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Removal of correlated speckle noise using sparse and overcomplete representations

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ABSTRACT

Recently, there has been a growing interest in the sparse representation of signals over learned and overcomplete dictionaries. Instead of using fixed transforms such as the wavelets and its variants, an alternative way is to train a redundant dictionary from the image itself. This paper presents a novel de-speckling scheme for medical ultrasound and speckle corrupted photographic images using the sparse representations over a learned overcomplete dictionary. It is shown that the proposed algorithm can be used effectively for the removal of speckle by combining an existing pre-processing stage before an adaptive dictionary could be learned for sparse representation. Extensive simulations are carried out to show the effectiveness of the proposed filter for the removal of speckle noise both visually and quantitatively.

1. Introduction

Ultrasound (US) images are corrupted by the multiplicative speckle noise when the sound wave used in the imaging, needs to travel through heterogeneous tissue having different acoustic properties before reaching the transducer. Since the speckle tends to blur the finer anatomical details, the reduction of speckle is an important task in US image processing. Recently multiscale redundant representation has been used for the removal of speckle noise in synthetic aperture radar (SAR) images. The use of stationary wavelet transform (SWT) can be seen as one of the approaches towards this [1–4]. In [5], the authors proposed a versatile de-speckling technique for medical ultrasound images using SWT. One advantage of these approaches is that they produce a sparse representation of the signal over an overcomplete or redundant dictionary where the number of basis functions are more than the dimensionality of the input. The overcomplete dictionary is important for denoising because of its robustness to noise and other form of image degradations [6]. Another advantage is that the overcomplete dictionary is shift invariant which allows for small translation or scaling of local image features to result in smooth and graceful change in the distribution of activity among the sparse coefficients [7], a distinctive feature not present in the transforms with a fixed basis set [8]. The constraints of sparsity and redundancy also resulted in the introduction of denoising techniques using new multiscale representations such as curvelets [9], contourlets [10,11] and many more. The discovery of the matching pursuit [12] and the basis pursuit [13] algorithms and the analytical justifications of their optimality conditions [14,15] have lead to a new thrust in the application of sparse decompositions over redundant dictionaries for image denoising.

In another approach called the example-based restoration [16], the dictionary is learned using a prior of sparsity and redundancy on the image itself. Aharon et al. [17] proposed the K-SVD algorithm as a generalization of the K-means algorithm for training a dictionary from a set of image-patches using the singular value decomposition (SVD) and sparse coding of image using orthogonal matching pursuit (OMP). This idea of learning a dictionary from a set of image-patches for sparse representation also appeared in [18].

In [19], the authors proposed a K-SVD based denoising algorithm for the removal of additive white Gaussian noise (AWGN). They proposed a global image prior that ensure sparsity over patches in every location in the image and a maximum *a posteriori* estimator to estimate the true signal.

The speckle noise in US images is multiplicative and correlated [20,21]. The K-SVD denoising algorithm is geared towards the removal of the AWGN. Therefore, applying the K-SVD directly on the US image will not be effective. There is a need for some pre-processing procedure which will modify the US speckle noise into the AWGN. In the so called homomorphic de-speckling (HDS) approach for US image denoising, the envelope detected image is first log-transformed to convert the multiplicative noise into an additive one followed by a suitable additive noise removal

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algorithm assuming that the noise is AWGN. In [20] it has been shown that such an assumption is oversimplified and leads to poor performance of any de-speckling method. They have proposed a pre-processing scheme to convert the correlated multiplicative speckle noise into AWGN.

In [1], the authors proposed a K-SVD based method for the removal of speckle noise from both the intensity based and log-transformed based SAR images and also compared their results with the state-of-the-art soft-thresholding based methods. To our knowledge, the authors in [1] for the first time demonstrate the application of sparse and redundant representation for the removal of speckle noise from SAR images. This paper aims at exploiting the concept of sparse and redundant representation in order to de-speckle US images. Here the main challenge is to remove the multiplicative correlated speckle noise without any loss of finer anatomical details. In this direction, some preliminary work by the authors of this paper can be found in [22]. However, the main contributions of the present work are: (1) an extensive study on sparse representation and its application in denoising, (2) estimation of the noise and a tuning parameter, controlling noise smoothing and finally (3) more experimental results to establish our claims.

The rest of the paper is organized as follows. Section 2 gives a short account on the various approaches on ultrasound de-speckling. Section 3 outlines a brief review of the sparse overcomplete representations and the K-SVD algorithms for the denoising of AWGN. Section 4 discusses about the speckle correlation and its statistical distribution under log transformation. The review of US image pre-processing is given in Section 5. Section 6 gives an account for the estimation of various parameters and also proposes a noise estimation algorithm. The proposed de-speckling algorithm is detailed in Section 7. Experimental results are discussed in Section 8 and finally, Section 9 concludes the paper.

2. Prior art

The speckle in medical ultrasound images is a signal-dependent and multiplicative noise as discussed earlier. In the following, we give a short account of the three *major* approaches, available in the ultrasound de-speckling literature which we mention here for reference.

(a) *Spatial filtering methods*: A spatially adaptive filter for smoothing speckle in ultrasound image was proposed in [23]. A spatial filter based on local statistics of the log-transformed ultrasound images using unsharp masking can be found in [24]. These filters fail to remove speckle near or on the edges. Similarly, filters based on the region growing technique have been proposed in [25,26]. The disadvantage of these methods is due to the lack of a universal criterion to select a similarity property on which region growing can be carried out. Some other well known spatial filters are the *Lee filter* [27] and the *Kuan filter* [28]. These filters perform spatial averaging in the homogeneous regions and perform no filtering where edges and point features are present. This is achieved by introducing a coefficient of variation inside the moving window. In [29], an adaptive weighted median filter is used due to its robustness against impulsive type noise and edge preserving characteristics. Another nonlinear filtering method using an edge sensitive diffusion called the *speckle reducing anisotropic diffusion* (SRAD) was proposed in [30] to suppress speckle in ultrasound image while preserving the edge information. In [31], the authors proposed a *SRAD based spatially adaptive maximum-likelihood* (ML) filter for the de-speckling of medical ultrasound images. This filter outperforms the classical spatial domain filters and some of the diffusion based methods for de-speckling.

(b) *Homomorphic filtering methods*: All the above filters are applied directly on the image having the multiplicative noise model. The *homomorphic* Wiener filter proposed in [32] first converts the multiplicative noise into an additive noise through the logarithmic transformation on the speckled image. Then the Wiener filter is used to reject the resultant additive noise followed by the exponential transformation on the filtered image.

Many multiscale methods based on the wavelet transform have also been proposed to *de-speckle* ultrasound images. These methods in general consist of five key operations: (1) logarithmic transformation (2) wavelet transformation (3) modification of wavelet coefficients using some thresholding (shrinkage) function (4) inverse wavelet transform and finally (5) exponential transformation. In the image denoising literature these methods are collectively referred to as the *homomorphic wavelet based de-speckling methods* (HWDS). The wavelet thresholding methods for the reduction of speckle can be found in [33,34]. These methods adopted a soft thresholding procedure which was originally proposed by Donoho [35,8] to remove noise within the finer scales and in the non-linear processing of feature energy for contrast enhancement. However, thresholding methods have two main limitations: (1) the choice of the threshold, the most important design parameter, is done in an ad hoc manner; and (2) the specific distributions of the signal and noise are not at all considered.

To address the above issues, Simoncelli and Adelson [36] developed non-linear estimators in the wavelet domain, based on the formal Bayesian theory. They used a generalized Gaussian model for the subband statistics of the signal at different scales and thereby estimated the signal using a maximum *a posteriori* (MAP) estimator. Achim et al. [37] developed a MAP estimator for the removal of speckle by modeling the signal wavelet coefficients by the alpha-stable distribution [38] and the noise wavelet coefficients by the Gaussian distribution for the wavelet decomposition at different scales. In [5], the authors proposed a versatile de-speckling method by modeling the noise wavelet coefficients by the generalized Nakagami distribution. Thus, the success of the Bayesian methods depends on the proper use of the statistical distributions to model the signal and the noise.

The main limitation of the HWDS methods is that it assumes that the speckle noise in the log-transformed image is white and Gaussian. However, they are correlated [39] and also cannot be modelled well by the Gaussian distribution after the logarithmic transformation. A modified HWDS is proposed in [20] to overcome these limitations.

(c) *Non-homomorphic filtering methods*: There is yet another class of algorithms for the reduction of speckle which do not apply the logarithm prior to the application of the wavelet transform. These *non-homomorphic methods* filter the wavelet coefficients of the original speckle corrupted image without log-transformation. Pižurica et al. [2] proposed a versatile denoising method in this category using the UDWT for medical ultrasound images. It considers the correlation of useful wavelet coefficients across scales. This method does not rely on the exact prior knowledge of the noise distribution and is more flexible and robust compared to other wavelet based methods. In [4,40], the authors proposed non-homomorphic approaches for filtering synthetic aperture radar (SAR) images.

The DWT and its shift-invariant version, the UDWT, are very successful for the sparse representation of one-dimensional signals. The performance of the DWT and the UDWT in images deteriorates because the 2D separable bases cannot have compact representations for lines and edges. The authors in [41] demonstrated that the localized structures such as step edges and the oriented structures