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Wavelet Based Approach to Multiple-Frame Denoising of OCT-Images

Abstract. Speckle noise is a major problem of optical coherence tomography images. It significantly decreases the image quality and therefore the usability for the diagnosis of eye diseases like glaucoma. Current OCT-Systems try to overcome this issue by averaging multiple frames of the same scene. The number of frames that can be recorded is limited by the eye movement and the time the eye can be kept open. We present a new approach that uses multiple frames to perform a more sophisticated denoising. The single frames are assumed to be identical except for noise and global motion that arises by reason of the eye movement. A local noise estimation is performed in the wavelet domain to calculate a weight for each detail coefficient. The final noise-suppressed image is calculated by averaging the weighted wavelet coefficients followed by a wavelet reconstruction. We will show that the algorithm achieves a signal-to-noise gain of more than 60% compared to simple averaging.

Introduction

Glaucoma is the most common reason for blindness in Europe [1] and second in the world [2]. It manifests through a continuous loss of nerve fibers and a loss of visual field. The symptoms are often recognized late because the defect regions (scotomas) are compensated by the healthy eye. Thus screening is an important issue as an early diagnosis can help to stop or slow down the progression of the disease.

Modern medical imaging techniques like *optical coherence tomography* (OCT) are able to visualize the microscopic layer structure of the human eye fundus. This allows for a quantitative analysis of the progression of the disease and gives the physician additional parameters for a reliable diagnosis. OCT-systems can gather images with very high axial and transversal resolution (up to 2 and 10 microns respectively). The optical density at a certain depth is measured by interference of light beams with short coherence length that are reflected by a mirror and particles within the sample object respectively. A full depth-scan is computed either by changing the position of the mirror by time (time-domain OCT) or by an analysis of the interference spectrum (Fourier-domain OCT).

However, the light beam is often not reflected directly by a particle in the sample but is scattered multiple times within the object until it reaches the detector. These multiple scatterers cause random interference between the reflected light waves that is known as laser speckle [3]. This speckle noise decreases the quality of OCT-images and thus complicates the diagnosis.

Previous Work

There have been different attempts to characterize the properties of speckle noise in OCT. *B. Karamata et al.* [4] showed that the OCT-signal at the detector obeys the *Rayleigh distribution.* Its appearance depends on the tissue type of the sample object and in Fourier domain OCT on the time delay between reference and sample beam. As speckle noise is a present signal, the speckles can spread over several pixels which results in correlated noise in adjacent pixels. Additionally noise in different images of the same object and the same recording parameters is correlated, too. The assumption of white Gaussian noise that is made by most standard image processing techniques is not appropriate for speckle noise in OCT-images.

A common approach to improve the image quality is to average multiple frames (compounding). The compounding methods that have been proposed for OCT denoising use generally either space [5], frequency [6] or polarization [7] diversity to physically decorrelate the noise between the single frames. Additionally digital filtering can be applied either to each single frame (pre-compounding) or to the averaged image (post-compounding) for a further reduction of noise. Especially wavelet thresholding methods have been shown to achieve good results removing speckle noise [8].

An enhancement to wavelet thresholding was proposed by *A. Borsdorf et al.* [9] for denoising of CT-images based on two separate CT-reconstructions. The two input datasets contain the same ideal signal and noise. The noise between the images is assumed to be uncorrelated. Both images are decomposed by a wavelet transformation. The correlation between the approximation coefficients within a small neighborhood around each coefficient and a local noise estimation on the detail coefficients is used to identify detail coefficients belonging to noise and structure respectively. The averaged coefficients of both images are weighted accordingly and reconstructed.

Method

The proposed algorithm is a wavelet shrinkage method based on the algorithm from *A. Borsdorf et al*. Figure 1 shows the work-flow of the method. We record m OCT-images (frames) F_i, where each contains the same ideal noise-free signal S and noise N_i. A logarithmic transformation is applied so that the noise can be assumed to be additive.

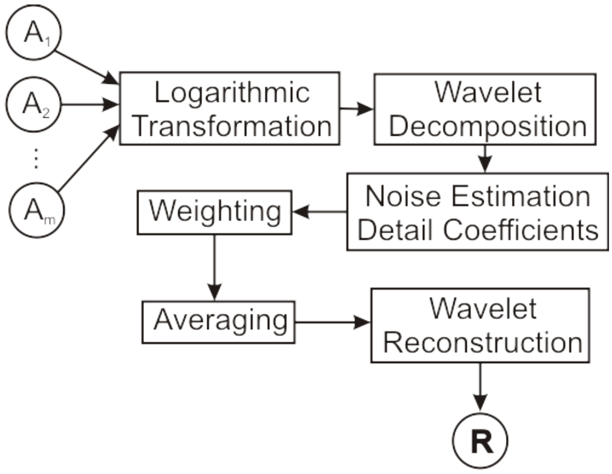

Fig. 1: Flowchart of the algorithm

Each frame can than be written as

$$F_i = S + N_i$$

where we assume

$$\mathrm{Cov}(N_i, N_j) = 0 \qquad | 0 \leq i, j < m \wedge i \neq j$$

The frames are decomposed by a wavelet transformation into approximation coefficients $A_i^{(l)}$ and detail coefficients $W_{i,d}^{(l)}$ where d corresponds to the direction and l is the decomposition level. For each detail coefficient in every image a weight is calculated based on an estimation of the local noise variance $\sigma_{i,d}^2(x)$.

$$\sigma_{i,d}^2(x) = \frac{1}{m-1} \sum_{j=0|j\neq i}^{m-1} (W_{j,d}(x) - W_{i,d}(x))^2$$

The weight for each detail coefficient is than calculated as

$$G_{i,d}^{(l)}(x) = \begin{cases} 1, & |W_{i,d}^{(l)}(x)| \geq k\sigma_{i,d}^{(l)} \\ \left(\frac{|W_{i,d}^{(l)}(x)|}{k\sigma_{i,d}^{(l)}}\right)^p & \text{else} \end{cases}$$

where the parameter k controls the amount of noise reduction, and p is a smoothing parameter. With increasing parameter p the weighting tends to a hard thresholding. The final detail coefficients $W_d^{(l)}$ are calculated by weighting and averaging the detail coefficients of all images.

$$W_d^{(l)}(x) = \frac{1}{m} \sum_{i=0}^{m-1} G_{i,d}^{(l)}(x) W_{i,d}^{(l)}(x)$$

The approximation coefficients are averaged. The final result is calculated by a wavelet reconstruction on the averaged coefficients.

Results

For the evaluation a gold-standard image of a pig's eye was created (see figure 3). Therefore 455 images were averaged where the position of the eye was changed at regular intervals. The algorithm is performed on subsets of 8 randomly selected images and compared to simple averaging. The amount of noise reduction is measured by the *SNR-gain*

$$SNR\text{-}gain = \frac{\sigma_{N_{avg}}}{\sigma_{N_{fil}}} - 1 = \frac{std(I_{avg} - I_{gs})}{std(I_{fil} - I_{gs})} - 1$$

where I_{avg} and I_{fil} are the averaged and the filtered image respectively and I_{gs} is the gold-standard image. The sharpness of the results is measured by the *full width half maximum* (FWHM) at different edges in the image. The FWHM is the width of the derivation of the edge response function at the half maximum.

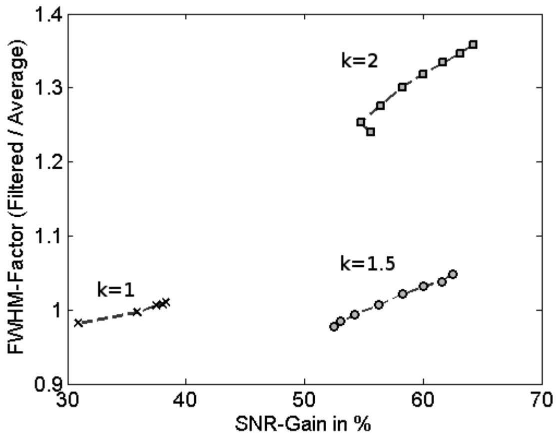

Fig. 2: Evaluation Results

Figure 2 shows the possible SNR-gain along with the factor that the FWHM increases for different parameters *k*. For *k=1* and *k=1.5* the sharpness reduction is very small (*0.98* to *1.04*) while for *k=2* there is a significant reduction of sharpness up to a factor of *1.35*. For *k<2* a SNR-gain of up to *62.5 %* is reached (for *k=2* up to *64.2 %*). Figure 3 shows the resulting images.

Conclusion

A wavelet shrinkage approach was presented here that uses a local noise estimation for denoising of multiple frame OCT-data. Compared to simple averaging, the method achieves a noticeable improvement of image quality (signal-to-noise gain of *62.5 %*) where only a slight reduction of sharpness is observed (about factor *1.04*). A larger SNR-gain is only achieved by taking an inadequate reduction of sharpness (more than factor *1.3*). The proposed algorithm provides a simple software approach to increase the quality of OCT-images using multiple frames.

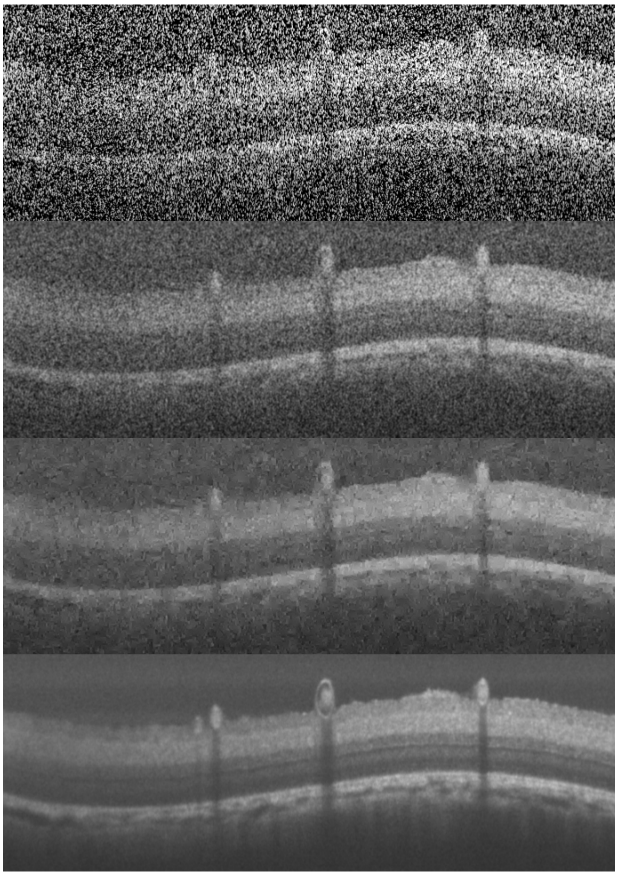

Fig. 3: From top to bottom: Single OCT-frame, average of 8 OCT-frames, result of the wavelet algorithm using 8 frames, gold-standard image (average of 455 frames)

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