

Restoration of Noisy Images using Wiener Filters Designed in Color Space

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Abstract

We propose a Wiener filtering method that can improve the total quality of images corrupted by additive noise without degrading the sharpness caused by the noise reduction process. In contrast with conventional Wiener filtering techniques,[1)-3)] the Wiener filters proposed in this paper are designed so as to minimize the mean square error between the original and restored images in RGB color space. The Wiener filters are calculated from the covariance matrices of the observed images on the basis of the assumptions that the original image and noise have no correlation each other, and the noise covariance can be estimated at system calibration stage or from a uniform density area in the image. The covariance matrices of the observed images are estimated from the neighboring pixels which are selected around the current pixel with a color classification technique. The noisy images generated by computer simulations were restored and evaluated both objectively and subjectively. As a result, we confirmed the proposed method is effective to improve the quality of noisy images compared with the conventional filters.

Introduction

Though spatially averaging filters have been widely used to improve the quality of noisy images, they degrade sharpness of the images. In this research, Wiener filtering in RGB color space is proposed to improve the quality of noisy images without degradation of the sharpness. The filters, named as color space Wiener (CSW) filters, are derived from the covariance matrix of the noisy image. In this derivation, we assumed that the original image and noise have no correlation, and noise statistics are obtained by some calibration techniques such as measurement of uniform density area. The effect of the noise reduction is highly affected by how to estimate the covariance matrix of the noisy image. In this paper, we examined three methods to calculate the covariance matrix. Those methods are based on color classification, neighboring pixel, and combination of those methods.

The performance of the proposed method is verified by computer simulations. In the simulations, a noise is added to the original images, then removed by the proposed methods. The performance of the noise reduction is evaluated by RMSE (root mean square error) and subjective evaluation experiments.

Color Space Wiener Filter

Formulation of CSW filter

In the RGB color space, the pixel vector of the observed image $\mathbf{g}_i$ is represented with the pixel vector of the original image $\mathbf{f}_i$ and noise vector $\mathbf{n}_i$ as

$$\mathbf{g}_i = \mathbf{f}_i + \mathbf{n}_i . \tag{1}$$

In Equation (1), i denotes the pixel number ($1 \le i \le XY$), X and Y are the number of pixels in the horizontal and vertical direction, respectively. Let the mean vector of the observed image be $\bar{\mathbf{g}}$, the pixel vector of the corrected image be $\hat{\mathbf{f}}_i$, and the mean vector of the corrected image be $\bar{\hat{\mathbf{f}}}$. Then these vectors are related by using the CSW filter G as

$$\hat{\mathbf{f}}_i - \bar{\hat{\mathbf{f}}} = \mathrm{G}\left(\mathbf{g}_i - \bar{\mathbf{g}}\right). \tag{2}$$

The filter G is determined so as to minimize the mean square error between the original and corrected images:

$$E = \left\langle \left\| \left(\mathbf{f}_i - \bar{\mathbf{f}}\right) - \mathrm{G}\left(\mathbf{g}_i - \bar{\mathbf{g}}\right) \right\|^2 \right\rangle \rightarrow \min, \qquad (3)$$

where $\langle \bullet \rangle$ is expectation operation with respect to i. If the original image has no correlation with the noise, G is calculated by

$$\mathrm{G} = \mathrm{C}_{ff}\left(\mathrm{C}_{ff} + \mathrm{C}_{nn}\right)^{-1}. \qquad (4)$$

Here, C_{ff} and C_{nn} are the covariance matrices of the original image and noise as follows.

$$\mathrm{C}_{ff} = \left\langle (\mathbf{f}_i - \bar{\mathbf{f}})(\mathbf{f}_i - \bar{\mathbf{f}})^{\mathrm{T}} \right\rangle \qquad (5)$$

$$\mathrm{C}_{nn} = \left\langle \mathbf{n}_i \mathbf{n}_i^{\mathrm{T}} \right\rangle \qquad (6)$$

The matrix C_{ff} is unknown generally, on the other hand the covariance matrix of the observed image, C_{gg}, can be obtained as

$$\mathrm{C}_{gg} = \left\langle (\mathbf{g}_i - \bar{\mathbf{g}})(\mathbf{g}_i - \bar{\mathbf{g}})^{\mathrm{T}} \right\rangle. \qquad (7)$$

Under the assumption of no correlation between original image and noise, C_{ff} can be represented as

$$\mathrm{C}_{ff} = \mathrm{C}_{gg} - \mathrm{C}_{nn}. \qquad (8)$$

Finally, the filter G is represented by

$$\mathrm{G} = \left(\mathrm{C}_{gg} - \mathrm{C}_{nn}\right)\mathrm{C}_{gg}^{-1}. \qquad (9)$$

The corrected pixel vector $\hat{\mathbf{f}}_i$ is obtained by the filter as

$$\hat{\mathbf{f}}_i = \mathrm{G}(\mathbf{g}_i - \bar{\mathbf{g}}) + \bar{\mathbf{g}}. \qquad (10)$$

In Equation (10), it is also assumed that $\bar{\hat{\mathbf{f}}} = \bar{\mathbf{g}}$ because mean of the noise is zero in this research.

To illustrate the effect of the filter G calculated by Equation (9), we performed a simple simulation. Figure 1 shows an original digital color patch image with RGB channels. Figure 2 shows the image corrupted by an additive noise. Figure 3 shows averaged image by using a conventional 3 x 3 pixels mask. The edge in Figure 3 is blurred by the averaging mask. Figure 4 shows the result of noise reduction by the filter calculated from Equation (9). Though the edge is preserved from sharpness degradation as shown in Figure 4, the performance of noise reduction is not sufficient. Then we propose modified CSW filters in the following section.

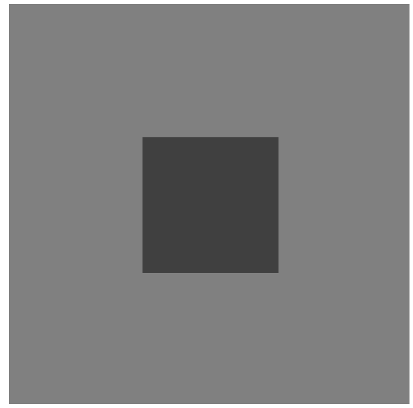

Figure 1. Digital color patch image (RGB channel image).

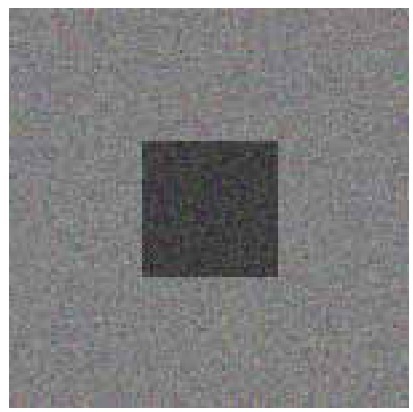

Figure 2. Noisy image corrupted by additive noise.

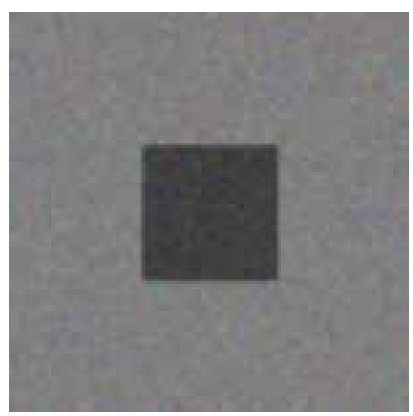

Figure 3. Averaged noisy image by a conventional mask.

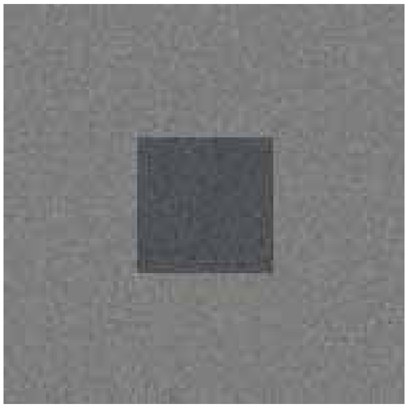

Figure 4. Corrected image by a CSW filter calculated by Eq. (9).

CSW Filter for White Noise

If the noise is white and uncorrelated to the original image, the CSW filter is formulated as follows.

The C_{gg} in Equation (7) can be expanded using diagonal matrix Λ_g,

$$C_{gg} = P_g \Lambda_g P_g^T \tag{11}$$

Here Λ_g has the eigen values in the diagonal components, and matrix P_g has eigen vectors of C_{gg} in the columns. The superscript T denotes transpose of the matrix. In the same manner, C_{nn} is also expanded using matrices Λ_n and P_n as,

$$C_{nn} = P_n \Lambda_n P_n^T . \tag{12}$$

An arbitrary orthonormal basis set can be selected as the eigen vectors of C_{nn} in the case of white noise. Thus we determine P_n as follows.

$$P_n = P_g \tag{13}$$

Substituting Equations (11), (12), and (13) into Equation (9), Equation (14) is obtained.

$$G = P_g \left(\Lambda_g - \Lambda_n \right) \Lambda_n^{-1} P_g^T \tag{14}$$

Equation (14) can be also represented using component representation as,

$$G = P_g \begin{bmatrix} \frac{\sigma_{g_1}^2 - \sigma_n^2}{\sigma_{g_1}^2} & 0 & 0 \\ 0 & \frac{\sigma_{g_2}^2 - \sigma_n^2}{\sigma_{g_2}^2} & 0 \\ 0 & 0 & \frac{\sigma_{g_3}^2 - \sigma_n^2}{\sigma_{g_3}^2} \end{bmatrix} P_g^T . \tag{15}$$

Here, σ_{g1}^2, σ_{g2}^2, σ_{g3}^2, and σ_n^2 are the eigen values of C_{gg} and C_{nn}, respectively.

The operation with G can be interpreted as 1) orthogonal transformation by P_g^T, 2) filtering using signal and noise variances, 3) inverse transform by P_g. It is of interest that this operation is similar to conventional spatial Wiener filtering.

Pixel Selection for Filter Calculation

Because the performance of the noise reduction depends on how C_{gg} is calculated, three kinds of calculation method have been examined and compared.

Method 1: At first the noisy images are classified into 10 color classes,[4)] then 10 kinds of C_{gg} are calculated using all of pixels classified into the same color class.

Method 2: d_x x d_y neighboring pixels of a current pixel are used, then the filter is calculated pixelwise. Figure 5 shows the calculation scheme of this method.

Method 3: This is a combination of Method 1 and 2. Neighboring pixels which are classified into the same color class as the current pixel are used, then the filter is calculated pixelwise. The number of pixels used for determining the filter, *T*, is introduced as a parameter.

Figure 6 shows the image corrected by Method 3. We can see that the noise is reduced well compared with Figure 4 and the edge remains sharp compared with Figure 3.

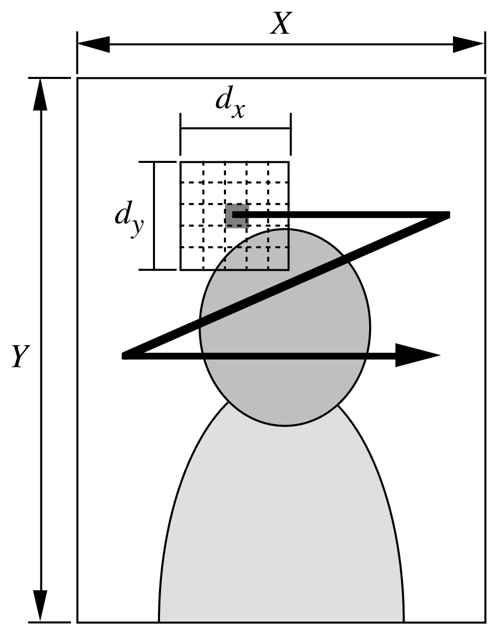

Figure 5. Sub block used for determination of Wiener filter.

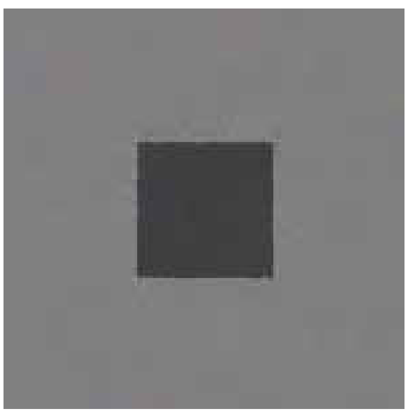

Figure 6. Corrected image by a CSW filter calculated by Method 3 (T = 81 pixels).

Noise Reduction Simulation

The simulation was carried out using samples made from the original images, ISO/JIS-SCID N1 to N8, degraded by additive white noise. The noise was reduced by the proposed methods. Figure 7 shows one of the original images used in the simulation. Figure 8 shows noisy image degraded by the noise. For comparison, four kinds of averaging mask were used as conventional noise reduction method. Figure 9 and 10 show the images corrected by the conventional mask and the proposed method.

Figure 7. Original image (SCID N1) used in the simulation.

Figure 8. Noisy image degraded by the additive noise.

The performance of the noise reduction was confirmed by RMSE (Root Mean Square Error) and subjective evaluation experiments.

Figure 9. The image corrected by conventional mask (Mask 4).

Figure 10. The image corrected by proposed method. (Method 3, T = 81 pixels)

Confirmation by RMSE

The RMSEs to the original images were calculated from noisy images, comparison images, and images corrected by Method 1 - 3. The averaged RMSEs over the SCID N1 to N8 are shown in Figure 11. The minimum RMSE was obtained by Method 3 (T=81).

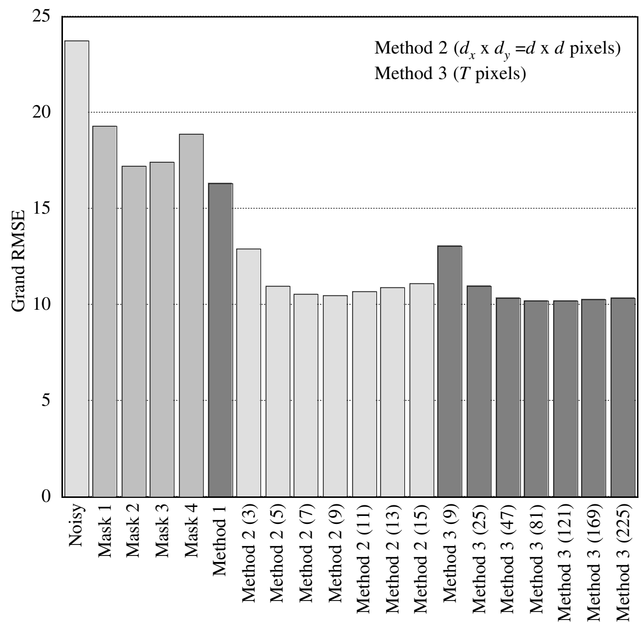

Figure 11. RMSE between original and sample images in RGB space.

Confirmation by Subjective Evaluation

Nine samples per SCID were displayed on the CRT monitor in a random order, then 20 observers rated the total image quality of each sample by five-rank successive category method at the viewing distance of 500 mm. The size of neighboring pixels d_x x d_y for Method 2 and the number of pixels T for Method 3 were chosen to minimize the RMSE as shown in Figure 11. The observer rating value (ORV) was calculated by the statistical method,[5)] then ORV was averaged over the SCID N1 to N8. Figure 12 shows the obtained ORV for each sample. The ORV means that a higher value corresponds to better image quality. The samples corrected by the proposed methods show the higher ORV compared with the images corrected by any conventional averaging masks. In the evaluation of the RMSE, the images corrected by Method 3 show the best result, however the best subjective image quality was obtained by the filter calculated from Method 2. One reason of this result is that the unfavorable pseudo contours appear in the images restored by Method 3 more strongly than that by Method 2.

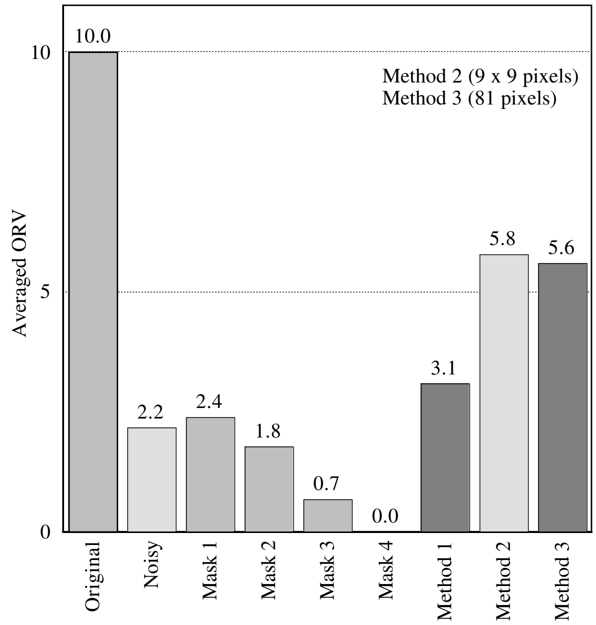

Figure 12. Results of the subjective evaluation experiment.

Summary

The CSW filters have been proposed for noise reduction without sharpness degradation. The experimental results show that the filters can improve the total image quality of noisy images corrupted by the additive noise. Consideration of the human visual system, comparison with the spatial Wiener filter, and confirmation using actual image data are required as future works.

References

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Biography

Kimiyoshi Miyata received his BE and ME degrees in imaging science from Chiba University in 1990 and 1992, respectively. The same year, he joined Mitsubishi Electric Corporation, Kamakura, Japan. His research activities have been the color reproduction of hardcopies, evaluation of image quality, and digital image processing technologies. Currently, he is also a graduate student for a doctorate at Chiba University.