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Reduction of Speckle Noise in SDOCT Retinal Images by Fuzzification and Anisotropic Diffusion Filtering

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Spectral Domain Optical Coherence Tomography (SDOCT) is a well accepted clinical standard for diagnosing and monitoring the pathological changes in optic disc and retinal layers. In recent times, even though spectral domain detection technique has proved higher potential in terms of extremely high sensitivity and image acquisition speed, the major shortcomings is existence of speckle and its effect on interpretation and diagnosis. In this paper, image enhancement is performed using fuzzification method followed by anisotropic diffusion filtering for effective reduction of speckle noise. Fuzzification technique uses the maximum fuzzy entropy principle. For the removal of speckles of size 2-3μm, anisotropic diffusion filtering is performed. On an average Structural Similarity Index Measure (SSIM) is calculated to be 0.9997 which proves that the image quality has been significantly improved. Moreover edges are perfectly preserved in this filtering technique.

Key words: Spectral Domain Optical Coherence Tomography, Speckle noise, Fuzzification, Anisotropic diffusion, Structural Similarity Index.

OCT is a non contact medical imaging modality to measure different aspects of biological tissues, where low coherence interferometer is used to produce two or three dimensional image of the internal tissues[1]. The OCT scanner can extract fine details of the retinal image which can be used to diagnose the systemic eye disease such as diabetic retinopathy, glaucoma, macular edema, age related macular degeneration etc[2]. The depth of OCT estimates the backscatter originated from its time of flight. The fine structures of micron scale images are acquired with high resolution in the order of up to 3µm[3]. Recently the spectral domain optical coherence tomography (SDOCT) is exploit to measure a three dimensional and two dimensional images by using spectrophotometer[4], thereby mechanical scanning of the reference arm is avoided. The principle of SDOCT scanner is shown in the figure 1.

The SDOCT retinal imaging can be used to diagnose the systemic eye diseases such as glaucoma, diabetic retinopathy, age related macular degeneration etc. Particularly in case of diabetic maculopathy fluid filled regions are developed which causes damage to the retinal layers. For the effective diagnosis of diabetic maculopathy and to aid the physician for analyzing the severity of the disease, algorithms are developed to automatically segment the macular edema regions. A variety of successful image processing algorithms are developed worldwide and commercially implemented for the diagnosis of retinal defects. But still it is a major challenge in automation of analysis and interpretation of OCT

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images[5]. Since SDOCT scanner uses coherent wave pattern to acquire images, inherently it has speckle noise. The speckle noise is a random granular texture spread in the image. Speckle is a multiplicative noise so it masks the low contrast lesion which misinterprets the physician in effective diagnosis [6,7]. Speckle noise reduction in OCT is particularly challenging because it is difficult to separate the noise and the information components in the speckle pattern[8].

The general form of speckle noise is given by equation 1.

$$g(n,m) = f(n,m) * u(n,m) + \delta(n,m) \qquad ...(1)$$

Where, g(n,m) is the observed image, u(n,m) and ä(n,m)are the multiplicative and additive object of the speckles. *f(*n,m) is the actual image present beneath.

Most of the cases, Speckle are introduced in the images, since its shape is too small to be resolved by large wavelength[9]. In general the reduction of speckles using Bayesian framework works well for multiplicative noise[10], but speckle reduction in OCT images will blur the edges. Previously, Universal adaptive filter is used for speckle reduction in synthetic aperture radar images[11]. It preserves most of the edges using high damping factor, but the low intensity portions in the image is affected. The speckle noise can be easily identified by using the properties of gray level co-occurrence matrix (GLCM). It trains the neural network and identifies the noise[12]. Simply, the median filter is used for speckle reduction by selecting the pixel randomly[13]. But all the existing speckle reduction approaches has its own practical limitations. In order to overcome these limitations, diffusion filtering method is proposed. In this approach diffusion and edge detection interact in one single process instead of two individual processes. Hence edges are preserved in this method. This paper focuses on the implementation of speckle reduction in MATLAB® as it is an advanced tool for image processing[14].

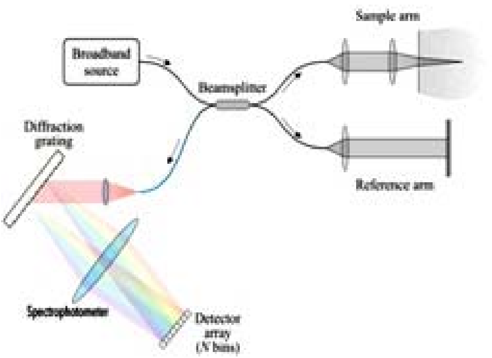

Fig 1. Spectral discrimination of OCT
Courtesy: http://biophotonics.illinois.edu/technology/oct

MATERIALS AND METHODS

The speckle noise occurring in the image degrades the quality of image. For effective elucidation of the image, speckle noise has to be reduced. The speckles can be classified as signal carrying speckle and signal degrading speckle[15]. The signal carrying speckle originates from the sample volume in the focal zone of the imaging optics. The signal degrading speckle consists of small speckle spots created by out of focus light that scatters multiple times and happens to return within the coherent delay time. Particularly, the component of the optical field corrupted by both speckle generates, on average, an interference signal of nearly zero amplitude that fluctuates little. Therefore, various methods have been developed for speckle reduction. In this work speckles are reduced initially, by fuzzification method which enhances the image quality. Then anisotropic diffusion filtering is used for efficient speckle reduction which preserves the edges. These techniques are implemented using MATLAB®.

Data Collection

The sample SDOCT retinal images of thirty subjects were collected from Aravind Eye hospital, Puducherry. All the images are acquired using Cirrus™ HD-OCT machine, in which two images are normal and the remaining 28 are abnormal. Cirrus HD-OCT is capable of 5-µm axial and 15-µm transverse resolution in tissue. The abnormal images are the edema formed retinal images which indicates the presence of diabetic maculopathy. A typical observed SDOCT retinal image with speckle noise is shown in figure 2.

Image Normalization

Normalization is a process of varying the pixel range. It converts an n- dimensional grayscale image with pixel values in the range (Min, Max), into a new pixel values in the range (NewMin, NewMax). It is performed using the formula given below,

$$G(x,y) = g_{min} + \frac{(g_{max} - g_{min}) * (G_o(x,y) - g_{o\,min})}{(g_{o\,max} - g_{o\,min})} \quad ...(2)$$

where $g_{o\,min}$ and $g_{o\,max}$ are the minimum and maximum intensity levels of the original image, whereas the g_{min} and g_{max} are the minimum and maximum intensity levels of the normalized image. $G_o(x,y)$ and $G(x,y)$ are the gray levels at the coordinates (x,y) before and after normalization, respectively.

Filtering Process

Fuzzy Logic Approach

Fuzzy image processing has three main stages viz., (i) assigning membership values (ii) calculating entropy using Shannon function and (iii) image fuzzification [16]. These steps are used to reduce speckle noise and enhance the images. If necessary, image defuzzification can be done. The basic processing flow of the method is shown in the figure below

membership functions in MATLAB® used fuzzy among which 'S' membership function is used in this proposed work. It is created by assigning three parameters a, b, c as shown in the equation below,

$$\mu(G(x,y)) = \begin{cases} 0 & G(x,y) \le a \\ \frac{(G(x,y)-a)^2}{(b-a)(c-a)} & a \le G(x,y) \le b \\ 1 - \frac{(G(x,y)-c)^2}{(c-b)(c-a)} & b \le G(x,y) \le c \\ 1 & G(x,y) \ge c \end{cases} \quad ...(3)$$

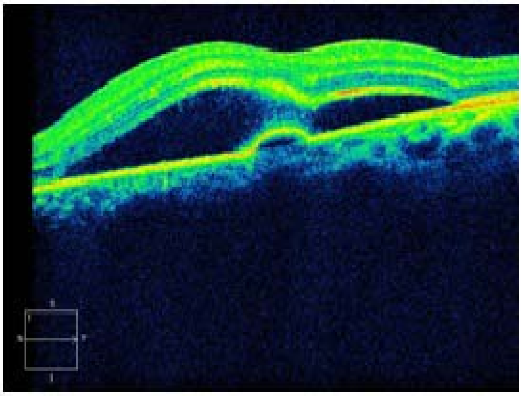

Fig 2. Typical SDOCT retinal image

The values of μ(G(x, y)) represent the brightness degrees of the pixel intensities; it is simplified as μ(x, y). The image is mapped to the fuzzy domain. The entropy is a measure variable of information content. This entropy is called Shannon entropy which quantifies the information content present in a message. Shannon function can be calculated by the following equation,

$$S_n(\mu(x,y)) = -\mu(x,y)\log_2 \mu(x,y) - (1 - \mu(x,y))\log_2(1 - \mu(x,y)) \quad ...(4)$$

The degree of fuzziness of a fuzzy set can be measured by its entropy[17]. By using maximum fuzzy entropy principle The fuzzy entropy is obtained for each b, where b then an optimum value b_{opt} can be calculated according to the following formula,

$$H_{max} = \{I, a, b_{opt}, c\} = max\{H(I, a, b, c)/(g_{min} \le a < b < c \le g_{max})\} \quad ...(5)$$

Anisotropic Diffusion Filter

Anisotropic diffusion filter removes noise in the image without any loss of detailed resolution. Anisotropic diffusion for digital images is given by partial differential equation (PDE)[18],

$$\frac{\partial I}{\partial t} = div(c(x,y,t)\nabla I) = \nabla c.\nabla I + c(x,y,t)\Delta I \quad ...(6)$$

Where D and Ñ are the laplacian and gradient operators respectively, div is the divergence operator. The variable *c* is the flux function. It controls the diffusion rate of the image. The locations of boundaries in the regions are absolute at the time t, for the scale space variables[19]. The divergence operator simplifies as,

$$div(c(x,y,t)\nabla I) = \frac{\partial}{\partial x}(c(x,y,t)I_X) \quad ..(7)$$

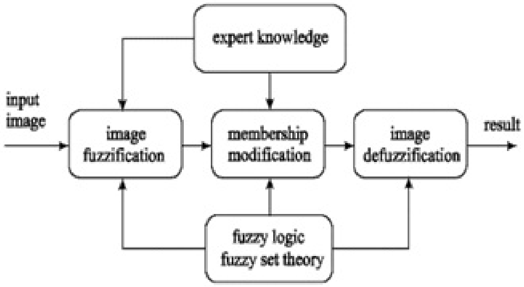

Fig 3. General structure of fuzzy image processing

The smoothing is done within a region, the interior of each region is set as one and the boundary of each region is set as zero. In anisotropic diffusion filtering, diffusion takes place according to a diffusion coefficient which is variable and adaptive in order to reduce smoothing effect near the edges. Diffusion and edge detection are performed in one single process instead of two processes[20]. Hence the boundary regions appear to be sharp by blurring each region individually without any interaction between them.

Image Quality Measurement

The filtered image quality is measured by using measurable index parameters, which helps to quantify the noise reduction and image enhancement. The parameters are computed from the original and processed image data.

Mean Squared Error (MSE) is the quantification of noisy image from noiseless image[20]. It is given by,

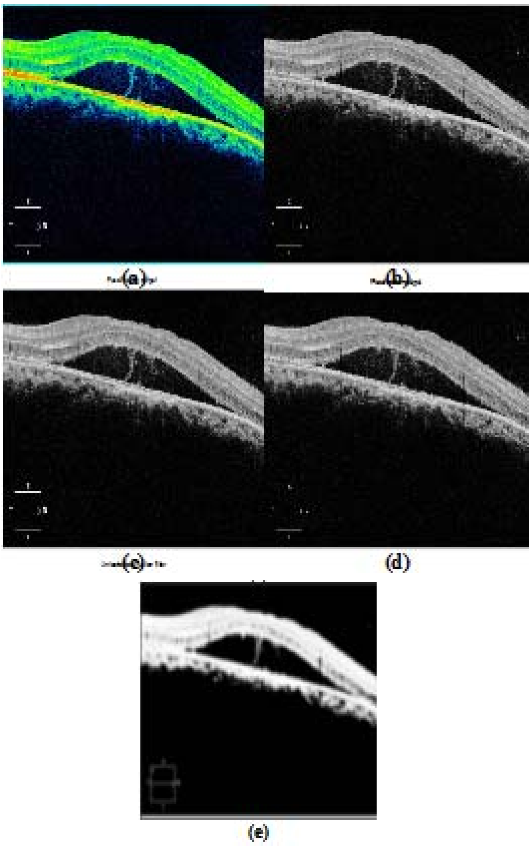

Fig.4. Output images a) Original image b) Normalized image c) Fuzzification output d) Median filter output e) Anisotropic diffusion filter output

$$MSE = \frac{sum(mseImage(:))}{m * n} \quad ...(8)$$

Peak Signal to Noise Ratio (PSNR) is the ratio between the power of signal and the noise. The PSNR value increases as the image quality increases[20]. PSNR is calculated as,

$$PSNR = 10 * log_{10}\left(\frac{256^2}{MSE}\right) \quad ...(9)$$

Signal-to-noise ratio is defined as the ratio between a meaningful information (signal) and unwanted signal (noise). It measures the additive noise suppression. The SNR is calculated using the formula,

$$SNR = 10 * \frac{log\left(\frac{A^2}{MSE}\right)}{log(10)} \quad ...(10)$$

The standard signal to noise ratio (SNR) is not adequate to evaluate the noise suppression in the case of multiplicative noise.

Contrast-to-noise ratio (CNR) is a measure which eliminates a term before applying the ratio. CNR gives an objective measure of useful contrast (difference of means) between a region of background noise and image featured target. The quality image has a high SNR value, but low CNR value. The formula to calculate CNR is given by,

$$CNR = 10 * log\left(\frac{(\mu_t - \mu_r)}{\left(\sqrt{\sigma_t^2 + \sigma_r^2}\right)}\right) \quad ...(11)$$

Where μ_t and μ_r represents the mean of filtered and noisy image. The denominator values

Table 1. Image Quality Measurement

Subject	MSE	PSNR (db)	SNR (db)	CNR	SSIM
1	0.020	65.16	49.19	4.38	0.9999
2	0.024	64.24	42.10	13.20	0.9998
3	0.021	64.95	58.37	9.66	0.9998
4	0.026	64.02	53.49	2.84	0.9999
5	0.026	63.99	47.67	7.40	0.9999
6	0.025	64.86	42.38	13.86	0.9995
7	0.019	65.27	44.86	5.13	0.9999
8	0.021	64.95	40.53	10.03	0.9996
Mean	0.023	64.68	47.33	8.32	0.9997

σ_t and σ_r are the standard deviation of filtered and noisy image respectively. C_1 and C_2 are constants. To compare the luminance, contrast and structure of two different images Structural Similarity Index Measure (SSIM) is calculated by the formula,

$$SSIM = \frac{(2\mu_x\mu_y + C_1)(2\sigma_{xy} + C_2)}{(\mu_x^2 + \mu_y^2 + C_1)(\sigma_x^2 + \sigma_y^2 + C_2)} \quad ...(12)$$

The SSIM takes the values between [0, 1], and it increases as the quality of the image improves[21].

RESULTS

The original image with speckle is shown in fig 4a. The original image is in the pixel range [500, 750]. In order to obtain desired pixel range, normalization is done, in which the size of each and every pixel is reduced as shown in fig 4b.

Fuzzification method is used for speckle reduction initially. In this method 'S' membership function is created by assigning the parameters a=0.2, b=0.4 and c=0.8 for each normalized image. The entropy generally calculates for a specific pixel. In order to calculate entropy for all the pixels in the image, Shannon function is used. The fuzzification based entropy is calculated to enhance the image. By initializing the maximum values of entropy and the membership function parameters, the speckle noise is reduced and the image is enhanced as shown in the fig 4c.

For further more efficient speckle reduction anisotropic diffusion filtering is used. This filter uses partial differential equation and convolution approach to filter the speckle noise. Anisotropic diffusion is an iterative process which makes use of simpler computation steps that compute each successive image in the family and this process is continued until sufficient smoothing is obtained. By this approach the speckle noise is removed and it preserves the edges and enhances the image for further processing, without any loss of information as shown in the fig 4e.

For comparison, median filter output is shown in figure 4d. The MSE value of the image using anistropic diffusion filtering is found to be 0.0248, whereas using median filter it is 0.8567. It is evident that the PSNR value has been significantly increased from 10.67 dB to 64.24 dB using anisotropic diffusion filtering rather than median filtering.

DISCUSSIONS

In order to quantify the results and obtain the quality of performance of the approach, the parameters such as mean square error (MSE), peak signal to noise ratio (PSNR), signal to noise ratio (SNR), contrast to noise ratio (CNR) and structural similarity index measure (SSIM) are calculated between the original and fuzzified image. To improve the PSNR and SNR value anisotropic diffusion filter is used. The performance of the filter is calculated by measuring all the parameters between the original and filtered image. These parameters are used to identify amount of speckle reduction and image quality. The results shown in table 1 measure the performance of anisotropic diffusion filter approach for eight different subjects' SDOCT retinal images.

CONCLUSIONS

In this proposed work, the speckle noise is suppressed by applying anisotropic diffusion filtering. Diagnosing the retinal disorders can be carried out by performing segmentation of region of interest in the processed image effectively. In this proposed work speckles are reduced by fuzzy logic approach. The peak signal to noise ratio is calculated to be 10.67db on an average. To improve peak signal to noise ratio and for further effective removal of speckles, anisotropic diffusion filter is used. The PSNR value is increased to about 64.5db on an average and further this filter enhances the image by preserving its edges.

Future Work

The filtered image can be used for the automated segmentation of various retinal layers, optic disc, optic nerve, macular region etc., From the segmented portion effective features could be extracted and analyzed which would aid the physicians to diagnose the severity of the systemic eye diseases such as diabetic retinopathy, glaucoma, macular degenerations etc.,

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