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Ultrasound echocardiography despeckling with non-local means time series filter

Yanfeng Gu [a,*], Zhaoyu Cui [a], Chunhong Xiu [b], Lanfeng Wang [b]

[a] School of Electronics and Information Engineering, Harbin Institute of Technology, PR China
[b] First Affiliated Hospital, Department of Cardiology, Harbin Medical University, PR China

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ABSTRACT

Ultrasound imaging is one of the most important instruments of modern medical imaging modalities. However, the usefulness of ultrasound imaging is degraded due to the presence of a signal-dependent noise known as speckle. Recently, lots of algorithms have been proposed for despeckling. Unfortunately, few attentions have been paid on time series of ultrasound images like echocardiography. In this paper, we address this problem by developing a time series non-local means (NLM) filter algorithm. A distance measure relevant to a speckle model is firstly introduced to take place of the Gaussian-weighted Euclidian distance according to a Bayesian formulation. By taking the information along the temporal axis into account, we further extend the NLM filter from single frame to image time series. To lighten the computational burden, a blockwise approach and a pre-classification process are used to accelerate the algorithm. In order to evaluate our method, experiments are conducted on both synthetic and in vivo ultrasound images. Experiments show that the proposed method achieves satisfactory results in terms of removing the speckle and preserving the edges and image details, compared with the state-of-the-art methods.

1. Introduction

Ultrasound imaging is considered to be noninvasive, practically harmless to the human body, accurate, and low-cost, compared with other medical imaging modalities. These features make ultrasound imaging the most prevalent diagnostic tool in hospitals. Images produced by ultrasound systems are generally influenced by a common phenomenon known as speckle [11]. Although speckle deteriorates the image quality, it is not always considered as a futile noise because its texture often carries useful information [6]. For example, speckle tracking methods are widely used for analyzing the motion pattern of myocardium [3,26]. However, the presence of speckle badly reduces the image contrast and blurs details of the images so that the quality and accuracy of diagnosis by means of those images decrease accordingly. Hence, despeckling is an important prerequisite, when ultrasound imaging is used for clinical diagnosis and organ segmentation.

Several statistical models were proposed to describe the speckle noise in ultrasound images in the past years. It is commonly accepted that speckle in the raw radio frequency (RF) signal provided by the ultrasound probe is spatially correlated multiplicative noise with Rayleigh distribution [11]. However, the RF signal is not usually available in the common ultrasound equipment. In order to improve image visualization, a sequence of standard processing needs to be performed on the RF signal by a typical ultrasound scanner before the exportation, such as nonlinear amplification, dynamic-range adjustment via log compression, low-pass filtering, interpolation, etc. These operations significantly change the statistical distribution of the original RF raw signal, and speckle is no longer multiplicative. A model for the ultrasound images displayed on screen was used successfully in many studies [17,25], and it can be expressed as

$$z(x) = u(x) + u^{\gamma}(x)\eta(x) \tag{1}$$

where $u(x)$ and $z(x)$ represent the observed image and the original image, respectively, and the noise $\eta(x) \sim N(0, \sigma^2)$. Loupas et al. [17] showed that $\gamma = 0.5$ fits well to the images displayed on screen.

Recently, many techniques have been widely studied for speckle reduction in the literature. Some classical filters like Lee [16], Kuan et al. [15], and Frost et al. [9] were designed for additive noise followed by exponential transform. The adaptive weighted median filter (AWMF) [17] performs as a low-pass filter, and it can effectively remove the speckle but easily causes blurring in edge region. Anisotropic diffusion [20,24] is a nonlinear iterative filter widely used in ultrasound despeckling in virtue of its properties of noise reduction and edge preservation [27,29,14]. Although these anisotropic diffusion based filters could improve the speckle reduction and edge preservation, the low-contrast edges are often smeared with speckle and the speckle is usually retained

* Corresponding author. Tel.: +86 451 86403020; fax: +86 451 86413583.
E-mail address: guyf@hit.edu.cn (Y. Gu).

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in high-intensity region. Wavelet decomposition is considered to be a powerful method of recovering signals [7,8]. The applications of wavelet denoising to the problem of despeckling in medical ultrasound imaging were reported in [30,1,25]. These wavelet based methods rely on the precondition of the multiplicative model of speckle and adopt the logarithmic transformation to convert the multiplicative noise into an additive one. Then the log-transformed speckle is regarded as the Gaussian white noise that is oversimplified and unnatural.

Non-local means (NLM) filter, introduced by Buades et al. [2], uses a weighted averaging scheme to perform image denoising. The NLM filter is proposed based on the fact that in natural images many structural similarities are present in different parts of the image, and has been proved as the state-of-the-arts in removing noise from images. Researches [13] have shown that the NLM filter emerges from a Bayesian approach, and the original NLM is related to additive Gaussian noise. Based on this observation, Coupé et al. [5] introduced a new statistical distance measure relevant to speckle model in medical ultrasound image to compare the similarity of patches, and formed the Optimized Bayesian Non-local Means speckle filter (OBNLM).

In ultrasound instruments, the data from one patient consist of a sequence of images at different time points of cardiac cycle. Most of the existing despeckling methods only restore each frame separately without taking the temporal correlation between image series into account. Since the NLM filter is based on the redundancy of natural image, the redundant information contained in temporal axis as well as that of spatial space can contribute to noise reduction. Actually, several approaches have been introduced using the above idea for noise suppression in other types of medical images (e.g. DCE-MR [10], CT [28]).

In this paper, we extend the NLM filter from single frame to volume by using the principle that ultrasound image time series contain repeated patterns. The contributions of this paper can be attributed to that we propose a practical algorithm for ultrasound echocardiography despeckling by integrating a few well designed image/video denoising techniques. We firstly extend the NLM filter from single frame to image time series. It means that we integrate NLM with temporal redundant information to improve the effect of ultrasound image despeckling. The large quantity of redundant information, which is contained in the high frame rate temporal axis, contributes to the denoising process. Besides, we integrate NLM with the block matching and proposed an accelerated algorithm, which guarantees the practicality of our method.

The rest of this paper is organized as follows. In Section 2, the theory of NLM and its Bayesian approach is introduced. In Section 3, the proposed method is illustrated in detail. In Section 4, we test our method on both synthetic and in vivo ultrasound images. Conclusions are drawn in Section 5.

2. Non-local means filter

2.1. Review of the non-local means filter

The NLM algorithm was proposed by Buades et al. [2]. In this method, the restored gray value of each pixel is obtained by the weighted average of the gray values of all pixels in the image. Each weight is proportional to the similarity between the local neighborhood of the pixel being processed and the neighborhood corresponding to the other image pixels. The basic idea is that images contain repeated structures, and averaging them will reduce the random noise.

Consider a gray-scale image $z=(z(x))_{x\in\Omega}$ defined over a domain $\Omega\subset R^2$. $z(x)$ is the noisy observed intensity at position x. As it shown in Fig. 1, the estimated denoised intensity $NL(z)(x)$ at position x is computed as a weighted average of the image pixels intensities

$$NL(z)(x)=\sum_{y\in\Omega}\omega(x,y)z(y) \tag{2}$$

where the weight value $\omega(x,y)$ depends on the similarity between the intensities of the local neighborhood blocks centered on pixel x and y. Moreover, the weights satisfy the conditions $\omega(x,y)\in[0,1]$ and $\sum_y\omega(x,y)=1$.

The values of the weights $\omega(x,y)$ generally rely on a similarity patch system and a distance measure between two patches. Let

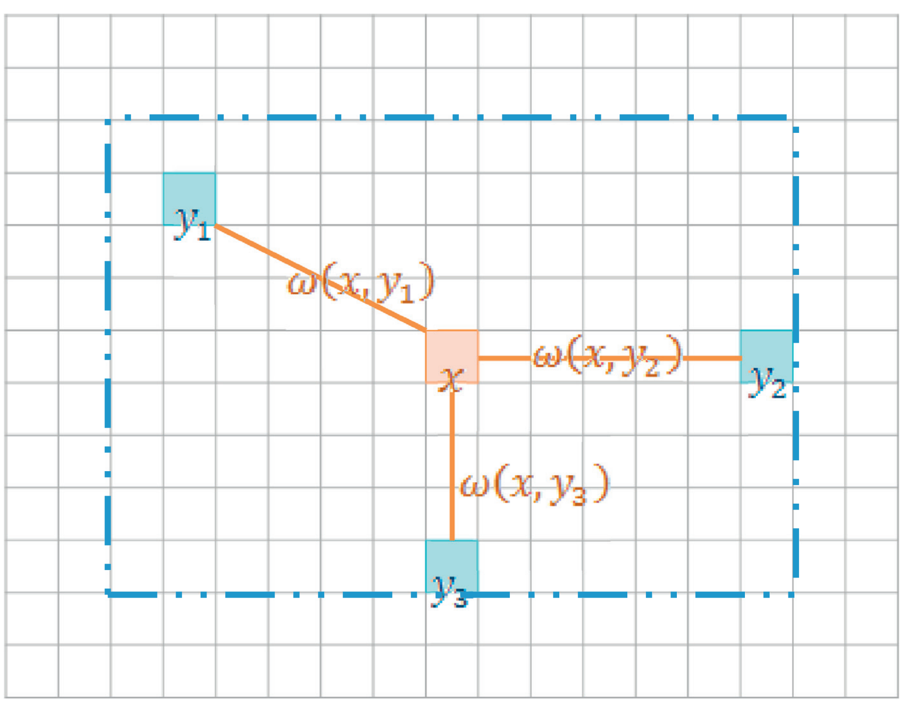

Fig. 1. Non-local means filter.