PAPER

A Fast Single Image Haze Removal Method Based on Human Retina Property

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SUMMARY In this paper, a novel and highly efficient haze removal algorithm is proposed for haze removal from only a single input image. The proposed algorithm is built on the atmospheric scattering model. Firstly, global atmospheric light is estimated and coarse atmospheric veil is inferred based on statistics of dark channel prior. Secondly, the coarser atmospheric veil is refined by using a fast Tri-Gaussian filter based on human retina property. To avoid halo artefacts, we then redefine the scene albedo. Finally, the haze-free image is derived by inverting the atmospheric scattering model. Results on some challenging foggy images demonstrate that the proposed method can not only improve the contrast and visibility of the restored image but also expedite the process.

key words: *Haze removal, dark channel prior, Tri-Gaussian, human retina property.*

1. Introduction

Bad weather can cause a number of problems in taking outdoor images, such as fuzziness, low contrast and poor detail [1]. However, most automatic systems, such as those for tracking and surveillance, cannot work properly due to degradation of the images. Therefore, simple and effective haze removal technology is highly desired in aerial imagery, image/video retrieval and consumer/computational photography.

Recently, single image dehazing methods, based on physical model have achieved a significant breakthrough [2-8]. Tan et al. [2] restored foggy images by means of maximizing the local contrast of the image to be restored. Fattal et al. [3] estimated the scene albedo in hazy atmosphere on the premise of the constraint that the surface's shading and scene albedo being locally statistically uncorrelated. However, its complexity is very high and it is not applicable to images not meeting the requirement of aforesaid premise. He et al. [4] first proposed a physical statistical law − dark channel prior. Initial atmospheric veil is estimated by dark channel prior and refined by soft matting. Nevertheless, it may fail in the cases when the image contains the sky and the complexity of soft matting is quite high, so it is difficult to be used in real time environment. Tarel et al. [5] estimated the atmospheric veil by median filtering. But, the median filtering can lead to color distortion and halo artifacts easily. Long et al. [6] refined the coarse atmospheric veil based on low-pass Gaussian filter. But, this filter can't keep the edge well, so the details information of image will be lost after processing.

The images processed by the above defogging methods are often lost in some detail and depth information. Although human visual system does not have dehazing function, it can keep the depth and the details information of the real scene. As is known to all, human visual system has been evolved to be perfect, is the most effective image processer, and can automatically improve the image quality which means that human visual system works fine in almost any kind of case. Biological studies have shown that there is a large range of disinhibition zone in the traditional receptive fields [9]. The activity of this zone can offset the antagonistic effect of peripheral area on central area. Consequently, it compensates decay of the low frequency components resulting from the traditional receptive field structure. According to this visual perception characteristics of human visual system, we adopt a Tri-Gaussian local convolution kernel to refine the atmospheric veil.

In this paper, based on the above visual perception characteristics of human visual system, we propose a highly efficient dehazing method for only single input image. The remaining paper is structured as follows: in section 2, atmospheric scattering model and dark channel prior are briefly introduced; in section 3, a concept of Tri-Gaussian model is discussed and a description of the proposed defogging method is presented in detail; in section 4, simulation and experimental results are presented and analyzed, where we compare the defogging effect of our proposed method with that of the other two state-of-the-art methods; in section 5, a conclusion is made.

2. Related Work

2.1 Atmospheric Scattering Model

As shown in Fig. 1, the atmospheric scattering model, which is usually used to describe the influence of bad weather conditions on the image, is an effective expressing form in the field of computer vision [10].

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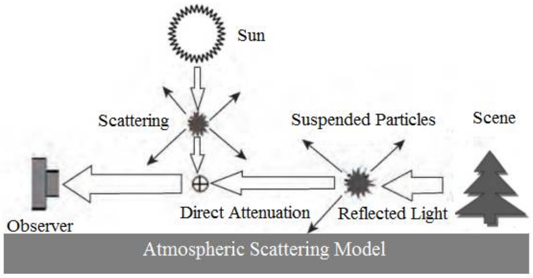

Fig.1 Atmospheric scattering model.

The atmospheric scattering model can be described as:

$$\mathbf{I}(\mathbf{x}) = \mathbf{J}(\mathbf{x})\mathbf{t}(\mathbf{x}) + \mathbf{A}(1-\mathbf{t}(\mathbf{x})) \tag{1}$$

where $\mathbf{x} = (x, y)$ is spatial coordinates of image pixels, $\mathbf{I}$ represents the degraded image, $\mathbf{J}$ is restored image, $\mathbf{A}$ is the value of global atmospheric light. $\mathbf{t}(\mathbf{x})$ is described as scene albedo. Obviously, it is easy to infer $\mathbf{J}(\mathbf{x})$ when $\mathbf{t}(\mathbf{x})$, $\mathbf{A}$ and $\mathbf{I}(\mathbf{x})$ are known.

2.2 Dark Channel Prior

In the vast majority of the local area of the image, the intensity value of some pixels is very low in at least one color channel [4]. For image $\mathbf{J}$, it can be defined as:

$$\mathbf{J}_{\text{dark}}(\mathbf{x}) = \min_{c\in\{r,g,b\})}\left(\min_{y\in\Omega(\mathbf{x})} \frac{\mathbf{J}_c(\mathbf{x})}{\mathbf{A}}\right) \to 0 \tag{2}$$

where $\mathbf{J}_c$ represents one color channel of $\mathbf{J}$. $\Omega(\mathbf{x})$ is a square area centre on $\mathbf{x}$. $\mathbf{J}_{\text{dark}}$ is referred to as dark channel of $\mathbf{J}$, whose value is extremely low and close to 0.

3. Image Dehazing

3.1 Estimate the global atmospheric light

For an degraded image $\mathbf{I}$, the brightness of its dark channel $\mathbf{I}_{\text{dark}}$ will increase obviously when haze concentration gets higher. Therefore, the global atmospheric light usually corresponds to the most concentrated areas of haze [15]. Based on this, the specific steps of estimating the atmospheric light are as bellow. To begin with, we choose the first 0.1% pixels with maximum brightness in the dark channel $\mathbf{I}_{\text{dark}}$. Then, we seek the point of $\mathbf{I}$, which is with the maximum brightness, corresponding to the region of above pixels.

3.2 Initial estimation of coarse atmospheric veil

If we express atmospheric veil $1-\mathrm{t}(\mathbf{x})$ as $\mathbf{V}(\mathbf{x})$, according to (1), atmospheric scattering model can be defined as:

$$\mathbf{I}(\mathbf{x}) = \mathbf{J}(\mathbf{x})\mathbf{t}(\mathbf{x}) + \mathbf{A}\mathbf{V}(\mathbf{x}) \tag{3}$$

We can obtain the global atmospheric light $\mathbf{A}$ according to Section 3.1, and the value of $\mathbf{A}$ is greater than 0, Now if we divide both sides by $\mathbf{A}$, formula (3) can be normalized as:

$$\frac{\mathbf{I}(\mathbf{x})}{\mathbf{A}} = \frac{\mathbf{J}(\mathbf{x})\mathbf{t}(\mathbf{x})}{\mathbf{A}} + \mathbf{V}(\mathbf{x}) \tag{4}$$

From (4), it can be observed that $\mathbf{V}(\mathbf{x})$ is positive and is less than or equal to the min color component of $\mathbf{I}(\mathbf{x})/\mathbf{A}$. Then we minimize both sides of (4), and according to (2) we can obain:

$$\mathbf{V}(\mathbf{x}) = \min_{c\in\{r,g,b\})}\left(\min_{y\in\Omega(\mathbf{x})} \frac{\mathbf{I}_c(\mathbf{y})}{\mathbf{A}}\right) \tag{5}$$

3.3 Refine the Atmospheric Veil

In order to improve the accuracy of the atmospheric veil and avoid color distortion, an optimization operation needs to be taken on $\mathbf{V}(\mathbf{x})$. Therefore, according to the visual perception characteristics of human visual system, we adopt a Tri-Gaussian local convolution kernel to refine $\mathbf{V}(\mathbf{x})$. This filtering method can not only enhance the edge of the image, but also combine the sensory characteristics of the retinal ganglion cells, effectively improving the regional brightness contrast and brightness gradient information.

In 1991, Li [11] found that there exists a disinhibitory zone outside the receptive field of classical retinal neurons, which is called the “Disinhibitory Properties of Concentric Receptive Field (DRF)”. DRF’s specific structure is as follows: excitement in the middle zone, inhibition in the surrounding zone and excitement in the edge zone (Fig.2.). As to the edge zone, its area is large but its overall excitement intensity is low; and it plays an important role in the transmission of a large area of brightness. Li proposed Tri-Gaussian model to stimulate the disinhibitory property structure of the receptive field of retinal neurons. The model is defined as bellow:

$$G(x,y) = A_1 \exp\left(-\frac{x^2+y^2}{2\sigma_1^{\,2}}\right) - A_2 \exp\left(-\frac{x^2+y^2}{2\sigma_2^{\,2}}\right) + A_3 \exp\left(-\frac{x^2+y^2}{2\sigma_3^{\,2}}\right) \tag{6}$$

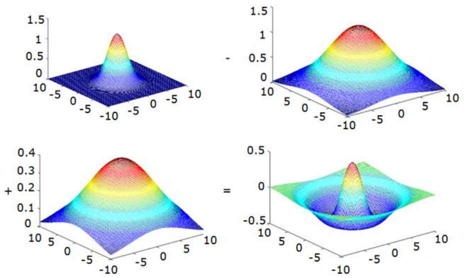

Fig.2 The specific structure of Disinhibitory Properties of Concentric Receptive Field

In (6), A_1, A_2, A_3 respectively represents the intensity of excitement in the middle, surrounding and edge zones; $\sigma_1, \sigma_2, \sigma_3$ respectively represents the radius of the corresponding region. Tri-Gaussian model can not only enhance the edge contrast of image, but also improve brightness contrast of the region. We difine the modified atmospheric veil $\tilde{\mathbf{V}}(\mathbf{x})$ as the following:

$$\tilde{\mathbf{V}}(\mathbf{x}) = G_{parak} \times (\mathbf{V}(\mathbf{x}) - \mathbf{V}_{\mathbf{G}}(\mathbf{x})) + \mathbf{V}_{\mathbf{G}}(\mathbf{x}) \quad (7)$$

where $G_{\text{parak}} = 1/\sigma(\mathbf{x})$ is gain factor, and $\sigma(\mathbf{x})$ is the variance of $\mathbf{x}$. $\mathbf{V}_{\mathbf{G}}(\mathbf{x})$ is the image after convolution of the Tri-Gaussion function. The calculation process is as follows:

$$V_G(x,y) = \sum_{i,j=-M}^{M} G_R V(x_i, y_j) / \sum_{i,j=-M}^{M} G_R \quad (8)$$

where, M is the window size; G_R is the tri-Gauss model function, which is shown in (6). Then, it is pretty easy to get the original scene albedo $\mathbf{t}(\mathbf{x})$ is $1 - \tilde{\mathbf{V}}(\mathbf{x})$.

3.4 Restoration

The method which based on the dark channel prior can achieve outstanding results. But when the region of image is full of light, such as sky region, color distortion will appear in the restored image. Accordingly, it is essential to restore the original scene albedo. So a parameter T is introduced to restore scene albedo by judging the absolute values of the subtraction between the value of the dark channel and the atmospheric light **A**. The refinement formula of $\mathbf{t}(\mathbf{x})$ is as follows:

$$\tilde{\mathbf{t}}(\mathbf{x}) = \min(k \times \mathbf{t}(\mathbf{x}), 1) \quad (9)$$

$$k = \begin{cases} 1, & |\mathbf{I}_{\text{dark}}(\mathbf{x}) - \mathbf{A}| > T \\ \frac{T}{|\mathbf{I}_{\text{dark}}(\mathbf{x}) - \mathbf{A}|}, & |\mathbf{I}_{\text{dark}}(\mathbf{x}) - \mathbf{A}| < T \end{cases} \quad (10)$$

The final restored image $\mathbf{J}$ is recovered by

$$\mathbf{J}(\mathbf{x}) = \frac{\mathbf{I}(\mathbf{x}) - \mathbf{A}}{\tilde{\mathbf{t}}(\mathbf{x})} + \mathbf{A} \quad (11)$$

4. Experiment And Results

This section provides a comparison of the proposed method with He *et al.* [4] and Zhu *et al.* [7] in two aspects: qualitative and quantitative. The experiments were carried out in VS 2013 environment on a 3.2GHz Intel Core i5 Processor PC. The size of dark channel patch is set to 15×15 and the value of T in formula (11) is set to be 35. Fig.3.shows the performance of the algorithm.

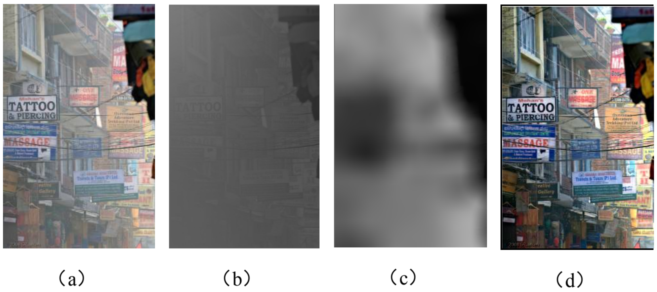
(a) (b) (c) (d)

Fig.3 Performance of the algorithm: (a) the original image taken as input (b) the processing output of coarser atmospheric veil (c) the processing output of atmospheric veil (d) the processing output of our proposed method.

4.1 Qualitative Comparison

It can be seen from Fig.4 and Fig.5 that all of these three approaches can eliminate the haze to a certain extent, but the details of each approach are different. As shown in Fig.4(b), most of the haze is eliminated by He's method, but the output image demonstrates severe color distortion. For example, the sky region in Fig.4 (b) is much darker than it is supposed to be and the sky color is distorted significantly. Zhu's result showed in Fig.4(c) is overall better than He's result of Fig. 4(b), however, its color distribution is not uniform and color distortion still exists in the white region. Fig.5 illustrates the comparison results on a challenging image having different depths. Both of He's method and Zhu's method can remove the haze, and them can obtain ideal defogging effect. However, the leaves in the treetops and grass are not easy to be distinguished in Fig.5(b) and Fig.5(c), one possibility is that the red wall and grass in the distance lack the sense of depth information. Meanwhile, although the red wall in Fig.5(b) and Fig.5(c) is brighter compared to the original image, the details of cracks between the bricks are not prominent. Compared with the results of the two methods, our result is rich in depth information, looks more hierarchical and more natural. Furthermore, our method can handle the sky images well. These advantages are consistent with human vision

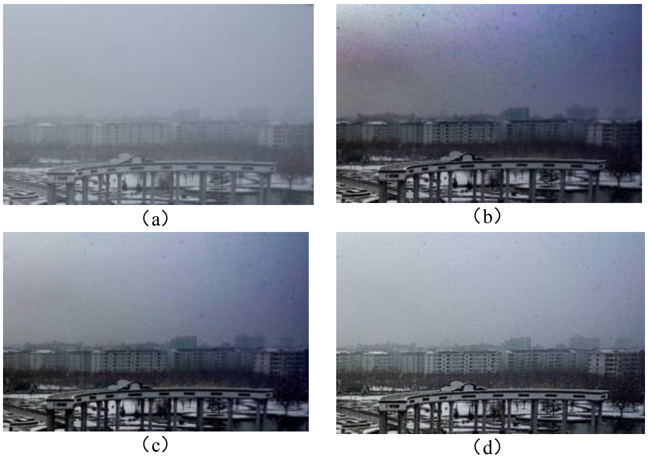
(a) (b) (c) (d)

Fig.4 Qualitative results of our proposed method and state-of-the-art methods. (a)Input image. (b) He's result. (c) Zhu's result. (d) Our result.


(a) (b) (c) (d)

Fig.5 Qualitative results of our proposed method and state-of-the-art methods. (a) Input image. (b) He's result. (c) Zhu's result. (d) Our result.

4.2 Quantitative Comparison

This section uses certain performance metrics, such as running time T and contrast gain C , to compare our result with the results of methods of He and Zhu. Running time is the time consumpion of an algorithm. Contrast gain represents the mean absolute contrast difference between fog-free image and fog-degraded image. Compared to fog-degraded image, the contrast gain of fog-free image is much higher. A fog-free image has higher contrast than a foggy image does. Therefore, this property can be used as a performance index for haze removal approaches in terms of quantitative analysis.

Table 1 Performance comparison for 4(a)

Method	T(ms)	C
He et al	458	0.206
Zhu et al	125	0.278
Proposed	134	0.286

Table 2 Performance comparison for Fig. 5(a)

Method	T(ms)	C
He et al	235	0.156
Zhu et al	78	0.204
Proposed	83	0.214

The results of processing time and contrast gain are shown in Table 1 and Table 2. It is clear that the overall performance of our proposed method is better than that of the state-of-art methods. In terms of processing time, the proposed method consumes significantly less time than He's method does and only takes a little more time than Zhu's method does. This metric of time consumption is very important for using in real time application systems. As to contrast gain, the gain value of our presented method is much higher than that of He's method, and is slightly better than Zhu's method for both Fig. 4(a) and 5(a). In summary, the experimental results have demonstrated that our proposed method is able to achieve superior image processing quality and take less defogging processing time.

5. Conclusion

In this paper, we propose a simple and effective method based on human retina characteristics for single image haze removal. Our proposed algorithm first extract the global atmospheric light and roughly estimate the coarse atmospheric veil based on the dark channel prior. Then, tri-Gaussian utilized to adjust the coarse atmospheric veil. In order to make the method applicable to all kinds of foggy images, we recomputed the scene albedo. Finally, the fog-free image is produced based on general atmospheric scattering model. Experimental results show that the proposed method achieves outstanding dehazing effects. Moreover, the proposed method does not require user intervention and takes much less computation time, paving the way for real-time implementation.

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