Improved non-local mean denoising algorithm based reliability of reference pixel

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Abstract. In this paper, we propose a method for improved the non-local mean denoising algorithm by using the similarity in comparison with reference pixels. The noise in image is eliminated by the calculation to follow values as the patterns are similar in non-local mean denoising algorithm. In the conventional algorithm, all the comparison results of the pixels are included in the denoising process, and even the low similarity result is included. The method causes the denoised effect to incorrect. In this paper, we propose an algorithm that reduces the influence of low-similarity reference pixels or improves the effect of high-similarity reference pixels. The proposed method improves both the object quality and the subject quality.

1. Introduction

The noise on image is added from the acquiring process in nature to the image of the digital, and also when the image is on the processes to communicate and compress. There are various method for image de-noising. Image denoising process has a goal that suppress the noise and preserve the shape and features of the original image.

There are 2 kinds of methods for image denoising process. One is a method on spatial domain and the other is a method on transform domain.

Typically, the denoising method on spatial domain are Gaussian filter[1], median filter[2], and bilateral filter[3]. The methods are categorized local denoising algorithm because they conjugate the neighboring pixels as reference pixels for denoising calculation. Budes’ non-local mean(NLM) denoising algorithm is representative of non-local denoising method. This method conjugates the whole pixels in the image for denoising calculation.

On the other hand, the denoising method on transform domain are wavelet transform[4-6] as orthogonal wavelet transform and non-orthogonal wavelet transform. The method are efficient tool for compression and denoising with thresholding process.

The conventional NLM denoising algorithm[7] calculates denoised pixel value through comparing the pixel and the other whole pixels. The comparison results of the pixels are included in the calculation. The low similarity reference pixel causes inaccuracy of the calculation.

In this paper, we propose the improved NLM denoising algorithm. Our proposed algorithm
supresses the effect of low-similarity reference pixel on the denoising calculation. Also, we apply the method on fast NLM denoising algorithm. In section 2, conventional denoising NLM algorithm and fast NLM denoising algorithm[8-9] will be discussed in details. Next, in section 3, we propose the method to improve NLM denoising algorithm. Finally, experimental results and the conclusion are shown in Section 4 and 5.

2. Non-local mean denoising algorithm

2.1. Conventional non-local mean denoising algorithm

The non-local mean denoising algorithm by Buades et al [7] belongs to the non-locally method. Unlike local denoising algorithm[1-3], the whole pixels participate in denoising calculation in non-local denoising algorithm.

The patch unit($P_i$) that is constructed by current pixel($u_i$) and the 8 neighboring pixels is used for denoising calculations in NLM denoising method. The weight is defined according to the similarity between current patch and reference patch. The more similar the current patch is to the reference patch, the higher the weight. The weight is calculated by the similarity between patches as follow:

$$w_{ij} = \frac{1}{z_i} \exp\left(-\frac{1}{h^2} \|P_i - P_j\|^2\right) ,$$

where the $\| . \|^2$ operation is Euclidean distance operator between two patches, $z_i$ is the normalized coefficient as eq. (2), and $h$ is the smoothing coefficient.

$$z_i = \sum_{j=0}^{8} \exp\left(-\frac{1}{h^2} \|P_i - P_j\|^2\right) ,$$

The denoised pixel value $\hat{u}_i$ is calculated by the weight for current pixel $u_i$ as follow:

$$\hat{u}_i = \sum_{j=0}^{8} w_{ij} u_j .$$

The whole pixels on the image affect the denoising calculation regardless of the weight.

2.2. Fast non-local mean denoising algorithm

The fast non-local mean denoising algorithm by Darbon et al [8] is faster on the calculation than conventional non-local mean denoising algorithm, because the method skips a process that is square operations of pixel difference.

$$w_{ij} = \frac{1}{z_i} \exp\left(-\frac{1}{h^2} \sum_{\delta=\Delta} (v(i + \delta) - v(j + \delta))^2\right) ,$$

The difference of patches on eq. (2) can be replaced the difference of pixels on patch $\Delta$ as like eq. (4). A symbol $\delta$, means the order of pixel on the patch $\Delta$. A new vector $d$ , is defined by the difference of each starting point as like eq. (5).

$$d_s = j - 1$$

The square operations are eliminated by a cumulative summation of squared difference pixel value. A new image $S_{d_s}$, is generated by the cumulative summation of squared difference pixel value as like eq. (6).

$$S_{d_s}(p) = \sum_{s=0}^{p} (v(k) - v(k + d_s))^2$$

The value $P$ has the domain $p \in [0,n-1]$, and the value $n$ is number of pixels on the image. The patch $\Delta$ is 1-dimension array as like $\Delta = [-P, P]$, and a new location vector $\hat{p}$ is defined as :

$$\hat{p} = i + \delta_s .$$

Then the eq. (4) can be rearranged with the vector $\hat{p}$ as :
\[ w_i = \frac{1}{z_i} \exp\left( -\frac{1}{h^2} \sum_{d_x,d_y} \exp\left( -\frac{1}{h^2} (v(p + d_x))^2 \right) \right) \]

The eq. (8) can be rearranged with the image \( S_d \) as:

\[ w_i = \frac{1}{z_i} \exp\left( -\frac{1}{h^2} (S_d (s + P) - S_d (s - P)) \right) \]

When 512x512 size image is calculated by NLM algorithm, the fast NLM algorithm is about 80 times faster than conventional algorithm.

3. Methods

3.1. Reliability of reference

The weight is calculated by the comparison between the patch including the current pixel and the other patches in the conventional NLM denoising algorithm. If the reference patch is not similar the current patch as including much noise or different pattern, it causes inaccuracy of the denoising calculation. Therefore, we call it is a low-reliability reference patch. We can calculate accurately the denoised pixel value, when we eliminate the effect of the low-reliability reference patch on the calculation. Not only elimination of low-reliability reference pixel, but also emphasis on high-reliability reference pixel is efficient for denoising.

3.2. Elimination of low-reliability reference

For elimination of low-reliability reference, we add the sorting and truncating process on the conventional NLM denoising algorithm, as figure 1.

![Figure 1. The block diagram of proposed method.](image-url)
We calculate the weight \( w_{ij} \), that is the comparison result between the current patch and the reference patch, and the normalized coefficient \( z_i \), that is the result of multiplying the weight by the pixel value. Sort by the weight \( w_{ij} \), and we give the zero weight to the k-minimum weights reference. After elimination of low-reliability reference, we calculate the denoised pixel value by eq. (3). In this paper, we use k from 2 to 7 for finding optimized k value.

3.3. Emphasis on high-reliability reference

In the fast NLM denoising algorithm, we apply the method to emphasize on high-reliability reference. The conventional fast NLM denoising algorithm makes an image by the cumulated summation of squared difference pixel value. Calculate a weight from difference vector value from new coordinate on the image.

In the algorithm, we calculate the weight by inverse proportion with normalized coefficient \( z_i \). It has smaller weight, the more similar it means. Therefore, by thresholding method[5] to the squared difference pixel value, we make the weight value is zero.

4. Experimental results

In this paper, we experiment on MATLAB with 4 images (Lena, Barbara, Boat, and House, 512x512 size). Each image uses white Gaussian noise variance from 10 to 60 in 10 steps.

For the experiment of section 3.2, we use the coefficient k from 2 to 7. For the experiment of section 3.3, we use hard thresholding method and soft thresholding method, when the squared difference pixel value is less than 5 reference values (5e-5, 1e-4, 5e-4, 1e-3, and the average value).

4.1. Elimination of low-reliability reference

Table 1 tabulates the object quality, PSNR, against the conventional NLM denoising algorithm in dB. The experimental results of elimination of low-reliability reference by section 3.2. From Exp 1 to Exp 6, the number of eliminate reference is from 2 to 7.

| Lena | σ=10 | σ=20 | σ=30 | σ=40 | σ=50 | σ=60 | Barbara | σ=10 | σ=20 | σ=30 | σ=40 | σ=50 | σ=60 |
|------|------|------|------|------|------|------|---------|------|------|------|------|------|------|
| NLM  | 31.7503 | 31.5885 | 29.5833 | 28.5571 | 27.5512 | 26.5925 | 15.9925 | 17.18 | 30.9347 | 30.7030 | 29.0076 | 27.5571 | 26.1599 | 25.1718 |
| Exp 1 | 31.7503 | 31.5885 | 29.5833 | 28.5571 | 27.5512 | 26.5925 | 15.9925 | 17.18 | 30.9347 | 30.7030 | 29.0076 | 27.5571 | 26.1599 | 25.1718 |
| Exp 2 | 31.7503 | 31.5885 | 29.5833 | 28.5571 | 27.5512 | 26.5925 | 15.9925 | 17.18 | 30.9347 | 30.7030 | 29.0076 | 27.5571 | 26.1599 | 25.1718 |
| Exp 3 | 31.7503 | 31.5885 | 29.5833 | 28.5571 | 27.5512 | 26.5925 | 15.9925 | 17.18 | 30.9347 | 30.7030 | 29.0076 | 27.5571 | 26.1599 | 25.1718 |
| Exp 4 | 31.7503 | 31.5885 | 29.5833 | 28.5571 | 27.5512 | 26.5925 | 15.9925 | 17.18 | 30.9347 | 30.7030 | 29.0076 | 27.5571 | 26.1599 | 25.1718 |
| Exp 5 | 31.7503 | 31.5885 | 29.5833 | 28.5571 | 27.5512 | 26.5925 | 15.9925 | 17.18 | 30.9347 | 30.7030 | 29.0076 | 27.5571 | 26.1599 | 25.1718 |
| Exp 6 | 31.7503 | 31.5885 | 29.5833 | 28.5571 | 27.5512 | 26.5925 | 15.9925 | 17.18 | 30.9347 | 30.7030 | 29.0076 | 27.5571 | 26.1599 | 25.1718 |

| Boat | σ=10 | σ=20 | σ=30 | σ=40 | σ=50 | σ=60 | House | σ=10 | σ=20 | σ=30 | σ=40 | σ=50 | σ=60 |
|------|------|------|------|------|------|------|-------|------|------|------|------|------|------|
| NLM  | 30.8758 | 30.8585 | 28.6785 | 27.6785 | 26.6785 | 25.6785 | 23.6785 | 21.6785 | 30.9132 | 30.9132 | 29.9132 | 28.9132 | 27.9132 | 26.9132 |
| Exp 1 | 30.8758 | 30.8585 | 28.6785 | 27.6785 | 26.6785 | 25.6785 | 23.6785 | 21.6785 | 30.9132 | 30.9132 | 29.9132 | 28.9132 | 27.9132 | 26.9132 |
| Exp 2 | 30.8758 | 30.8585 | 28.6785 | 27.6785 | 26.6785 | 25.6785 | 23.6785 | 21.6785 | 30.9132 | 30.9132 | 29.9132 | 28.9132 | 27.9132 | 26.9132 |
| Exp 3 | 30.8758 | 30.8585 | 28.6785 | 27.6785 | 26.6785 | 25.6785 | 23.6785 | 21.6785 | 30.9132 | 30.9132 | 29.9132 | 28.9132 | 27.9132 | 26.9132 |
| Exp 4 | 30.8758 | 30.8585 | 28.6785 | 27.6785 | 26.6785 | 25.6785 | 23.6785 | 21.6785 | 30.9132 | 30.9132 | 29.9132 | 28.9132 | 27.9132 | 26.9132 |
| Exp 5 | 30.8758 | 30.8585 | 28.6785 | 27.6785 | 26.6785 | 25.6785 | 23.6785 | 21.6785 | 30.9132 | 30.9132 | 29.9132 | 28.9132 | 27.9132 | 26.9132 |
| Exp 6 | 30.8758 | 30.8585 | 28.6785 | 27.6785 | 26.6785 | 25.6785 | 23.6785 | 21.6785 | 30.9132 | 30.9132 | 29.9132 | 28.9132 | 27.9132 | 26.9132 |
From the table, the proposed algorithm shows better noise reduction effect to the much noisy image against the conventional algorithm. When the noise variance is 20, the PSNR results are less only 0.0028–0.07 dB by conventional algorithm. Especially, when the noise variance is 60, the PSNR results are more from minimum 0.3383 dB to maximum 0.4613 dB.

![Figure 2. The comparison of conventional NLM denoising algorithms and proposed algorithm.](image)

The proposed method when it uses soft thresholding effects efficient and almost same as conventional fast NLM algorithm on subjective quality, and the comparison of the result images are identified by figure 2. From figure 3, the part of Barbara image, we can verify the improvement of subject quality on proposed algorithm. There are vertical, diagonal stripe patterns and flat patterns on the part. The left side diagonal stripe patterns and the right-down side vertical stripe patterns are more restored from proposed algorithm by conventional algorithm.

The proposed method is robust to much noisy image, and is especially efficient when there are repeated patterns.

![Figure 3. The part of Barbara image (σ=60, k=7).](image)

4.2. Emphasis on high-reliability reference
Table 2 tabulates the PSNR result of using hard thresholding method against the conventional fast NLM denoising algorithm in dB. Table 3 tabulates the PSNR result of using soft thresholding method. Each table, from Experiment 1 to Experiment 5, the threshold coefficients are set up the values(5e-5, 1e-4, 5e-4, 1e-3, and average value).

| Table 2. PSNR [dB] result of comparison fast NLM algorithm and proposed algorithm (with hard thresholding). |
|---------------------------------------------|
| Lena | σ=10 | σ=20 | σ=30 | σ=40 | σ=50 | σ=60 | Barbara | σ=10 | σ=20 | σ=30 | σ=40 | σ=50 | σ=60 |
| NLM  | 30.510 | 29.547 | 28.487 | 27.049 | 25.976 | 25.124 | 25.124 | 25.076 | 25.076 | 25.076 | 25.076 | 25.076 | 25.076 |
| Exp 1| 30.509 | 29.545 | 28.483 | 27.045 | 25.975 | 25.124 | 25.076 | 25.076 | 25.076 | 25.076 | 25.076 | 25.076 | 25.076 |
| Exp 2| 30.507 | 29.542 | 28.479 | 27.042 | 25.973 | 25.124 | 25.076 | 25.076 | 25.076 | 25.076 | 25.076 | 25.076 | 25.076 |
| Exp 3| 30.489 | 29.550 | 28.487 | 27.047 | 25.977 | 25.124 | 25.076 | 25.076 | 25.076 | 25.076 | 25.076 | 25.076 | 25.076 |
| Exp 4| 30.463 | 29.540 | 28.486 | 27.046 | 25.977 | 25.124 | 25.076 | 25.076 | 25.076 | 25.076 | 25.076 | 25.076 | 25.076 |
| Exp 5| 31.982 | 29.888 | 28.387 | 27.387 | 25.981 | 25.125 | 25.076 | 25.076 | 25.076 | 25.076 | 25.076 | 25.076 | 25.076 |
| Boat | 30.549 | 27.957 | 26.510 | 24.876 | 23.742 | 22.982 | 22.982 | 22.982 | 22.982 | 22.982 | 22.982 | 22.982 | 22.982 |

| Table 3. PSNR [dB] result of comparison fast NLM algorithm and proposed algorithm (with soft thresholding). |
|---------------------------------------------|
| Lena | σ=10 | σ=20 | σ=30 | σ=40 | σ=50 | σ=60 | Barbara | σ=10 | σ=20 | σ=30 | σ=40 | σ=50 | σ=60 |
| NLM  | 30.510 | 29.547 | 28.487 | 27.049 | 25.976 | 25.124 | 25.124 | 25.076 | 25.076 | 25.076 | 25.076 | 25.076 | 25.076 |
| Exp 1| 30.511 | 29.551 | 28.483 | 27.043 | 25.975 | 25.124 | 25.076 | 25.076 | 25.076 | 25.076 | 25.076 | 25.076 | 25.076 |
| Exp 2| 30.514 | 29.557 | 28.482 | 27.042 | 25.975 | 25.124 | 25.076 | 25.076 | 25.076 | 25.076 | 25.076 | 25.076 | 25.076 |
| Exp 3| 30.595 | 29.564 | 28.482 | 27.049 | 25.977 | 25.124 | 25.076 | 25.076 | 25.076 | 25.076 | 25.076 | 25.076 | 25.076 |
| Exp 4| 30.641 | 29.579 | 28.483 | 27.048 | 25.977 | 25.124 | 25.076 | 25.076 | 25.076 | 25.076 | 25.076 | 25.076 | 25.076 |
| Exp 5| 32.475 | 30.117 | 28.348 | 26.907 | 25.876 | 25.052 | 25.052 | 25.052 | 25.052 | 25.052 | 25.052 | 25.052 | 25.052 |
| Boat | 30.549 | 27.957 | 26.510 | 24.876 | 23.742 | 22.982 | 22.982 | 22.982 | 22.982 | 22.982 | 22.982 | 22.982 | 22.982 |

From table 2 and table 3, when the white Gaussian noise variance is 10 and using threshold
coefficient is average value, the proposed method improves the reduction effect on PSNR, from minimum 0.4935 dB to maximum 1.9175 dB.

When the noise variance over 30, using hard thresholding method is better reduction noise effect and using average value for coefficient is the best efficient. But, when the noise variance over 30, using soft thresholding method is worse reduction noise effect against conventional algorithm.

In terms of subject visual quality, the irregular patterns as the hat shape of Lena image, are smoothed by the proposed algorithm. But the reduction noise effect is efficient when there are repeated patterns as Barbara image.

5. Conclusion
This paper presents improved NLM denoising algorithm. The proposed methods induce more reduction noise effect by the consideration of reliability from reference pixel / patch. The conventional NLM denoising algorithm use the whole reference pixel / patch on the image for denoising calculation. The low-reliability reference bring about inaccuracy of the calculation.

The elimination of low-reliability reference method, when the noise variance over 30, is better PSNR result from minimum 0.0158 dB(σ=30) in average to maximum 0.3884 dB(σ=60) in average. The emphasis on high-reliability reference method on fast NLM algorithm, when the noise variance are 10–20, using soft thresholding method is better 0.7624 dB PSNR result in average. And when the noise variance are 50–60, using hard thresholding method is better 0.0111 dB PSNR result in average.

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