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A Low Distortion Image Defogging Method Based on Histogram Equalization in Wavelet Domain

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Abstract: With the development of computer vision, the requirement of image sharpness in production is increasing. Fog, as a common weather phenomenon, will affect the image quality, so it is necessary to defog the image. In the image defogging technology, the image enhancement method based on non-physical model represented by histogram equalization has the advantage of its relatively mature and simple algorithm, but the disadvantage is that, because of the enhancement effect on the image on the global scale, defogging the detail information will also affect the contour information, resulting in distortion.In this paper, an image defogging method with low distortion based on the histogram equalization in the wavelet domain is proposed, which uses the nondestructive and reversible properties of the integer wavelet transform to separate the detail information and contour information of the image. We equalize the histogram generated by the low-frequency coefficient of the image extracted by the integer wavelet transform, then carry out the inverse integer wavelet transform, and fuse the processed low-frequency coefficient with the high-frequency coefficient of the original image to generate the defogging image. Experimental results show that, compared with the common physical model and non-physical model algorithms, the characteristic of our method is that it has low distortion, on the basis of obvious fog removal effect, it retains the contour completely and meets the application requirements.

1. Introduction

Fog is equivalent to a kind of noise. When its concentration is high, it will affect the brightness and contrast of the image [1], and then affect the accuracy of the image recognition system. Therefore, it is necessary to study the image defogging technology. Different defogging algorithms have different effects. In the living scene, the algorithm with low distortion has better visual effect. There are two kinds of existing defogging algorithms: physical model based image restoration and non physical model based image enhancement.

Based on the physical model, the demisting method establishes the physical model by analyzing the causes of fog, and achieves the demisting effect. Representative restoration algorithms such as the fast image defogging algorithm proposed by tarel et al. [2] and the prior dark channel algorithm proposed by he et al. [3]. With the help of prior theory and auxiliary equipment, the effect of this method is significant, but the physical model can not be applied to all fog scenes [4].

The non-physical model based defogging method only improves the image presentation effect. Traditional enhancement methods are generally based on spatial domain, representative algorithms such as histogram equalization and land e h. [5] Retinex algorithm. Histogram equalization is a global enhancement algorithm. It is easy to cause distortion because of ignoring the local characteristics of the image. Subsequent improvements include the local histogram equalization algorithm proposed by Kim et al. [6], the contrast limited adaptive histogram equalization (CLAHE) algorithm [7], etc. The improved Retinex algorithm can further improve the effect of fog removal. The representative algorithm based on frequency domain enhancement method is homomorphic filtering method [8], but it is easy to lose details. In order to solve this problem, there are enhancement methods based on wavelet transform [9,10], which make up for the deficiency that single space domain and frequency domain can not take care of local details, but the disadvantage is that the effect is not stable enough.

Because of its strong practicability, histogram equalization algorithm is still a hot spot in the field of image de fogging. However, because of its global equalization, it can not fully adapt to the needs of low distortion image enhancement because it also affects the contour information while de fogging the detail information. Based on reference [11], it can be seen that fog occlusion has little effect on the contour information of the image. Therefore, the problem of the existing methods is that the contour information which is less affected by fog noise is distorted obviously by image enhancement.

Considering that wavelet transform can extract image details and contour information, this paper uses integer wavelet transform based on lifting algorithm [12, 13] (IWT), which separates the details and the contour of the image in the frequency domain, equalizes the low-frequency coefficients of the obtained representative details in the spatial domain, and then returns the fusion of the high-frequency coefficients of the frequency domain and the representative contour information to realize the image defogging. In this process, the contour information is not distorted because it does not participate in the equalization processing. The lossless IWT ensures that the image details and contour information are not damaged in the process of decomposition and fusion.

In this paper, a low distortion image de fogging method based on wavelet domain histogram equalization is proposed. The innovation is to generate wavelet domain histogram from wavelet low frequency coefficient obtained by IWT of image in frequency domain. The principle of histogram equalization is used to equalize wavelet low frequency coefficient instead of traditional pixel value. In this method, low distortion image de fogging is realized by the lossless image decomposition and fusion in frequency domain.

2. Method architecture

2.1 Overview of ideas

The high-frequency and low-frequency coefficients of the image can be obtained by using wavelet transform, where the high-frequency coefficients represent the details of the image and the low-frequency coefficients represent the outline of the image. IWT can ensure that the decomposition coefficients are all integers, according to which the histogram in the wavelet domain can be drawn. Because the energy of the low-frequency coefficient is low, it is a grayscale image, where the high brightness is the contour of the original image. Considering fog as occlusion to the global scene, based on literature [11], it can be seen that occlusion has less effect on the higher brightness in the image, so fog occlusion has less effect on the contour represented by the low frequency coefficient.

After the histogram equalization algorithm dehazes, the pixel values of the image will be partially lost and reflected on the contour. This effect is further amplified, and the resulting loss of contour and overexposure will have a greater disadvantage to the scene restoration.

In view of the above analysis, the haze has little effect on the image contour, and the global enhancement of the histogram equalization algorithm makes the contour distortion larger. Therefore, in this paper, IWT is used to extract the image contour, and only the remaining high-frequency coefficients are applied to the histogram equalization algorithm to dehaze, so as to avoid the distortion of the picture caused by the processing of the contour.

The characteristic of this method is the histogram equalization in wavelet domain. The object of traditional histogram equalization is the pixel value of the image. This method applies it to the wavelet high-frequency coefficients extracted by IWT.

2.2 Demisting process

Because IWT is lossless and completely reversible, this paper uses only the simplest Haar wavelet to perform the simplest S integer wavelet transform [1], and the transformation scale i represents the scaling factor of the original Haar wavelet.

2.2.1 IWT high frequency coefficient extraction

Suppose the image input sequence $s_{0,j} = x_j$ is an integer sequence, and use $s_{i,j}, d_{i,j}$ to denote the scale factor and wavelet coefficient of decomposition respectively:

$$s_{i,j} = \lfloor (s_{0,2j} + s_{0,2j+1})/2 \rfloor \quad (1)$$

$$d_{i,j} = s_{0,2j+1} - s_{0,2j} \quad (2)$$

2.2.2 Generate a histogram in the wavelet domain

Suppose the wavelet high-frequency coefficient extracted in step 1 is a matrix A of m * n, and the value of the wavelet coefficient at any position (x, y) (1≤x≤m, 1≤y≤n) is g (x , y) (0≤g (x, y) ≤L-1, L is the largest element in A), the integer high-frequency coefficient is recorded as t, then the probability of integer high-frequency coefficient Pt (0≤t <L) Can be expressed as:

$$p_t = \frac{1}{m \times n} \sum_{x=1}^{m} \sum_{y=1}^{n} \mathrm{r}(\mathrm{g}(x,y) - t), 0 \le t \le \mathrm{l} \quad (3)$$

Here, $\mathrm{r}(x) = \begin{cases} 1, x = 0 \\ 0, x \neq 0 \end{cases}$

The function f (t) = t’ is the calculation formula of integer high-frequency wavelet coefficient equalization:

$$\sum_{k=0}^{\mathrm{t}} p_k - \frac{f(t)}{\mathrm{L}-1} \ge 0, 0 \le \mathrm{t} \le \mathrm{L} \quad (4)$$

After processing by formula (4), the value of each element of A is updated to obtain A '.

2.2.3 Integer wavelet image fusion

The equalized integer wavelet high-frequency coefficients represented by A’ and the low-frequency coefficients extracted in step 1 are calculated according to formulas (5) and (6) to complete image fusion:

$$s_{0,2j} = s_{i,j} - d_{i,j}/2 \quad (5)$$

$$s_{0,2j+1} = s_{i,j} + d_{i,j}/2 \quad (6)$$

At this point the algorithm ends.

As shown in Fig. 1, the scale of IWT is 2, high frequency coefficient and low frequency coefficient are LH_1, HH_1, HL_1, LH_2, HH_2 and HL_2 respectively, $LL_{2'}$ is the high frequency coefficient of LL_2 after ① wavelet histogram equalization.

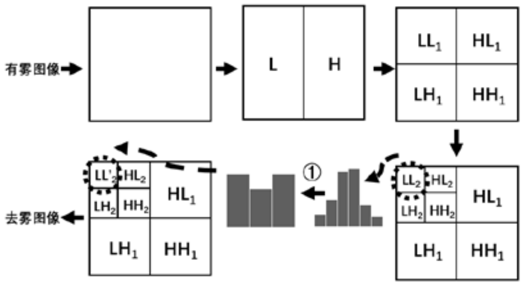

Figure. 1 Flow chart of defogging method in this paper when the transformation scale is 2

3. Simulation experiment and analysis

3.1 Experiment framework

In order to verify the effectiveness of the algorithm described in this paper, we will compare it with the classical image defogging algorithm. The experiment is divided into four groups. For four foggy images, the Tarel algorithm based on the physical model [2], the CLAHE algorithm based on the non-physical model [7], the improved Retinex algorithm [14] and the method in this paper were respectively applied to remove fog. Since the algorithm based on the principle of histogram equalization has a good effect in processing thick fog images [4], the experiment selected thick fog image materials in different scenes from the test set, as shown in figure 2. From top to bottom, the foggy image scenes are the urban foggy and wharf foggy from the perspective of overlooking, and the sea foggy and water foggy from the perspective of looking up. Images with relatively simple scenes were selected to minimize the adverse effects of visual attention [15] and masking effect [16] on subjective evaluation of image quality.

For the subjective evaluation of image quality, the experiment in this paper adopted the Double Stimulus Injury Staging method (DSIS) [17]. The scoring criteria are shown in table 1. There were 10 professionals in the evaluation staff, and the obstacle scale was adopted. Non-professional staff of 10, using quality standards.

In terms of the objective evaluation of image quality, the experiment in this paper chose to evaluate the image quality by solving the average gradient [18], average brightness [19], contrast [20] and Edge Preservation Index (EPI) [21]. The average gradient is used to evaluate the sharpness of the image, the average brightness and contrast are used to evaluate the defogging effect and color effect, and the edge retention coefficient is used to evaluate the edge retention ability.

The experimental test Image set in this paper is from Retinex Image Processing at NASA Langley Research Center, which was updated in April 2020 for the Image test set [22] used to test the defogging algorithm.

In this paper, the experimental software platform is MATLAB R2018a, the test images are different kinds of foggy images in the test set, and the experimental value is the average value of the three processing results.

3.2 Experiment effect

Figure 2(a) (b) (c) (d) from left to right: input image, Tarel algorithm processing result, CLAHE algorithm processing result, Retinex algorithm processing result after improvement and algorithm processing result in this paper.

(a)

(b)

(c)

(d)

Figure. 2 Defogger experiment, from left to right is the following: input image, Tarel algorithm processing result, CLAHE algorithm processing result, modified Retinex algorithm processing result and the method in this paper
(a) A bird's-eye view of the city's smog scene
(b) A bird's-eye view of the pier haze scene
(c) A head-up view of the sea fog scene
(d) A head-up view of the water mist scene

The Tarel algorithm has serious color distortion when processing dense fog images. The processed results in figure 2(a) and (b) are greenish in hue, the upper right part of figure 2(c) is noisy, and the processed results in figure (d) are bluish in hue. The CLAHE algorithm is characterized by good color retention ability, but when processing dense fog images, the fog removal effect is not obvious enough, and the processing results in FIGURE 2(a) (b) can be intuitively perceived as the presence of fog in the overall situation. In FIG. (d), there are still obvious unremoved fog at the top and bottom right of the processing results. The image processed by the improved Retinex algorithm has high definition, but there is overexposure phenomenon, such as the blue exposure on the right edge of the processing result in figure 2(a) (b), and the color noise on the sky and water surface in figure 2(c) (d). Compared with the former three, treated by the method of image in has the obvious to the fog effect at the same time, relatively intact the details of the input image, as shown in figure 2 (a) in the upper right beside the road markers are restored, and there is no exposure occurred, figure 2 (a) (b) the processing results uniform brightness, image smoothing, edge image, figure 2 (c) (d) in the sky and the water reduction degree is better also, noise, low distortion degree.

3.3 Subjective evaluation of experimental results

In this experiment, DSIS method was adopted to present the fogging image (baseline image) to 20 evaluation personnel, and then the fogging image (test image) processed by one of the above-mentioned defogging methods was displayed. They were asked to score the overall quality of the test image. The scoring standard [23] is shown in table 1.

Table 1 Absolute evaluation scale

Level	Hindrance scale	Quality scale
5 points	There was no sign that the image was getting worse	Very good
4 points	You can see the quality of the image but it doesn't prevent you from seeing it	Good
3 points	It is clear that the image quality has deteriorated, which slightly interferes with viewing	General
2 points	It interferes with the viewing	Bad
1 point	Very serious obstruction to viewing	Very bad

Mean Opinion Score (MOS) [24]. The higher the MOS value is, the better image quality the reviewer thinks. The calculation formula is as follows:

$$MOS = \frac{\sum_{i=1}^{K} N_i \times OS_i}{\sum_{i=1}^{K} N_i} \quad (7)$$

Where K refers to the total number of participants in the evaluation, OS_i refers to the classification number of the image as class I, and N_i refers to the classification number of N raters who judge the image as class I.

The scoring results are shown in table 2:

Table 2 MOS (K=20) under DSIS method

	Tarel	CLAHE	Modified Retinex	Method in this paper
Fig.3(a)	2.65	3.25	4.05	4.25
Fig.3(b)	2.25	3.05	3.55	3.90
Fig.3(c)	1.40	3.45	1.65	3.85
Fig.3(d)	3.25	3.25	3.65	4.05
$\overline{MOS}$	2.39	3.225	3.225	4.0125

According to table 1 and 2, the MOS method in this paper is the highest, which means that the image quality can be seen but does not hinder the viewing, and the image quality is high; CLAHE algorithm and the improved Retinex algorithm, MOS, took the second place, indicating that the image quality could be clearly seen to be worse, which slightly hindered the viewing, and the image quality was mediocre. The Tarel algorithm, MOS, is the lowest, which hides the view and results in poor image quality.

The average gradient reflects the image's tiny detail contrast and texture changes, and is used to evaluate the image's sharpness: the larger the average gradient, the clearer the image. The calculation formula is:

$$G = \frac{1}{M \times N} \sum_{i=1}^{M} \sum_{j=1}^{N} \sqrt{\frac{\left(\frac{\partial f}{\partial x}\right)^2 + \left(\frac{\partial f}{\partial y}\right)^2}{2}} \quad (8)$$

Where, M×N represents the size of the image, $\frac{\partial f}{\partial x}$ represents the gradient in the horizontal direction, $\frac{\partial f}{\partial x}$ represents the gradient in the vertical direction. The experimental results are shown in table 3:

Table 3 Comparison of average gradient enhancement degree

	Input image	**Tarel**	**CLAHE**	**Modified Retinex**	**Method in this paper**
Fig.3(a)	0.0040	0.0068	0.0108	0.0212	0.0134
Fig.3(b)	0.0034	0.0060	0.0119	0.0221	0.0153
Fig.3(c)	0.0059	0.0107	0.0140	0.0177	0.0170
Fig.3(d)	0.0082	0.0143	0.0126	0.0220	0.0135

According to table 3, in FIGURE 2 (a) (b), the enhancement degree of the average gradient of several fogless methods used for comparison is from large to small: the improved Retinex algorithm, the method in this paper, CLAHE algorithm and Tarel algorithm, with the average enhancement degree of 286%, 175%, 129% and 75% successively, indicating that the clarity degree of the processed image decreases successively. The average gradient can be used as a reference, but it cannot directly reflect the degree of distortion.

The average brightness reflects the effect of defogging to some extent. As the overall brightness of the image increases due to fog noise, the overall brightness of the image decreases due to defogging [1]. The value range of the average brightness is [0,255]. The higher the value is, the higher the image brightness is. The calculation formula is:

$$Lum_{ave} = exp\left(\frac{1}{N}\sum_{x,y}\ln\left(\delta + Lum(x,y)\right)\right) \quad (9)$$

Where represents a small constant, which can be 0.0001. N represents the total number of pixels in the image. Lum (x, y) represents computing the brightness value y for each pixel x in the image. The experimental results are shown in table 4:

Table 4 Comparison of average brightness enhancement

	Input image	**Tarel**	**CLAHE**	**Modified Retinex**	**Method in this paper**
Fig.3(a)	116.7871	127.8342	115.3235	94.2379	32.2057
Fig.3(b)	117.0606	120.8579	115.8098	102.2824	42.5363
Fig.3(c)	151.0125	104.8877	153.5905	179.1374	168.5866
Fig.3(d)	168.4813	134.5395	156.7375	147.1776	145.5961

According to table 4, the Tarel algorithm and CLAHE algorithm always change the average brightness of the input image to a small extent, with an average change of -10.01% and -2.03%, which to some extent reflects their weak antifogging ability. The improved Retinex algorithm showed a general decrease in the average brightness of the input image in figure 2(a)(b)(d), which was -20.24%, -13.56%, and -12.52%, respectively, while the average brightness of the input image in figure 2(c) was +18.54% after processing by this algorithm. According to the algorithm obtained from table 2, it has an obvious defogging effect. The numerical change here should be the overall decline. The reason for this abnormal phenomenon is that the brightness is not increased reasonably due to overexposure. After processing by the method in this paper, the average brightness of the input image in FIGURE 2(a) (b) is significantly reduced, the average brightness of the input image in FIGURE 2(c) is improved, and the average brightness of the input image in FIGURE 2(d) is slightly reduced, with the changes of -72.41%, -64.10%, +11.26%, and -13.69%, respectively. Combined with figure 2(a) (b), the analysis is based on the fact that the method in this paper can effectively remove fog and avoid the occurrence of overexposure. In figure 2(c), the light source at the upper right and the white spray at the lower right in figure 2(d) are restored after defogging. The appearance of these high brightness areas increases the average brightness.

The contrast also reflects the defogging effect to some extent. As the image contrast is reduced by fog noise [1], defogging will increase the image contrast. The larger the contrast, the more colorful the image. The calculation formula is:

$$C = \sum_{\delta} \delta(i,j)^2 P_{\delta}(i,j) \tag{10}$$

Where $\delta(i,j) = |i-j|$, that is, the gray difference between adjacent pixels; $P_{\delta}(i,j)$is the pixel distribution probability where the gray difference between adjacent pixels is. The experimental results are shown in table 5:

Table 5 Comparison of contrast enhancement degree

	Input image	Tarel	CLAHE	Modified Retinex	Method in this paper
Fig.3(a)	8.2844	10.8327	14.0922	19.1395	11.6775
Fig.3(b)	10.1395	12.4164	15.5939	35.1865	16.8385
Fig.3(c)	12.1008	24.2153	16.0155	43.5223	30.9218
Fig.3(d)	24.8544	11.3498	35.0356	46.8385	40.8986

According to table 5, the contrast enhancement degree of several fog removal methods used for comparison ranges from large to small: the improved Retinex algorithm, the method in this paper, CLAHE algorithm and Tarel algorithm, with an average change of +184.16%, +78.63%, +51% and +22.75%, respectively. The improved Retinex algorithm has the highest enhancement degree to the contrast of the input image, which, combined with the above analysis, shows that it has obvious color distortion. The method in this paper enhances the contrast of the image to a moderate degree, which shows that it avoids color distortion and color noise while restoring color. The CLAHE algorithm and Tarel algorithm always enhance the contrast of the input image to a small extent. Combined with the analysis in table 3 and 4, this phenomenon to some extent reflects its low color reduction and weak defogging ability.

EPI is used to evaluate edge retention. The higher the EPI value, the stronger the edge retention ability of the processed image. The calculation formula is:

$$EPI = \frac{\sum_{i=1}^{m} |G_{R1} - G_{R2}|_{\text{after filter}}}{\sum_{i=1}^{m} |G_{R1} - G_{R2}|_{\text{before filter}}} \tag{11}$$

Where, m is the number of image pixels, and GR1 and GR2 are the gray values of left and right or upper and lower adjacent pixels, respectively. The experimental results are shown in table 6:

Table 6 Comparison of edge retention capabilities

	Input image	Tarel	CLAHE	Modified Retinex	Method in this paper
Fig.3(a)	1	3.0905	2.7977	7.8830	5.7882
Fig.3(b)	1	2.9941	2.3643	6.1865	3.5152
Fig.3(c)	1	3.0728	2.6752	5.0147	2.9979
Fig.3(d)	1	3.6782	3.5334	7.0041	4.0561

According to table 6, the enhancement degree of edge retention ability of several defogging methods for comparison is from large to small: the improved Retinex algorithm, the method in this paper, Tarel algorithm and CLAHE algorithm. The average value of EPI is 6.5241, 4.0928, 3.2089 and 2.1738 respectively. Combined with the image, the image edge processed by the improved Retinex algorithm was the clearest, but the sharpening degree was obvious, and the contour was convex. In this paper, the edge of the processed image is clear and smooth, and the visual effect is good. The edge holding capability of Tarel algorithm and CLAHE algorithm is weak.

To sum up, Tarel algorithm and CLAHE algorithm have poor fog removal effect, and the improved Retinex algorithm has obvious fog removal effect, but serious distortion and poor visual effect. The method in this paper can make the brightness as small as possible and the contrast as close to the original image as possible while effectively increasing the average gradient and EPI, so as to avoid the distortion phenomenon such as overexposure to the greatest extent. The advantages of this method are obvious fog removal effect, low distortion, high visual quality of the processed image, close to the reality, smooth image, suitable for fog removal.

4. Summary and prospect

In this paper, the histogram equalization image defogging algorithm based on spatial domain is studied, and the equalization image defogging algorithm based on integer wavelet domain is proposed. The innovation of this method lies in the equalization of the wavelet coefficients representing the image details, which avoids the influence of image enhancement on the contour information. Finally, through the experimental simulation, it is compared with the image restoration and fogging algorithm based on the physical model and the image enhancement and fogging algorithm based on the non-physical model, and the validity and low fallibility of the proposed algorithm are proved. However, there are still some shortcomings to be improved, such as the loss of clarity and the inability to implement batch processing in order to ensure low distortion. To improve and perfect these deficiencies is the focus of the next step.

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