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Noise suppression in brain magnetic resonance imaging based on non-local means filter and fuzzy cluster

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ABSTRACT

Combining Non-Local Means (NLM) filter with appropriate fuzzy cluster criterion, denoising in synthetic brain magnetic resonance imaging (MRI) are evaluated. Experimental results show that noise is effectively suppressed while image details are well kept, compared with the traditional NLM method and wavelet method. Quantitative and qualitative results indicate that the continuous edge and detailed structure are well preserved, artifacts are greatly reduced and brain MR images are typically enhanced. In addition, the computational time is reduced greatly.

1. Introduction

Image denoising is important for medical imaging and diagnosis. Due to the interference of other factors, noise is inevitably introduced in medical image. The noise in brain magnetic resonance imaging (MRI) degrades the performance of computer-aided analysis of the images. The process of denoising often involves estimating the parameters of the noise induced in a digital image and then devising an algorithm to cancel the effects of such noise in the most non destructive manner possible [1].

A main challenge for denoising schemes is to separate the noise from the original ground truth images [2,3]. Optimal denoising methods should not only preserve edges best but also eliminate noise without artifacts, which can improve image quality without compromising imaging speed. Various denoising algorithm in the last decade were presented. Wavelet-based algorithm often incurs artifacts originating from noise [4,5]. Non-local means (NLM) algorithm can efficiently eliminate noise without artifacts, but details in images are often lost.

NLM is one of the classical algorithms for image denoising [6,7], which exhibits an outstanding performance for denoising of brain MRI. NLM calculates the filtered pixel. Each filtered pixel is a weighted average of all pixels in the image. The weights reflect the similarity between the patterns of neighboring pixels of the current pixel and those of the contributing pixels. The advantage of NLM method is to remove the noise and greatly reduce artifacts. However, the calculation time and the continuous degree of the boundary are the main drawbacks. Fuzzy cluster method is the non-surveillance clustering algorithm, which can analyze the relation between different image pixels, and it can retain more information of the primitive image. Meanwhile, the computational time of fuzzy cluster is greatly reduced compared to other algorithms. To achieve noise removal and detail enhancement simultaneously, a novel scheme to improve the quality of brain MRI processing is presented, which combines fuzzy cluster strategy and NLM method.

2. 2 Principle and method

2.1. NLM

The key idea of the NLM filter is to consider the data redundancy among the "patches" of a noisy image, and restore the noise free pixel using weighted average of non local pixels [8].

$$\mathrm{NL}(u(x_i)) = \sum_{x_j \in V_i} w\left(x_i, x_j\right) u\left(x_j\right) \tag{1}$$

The classical formulation of the NL-means filter is shown in (1), the restored intensity $\mathrm{NL}(u(x_i))$ is the restored intensity of the noisy pixel $u(x_i)$ in the "search window" V_i of radius M, where

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$w(x_i, x_j)$ is the weight assigned to the noisy value $u(x_j)$ to restore the intensity $u(x_i)$ at voxel x_i. This weight evaluates the similarity between two neighbourhoods N_i and N_j centered on pixels x_i and x_j called “patches” or “similarity window”. The original non local means filter considers the pixel intensities of the whole image in the weighted average, while for practical and computational reasons this is restricted to a neighbourhood called “search window”. More precisely, the weight evaluates the similarity between the intensity of the patches N_i and N_j centred on voxels x_i and x_j, such that $w\left(x_i, x_j\right) \in [0, 1]$ and $\sum_{x_j \in V_i} w\left(x_i, x_j\right) = 1$.

For each voxel x_j in V_i, the computation of the weight is based on the squared Euclidean distance between intensity patches $u(N_j)$ and $u(N_i)$, defined as [9,10]:

$$w\left(x_i, x_j\right) = \frac{1}{Z_i} \exp\left(-\frac{\left\|u\left(N_i\right) - u\left(N_j\right)\right\|_2^2}{h^2}\right) \tag{2}$$

where Z_i is a normalization constant ensuring that $\sum_j w\left(x_i, x_j\right) = 1$ and h is a parameter for exponential decay control, $h = k\sigma$ where k is the smoothing parameter and σ is the noise standard deviation.

The main limitation of the NL-means filter is its computational burden, especially in three-dimensional (3D). Therefore we used the combination approach of non local mean method of fuzzy clustering criterion to drastically reduce the computational time. The combination approach consists in denoising the entire patch at the same time. In this way, we obtained restored values for all the elements of the patch.

2.2. Fuzzy cluster

The fuzzy set theory was first used in the cluster analysis in 1969, the fuzzy cluster algorithm was proposed, which is still used commonly in image enhancement. Standard fuzzy cluster is the non-surveillance clustering algorithm, and its success is mainly due to that in order to solve the membership of each image pixel, the fuzziness cluster can retain more information of the primitive image compared with the other crisp or the hard methods. The steps of fuzzy cluster method [11]:

(1) Input training samples prior known, n is the number of the samples. $x_i = (x_{i1}, x_{i2}, \ldots, x_{ip})$, $i = 1, 2, \ldots, n$.
(2) Using the immune network algorithm to obtain the clustering center M_j, $j = 1, 2, \ldots, c$, and the corresponding cluster are supposed as follows: $A_1, A_2, \ldots, A_c$.
(3) $i = 1$, calculate the membership degree that x_i to the c classifications prior known:

$$\mu_j\left(x_i\right) = \frac{\left(1/\left\|x_i - M_j\right\|^{2/(b-1)}\right)}{\sum_{k=1}^{c}\left\|x_i - M_k\right\|^{2/(b-1)}} \tag{3}$$

where b is the measurement constant of clustering fuzzy degree.
(4) Get c membership degree values $\mu_j(x_i)$, the maximum is $\mu_{\mathrm{max}i}$, try to find the classes which make $\mu_j(x_i) = \mu_{\mathrm{max}i}$ established, and the classes are supposed as: $A_1, A_2, \ldots, A_{c_0}$.
(5) If $c_0 = 1$, x_i is converged to A_{c_0}, else if $c_0 > 1$, go to next step.
(6) According to the fuzzy regulation, A_{ik} is chosen from $A_1, A_2, \ldots, A_{c_0}$, making x_i and A_{ik} are most close to fuzzy condition, then x_i is converged to A_{ik}.

Fuzzy cluster is widely used because of its unique advantages in the image enhancement. However, when clustering the big data set, fuzzy cluster algorithm is extremely time-consuming, moreover, regarding to the image of low signal-to-noise ratio, the result is not very ideal. To further enhance the operating performance of the fuzzy clustering algorithm, and reduce the time complexity, an improved fuzzy cluster algorithm is introduced [12].

The region from which the image signal is gained:

$$Y_K = X_K G_K \quad \forall k \in \left\{1, 2, \ldots, N\right\} \tag{4}$$

where X_K, Y_K and G_K are the real intensity, the observational intensity and the region gained from kth pixels, N is the total number of pixels.

The permitting bias during the process of the image transforming:

$$y_k = x_k + \beta_k \quad \forall k \in \left\{1, 2, \ldots, N\right\} \tag{5}$$

where x_k, y_k and β_k are the real value, the value represented in kth pixels after in logarithmic transformation and the bias in kth pixels, respectively. If the region is known, the common enhancement methods based on the intensity can evaluate the region of interest on medical image easily, thus the correct data is achieved.

The following are the improvement for the algorithm [13].

$$J_m = \sum_{i=1}^{c}\sum_{K=1}^{N} u_{ik}^{p}\left\|y_k - \beta_k - v_i\right\|^2 + \sum_{i=1}^{c}\sum_{k=1}^{N} u_{ik}^{p} \sum_{y_r \in N_K} w\left(y_k, y_r\right)\left\|y_r - \beta_r - v_i\right\|^2 \tag{6}$$

where $w(y_k, y_r)$ is the weight function, satisfying the condition below:

$$\sum_{y_r \in N_k} w\left(y_k, y_r\right) = \alpha, \quad 0 \le \alpha \le 1, \quad \forall k \in \left\{1, 2, \ldots, N\right\} \tag{7}$$

With $w\left(y_k, y_r\right) = \alpha/N_R, J_m$ is the optimum solution to the problem of fuzzy clustering algorithm.

Medical images are first segmented to get the region of interest through the improved fuzzy clustering algorithm. Second, the segmented medical images are denoised by NLM algorithm. From the first step, medical images can retain more of the information of the original images which can enhance the region of interest at the same time. The ideal denoising medical images can be obtained through the NLM method at the second step.

3. Experimental results

The combined method is evaluated both qualitatively and quantitatively with synthetic MR images of human brain from the ‘BrainWeb’ website [14–16]. T1-weighted synthetic MR images (3D brain MRI spatial resolution is 181 × 217 × 181, and slice thickness is 1 mm) are used in our experiments. Different levels of Rician noise (1–7%, respectively) are added to the original brain MRI in which to create noisy images.

Three important performance metrics are introduced to analyze the performance of the proposed method, the NLM method and the wavelet method which are root mean square error (RMSE), peak signal-to-noise ratio (PSNR) and structural similarity (SSIM).

MSE is the mean square error between ground truth and result images, which is define as

$$\mathrm{MSE} = \frac{1}{M}\sum_{x=1}^{M}\left[f(x) - g(x)\right]^2 \tag{8}$$

where f is the noise-free image and g denotes the processed image.

RMSE is the root mean square error, the relationship of MSE and RMSE is defined as follows:

$$\mathrm{RMSE} = \sqrt{\mathrm{MSE}} \tag{9}$$