L = \{1, 2, 3, 4\}$ mm, $F = 60$ [BPM] and $\Delta L = 3$ mm, $F = \{50, 60, 70, 80\}$ [BPM]). Each sequence contains 1000 frames, of 33.3 s duration. It is worth to note that the maximal frequency resolution using a 30 *frame/s* acquisition setup is of 0.06 Hz (4 BPM) and that the methodological incertitude induced by the power supply, (approximately ± 0.5 V), produces a methodological error in the oscillation frequency of ± 2 [BPM]. Such uncertainties must be accounted in the method evaluation. The sequences are available for research purpose and can be obtained under request.

Fig. 3. Picture of the ad-hoc oscillating device and its power supply

3.2 Quantitative Evaluation

To quantitatively and fairly assess the performance of each image gating methods, we designed a measure that is robust to the methodological uncertainties.

Fig. 4. An example of $|S(\xi)|$ and the filter $H_{f_N}(\xi)$, in solid and dashed lines respectively; in this example $f_N = 1.16$ Hz (70 BPM)

Fig. 5. SNR performance of different gating algorithms applied to three *post-mortem* arteries (a,b and c). Dots indicate the performance for each sequence while the gray bar is the average score. The plot in (d) shows the average computation (1000 frame sequence) for the 4 tested algorithms; it is important to note that the times scale is logarithmic.

For every sequence the nominal oscillation frequency f_N is known. Thus, we introduce the Signal to Noise Ratio (in dB) defined as follows:

$$SNR_{dB} = 20 \log \left(\frac{\int_{\xi} |S(\xi)| H_{f_N}(\xi)}{\int_{\xi} |S(\xi)| (1 - H_{f_N}(\xi))} \right) \quad (2)$$

Fig. 6. Longitudinal cut of an input IVUS sequence and the reconstructed longitudinal cuts obtained using different image-based gating algorithms

where $S(\xi)$ is the Fourier transform of the signal $s(t)$ produced by a given algorithm; H is a frequency filter designed to filter out the frequencies that are not related with the nominal one (f_N). Hence, the numerator of equation (2) represents the energy of the signal, related to the nominal frequency f_N , while the denominator corresponds to the energy of the signal not related with the oscillation, i.e. the noise of the signal. In such way, the higher is the SNR, the better the image-gating technique extracts the oscillatory component from the image sequence. The filter $H(\xi)$ is designed as follows:

$$H_{f_N}(\xi) = \sum_{n=1}^M \exp \left(-\frac{(\xi - n f_N)^2}{2\sigma_M^2} \right) \quad (3)$$

An example of $|S(\xi)|$ and the filter $H_{f_N}(\xi)$, are shown in figure 4 in solid and dashed lines respectively. Since the catheter can bend inside the artery, the catheter tip oscillation is not perfectly sinusoidal. To account for this mechanical limitation, the filter of equation (3) includes higher harmonics. Using the defined SNR measure, we tested the methods in [3] (AID method), [4] (OM algorithm) and [5] (GA) compared with our technique (MOT). Figure 5 (a-c) shows the results on three different post-mortem arteries. As it can be notice, the proposed method outperforms other methods in all three arteries. However, for the artery in figure 5 (b), the dispersion of AID and MOT is large. The ANOVA test confirmed that the results of our method are statistically significant with respect to AID for the first two arteries, while it is not for the third one. Figure 5 (d) shows the average computational time, for a 1000 frame sequence, in

seconds. The computational time of our method is of the same order of the fastest algorithm (AID) as it can be seen in figure 5 (d).

3.3 Qualitative In-vitro Evaluation

A qualitative comparison of the image-gating methods is illustrated in figure 6, showing a longitudinal cut of an IVUS sequence and the resulting longitudinal cuts obtained using the four gating algorithms. The input longitudinal cut has been obtained from a sequence of the proposed ground-truth data; its appearance is very similar to in-vivo acquired sequences, showing the typical saw-tooth shaped artifact. It can be noticed that the result of OM and GA are very similar since GA is an improvement of OM. In this sequence, the difference between AID and MOT is not easily noticeable, while their superior performance with respect to OM and GA is evident, especially observing the arterial tissue sharpness.

4 Conclusion

In this paper we proposed a real-time gating algorithm based on the analysis of *motion blur* variations during the IVUS sequence. For the first time in literature, a reliable validation of image-based gating techniques is performed. The algorithm have been tested on ground-truth data generated by an ad-hoc oscillating mechanical device. The proposed method outperforms the other state-of-the-art algorithms both in SNR and computational complexity. Future work will be addressed to an extensive validation of the method with several post-mortem arteries.

Acknowledgments

This work was supported in part by the research projects TIN2009-14404-C02-02, FIS PI061290 y CSD2007-00018. The work of C. Gatta and S. Balocco is supported by the Catalan Agency for Administration of University and Research (AGAUR) under a Beatriu de Pinos Fellowship.

References

1. Arbab-Zadeh, A., DeMaria, A.N., Penny, W., Russo, R., Kimura, B., Bhargava, V.: Axial movement of the intravascular ultrasound probe during the cardiac cycle: Implications for three-dimensional reconstruction and measurements of coronary dimensions. *American Heart Journal* 138, 865–872 (1999)
2. Bruining, N., von Birgelen, C., de Feyter, P.J., Ligthart, J., Li, W., Serruys, P.W., Roelandt, J.: Ecg-ated versus nongated three-dimensional intracoronary ultrasound analysis: Implications for volumetric measurements. *Catheterization and Cardiovascular Diagnosis* 43, 254–260 (1998)
3. Zhu, H., Oakeson, K.D., Friedman, M.H.: Retrieval of cardiac phase from IVUS sequences. In: *Medical Imaging 2003: Ultrasonic Imaging and Signal Processing*, vol. 5035, pp. 135–146 (2003)

4. O'Malley, S.M., Granada, J.F., Carlier, S., Naghavi, M., Kakadiaris, I.A.: Image-based gating of intravascular ultrasound pullback sequences. *IEEE Transactions on Information Technology in Biomedicine* 12(3), 299–306 (2008)
5. Gatta, C., Pujol, O., Leor, O.R., Ferre, J.M., Radeva, P.: Robust image-based ivus pullbacks gating. *Med. Image Comput. Assist. Interv. Int.* 11(Pt 2), 518–525 (2008)
6. O'Malley, S.M., Carlier, S.G., Naghavi, M., Kakadiaris, I.A.: Image-based frame gating of IVUS pullbacks: A surrogate for ecg. In: *Proc. IEEE International Conference on Acoustics, Speech and Signal Processing, ICASSP 2007, April 15-20, vol. 1*, pp. I-433–I-436 (2007)
7. Yitzhaky, Y., Kopeika, N.S.: Identification of blur parameters from motion blurred images. *Graphical Models and Image Processing* 59(5), 310–320 (1997)
8. Dai, S., Wu, Y.: Motion from blur. In: *IEEE Conference on Computer Vision and Pattern Recognition, CVPR 2008*, pp. 1–8 (June 2008)