LETTER

Application of RPCA in optical coherence tomography for speckle noise reduction

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Abstract
Optical coherence tomography (OCT) is a promising technology, which could be used in a variety of imaging applications. However, OCT images are usually degraded by speckle noise. Speckle noise reduction in OCT is particularly challenging because it is difficult to separate the noise and the information components in the speckle pattern. In this study, a novel speckle noise reduction technique, based on robust principal component analysis (RPCA), is presented and applied to OCT images for the first time. The proposed technique gives an optimal estimate of OCT image domain transformations such that the matrix of transformed OCT images can be decomposed as the sum of a sparse matrix of speckle noise and a low-rank matrix of the denoised image. The decomposition is a unique feature of the proposed method which can not only reduce the speckle noise, but also preserve the structural information about the imaged object. Applying the proposed technique to a number of OCT images showed significant improvement of image quality.

(Some figures may appear in colour only in the online journal)

1. Introduction
Optical coherence tomography (OCT) is a modern biomedical imaging technology based on low coherence interferometry (LCI). OCT allows for non-contact, high-resolution imaging of biological tissues [1]. Over the past 20 years, OCT’s development has been remarkable. With rapid progress, OCT is now often cited as a promising tool, which could be used in a variety of imaging applications. Since OCT is based on detection of coherent waves, OCT images contain speckle. Speckle in OCT is dependent on the wavelength of the imaging beam and the structural details of the imaged object [2]. Time varying speckle in OCT structural images can be used in the analysis of tissue structure and flow information [3–5]. In [6] it is mentioned that the speckle content present in depth OCT images can be utilized to differentiate various tissue types, such as skin, lung, fat and breast tissue. The speckle variance OCT method can also be used to delineate tissue micro vasculature in vivo according to its different temporal speckle decorrelation characteristics [7, 8]. Speckle variance imaging provides a more accurate representation of the vascular structure [9]. As mentioned above, we believe that there are information components representative of the imaged object in the speckle pattern. Unfortunately, speckle also carries a noise component, which is responsible for the grainy appearance of OCT images [10–12]. Reduction of speckle noise can increase the image contrast and spatial resolution, therefore allowing further visualization of the imaged object [13]. However, speckle noise reduction in OCT is particularly challenging because it is difficult to separate the noise and the information components in the speckle pattern [10–12]. Much
research has been performed over the years on OCT speckle noise reduction. The results presented in [13] demonstrate that speckle noise can be reduced by using optical clearing osmotic agents, however this kind of technique requires modifications to the OCT system design. Therefore, the development of post-processing techniques for speckle noise attenuation is preferable to design modification, and it is an important part of the OCT imaging [10, 14]. In order to reduce speckle noise, two-dimensional OCT images are averaged in the lateral direction into a single curve [15–19]. In some research, an averaging technique is employed for speckle noise suppression [20–23], however it results in a one-dimensional curve that impedes further performance, such as image segmentation and pattern recognition. Wavelet transforms have also been applied in the OCT images for speckle noise reduction and obscured pattern recognition [35, 36] as well as other applications in the fields of laser physics [24–34]. For example, [36] indicates wavelet analysis can enhance the OCT imaging capabilities and reduce the statistical noise associated with multiple scattering.

Principal component analysis (PCA) has been widely used for data processing, analysis and dimensionality reduction in the fields of laser physics. For example, in order to derive knowledge of the reference spectra database, the PCA approach is applied to determine individual autofluorescence components [37]. The PCA method is used to identify different isolates for the detection of biofilm-positive and biofilm-negative staphylococcus epidermidis strains [38]. In a different study, PCA is employed to identify malignant tissue/cells and classify the data, and the results are indicated to be effective for the Raman spectral diagnosis of oral mucosal diseases [39]. However, many research works in the literature have proposed ways of addressing the limitations of classical PCA with respect to outliers and gross corruption over recent decades, yielding the field of robust PCA (RPCA) [40–44]. In this paper, a novel speckle noise reduction technique, based on the RPCA technique, is presented and applied to OCT images for the first time. The proposed technique gives an optimal estimate of OCT image domain transformations such that the matrix of transformed OCT images can be decomposed as the sum of a sparse matrix of speckle noise and a low-rank matrix of the denoised image. We verified the efficacy of the proposed technique with a number of experiments on both posterior and anterior eye OCT images.

2. Materials and methods

In OCT, the observed image is a superposition of the information component and the noise component in the speckle pattern, therefore, the component of the OCT image has low intrinsic dimensionality, i.e., it lies in some low-dimensional subspace, or it is sparse. Mathematically, this means the observed OCT image \( \mathbf{X} \) can be decomposed into a low-rank matrix and a sparse matrix such that \( \mathbf{X} = \mathbf{X}_L + \mathbf{X}_S \), where \( \mathbf{X}_L \) has low rank and \( \mathbf{X}_S \) is sparse. Obviously, the component \( \mathbf{X}_L \) carries the information of the imaged object, and the component \( \mathbf{X}_S \) carries the speckle noise. Given these properties of RPCA, we present in this work a novel approach based on RPCA to reduce speckle noise in OCT images. Our results indicate that the image quality is significantly improved. The proposed approach is defined as the following constrained minimization of a cost function,

\[
\min_{\mathbf{X}_L, \mathbf{X}_S} \|\mathbf{X}_L\|_* + \gamma \|\mathbf{X}_S\|_1 \quad \text{subject to } \mathbf{X} = \mathbf{X}_L + \mathbf{X}_S \quad (1)
\]

where \( \|\cdot\|_* \) denotes the matrix nuclear norm, \( \|\cdot\|_1 \) denotes the L1 norm, and \( \gamma \) is a positive weighting parameter to balance the two terms, with \( \gamma = 1/\sqrt{\max(D, T)} \), where \( D \) is the number of axial pixels of the observed OCT image, and \( T \) is the number of transverse pixels of the OCT image. For the OCT imaging problem, we do not know the low-dimensional subspace of \( \mathbf{X}_L \) or the locations and number of the nonzero entries of \( \mathbf{X}_S \). There are several algorithms for solving the RPCA problem [40–44]. In this work, we adopt a fast and accurate algorithm for the low rank and sparse decomposition of OCT images, namely the inexact augmented Lagrange multiplier (IALM) method [40].

The approach was tested on the retinal image of ophthalmic OCT. The Copernicus SD OCT HR (Optopol Technology S.A., Zawiercie, Poland) instrument was used to collect the OCT data. The details of the OCT image information have been previously described in [45]. To quantify the performance of the proposed method, well-known speckle noise reduction performance metrics such as peak-signal-to-noise ratio (SNR), contrast-to-noise ratio (CNR), equivalent number of looks (ENL), and cross correlation (XCOR) were computed. CNR measures the contrast between image features and noise. ENL measures the smoothness of areas that should have a homogeneous appearance but are corrupted by speckle noise. XCOR

![Figure 1. Original posterior eye OCT image with ROIs overlaid in white. Region 1 was used to calculate the background noise level. A total of three inhomogeneous regions (2, 3 and 4) along with three homogeneous regions (5, 6 and 7) were considered.](image-url)
measures the similarity between the images before and after denoising. The image quality metrics used are the same as the metrics described in [10–12, 14, 35, 45, 46].

3. Results and discussion

The proposed method was first applied to the posterior eye OCT image. Figure 1 shows the original image with six regions of interest (ROIs) overlaid in white. The unprocessed OCT image has a grainy appearance because of the presence of speckle. Three inhomogeneous ROIs (labelled 2, 3 and 4), three homogeneous ROIs (labelled 5, 6 and 7), and a background region (labelled 1, for the retinal image it is the vitreous-humour area) were manually selected and marked on the image.

As shown in figure 2, much of the speckle noise in the original image has been suppressed by using RPCA, making some image features hidden in the original image...
more obvious. A zoomed region was added in the images in order to illustrate the speckle reduction and any potential loss of spatial resolution. The RPCA improves the visualization of small morphological features such as the junction between the inner and outer segment of the photoreceptors (IS/OS) and retinal pigment epithelium (RPE), as indicated in the zoomed regions. Quantitative comparison of the denoising effect for the RPCA-based method was performed by evaluating the image quality metric values for the original and the denoised images. The results from the quantitative analysis are presented in the lower left corner of figures 2(a) and (b). The CNR values are averaged over six ROIs (2–7). The ENL values are averaged over the three homogeneous ROIs (5–7). The first ROI is used to calculate the background noise level. The application of the proposed method resulted in significant performance improvements over the original image, with an ENL improvement of 25.1692 compared to the original image. Moreover, CNR and SNR improvements are also observed. The CNR improves by 0.9643 and the SNR improves by 2.9775 with a similarity (XCOR) degradation of only 1.63%. The results demonstrated the effectiveness of the proposed approach for speckle noise reduction. Although the XCOR of the RPCA technique is slightly lower than the original one, the reduction in speckle noise with the RPCA allows the layered structure in the image to be more clearly delineated when looking at a cross section signal. Figure 3 presents a one-dimensional cross section of the denoised image at the indicated white solid line in figure 1(b). Figure 3 indicates that, after RPCA denoising, both the layer/edge separation of the retina and the image features of the original signal are well preserved. All of those demonstrated the ability of the RPCA in reducing noise while preserving signals.

The RPCA method was also applied to the OCT image of an anterior eye with a contact lens. Significant smoothness enhancement can be clearly seen in figure 4(b) when compared with figure 4(a). The denoised image is much cleaner than the original one, and the features of the object are more obvious with the proposed technique. It is worth noting that the RPCA also increased the CNR, ENL and SNR. The CNR, ENL and SNR were improved by 0.5227, 4.4226 and 2.7532, respectively, while image similarity was degraded by only 3.52%. These results suggest that the improvement of image quality was obtained again by using the RPCA technique.

4. Conclusion

In this study, we demonstrated the efficacy of a RPCA-based technique to reduce speckle noise in OCT images. The decomposition of the OCT image matrix into a sparse matrix of speckle noise and a low-rank matrix of denoised image is a unique feature of the proposed method which can not only reduce the speckle noise, but also preserve the structural information about the imaged object. In general, the application of this technique to the post-processing of OCT images significantly improved the image quality. The results suggest that RPCA-based speckle noise reduction could be a powerful technique for many future OCT imaging applications.

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References
