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Enhancement and bias removal of optical coherence tomography images: An iterative approach with adaptive bilateral filtering

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ABSTRACT

Optical coherence tomography (OCT) has continually evolved and expanded as one of the most valuable routine tests in ophthalmology. However, noise (speckle) in the acquired images causes quality degradation of OCT images and makes it difficult to analyze the acquired images. In this paper, an iterative approach based on bilateral filtering is proposed for speckle reduction in multiframe OCT data. Gamma noise model is assumed for the observed OCT image. First, the adaptive version of the conventional bilateral filter is applied to enhance the multiframe OCT data and then the bias due to noise is reduced from each of the filtered frames. These unbiased filtered frames are then refined using an iterative approach. Finally, these refined frames are averaged to produce the denoised OCT image. Experimental results on phantom images and real OCT retinal images demonstrate the effectiveness of the proposed filter.

1. Introduction

Optical coherence tomography (OCT) is a noninvasive imaging modality that yields high resolution images of tissue structures and cross-sectional imaging of many biological systems [1]. As an optical equivalent of ultrasound (US) imaging, it uses echoes of light rather than sound [2]. Major OCT applications include detection of eye diseases and skin disorders [3,4].

In ophthalmology, assessment and observation of visual ailments require details about the inner retinal structure of the eye. OCT images are used to visualize the morphological structures of the retina and iris macula and evaluate the retinal nerve fiber layer thickness in the peripapillary region as well as other inner tissue lines associated with the anterior and posterior sections of the eye [5]. The ophthalmologists can observe and measure the anatomical correspondence of the intra-retinal layers viz. retinal nerve fibre layer (RNFL), ganglion cell layer (GCL), inner-plexiform layer (IPL), inner-nuclear layer (INL), outer-plexiform layer (OPL), inner and outer segment of the photoreceptors (IS/OS), the retinal pigment epithelium (RPE) and choriocapillaris (CC)) by performing anterior and posterior imaging of the eye using OCT [6,7]. These are clinically important in case of many ophthalmic diseases such as early detection and diagnosis of eye diseases, including glaucoma, age-related macular degeneration, macular edema, and diabetic retinopathy.

Nevertheless, the visual quality of OCT images can be deteriorated by speckle noise arising due to the interference of photons that undergo multiple scattering in reverse and forward direction, when photons propagate inside tissue [8,9]. It is important to remove unwanted speckle noise from OCT images since the automated segmentation of the inner tissue lining of eye images (e.g., optic nerve head layers, retinal layers, drusens) and its measurement are clinically important for the diagnosis of eye diseases and noise can influence the automatic segmentation process [10]. Apart from OCT images, speckle noise reduction is a significant research topic in other imaging modalities such as synthetic aperture radar (SAR) and US images.

In the literature, various speckle reduction algorithms have been explored for OCT images. In [11], Rogowska et al. have discussed techniques such as image averaging, mean, median and Gaussian filters for removing unwanted components from OCT images. The Lee filter [12], Frost filter [13] and Kuan filter [14] are the most widely discussed spatial adaptive filters to attenuate speckle noise. Improved versions of the Lee and Frost filters are

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proposed in [15]. Computationally efficient speckle noise reduction algorithms using an adaptive Wiener filter [16] and diffusion filtering techniques [17–20] have also been proposed for speckle reduction.

In the past several methods are proposed for OCT denoising. A complex diffusion filter was proposed in [21] and its improved adaptive technique was discussed in [22]. A combined filter by integrating the benefits of PDE-based approach and the wavelet transform is employed in [23]. Multi-resolution based spatially adaptive discrete wavelet filter [24], complex wavelet filter [25], and curvelets filters [26] are other significant methods proposed in the literature to remove speckle noise. Ozcan et al. have compared various filters including non-orthogonal wavelet transform based filters together with enhanced Lee and adaptive Wiener filters for OCT speckle denoising [27]. I-divergence regularization approach [28] and general Bayesian estimations [29] have also been proposed for speckle reduction in OCT imaging. Moreover, different patch based non-local recovery paradigms have recently introduced for speckle noise reduction in OCT images [30–32].

A better statistical characterization of the observed (noisy) images can help in developing effective despeckling methods. In the literature, different statistical models such as Gaussian, Rayleigh and Log-normal have been investigated to address the restoration of speckled images [11,33]. In this work, a Gamma model is followed for multi-frame OCT images and a three parameter Gamma distribution function is used to fit the observed OCT data. Three parameter Gamma distribution is able to include several well known models such as exponential, Rayleigh, Gamma, Chi-square and normal distribution as subfamilies.

In this paper, we propose an adaptive and unbiased bilateral (AUB) filter to account for the Gamma characteristics of the data and then, incorporated the idea of iterative filtering to refine the AUB filter result. This iterative AUB (IAUB) filtering technique is performed on each single frame, and the outputs of the IAUB filter are averaged to obtain the final despeckled image. The excellent functioning of the proposed filter is well validated by experiments using both simulated and real OCT images and the simulations show that it provides better speckle removal without affecting noticeable structures in the image.

This paper is organized as follows: The noise model for OCT images is briefly described in Section 2, and the proposed methodology is presented in Section 3. Section 4 discusses the experimental results and the evaluation process. Finally, we conclude the paper in Section 5.

2. Noise characteristics in OCT images

The quality of images obtained by any image acquisition system employing coherent wave fields is degraded by speckle noise, an insidious form of noise produced by the interference of waves with random phases [34,35]. The speckle noise manifests itself as a fast fluctuation of the detected intensity (or field envelope) over the spatial extent of the image, conveying a granular texture [36]. High-speed OCT imaging quality is restricted due to the presence of speckle noise [37]. With a large number of polarized quasimonochromatic waves with random phase, a fully developed speckle pattern is formed [38].

In [39], Goodman et al. find a relation for the speckle field using a Rayleigh distribution function. More attempts to model speckle patterns are found in the US literature than in the OCT literature. Despite the fact that a multiplicative model and empirical distributions with useful probabilistic models, e.g., Nakagami, generalized Nakagami, Weibull and Rician inverse Gaussian (RiIG) distributions, have been studied [40–45] for modeling speckle noise in ultrasound, Vegas-Sánchez-Ferrero et al. [46] show that Gamma distribution, which is a good approximation for the weighted sum of Rayleigh variables, accurately fits interpolated B-mode US images, when compression-less data with fully developed speckle is considered.

Motivated by the above studies, we assume the noise field in OCT images is due to fully developed speckle (as discussed in [34]), and hence, we model the OCT data distribution by Gamma probability density function (PDF). Let us consider that there are k frames in the OCT data, and the dimension of each frame is $r \times c$. If the noisy OCT data, their noiseless version, and the noise are denoted as $\mathbf{M}, \mathbf{C}$ and $\mathbf{N}$, respectively, we can express the relation between them as

$$\mathbf{M} = \mathbf{C} + \mathbf{N} \tag{1}$$

where the dimensions of the vectors $\mathbf{M}, \mathbf{C}$, and $\mathbf{N}$ are all $(r \times c) \times k$. In other words, $\mathbf{N}$ denotes a fading variable and takes random numbers from the Gamma distribution with shape and scale parameters ρ and β respectively.

3. Methodology

In this section, we concisely present the concept of bilateral filtering, and then propose two filters to reduce speckle from the Gamma distributed OCT data, namely, an adaptive and unbiased bilateral (AUB) filter and the iterative adaptive and unbiased bilateral (IAUB) filter. These filters are suitable for enhancing both single-frame and multiframe OCT images.

The conventional bilateral (CB) filter is a nonlinear spatial filter developed by Tomasi and Manduchi [47]. CB filter is very popular for edge preserved smoothing of images, which are Gaussian distributed. The kernel of the CB filter is composed of two components, namely a range filter kernel and domain filter kernel. The response of the CB filter at a pixel location m can be calculated as [47]

$$\hat{I}(m) = \frac{1}{Z} \sum_{n \in N(m)} w_D(m,n) w_R(m,n) I(n), \tag{2}$$

where $N(m)$ represents the neighborhood region around m, and n is the position in the neighborhood. The normalization constant Z is given by

$$Z = \sum_{n \in N(m)} w_D(m,n) w_R(m,n). \tag{3}$$

The weight function w_D is linked to the domain filter and measures the photometric similarity of a pixel around its neighborhood. Similarly, the other weight function w_R is related to range filtering and the computed weights are proportional to the radiometric distance around the neighborhood of a pixel. These weight functions can be defined as

$$w_D(m,n) = \exp\left(-\frac{|m-n|^2}{2\sigma_d^2}\right) \tag{4}$$

and

$$w_R(m,n) = \exp\left(-\frac{|I_m - I_n|^2}{2\sigma_r^2}\right) \tag{5}$$

where I_m and I_n are the intensities at m and n, respectively. The geometrical spread σ_d in the domain determines the amount of low pass filtering in the form of blur, and its optimal value is relatively insensitive to noise. However, the photometric spread σ_r in the image range is almost linearly related to the true noise standard deviation σ [48,49].

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